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Handbook of gamma spectrometry
For Non-destructive Assay of Nuclear Materials

P. Mortreau, R. Berndt

INSTITUTE FOR THE PROTECTION AND SECURITY OF THE CITIZEN

2006

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Directorate-General Joint Research Centre
Institute for the Protection and Security of the Citizen (IPSC)

Contact information
Address: via Fermi, 1 – Ispra (VA) Italy
E-mail: patricia.mortreau@jrc.it
Tel.: +39(0332)78 9211
Fax: +39(0332)78 5072

http://www.ipsc@jrc.it
http://www.jrc.cec.eu.int

Handbook of Gamma Spectrometry Methods
for Non-destructive Assay of Nuclear Materials

P.Mortreau, R.Berndt

EUR 19822 EN, Joint Research Centre, Ispra

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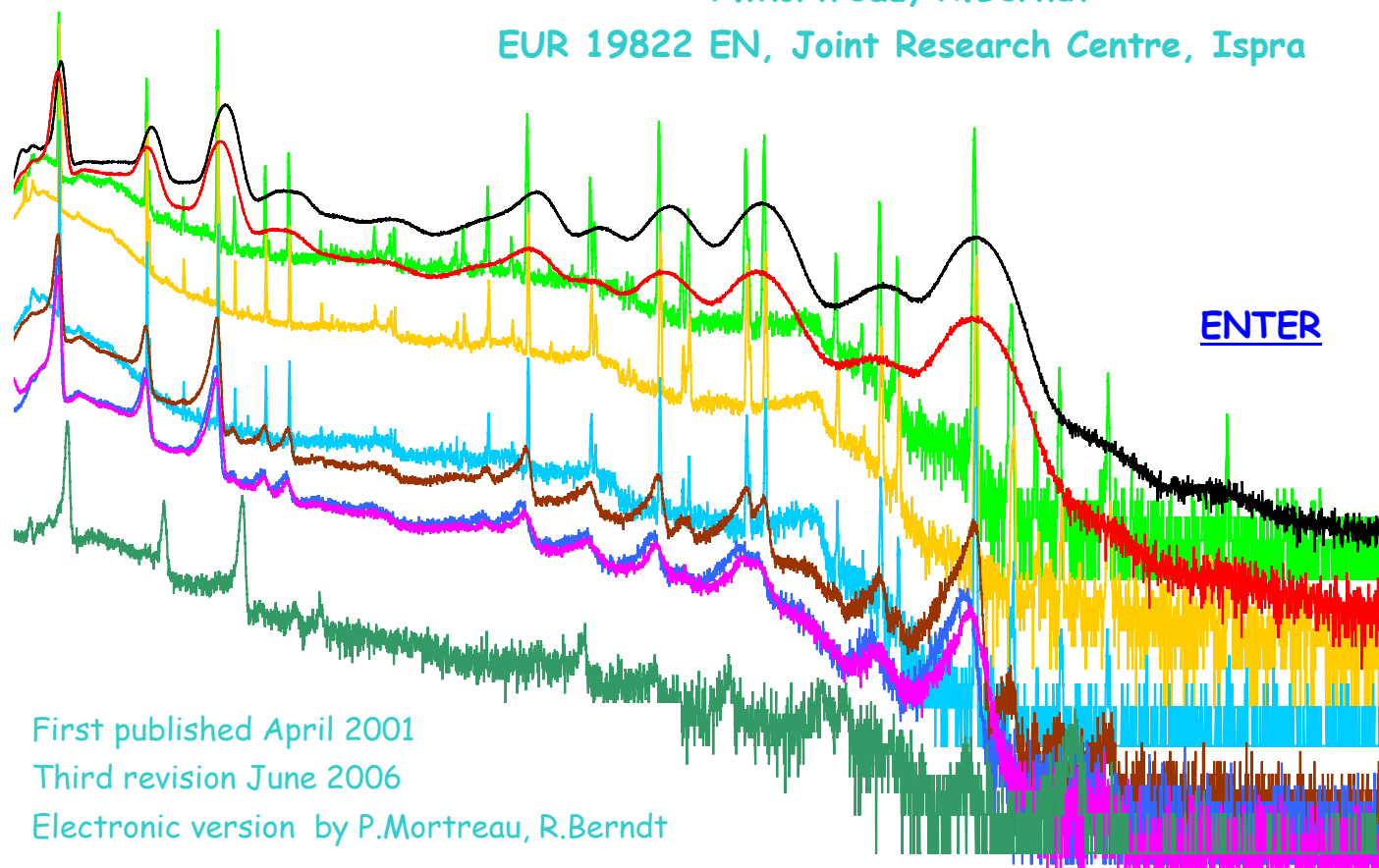
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PREFACE

This handbook of gamma spectrometry is intended for use by nuclear material inspectors and concentrates on non-destructive assay of such material using the MCA-166 spectrometer (GBS Rossendorf) and its software together with a HP-200 palm-top computer. It does not replace manuals for specific training courses or even textbooks, but summarizes and recalls basic knowledge and technical and nuclear data shared by different applications of gamma spectrometry in that field.

The first part of the handbook comprises detailed user instructions for a series of measurement programs in the form of step-by-step procedures. They are intended for inspectors who must use a device occasionally. Typically, the measurement programs present many options. Often it would have been possible to write the instructions in a different sequential order. The authors signed out the one, which seemed the most logical. The user is requested to follow all the instructions in the order in which they were written otherwise these instructions are no longer valid.

The second part of this handbook contains a glossary with some basic concepts of nuclear physics and gamma radiation measurements, technical data and information concerning the software used in the step-by-step procedures. All these data were deliberately put in one and the same glossary to simplify the structure of the handbook.

The last part of the handbook contains a small library of spectra (U, Pu, Th, MOX and spent fuel measured with different detectors), nuclear data useful for some applications of gamma spectrometry, some hints concerning trouble shooting with measurements and radioprotection.

The authors tried to make this handbook as useful and practical as possible for inspector use by selecting a limited number of essential data. This choice is not exhaustive but such was not the purpose of the present handbook. The users are requested to refer to the books mentioned in the bibliography for more specific questions.

Users of this handbook who wish to send remarks or suggestions to the authors are invited to contact them at the following addresses:

Patricia.Mortreau@jrc.it   Reinhard.Berndt@jrc.it

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PROCEDURE P1

URANIUM ENRICHMENT MEASUREMENT WITH Ge DETECTOR, MCA-166, HP-200 AND UF6 CODE UF6.EXE Version 1.06.07(b) 1998/06/16)

Short instructions for inspector use
P.Mortreau, R.Berndt
JRC Ispra, March 2001

Before leaving:

0. Packing list
1. Preliminary check

In field:

2. Instrument assembly
3. Set-up
4. Background measurement
5. Enrichment calibration
6. Enrichment measurement of unknown samples
7. Re-evaluation
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0. PACKING LIST:

Ge Detector
HP-200 (or HP-100)
MCA-166 with HV module installed
MCA-166 charger with mains cable power supply for HP-200: adapter F1011A

Cables:
HP-200 - MCA-166 connection cable
short (violet) adapter cable with three connectors for HV inhibit signal
HV cable
Preamplifier power cable

BNC signal cable
BNC cable for inhibit signal

Collimators
Cd filters
2 AA Alkaline batteries and 1 back-up battery for the
HP-200
HV module with a polarity opposite to that installed in the MCA-166.

1. PRELIMINARY CHECK

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.
Connect the MCA-166 to the charger:

First connect the Lemo to the MCA-166. **Then** connect the power plug to the mains.

If the orange light of the charger is
   steady: charging,
   flashing: not charging.
       (In this case, re-connect the mains power with the MCA-166
       connected to the charger)
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

Switch on the HP-200.
If the HP-200 cannot be switched on or if you see a low battery message:

"Main batteries low, press ESC" or
"Bkup battery low, press ESC", you must change the batteries.

If you can switch on the HP-200, check the battery status by pressing the menu command HP-200 battery.
The main battery should have >2.4 V, the back-up battery >2.7 V. If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline *AA* batteries (on the back) or the back-up battery (on the right side).
Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the UF6 program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.

Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.

If the polarity does not correspond to that written on the detector contact E4b Luxembourg.

Switch off the instrument:
Press **ESC** twice.
Select **"File"** and press **ENTER**.
Select **"Exit"** and press **ENTER** (or press **"X"**) to return to the main menu.
A message appears: **"Attention: don't forget to turn off the MMCA"**.
FIRST press **ENTER**, *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200

You see the main menu.(If not, press "CTRL" "ALT" "DEL" simultaneously).
Press **"9"** to go to DOS.
Type DIR to check the free space on the drive A.
(1 file with a spectrum of 4096 channels occupies 42 kbytes, 1 report file occupies 1.2 kbytes).
Type DATE, enter the DATE or press space bar if there is no correction to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction to be made. Press **ENTER**.
Press **"CTRL" "ALT" "DEL"** simultaneously to return to the main menu.
Switch off the HP-200.

2. INSTRUMENT ASSEMBLY

Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

Set up the Ge detector in the desired location.

Connect cables from the detector:

Preamplifier power supply cable to DB9 connector of the adapter cable, and attach it with the clamps.
Then, the adapter cable to the MCA-166 DB9 connector **"Preamp."**.
Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to high voltage output **"HV"**.

Connection cable from MCA-166 **"PC"** to HP-200.

HV inhibit cable to the BNC adapter cable connector.

3. SET-UP

3.a. Starting the UF6 code

Switch on HP-200 and MCA-166.

The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the UF6 code.
Press **"Y"**, then press any key to reset MCA-166.

Go to **"Setup"**, press **ENTER**.
If you have a setup file, go to instruction 3.b., if not go to instruction 3.c.

3.b. MCA set-up with setup file

3. b1.

Go to **" Read setup file"**, press **ENTER**.
You see a set-up file list in the directory A:\setup
With the ↓ arrow key select the setup file. Press **ENTER** twice.
If you see an error message ("Error : Format data File!"), the selected set-up file is wrong. Press **ENTER** twice and return to instruction 3.b1. to select another file.

3.b2.

You see the set-up file comment, press **ESC**.
When you see the setup spectrum, press the **F10** key to return to the setup menu.

3.b3. High voltage

3.b3.1.

Select **"Detector high voltage setup"**.
Press **ENTER**.

Check that the value of the HV and its polarity correspond to that written on the detector.

Switch on the high voltage by pressing **ESC**, then **ENTER**.
If you see the message : **"HV Inhibit! Check detector!",** the detector is not cold. In this case, see instruction 3.b3.2. if not 3.b4.

3.b3.2.

Press **ENTER,** then **ESC.**
Go to **"File"**, press **ENTER**
Select **"Exit"**, and press **ENTER**
Press **ENTER**
Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.
When the detector is cold, repeat the previous instructions.

3.b4. Amplifier setup

The amplifier settings are done. Nevertheless check them:
Place an Uranium source in front of the detector.
Go to **"Amplifier setup"**, press **ENTER.**

3.b4.1. Pole zero adjustment

Select **" Switch to visual PZC adjustment"**
Press **ENTER.**
If necessary, adjust the PZC with the keys **"+"** and **"–"** to minimize the absolute value of the zero offset.
When it is close to zero, press **ESC**, then press **"Y"** to save the adjustment.

3.b4.2. Amplifier gain adjustment

Select **"Switch to visual gain adjustment"**, press **ENTER**
Adjust the fine gain with the **"+"** and **"–"** keys to
place the 185.7 keV peak in channel 3320+/-3. To extend the peak region, press the soft key F7.
Press **ESC** and then press **"Y"** to save the gain.
Press **ESC**, then press **ENTER** to accept the amplifier settings.
Press **ESC** to return to the UF6 menu. Go to instruction 4.

3.c. MCA set-up without setup file

3.c1.HV set-up

Select **"Detector High voltage setup"**,
Press **ENTER**.
Type the value of the high voltage (written on the detector).
Press the ↓ arrow key .
With the space bar, toggle the type of detector you use.
Press **ESC**, then press **ENTER** to turn on the high voltage.
If you see the message : "H.V inhibit! Check detector!", the detector is not cold.
In this case:
Go to **"File"**, press **ENTER.**
Select **"Exit "**, and press **ENTER.**
Press **ENTER**, when you see the message:
"Attention! Don't forget to turn off the MMCA".
Fill the dewar with liquid nitrogen .The detector
will be operational after 4 to 6 hours.

3.c2. Amplifier set-up

Place an Uranium source close to the detector.

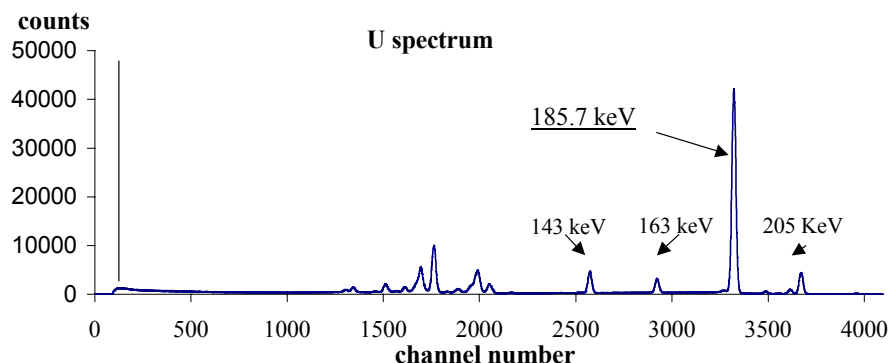Go to **"Amplifier setup"**, press **ENTER**.

3.c2.1. Set-up of the polarity of the input pulse

Press the ↓ arrow key 4 times.
Toggle the polarity (**"neg"** or **"pos"**) of the input signal with the space bar.

3.c2.2. Gain set-up

The 185.7keV peak must be in channel 3320 +/- 3. (see figure below)

U spectrum

Select **"switch to visual gain adjustment"**,
Press **ENTER**.

3.c2.2.1. Coarse gain

Press **ESC** and then press **"N"**.
Toggle the value of the coarse gain with space
bar.
Go back to **"Switch to visual gain adjustment"**,
Press **ENTER**.
Repeat instruction 3.c2.2.1 until the 185.7 keV peak is in the closest
position to channel 3321.
Then go to instruction 3.c2.2.2.

3.c2.2.2. Fine gain

Adjust the fine gain with the **"+"** and **"-"** keys to place the 185.7 keV
peak in channel 3320+/-3. To extend the peak region, press the F7 key.
Press **ESC** and then press **"Y"** to save the gain.

3.c2.3. Pole zero cancellation

With the ↓ arrow key, select **"Switch to visual PZC adjustment"**,
Press **ENTER**.
If necessary, adjust the PZC with the **"+"** and
"-" keys to minimize the absolute value of the zero
offset. When it is close to zero, press **ESC**, then
press **"Y"** to save the value.

Readjust the fine gain to place the 185.7 keV peak in channel 3320:
Select **"Switch to visual PZC adjustment"**,
Then, repeat instruction 3.c2.2.2.
When the fine gain adjustment is done, press **ESC**
and **ENTER** to accept the amplifier settings.

3.c3. Stabilisation set-up

Select **"Stabilisation setup"**, press **ENTER**.
Toggle **"on"** with the space bar.
Press **ESC**, then **ENTER,**
Press **ESC** to return to the UF6 menu.
Remove the Uranium source.

4. BACKGROUND MEASUREMENT

4.a. Preset time :

Go to **"Setup"**, press **ENTER**.
Select **"MCA presets"**, press **ENTER**
Toggle **"Live time(sec)"** with the space bar if necessary.
Press the ↓ arrow key.
Type the value of the live time.
Press **ESC**, then **ENTER**
Press **ESC**.

4.b. Measurement :

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.
If the message **"No valid Calibration Table! Continue?"** appears, answer
"yes" by pressing **ENTER**.
Go to **"Next screen - press ENTER"**.
Press **ENTER**.
With the ↓ arrow key, go to **"Switch to graphic screen to measure"**.
Press **ENTER**.
You see the graphic screen.
Press the **F4** key to start the measurement.

Press **"Y"** to erase the previous spectrum, if necessary.
At the end of the measurement, press the **F4** key to save the spectrum.
Write the name of the spectrum and press **ENTER** twice.
Write your comment.
Press **ESC**.
Press **ESC** 3 times to return to the menu.

5. ENRICHMENT CALIBRATION

If the calibration table already contains the calibration constant you want to use, go to 5.c.

If you want to use existing spectra to calculate your calibration constant, go to 5.a.

If you want to make calibration measurements, go to 5.b.

5.a. Calibration with existing spectra

5.a1.

Go to **"Data acquisition"**, press **ENTER**
Go to **"Calib.Table"**, press **ENTER**.
Select **"Clear Calib.Table"**, press **ENTER** twice. The previous calibration constant is cancelled.

Select **"Calib.Table"**, press **ENTER**.
Go to **"Add entries"**, press **ENTER**
You see a list of files.

5.a2.

With the ↓ arrow key, select your calibration
spectrum and press **ENTER** twice. You see the comment corresponding to the selected spectrum.
Press **ESC** to go out of the comment if necessary.

Now you see the calibration spectrum.
Press the **F10** key.
If you want to use more calibration spectra, go to **"Add entry (read file)"** press **ENTER** and go to 5.a2, if not press **ESC** twice and go to instruction 5c.

5.b. Calibration measurements

5.b1.

Measure the container wall thickness of the calibration sample with the ultrasonic gauge.

5.b2.

Go to **"Setup"**, press **ENTER**.
Select **"MCA presets"**.
Press **ENTER**.
Toggle **" Live time(sec)"** with space bar if necessary.
Press **ESC** then **ENTER**.
Press **ESC**.

5.b3.

Go to "Data acquisition", press ENTER.
Go to **"Calib.Table"**, press **ENTER**.
Select **"Clear Calib.Table"**, press **ENTER** twice. The preceding calibration constant is cancelled.

5.b4.

Select **"calibration"**, press **ENTER** .
Press **ENTER** when you see the message "Attention- No valid calibration table. Continue?"

5.b5.

You see the "Inspection Information screen 1/2"

Press the ↑ arrow key and enter data (Inspector ID. Facility code).
After each entry, press **ENTER**.
Select **"Next screen"**, press **ENTER** .

Enter the technical information concerning the calibration sample. After each entry
Press **ENTER**.

Use <u>space bar</u> to toggle to:
- **"unit"** of the enrichment (**"wt"** or **"At"**)
- the container material (AtC) and the sample material (MCF).

WARNING: if you select "XXX" for the sample material, you go out of the program and your measurement is lost.

Select **"Switch to graphic screen to measure"**,
Press **ENTER**. You see the graphic screen.

Place an "infinitely thick" calibration standard in front of the collimator.
Press the **F3** key
Enter the counting time
Press **ESC**, then **ENTER**

Press the **F4** key to start the measurement.
Press **"Y"** to erase the preceding spectrum, if necessary.

At the end of the measurement, to save the spectrum, see instruction 5.b5.1. if not 5.b5.2.

WARNING:
If the spectrum is not saved, the measurement is not   taken into account to calculate the calibration constant.

5.b5.1.

Press the **F4** key.
Type the name of the spectrum.
Press **ENTER** twice, write the comment, then press **ESC**.

Press **ESC** 3 times to return to the menu.
Go to instruction 5.b5.3.

5.b5.2.

To return to the menu, press the **F10** key and **ESC** 3 times.
If you want to measure another calibration sample, repeat instruction
5.b1. to 5.b5.

5.b5.3.

If you want to measure another calibration sample, repeat the instruction
5.b1. then select **"Data acquisition"**, press ENTER select **"Calibration"**,
press **ENTER** and go to instruction 5.b5.

5.c. Checking the calibration constant

To read the calibration constant, go to **"Data acquisition"**. Press **ENTER**.
Select **"Calib.Table"**, press **ENTER**.
Select **"View entries"**, press **ENTER**.
You can read the calibration constant and the characteristics of your
calibration.

Press **ESC** twice to return to the menu.

6. ENRICHMENT MEASUREMENT OF UNKNOWN SAMPLE

6.a.

Measure the container wall thickness of the unknown sample with the
ultrasonic gauge.

Place the "infinitely thick" unknown sample in front of the detector.

6.b.

Go to **"Setup"**, press ENTER.

Select **"MCA presets"**, press **ENTER**.
With the space bar, select "Live time".
Press **ESC**.
Press **ENTER**, then press **ESC**.

6.c.

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.
Press the ↑ arrow key 3 times and enter the data. After each entry, press **ENTER**.
Then select **"Next screen"** and press **ENTER**.

6.d.

Enter technical information concerning the sample.
After each entry, press **ENTER**.
Use space bar to toggle to:
- **"unit"** of the enrichment (**"wt"** or **"At"**)
- the container material (AtC) and the sample material (MCF).
Select **"Switch to graphic screen to measure"**.
Press **ENTER**.
Press the **F3** key.
Enter the counting time.
Press **ESC**, then **ENTER**.

Press the **F4** key to start the measurement and **"Y"**
to erase the previous spectrum, if necessary.

At the end of the measurement, to save the spectrum, go to instruction 6.d1. if not 6.d2.

6.d1.

Press the **F4** key.
Type the spectrum name, press **ENTER** twice, write the comment and then press **ESC**.
Go to instruction 6.d3.

6.d2.

Press the **F10** key to return to the menu.
Go to instruction 6.d3.

6.d3.

To measure another sample, repeat instructions 6.a. and 6.d.
To return to the menu, press **ESC** 3 times.

7. RE-EVALUATION

To re-evaluate the enrichment of an unknown sample by:

- modifying the technical information concerning the sample (chemical composition, wall thickness or wall material) without changing the calibration constant, go to 7.a.

- modifying the calibration constant, go to 7.b.

7.a.

Go to **"Data acquisition"**, press ENTER.
Select **"Re-evaluation"**.
You see a list of files.
With the ↓ arrow key, select the file corresponding to the measurement to be re-evaluated.
Press **ENTER** twice, then **ESC** to go out of the comment (if necessary).
You see the **"Inspection Info Re-eva**l" screen.
Type the new values and then press **ESC.**
On the MCA-evaluation screen, you can read the new enrichment value.
To return to the menu without saving this new evaluation, press the **F10** key then **ESC.**
To save this new evaluation, press the **F4** key, then write the name of the file, press **ENTER** twice.
Write the comment and press **ESC** twice to return to the menu.

7.b.

You want to change the calibration by:
- adding an entry, see instruction 7.b1.
- suppressing an entry, see instruction 7.b2.
- completely restarting a new calibration , see instruction 7.b3.

7.b1.

Go to **"Data acquisition"**, press **ENTER**.
Select **"Calib.Table"**, press **ENTER**.
Select **"Add Entry"**, press **ENTER**.
You see a list of files.
With the ↓ arrow key, select your calibration spectrum and press **ENTER**
twice and then **ESC**.
When you see your comment.
You see your calibration spectrum.
Press the **F10** key.
Press **ESC** twice.
If you want to read the new calibration constants,
see instruction 5.c.

7.b2.

Go to **"Data acquisition"**, press **ENTER**
Select **"Calib.Table"**, press **ENTER**
Select **"Edit Entry"**, press **ENTER**
You see the Calibration Table.
With the number key, type the number of the measurement you want to
suppress, and press **ENTER.**
You can read the file name and the data concerning the measurement you
want to suppress. Then with the ↓ arrow key, go to the line corresponding
to status and press the space bar to show the message **"Remove this
entry"** .
Press **ESC** and **ENTER** to validate.
Press **ESC**.
If you want to read the new calibration constants,

see instruction 5.c.

7b3.

To redo a calibration calculation completely with :
- existing spectra, go to instruction 5.a.
    - measurements, go to instruction 5.b.
    -

8. SWITCHING OFF

Select **"File"**, press **ENTER**,
Press **"X"** (or select **"Exit")**.
Press **ENTER** to turn off the high voltage.
When the HV is zero, press **ENTER** and switch off the
MCA-166 and the HP-200.

PROCEDURE P2

URANIUM ENRICHMENT MEASUREMENT WITH PLANAR Ge DETECTOR, MCA-166, HP-200, SPEC CODE AND MGAU CODE .
 (SPEC.EXE Version 1.23.12(r) 1998/06/16 FZ Rossendorf)
(MGAU Version 3.1)

Short instructions for inspector use
P. Mortreau, R. Berndt
JRC Ispra, March 2001

Before leaving:

0. Packing list
1. Preliminary check

In field:

2. Instrument assembly
3. Set-up
4. Measurement
5. Switching off
6. Evaluation with MGAU

0. PACKING LIST:

Planar Ge Detector
HP-200 (or HP-100)
MCA-166 with HV module installed
MCA-166 charger with mains cable power supply for HP-200: adapter
F1011A

Cables:
HP-200 - MCA-166 connection cable
HV cable
short (violet) adapter cable with three connectors for HV inhibit signal.
Preamplifier power cable.
BNC signal cable.

BNC cable for inhibit signal.

Collimators
Cd filters
2 AA Alkaline batteries and 1 back-up battery for the
HP-200.

HV module with a polarity opposite to that installed in the MCA-166.

1. PRELIMINARY CHECK

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.

Connect the MCA-166 to the charger:
First connect the Lemo to the MCA-166. **Then** connect the power plug to the mains.

If the orange light of the charger is
   steady: charging,
   flashing: not charging.
         (In this case, re-plug mains power with MCA-166 connected to
         charger)
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

Switch on the HP-200.
If the HP-200 cannot be switched on or if you see a low battery message:

     "Main batteries low, press ESC" or

"Bkup battery low, press ESC",
you must change the batteries.

If you can switch on the HP-200, check the battery status by pressing the menu command **"HP-200 battery"**.
The main battery should have >2.4 V, the back-up battery >2.7 V. If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline AA batteries (on the back) or the back-up battery (on the right side).

1.b. Check the high voltage polarity

Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the UF6 program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.
Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.

If the polarity does not correspond to that written on the detector contact E4b Luxembourg.

Switch off the instrument:
Press **ESC** twice.

Select **"File"** and press **ENTER**.
Select **"Exit"** and press **ENTER** (or press **"X"**) to return to the main menu.

A message appears: **"Attention: don't forget to turn off the MMCA".**
FIRST press **ENTER**, *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200.
You see the main menu.
Press **"9"** to go to DOS.
Type DIR to check the free space on drive A.
(1 spectrum file occupies 42 kbytes,1 report file occupies 1.2 kbytes)
Type DATE, enter the Date or press space bar if there is no correction
to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction
to be made. Press **ENTER**.

Press **"CTRL" "ALT" "DEL"** simultaneously to return to the main menu.
Switch off the HP-200.

2. INSTRUMENT ASSEMBLY:

Fill dewar with liquid nitrogen. The detector will be operational after 4 to
6 hours.

Set up the Ge detector in the desired location.

Connect cables from the detector:

Preamplifier power supply cable to DB9 connector of the adapter cable,
and attach it with the clamps.

Then, the adapter cable to the MCA-166 DB9 connector **"Preamp."**.

Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to high voltage output **"HV"**.

Connection cable from MCA-166 **"PC"** to HP-200.

HV inhibit cable to the BNC adapter cable connector.

3. SET-UP

Place an Uranium source close to the detector.

3.a. Starting with the SPEC code

Switch on HP-200 and MCA-166.
The main menu appears (if not, press **"CTRL"** **"ALT"** **"DEL"** simultaneously).

Press the number corresponding to the SPEC program.
Press **"Y"**, then press **any key**.

Go to **"Setup"**, press **ENTER**.
If you have a setup file, go to instruction 3b, if not go to 3c.

3.b. MCA set-up with setup file

3.b1.

Go to **"Read setup file"**, press **ENTER**.
You see: **Dir   A:\SETUP**
With the arrow down key select the setup file.
Press **ENTER** twice.

3.b2.

You see the comment of the setup file.
Press **ESC**, the setup spectrum appears.
Press the **F10** key to return to the setup menu.

3.b3. High voltage

3.b3.1.

Select **"Detector high voltage setup"**,

Press **ENTER**.

Check that the value of the HV and its polarity correspond to that written on the detector.

Press **ESC**, then press **ENTER** to turn on the high voltage.
If you see the message "HV Inhibit! Check detector!", go to instruction 3.b3.2. if not, go to instruction 3.b4.

3.b3.2.

The detector is not cold or the inhibit signal cable is not connected or the connections of the amplifier input signal and of the inhibit signal cable are inverted.
Check the cable connections. If the cables are properly connected, it means that the detector is not cold.

Press **ENTER**, Press **ESC**.
Select **"File"**, press **ENTER** then press **"X"**
Press **ENTER** twice to return to the general menu.
Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

3.b4. Amplifier settings

The amplifier setting are already done.
Nevertheless check them.
Place an U source in front of the detector

3.b4.1 Pole zero adjustment

Go to **"Amplifier Setup",** press **ENTER**.

Select **"Do visual PZC adjustment"**, press **ENTER**.
With the **"+"** or **"-"** keys, adjust the PZC if necessary to minimize the zero offset.
When it is close or equal to zero, press **ESC**, then **"Y"** to save the value.

3.b4.2. Gain adjustment

Select **"Do visual gain adjustment"**, press **ENTER**
Check that the 185 keV peak is in channel 2476.
If not, adjust the fine gain with the **"+"** and **"-"** keys.
Expand (or compress) the x-axis with the F7 (or F8) key.
To accept the adjustment, press **ESC**, then press **"Y".**
Press **ESC**, then press **ENTER** to accept the amplifier settings.

3.b4.3. Stabilisation setup

Select **"Stabilisation Setup"**, press **ENTER**.
If the stabilization is **off**, press on the space bar to toggle on **"on"**.
Press **ESC**, then press **ENTER**.
Press **ESC**.
Remove the Uranium source and go to instruction 4.

3.c. MCA set-up without setup file

Place a Uranium source in front of the detector

3.c1. HV set-up

3.c1.1.

Select **"Detector High voltage setup"**
Press **ENTER**.
Type the high voltage value.
Press the ↓ arrow key.
Toggle the type of detector you use with the space bar.
Press **ESC**, then press **ENTER** to turn on the high voltage.
If you see the message "HV Inhibit! Check detector!", go to instruction 3.c1.2. if not, go to instruction 3.c2.

3.c1.2.

The detector is not cold or the inhibit signal cable is not connected or the connections of the amplifer input signal and the inhibit signal are inverted.

Check the cable connections. If the cables are properly connected, it means that the detector is not cold.
Press **ENTER**, Press **ESC**.
Select **"File"**, press **ENTER** then press **"X"**.

Press **ENTER** twice to close the program.

Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

3.c2. MCA-166 setup

Select **"MCA setup"**, press **ENTER**.

The cursor is on the line corresponding to **"Channels"**
Press the space bar to toggle on 4096.
Press **ESC**.
Press **ENTER**.

3.c3. Amplifier set-up

Go to **"Amplifier setup"**, press **ENTER**.

3.c3.1. Set-up of the polarity of the input pulse

Press the ↓ arrow key four times to select **"Input polarity"**.
Press the space bar to select the polarity of the input signal .

3.c3.2. Gain set-up

The 185.7 keV peak is in channel 2476.(see figure below).
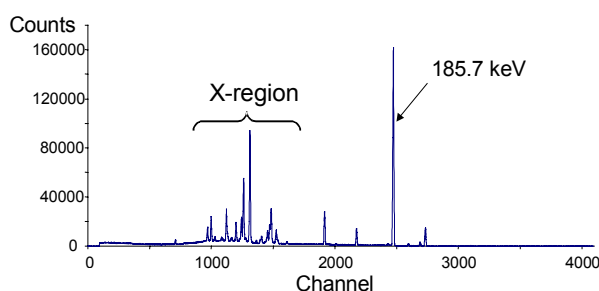
3.c3.2.1. Coarse gain

Select **"Do visual gain adjustment"**,
Press **ENTER**.
If you see that the 186 keV line is not visible or is far from the channel 2476, the coarse gain must be changed.
To do that:
Press **ESC** and then press **"N"**.
With the ↑ arrow key , go to the line corresponding to the coarse gain.
Press on the space bar to select the new value of the
coarse gain.
Go again to **"Switch to visual gain adjustment"**.
Press **ENTER**.
Repeat the instruction until the 185.7 keV peak is as close as possible to channel 2476 and then go to instruction 3.c3.2.2.

3.c3.2.2. Fine gain

Adjust the fine gain with the **"+"** and **"-"** keys to place the 185.7 keV peak in channel 2476+/-3. To extend the peak
region, press the **F7** key.
The centroid indicates the position of the peak.
When the fine gain is adjusted, press **ESC** and then press **"Y"** to save the gain adjustment.

3.c3.3. Pole zero cancellation
Select **"Do visual PZC" adjustment"**, press **ENTER**.
If necessary, adjust the PZC with the **"+"** and **"-"** keys to minimize the offset. When it is close to zero, press **ESC**, then press **"Y"** to save the value.
Then, readjust the fine gain.

To do that:
Select: **" Do visual gain adjustment"**,
Press **ENTER**
Adjust the fine gain with the **"+"** and **"-"** keys to place the 186 keV peak in channel 2476+/-3. To extend the peak region, press the **F7** key.

When the fine gain is adjusted, press **ESC** and then press **"Y"** to save the gain adjustment.
Press **ESC**, then press **ENTER** to accept the amplifier settings.

3.c3.4. Stabilisation set-up

Select **"Stabilisation setup"**.
Press **ENTER**.
Press on the space bar to toggle to **"on"** to activate the stabilisation.

Select **" Do Visual Stab. Setup"**,
Press **ENTER**
You see the message:**"** Accept Stabilisation ROI settings (Y/N)**?"**
Press **"N"**.
Move the cursor to channel 2436, (use the F7/F8 keys), then press **ENTER.**
Move the cursor to channel 2516, then press **ENTER.**
Press **"Y"** to store the parameters of the stabilisation.
Press **"N"**, not to define a target channel.
Press **ESC**.
Press **ENTER,** then **ESC** to return to the menu.

Remove the Uranium source and go to instruction 4.

4. MEASUREMENT

4.1. Set measurement time

Select **"Setup"**, press **ENTER**
Select **"Presets"**, press **ENTER**.
If necessary, press on the space bar to toggle to
"Live Time (sec) on the line **"choice"**
Press the ↓ arrow key and type the desired measurement live time.

Press **ESC** and **ENTER**.

Press **ESC**.

4.2. Sample measurement

Place the sample to measure in front of the detector.
Check that the container wall has a thickness of less than 10mm steel. If this condition is not fulfilled, the analysis with the MGAU cannot be performed.
Check that the date of complete Th-U separation is at least 6 months (the time necessary to reach the parent-daughter secular equilibrium). If it is not the case, you must enter the date of <u>complete</u> Thorium removal. If you do not know this date or if this date is prior to the year 2000, you cannot use the MGAU for your analysis.
If one of these conditions is not fulfilled, the analysis with the MGAU cannot be performed.

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.

Press **F4** to start the measurement.

Press **"Y"** to erase the previous spectrum, if necessary.

The measurement starts.

During the measurement you can:
- Check the dead time is <u>below 20%.</u>

- Check the count rate.
- Use **F7** and **F8** to change the x scale.
- Use **F6** to change the y scale:
    aLin: linear, automatic
    mLin: linear, manual, use up / down arrows to
      change the scale
    Log: logarithmic scale
After the measurement, to save the spectrum:
Press the **F4** key.
Type the spectrum name.
Press **ENTER** twice, write the comment and then press **ESC**.
When the spectrum is saved, press the **F10** key.

Press **ESC**.
Go to instruction 4 to perform another measurement.

5. SWITCHING OFF

After measuring and saving the files switch off the high voltage, the MCA-166 and the HP-200:
Select **"File"** press **ENTER**, press **"X"**.
Press **ENTER** to turn off the high voltage.
When the high voltage is off, a message appears: **"Don't forget to turn off MMCA!"**.
FIRST press **ENTER**.
THEN switch off the MCA-166 and the HP-200.
Disconnect the cables.

6. EVALUATION WITH THE MGAU code

Open the MGAU code.
On the "View" menu, select the "+100keV region" option
On the "Analyse mode", select " Std. MGAU Analysis (Ge)" option.
In the screen display box, select the "pause" mode.
In the file default box, select the file format *.spe
Select the directory in which the files are located.
Highlight the spectrum to be analysed, then click twice on the "Analyse" button.
Then, follow the instructions on the screen.

PROCEDURE P3

URANIUM ENRICHMENT MEASUREMENT WITH NaI DETECTOR, MCA-166, HP-200 AND U235 CODE

(U235.EXE Version 1.35, 1998/06/16 FZ Rossendorf)

Short instructions for inspector use
P. Mortreau, R. Berndt
JRC Ispra, March 2001

Before leaving:

0. Packing list
1. Preliminary check

In field:

2. Instrument assembly
3. Set-up
4. Background measurement
5. Enrichment calibration
6. Enrichment measurement of unknown samples
7. Re-evaluation
8. Switching off

0. PACKING LIST:

NaI detector
HP-200 (or HP-100)
MCA-166 with HV converter installed
MCA-166 charger with mains cable
Power supply for HP-200: F1011A adapter

Cables:
HP-200 - MCA-166 connection cable
HV cable
Preamplifier power cable

BNC signal cable

Collimators
Cd filters
2 AA Alkaline batteries and 1 back-up battery for the

HP-200.

HV module with a polarity opposite to that installed in the MCA-166.

1. PRELIMINARY CHECKING

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.

Connect the MCA-166 to the charger:
First connect the Lemo to the MCA-166. **Then,** connect the power plug to the mains.

If the orange light of the charger is
   steady: charging,
   flashing: not charging.
        (In this case, re-plug mains power with MCA-166 connected to
        charger)
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

If the HP-200 cannot be switched on or if you see a low battery message:

"Main batteries low, press ESC" or
"Bkup battery low, press ESC",

you must change the batteries.
If you can switch on the HP-200, check the battery status by pressing the menu command "HP-200 battery".
The main battery should have >2.4 V, the back-up battery >2.7 V. If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline AA batteries (on the back) or the back-up battery (on the right side).

1.b. Check the high voltage polarity

Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the U235 program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.
Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.

If the polarity does not correspond to that written on the detector contact E4b Luxembourg.

Switch off the instrument:
Press **ESC** twice.
Select **"File"** and press **ENTER**.
Select **"Exit"**and press **ENTER** (or press **"X"**) to return to the main menu.
A message appears: **"Attention: don't forget to turn off the MMCA"**.
FIRST press **ENTER,** *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200.
You see the main menu.
Press **"9"** to go to DOS.
Type DIR to check the free space on drive A (a 511 channel spectrum file occupies 7 kbytes).
Type DATE, enter the Date or press space bar if there is no correction to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction to be made. Press **ENTER**.
Press **"CTRL" "ALT" "DEL"** simultaneously to return to the main menu.
Switch off the HP-200.

2. INSTRUMENT ASSEMBLY:

Set up the NaI detector in the desired location.

Connect the cables from the detector:

Preamplifier power supply cable to MCA D9 connector **"Preamp"**, attach it with the clamps.

Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to high voltage output **"HV"**.

Connection cable from MCA-166 **"PC"** to HP-200.

3. SET-UP

Place a Uranium source close to the detector.

3.a. Starting the U235 code

Switch on HP-200 and MCA-166.

The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press on the numerical key corresponding to the U235 code.
Press **"Y"**, then press **any key**.
Go to **"Setup"**, press ENTER.
If you have a setup file, go to instruction 3.b., if not go to 3.c.

3.b. MCA set-up with setup file

3.b1.

Go to **"Read setup file"**, press ENTER.
You see: **Dir A:\SETUP\.**
With the arrow down key select the setup file, press **ENTER** twice.
If you see an error message ("Error : no U235 setup file!"), the selected set-up file is wrong. Press **ENTER** twice and return to the instruction 3.b1. to select an other file, if not go to 3.b2.

3.b2.

Read the comment describing the detector, the collimator and the filter carefully. The calibration constants of the setup file are valid only for this special hardware.
Then press **ESC**.

You see the setup spectrum.

Press the **F10** key. You see the setup menu.

3.b3. High voltage

Select **"Detector high voltage setup"**. Press **ENTER**.

Check that the HV value is correct.

Press **ESC**, then press **ENTER** to turn on the high voltage.

3.b4. Amplifier settings

The amplifier settings are already done. Nevertheless check them.

3.b4.1. Pole zero adjustment

Go to **"Amplifier Setup"**, press **ENTER**.

Select **"Switch to visual PZC adjustment"**, press **ENTER**.

With the **"+"** or **"-"** keys, adjust the PZC if necessary to minimize the zero offset.
When it is close or equal to zero, press **ESC**, then **"Y"** to save the value.

3.b4.2. Gain adjustment

Select **"Switch to visual gain adjustment"**, press **ENTER**.
Check that the 185 keV peak is in channel 300.
If not, adjust the fine gain with the **"+"** and **"-"** keys.
To accept the adjustment, press **ESC**, then press **"Y"**
Press **ESC**, then press **ENTER** to accept the amplifier settings.

3.b4.3. Stabilisation

Select **"Stabilisation Setup"**, press **ENTER**.
If the stabilisation is **off**, press on the space bar to toggle to **"on"** .
Press **ESC**, then press **ENTER**.
Press **ESC**.
Remove the Uranium source and go to instruction 4.

3.c. MCA set-up without setup file

3.c1. HV set-up

Select **"Detector High voltage setup"**,
Press **ENTER**.
Type the high voltage value.
Press **ESC**, then press **ENTER** to turn on the high voltage.

3.c2. Amplifier set-up

Go to **"Amplifier setup"**, press ENTER.

3.c2.1. Set-up of the polarity of the input pulse

Press the ↓ arrow key four times to select **"Input polarity"**.
Press the space bar to select the polarity of the input pulse (NaI detectors: normally pos.)

3.c2.2. Gain set-up

The gain must be adjusted so that the 185.7 keV is in channel 300 (see picture).
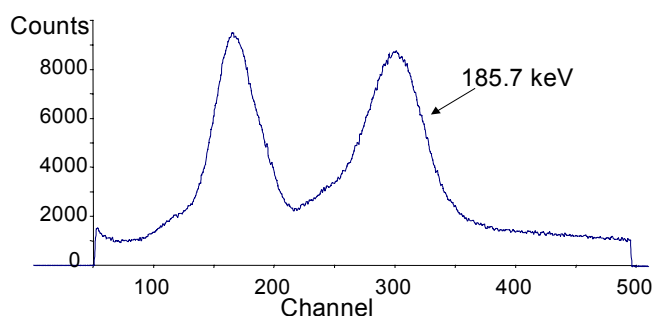
3.c2.2.1. Coarse gain

Select **"switch to visual gain adjustment"**,
Press **ENTER**.
If the 185.7 keV peak is not visible or is far from the channel 300, it is necessary to change the coarse gain:
Press **ESC** and then press **"N"**.
Select the new value of the coarse gain by pressing on the space bar.
Go back to **"Switch to visual gain adjustment"**,
Press **ENTER**.
Repeat the instruction until the 185.7 keV is as close as possible to channel 300.
Then, go to instruction 3.c2.2.1.

3.c2.2.1. Fine gain

Adjust the fine gain with the **"+"** and **"-"** keys to place the 185.7 keV peak in channel 300.
The centroid indicates the position of the peak.
Press **ESC** and then press **"Y"** to save the gain.

3.c2.3. Pole zero cancellation

Select **"Switch to visual PZC" adjustment"**.
Press **ENTER**.
If necessary, adjust the PZC with the **"+"** and **"-"** keys to minimize the offset. When it is close to zero, press **ESC**, then press **"Y"** to save the value.
Readjust the gain:
Select **" Switch to visual gain adjustment"**
With the **"+"** and **"-"** keys, place the 186 keV peak in channel 300.
Press **ESC**, then press **ENTER** to accept the amplifier settings.

3.c2.4. Stabilisation set-up

Select **"Stabilisation setup"**, press **ENTER**.

Press the space bar to select **"on"**.
Press **ESC**, **ENTER,** then **ESC** to return to the menu.

Remove the Uranium source and go to instruction 4.

4. BACKGROUND MEASUREMENT

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.

You see the **"Inspection Information"** menu.

Press the arrow down key 8 times.
Type the preset live time LT (s).

Press the ↓ arrow key to select **"Switch to graphic screen to measure"**.

Press **ENTER**
If you see the message "No calibration constant(s) A/B", press **ENTER**

Then press the **F4** key to start the measurement.
Press **"Y"** to erase a spectrum, if necessary.

After the measurement, press the **F4** key to save the spectrum, follow the instructions on the screen.

When the spectrum is saved, press the **F10** key, press **ESC**.

5. ENRICHMENT CALIBRATION

Three possibilities:
1.
You have opened a set-up file containing the calibration constants.
Make sure that the measurement geometry you have are **perfectly** the conditions for which the calibration constants have been determined.
Then go to instruction 6.

2.
You want to enter your calibration constants manually. Make sure that the measurement geometry you have are **perfectly** the conditions for which

the calibration constants have been determined. Then go to instruction 5.a.

3.
You want to make the calibration, then go to instruction 5.a.
5.a.

Go to **"Data acquisition"**, press **ENTER**.
Select **"calibration"**, press **ENTER**
To enter the A and B calibration constants manually, see instruction 5.b., to do the calibration, see instruction 5.c.

5.b. Use of known calibration constants

Press **ENTER** 5 times.

Enter the calibration constants and the uncertainties, use number and **ENTER** keys and toggle + or - with the space bar.

Press **ESC**, then press **ENTER** to accept the calibration parameters.

Press **ESC** and go to instruction 6.

5.c. Make a new calibration

Place standard 1 in the measurement position.

With the number and **ENTER** keys, input the value of the enrichment and its error for the two standards.

Then select **"standard 1"**.

Press **ESC** and then **ENTER**.

5.c1.

Enter the technical information and the value of the preset live time.

Press **ENTER** after each entry.

Select **"Switch to graphic screen measurement"**,

Press **ENTER**.

You can see the graphical screen.

Press the **F4** key to start the measurement and **"Y"** to erase the previous spectrum if necessary.

At the end of the measurement, press the **F4** key to save the spectrum, follow the instructions on the screen.

When the spectrum is saved, press the **F10** key to return to the **"Data Acquisition"** menu.

5.c2.

Replace standard 1 by standard 2.

Select **"Calibration"** and press **ENTER** to measure standard 2.

Select **"standard 2"**, press **ESC** and then **ENTER** to
accept the parameters.
Repeat instruction 5.c1., then go to 5.c3.

5.c3.

To read your calibration constants, select **"Calibration"**, press **ENTER**.

You can read the two constants A and B (**"Active Calibration"**).

Press **ESC**, then press **ENTER**. Press **ESC** twice to go back to the menu.

6. ENRICHMENT MEASUREMENT OF UNKNOWN SAMPLES

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.

Enter the information about the sample and the preset live time.

Select "Switch to graphic screen to measure", press **ENTER**, then
press the **F4** key to start the measurement.

If necessary, press **"Y"** to erase an old spectrum.

At the end of the measurement, press one of the following keys :
F4 to save the spectrum, or **ESC** to repeat the measurement, or **F10** to
return to the menu.
Press **ESC**.

7. RE-EVALUATION

Go to **"Data acquisition"**, press **ENTER**
Select **"Re-evaluation"**, press **ENTER**

If you want to re-evaluate an enrichment sample without changing the
calibration constants, go to instruction **7**.a.

If you want to re-determine the calibration constants by using another
already stored calibration standard measurement, go to instruction **7**.b.

7.a. Re-evaluation of the enrichment sample

With the space bar, toggle **"Unknown"**
With the ↓ arrow key, select **"File selection"**
You see a list file.
With the ↓ arrow key, select your file .
Press **ENTER** twice
You see your spectrum and you can read the new enrichment value.
Press the **F10** key and then **ESC** to return to the menu.

7.b. Re-evaluation of the calibration constants by changing the calibration standard

With the space bar, toggle the standard you want to change ("Standard1" or "Standard2").

Then with the ↓ arrow key , select **"File selection"**
Press **ENTER**.
You see a list file. Select your file with the ↓ arrow key.
Press **ENTER** three times.
You see the spectrum. Press the **F10** key.

To read the new calibration constants :
Go to **"Calibration"**, press **ENTER**
In the **"Active calibration"** menu, you can read the new values of the calibration constants.
Press **ESC**, **ENTER**.
Press **ESC** twice to return to the menu.

8. SWITCHING OFF

Select **"File"**, press **ENTER**, press **"X"**.
Press **ENTER** to turn off the high voltage.
When the high voltage is off, a message appears: "Don't forget to turn off MMCA!".
First, press **ENTER** and then switch off the MCA-166 and the HP-200.

PROCEDURE P4

URANIUM ENRICHMENT MEASUREMENT WITH NaI DETECTOR, MCA-166, HP-200, SPEC CODE AND NaIGEM CODE

(SPEC.EXE Version 1.23.12(r) 1998/06/16 FZ Rossendorf)
(NaIGEM Version 1.5)

Short instructions for inspector use
P. Mortreau, R. Berndt
JRC Ispra, February 2001

Before leaving:

0. Packing list
1. Preliminary check

In field:

2. Instrument assembly
3. Set-up
4. Measurement
5. Switching off
6. Evaluation with NaIGEM code

0. PACKING LIST:

NaI detector
MCA-166 with HV converter installed
MCA-166 charger with mains cable
Power supply for HP-200: F1011A adapter

Cables:
HP-200 - MCA-166 connection cable
HV cable
Preamplifier power cable
BNC signal cable

Collimators
Cd filters
2 AA Alkaline batteries and 1 back-up battery for the
HP-200.

HV module with a polarity opposite to that installed in the MCA-166.

1. PRELIMINARY CHECK

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.
Connect the MCA-166 to the charger:
First connect the Lemo to the MCA-166. **Then** connect the power plug to the mains.
If the orange light of the charger is:
   steady: charging,
   flashing: not charging.
          (In this case, re-connect the mains power with the MCA-166
          connected to the charger)
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

Switch on the HP-200.

If the HP-200 cannot be switched on or if you see a low battery message:

"Main batteries low, press ESC" or
"Bkup battery low, press ESC",
you must change the batteries.

If you can switch on the HP-200, check the battery status by pressing the menu command HP200 battery.
The main battery should have >2.4 V, the back-up battery >2.7 V. If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline AA batteries (on the back) or the back-up battery (on the right side).

1.b. Check the   high voltage polarity

Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the UF6 program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.
Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.

If the polarity does not correspond to that written on the detector contact E4b Luxembourg.

Switch off the instrument:
Press **ESC** twice.
Select **"File"** and press **ENTER**.
Select **"Exit"**and press **ENTER** (or press **"X"**) to return to the main menu.
A message appears: **"Attention: don't forget to turn off the MMCA"**.
FIRST press **ENTER**, *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200.
You see the main menu.
Press **"9"** to go to DOS.
Type DIR to check the free space on the drive A.
(a 511 channel spectrum file occupies 7kbytes).
Type DATE, enter the Date or press space bar if there is no correction to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction to be made. Press **ENTER**.

Press the "CTRL" "ALT" "DEL" **keys simultaneously to return to the main menu.**
Switch off the HP-200.

2. INSTRUMENT ASSEMBLY:

Set up the NaI detector in the desired location.

Connect cables from the detector:

Preamplifier power supply cable to MCA D9 connector **"Preamp"**, attach it with the clamps.

Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to high voltage output **"HV"**.

Connection cable from MCA **"PC"** to HP-200.

3. SET-UP

Place a Uranium source close to the detector.

3.a. Start with the SPEC code

Switch on HP-200 and MCA-166.

The main menu appears (if not, press the **"CTRL" "ALT" "DEL"** keys simultaneously).
Press the number corresponding to the SPEC program.
Press **"Y"**, then press **any key**.

Go to **"Setup"**, press ENTER.

If you have a setup file, go to instruction 3.b, if not go to 3.c.

3.b. MCA set-up with setup file

3.b1.

Go to **"Read setup file"**, press ENTER.
You see: **Dir   A:\SETUP**

With the arrow down key select the setup file, press **ENTER** twice. (If the file is not a SPEC setup file, a warning appears.

Press **ENTER** and try another file or go to the annex to make a set-up without the setup file.)

3.b2.

Read the comment describing the detector, the collimator and the filter carefully. The calibration constants of the setup file are valid only for this special hardware.

Press **ESC**, the setup spectrum picture appears.
Press **F10** to return to the setup menu.

3.b3. High voltage

Select **"Detector high voltage setup"**,
Press **ENTER**.

Check that the HV value is correct.

Press **ESC**, then press **ENTER** to turn on the high voltage

3.b4. Amplifier settings

The amplifier setting are already done.
Nevertheless check them.
Place an U source in front of the detector

3.b4.1. Pole zero adjustment

Go to **"Amplifier Setup"**, press **ENTER**.

Select **"Do visual PZC adjustment"**,

Press **ENTER**.

With the **"+"** or **"-"** keys, adjust the PZC if necessary to minimise the zero offset.

When it is close or equal to zero, press **ESC**,
then **"Y"** to save the value.

3.b4.2. Gain adjustment

Select **"Do visual gain adjustment"**. Press **ENTER**

Check that the 185 keV peak is in channel 300.
If not, adjust the fine gain with the keys **"+"** and **"-"**.
Expand (or compress) the x-axis with the F7(or F8) key.

To accept the adjustment, press **ESC**, then press **"Y"**

Press **ESC**, then press **ENTER** to accept the amplifier settings.

3.b4.3. Stabilisation

Select **"Stabilisation Setup"**, press **ENTER**.

If the stabilisation is **off**, toggle to **"on"** with the space bar.

Press **ESC**, then press **ENTER**.
Remove the Uranium source and go to instruction 4.

3.c. MCA set-up without setup file

Place a Uranium source in front of the detector

3.c1. HV set-up

Select **"Detector High voltage setup"**,
Press **ENTER**.
Type the value of the high voltage.
Press **ESC**, then press **ENTER** to turn on the high voltage.

3.c2. MCA setup

Select **"MCA setup"**, press **ENTER**.

Go to **"Channels"** and toggle the number of channels with the space bar to 511, then press **ESC**, press **ENTER**.

3.c3. Amplifier set-up

Go to **"Amplifier setup"**, press **ENTER**.

3.c3.1. Set-up of the input pulse polarity

Press the ↓ arrow key four times to select **"Input polarity"**.

If necessary, press on the space bar to select the polarity of the input signal (NaI detectors: normally positive.)

3.c3.2. Gain set-up

Select **"Do visual gain adjustment"**, press **ENTER**.

The 185.7 keV peak must be placed in channel 300 (see figure).
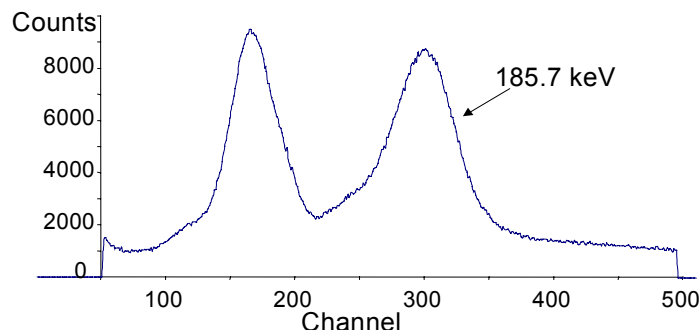
3.c3.2.1. Coarse gain

If the 186 keV peak is not visible or is far from the channel 300, then change the coarse gain value:

Press **ESC** and then press **"N"**.
Select another coarse gain value by pressing the space bar.
Go back to **"Do visual gain adjustment"**.
Press **ENTER**.
Repeat the instruction until the 186 keV peak is as close as possible to channel 300.
Then, go to instruction 3.c3.2.2.

3.c3.2.2. Fine gain

Adjust the fine gain with the keys **"+"** and **"-"** to place the 185.7 keV peak in channel 300± 3.
Press **ESC** and then press **"Y"** to save the gain.

3.c3.3. Pole zero cancellation

Select **"Do visual PZC" adjustment"**, press **ENTER**.

If necessary, adjust the PZC with the **"+"** and **"–"** keys to minimise the offset. When it is close to zero, press **ESC**, then press **"Y"** to save the value.

Readjust the fine gain. To do that:

Select: **"Do visual gain adjustment"**, press **ENTER**.

Press the **"+"** and **"-"** keys, to place the 186 keV peak in channel 300.

Press **ESC**, then **Y** to accept the gain.

Press **ESC**, then **ENTER** to accept the amplifier settings.

3.c3.4. Stabilisation set-up

Select **"Stabilisation setup"**, press **ENTER**.

Press the space bar to select **"on"**.

Select **"Do Visual Stab. Setup"**, press **ENTER**

You see the message: **"Accept Stabilisation ROI settings (Y/N)?"**, press **"N"**.

Move the cursor to channel 260 (use the F7/F8 keys), then press **ENTER**.

Move the cursor to channel 340, then press **ENTER**

Press **"Y"** to store the stabilisation parameters.

Press **"N"**, not to define a target channel.

Press **ESC**, **ENTER**, then **ESC** to return to the menu.

Remove the Uranium source and go to instruction 4.

4. MEASUREMENT

4.a. Set measurement time

Go to **"Setup"**, press **ENTER**

Select **"Presets"**, press **ENTER**.

If necessary, on the **"choice"** line, press the space bar to toggle to Live Time (sec).

Press the ↓ arrow key and type the desired measurement live time (e.g. 100 seconds).

Press **ESC** and **ENTER**.

Press **ESC**.
4.b. Sample measurement

Place the sample to be measured in front of the detector.
Check that the condition of infinite thickness is fulfilled.

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.

Press **F4** to start the measurement.

If necessary, press **"Y"** to erase the previous spectrum.

To save the spectrum after the measurement, press **F4** and follow the instructions on the screen.

When the spectrum is saved, press the **F10** key.
Press **ESC**.

5. SWITCHING OFF

After measuring and saving the files switch off the high voltage, the MCA-166 and the HP-200:
Press **F10**, press **ESC** .
Select **"File"** press **ENTER**, press on **"X"**.
Press **ENTER** to turn off the high voltage.
When the high voltage is off, a message appears: **"Don't forget to turn off MMCA!"**.
FIRST press **ENTER**.
THEN switch off the MCA-166 and the HP-200.
Disconnect the cables.

6. EVALUATION WITH THE NaIGEM code

Open the visual basic code NaIGEM.

6.a. Setup.gem file

The setup.gem file contains the setting parameters (zero, gain and resolution of the detector) and the enrichment calibration constant corresponding to the considered geometry.
If there is a setup.gem file for the detector you use, go to instruction 6.a1, if not go to 6.a2.

6.a1.

In the box **"System settings"**, select the number of the detector you use.
Go to instruction 6.c.

6.1.2.

Create a setup.gem file:

Select the directory in which the file used to determine the system settings is stored
Select the appropriate file format in the box **"File defaults"**.

depth.
In the **"Measurement parameters"** box, input all the values corresponding to the geometry.
In the **"File defaults"** box, select the file.
In the **"Options"** menu, select **"Energy resolution calibration only"**.
Select **"Analyse"**.
When the **"Energy calibration"** is completed, go to instruction 6.b.

6.b. Determination of the enrichment calibration constant

Input the measurement parameters.
Select the file corresponding to the measurement of the calibration standard.

Select the **"Option"** menu.
Select the **"U235 Calibration"**.
Enter the value of the enrichment and its associated error.
Then, click twice on **"Analysis"**.
You see the spectrum.
Strike a key.
You can read the calibration constant value.
Strike a key to return to the **"visual basic window"**

6.c. Analysis

Input the measurement parameters.
The collimator parameters (diameter and thickness) must be the same as those of the calibration.

To save the analysis results, **before** performing the analysis:
Select File, then **"Report to"**, then press **ENTER**.
Select the directory where the file must be stored, enter the file name and click on **"Save"**.

Select the spectrum corresponding to the sample, whose enrichment you want to determine .
Click on **"Analyse"**.
You see the spectrum and the enrichment value.
Then, follow the instructions on the screen.

PROCEDURE P5

PLUTONIUM ISOTOPIC COMPOSITION DETERMINATION WITH PLANAR Ge DETECTOR, MCA-166, HP-200, SPEC CODE AND MGA CODE

(SPEC.EXE Version 1.23.12(r) 1998/06/16 FZ Rossendorf)
(vbMGA Version 9.65)

Short instructions for inspector use
P. Mortreau, R. Berndt
JRC Ispra, March 2001

Before leaving:

0. Packing list
1. Preliminary check

In field:

2. Instrument assembly
3. Set-up
4. Measurement
5. Switching off
6. Evaluation with MGA

0. PACKING LIST:

Ge Detector
HP-200 (or HP-100)
MCA-166 with HV converter installed
MCA-166 charger with mains cable power supply for HP-200: adapter F1011A

The measurements can be performed with the HP-200 palm top computer (or with another PC or lap-top, using SPEC or WinSPEC). The spectrum evaluation with vbMGA Version 9.65 requires Windows.

Cables:
HP-200 - MCA-166 connection cable

HV cable
short (violet) adapter cable with three connectors for HV inhibit signal
Preamplifier power cable
BNC signal cable
BNC cable for inhibit signal

Collimators
Cd filters
2 AA Alkaline batteries and 1 back-up battery for the
HP-200.

1. PRELIMINARY CHECKING

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.

Connect the MCA-166 to the charger:
First connect the Lemo to the MCA-166, **then** connect the power plug to the mains.

If the orange light of the charger is
   steady: charging,
   flashing: not charging.
        (In this case, re-connect mains power with the MCA-166
        connected to the charger).
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

Switch on the HP-200.

If the HP-200 cannot be switched on or if you see a low battery message:

"Main batteries low, press ESC" or
"Bkup battery low, press ESC",
you must change the batteries.

If you can switch on the HP-200, check the battery status by pressing the menu command HP-200 battery.
The main battery should have >2.4 V, the back-up battery >2.7 V. If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline AA batteries (on the back side) or the back-up battery (on the right side).

1.b. Check the high voltage polarity

Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the SPEC program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.
Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.

If the polarity does not correspond to that written on the detector contact E4b Luxembourg.
Switch off the instrument:
Press **ESC** twice.
Select **"File"** and press **ENTER**.
Select **"Exit"**and press **ENTER** (or press **"X"**) to return to the main menu.
A message appears: **"Attention: don't forget to turn off the MMCA"**.
FIRST press **ENTER**, *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200.
You see the main menu.
Press **"9"** to go to DOS
Type DIR to check the free space on drive A
(1 spectrum file occupies 42 kbytes,1 report file occupies 1.2 kbytes).
Type DATE, enter the Date or press space bar if there is no correction to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction to be made. Press **ENTER**.

Press **"CTRL" "ALT" "DEL"** simultaneously to return to the main menu.
Switch off the HP-200.

2. INSTRUMENT ASSEMBLY

Put up the Ge detector in the desired location and fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

Connect cables from the detector:

Preamplifier power supply cable to DB9 connector of the adapter cable, and attach it with the clamps.
Then, the adapter cable to the MCA-166 DB9 connector **"Preamp."**.

Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to high voltage output **"HV"**.
Connection cable from MCA-166 **"PC"** to HP-200.

HV inhibit cable to the connector of BNC adapter cable.

3. SET-UP

3.a. Starting the SPEC code

Switch on HP-200 and MCA-166.
The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).

Press the number corresponding to the SPEC program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Go to **"Setup"**, press **ENTER**.

If you have a setup file, go to instruction 3.b, if not go to 3.c.

3. b. MCA-166 set-up with setup file

3.b1.

Go to **"Read setup file"**, press **ENTER**.
You see: **Dir   A:\SETUP**
With the arrow down key select the setup file. Press **ENTER** twice.

3.b2.

You see the comment of the setup file.
Press the **F10** key to return to the setup menu.

3.b3. High voltage

Select **"Detector high voltage setup"**, press **ENTER**.

Check that the value of the HV and its polarity correspond to that written on the detector.

Press **ESC**, then press **ENTER** to turn on the high voltage.
If you see the message **"HV Inhibit! Check detector!"**, go to instruction 3.b3.1. if not, go to instruction 3.b4.

3.b3.1.

The detector is not cold, the inhibit signal cable is not connected or the wrong detector manufacturer was chosen.
Check the cables and manufacturer. If you continue to see the same message, it means that the detector is not cold.
Press **ENTER**, press **ESC**.
Select **"File"**, press **ENTER** then press **"X"**
Press **ENTER** twice to return to the general menu of the HP-200.
Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

3.b4. Amplifier settings

The amplifier settings are already done (from the setup file).
Nevertheless check them:

Place a Plutonium source in front of the detector.
Place a 1 mm thick Cd filter between the source and the detector.

3.b4.1. Pole zero adjustment

Go to **"Amplifier Setup"**, press **ENTER**.

Select **"Do visual PZC adjustment"**, press **ENTER**.

With the **"+"** or **"–"** keys, adjust the PZC if necessary to minimise the zero offset.

When it is close or equal to zero, press **ESC**,
then **"Y"** to save the adjustment.

3.b4.2. Gain adjustment

Select **"Do visual gain adjustment"**,
Press ENTER.

Check that the 208 keV peak is in channel (2773 ± 40).
If not, adjust the fine gain with the **"+"** and **"-"** keys.

Expand (or compress) the x-axis with the F7 (or F8) key.

To accept the adjustment, press **ESC**, then press **"Y"**

Press **ESC**, then press **ENTER** to accept all amplifier settings.

3.b4.3. Stabilisation set-up

Select **"Stabilisation Setup"**, press **ENTER**.

If the stabilisation is **off**, toggle to **"on"** by pressing on the space bar.

Press **ESC**, then press **ENTER**.

Remove the Plutonium source and go to instruction 4.

3.c. MCA set-up without setup file

Place a Plutonium source in front of the detector and a 1mm thick Cd
filter between the source and the detector.

3.c1. HV set-up

3.c1.1.

Select **"Setup"**
Select **"Detector High voltage setup"**

Press **ENTER**.
Type the high voltage value.
Press the ↓ arrow key.
Toggle the type of detector you use with the space bar.
Press **ESC**, then press **ENTER** to turn on the high voltage.
If you see the message **"HV Inhibit! Check detector!"**, go to instruction 3.c1.2. if not, go to instruction 3.c2.

3.c1.2.

The detector is not cold, the inhibit signal cable is not connected or the wrong detector manufacturer was chosen.
Check the cables and manufacturer. If you continue to see the same message, it means that the detector is not cold.
Press **ENTER**, press **ESC**.
Select **"File"**, press **ENTER** then press **"X"**.
Press **ENTER** twice to return to the general menu of the HP-200.
Fill the dewar with liquid nitrogen. The detector will be operational after 4 to 6 hours.

3.c2. MCA setup

Select **"MCA setup"**, press **ENTER**.
Go to **"Channels"** and toggle the number of channels with the space bar to **4096.**
Press **ESC**, press **ENTER**.

3.c3. Amplifier set-up

Place a Plutonium source in front of the detector.

Go to **"Amplifier setup"**, press **ENTER**.

3.c3.1. Set-up of the polarity of the input pulse

Press the ↓ arrow key four times to select **"Input polarity"**.

Toggle the polarity (**"neg**" or **"pos"**) by pressing on the space bar.

3.c3.2. Gain set-up

Select **"Do visual gain adjustment"**, press **ENTER**
The 208 keV peak must be in channel (2773 ± 40).see figure below).
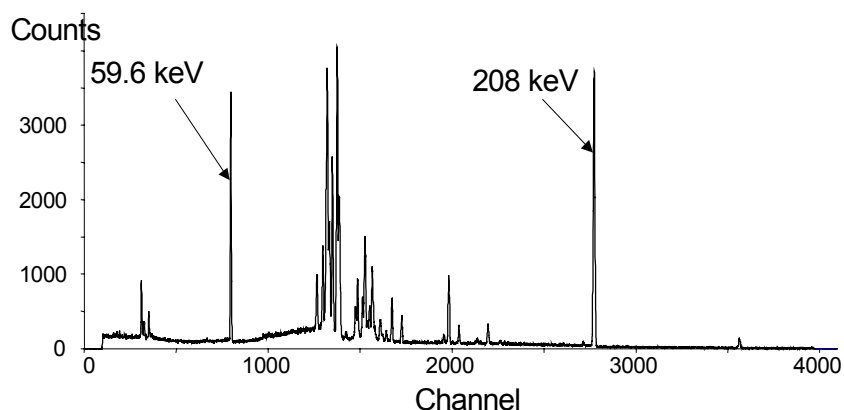
3.c3.2.1. Coarse gain

Select **"Do visual gain adjustment"**,
Press **ENTER**.
If you see that the 208 keV line is out of the range of the 4096 channels
or far from channel 2773, the coarse gain must be changed.
To do this:
Press **ESC** and then press **"N"**.
Toggle the value of the coarse gain with space bar.
Go back to **"Switch to visual gain adjustment"**.

Repeat the instruction until the 208 keV peak is close to channel 2773.

3.c3.2.2. Fine gain

Adjust the fine gain with the **"+"** and **"-"** keys to place the 208 keV peak
in channel (2773 ± 40). To extend the peak region, press the **F7** key.
The centroid indicates the position of the peak.
When the fine gain is adjusted, press **ESC** and then press **"Y"** to save the
gain adjustment.

3.c3.3. Pole zero cancellation

Select **"Do visual PZC" adjustment"**, press **ENTER**.

If necessary, adjust the PZC with the **"+"** and **"-"** keys to minimise the offset. When it is close to zero, press **ESC**, then press **"Y"** to save the value.

Readjust the fine gain. To do this:
Select: **"Do visual gain adjustment"**, press **ENTER**.
Adjust the fine gain with the **"+"** and **"-"** keys to place the 208 keV peak in channel (2773 ± 40). To extend the peak region, press the **F7** key.
When the fine gain is adjusted, press **ESC** and then press **"Y"** to save the gain adjustment.
Then, press **ESC** and **ENTER** to accept all amplifier settings.

3.c3.4. Stabilisation set-up

Select **"Stabilisation setup"**, press **ENTER**.
Toggle **"on"** with the space bar to activate the stabilisation.
Select **"Do Visual Stab. Setup"**, press **ENTER.**

You see the message:
"Accept Stabilisation ROI settings (Y/N)?"
Press **"N"**.
Move the cursor to channel 2753 (20 channels before the peak) then press **ENTER.**

Press **ENTER**.
Move the cursor to channel 2793 (20 channels after the peak), then press **ENTER.**
Press **"Y"** to store the parameters of the stabilisation.
Press **"N"**, not to define a target channel.
Press **ESC**.
Press **ENTER,** then **ESC** to return to the menu.

Remove the Plutonium source and go to instruction 4.

4. MEASUREMENT

4.a. Set measurement time

Select **"Presets"**, press **ENTER**.

Toggle **"choice"** to Live Time (sec).
Press the ↓ arrow key.
Type the desired measurement live time (e.g. 600 seconds).
Press **ESC** and **ENTER**.
Press **ESC**.

4.b. Sample measurement

Place the sample to be measured in front of the detector.

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.

Press the **F4** key to start the measurement.
Press **"Y"** .

The measurement starts.

To obtain reliable and good results measuring with a dead time below <u>20%</u>
(or a count rate in the order of <u>15000cps</u>) is recommended.
If necessary, take a collimator with a smaller diameter or increase the
distance from the sample to the detector.
Restart the measurement.

The 59.6 keV peak and the 208 keV peak should have about the same
height.
If this is not the case, change the Cd filter thickness.

The counting time must be long enough to collect approximately 10 million
counts in the total spectrum (they are collected in about 700 seconds
with a count rate of 15000cps).

To save the spectrum:

Press the **F4** key, type the spectrum name, press **ENTER** twice, write the comment and then press **ESC**.

When the spectrum is saved, press the **F10** key.

Press **ESC**.

5. SWITCHING OFF

After measuring and saving the files switch off the high voltage, the MCA-166 and the HP-200:

Press the **F10** key, press **ESC**.

Select **"File"** press **ENTER**, press **"X"**.

Press **ENTER** to turn off the high voltage.

When the HV value is zero, a message appears: **"Don't forget to turn off MMCA!"**.

FIRST press **ENTER**.

THEN switch off the MCA-166 and the HP-200.

Disconnect the cables.

6. EVALUATION WITH MGA (Version 9.65)

The spectrum evaluation requires a computer with Windows.

Open the VBMGA code.

Select the folder where the spectrum to be analysed is stored.

In the box **"File defaults"**, select the file format *.spe.

Enter the declaration date.

Highlight the spectrum to be analysed and select **"Analyse"**.

Then, follow the instructions on the screen.

To save the results:

BEFORE performing the analysis, select **"File"**, then **"Report to"**, then **"File"**.

Select the directory and folder where the results must be stored.

Enter the file name and press **"Save"**.

PROCEDURE P6

FISSION PRODUCT VERIFICATION ON SPENT FUEL WITH GAMMA-TAUCHER, MCA-166, HP-200 AND FP CODE

(FP code . Version 1.00.00(b) 2001/03/04. JRC Ispra)

Short instructions for inspector use
R. Berndt, P.Mortreau,
JRC Ispra, March 2001

Before leaving:
0. Packing list
1. Preliminary checking

In field, before putting the Gamma-Taucher into the water:
2. Gamma Taucher assembly
3. Set-up of the MCA-166
4. Test Measurement
5. Save spectrum

Inspection measurements under water:
6. Switching off
7. Launch and move the Gamma-Taucher
8. First measurement - a recommendation
9. Inspection measurement

Annex:
10. MCA set-up without setup file

0. PACKING LIST

0.a. Gamma Taucher

lower end tube (5):

(5)
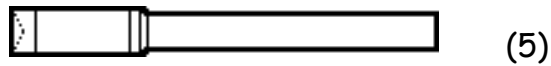
prolongation tube (6)

... (6)
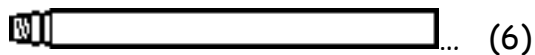
detector tube (7) with fork (18) and cable:

(7), (18)
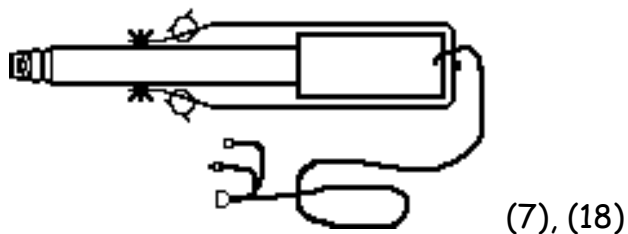
buoy (20):

(20)
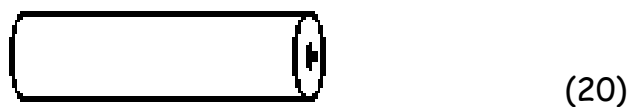
cable holder bar (19):

(19)

cable holder ring (4):

(4)
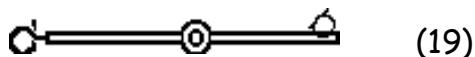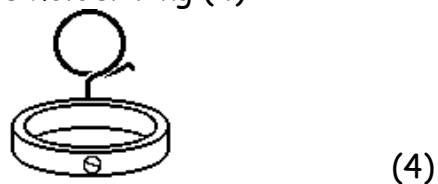
guide ring (1):

(1)

guide ring (3):
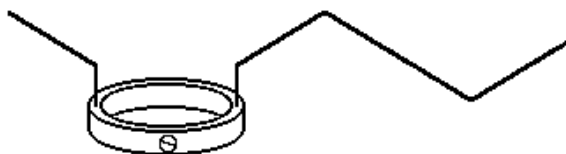
(3)
fishing line (23) for > 10 kg, >15 m
screw driver,
scissors,
sticky tape,
rubber gloves,
paper for cleaning

^{137}Cs (or ^{60}Co) calibration source, if possible

0.b. MCA-166 and HP-200

MCA-166 with HV converter installed
with charger and net cable

HV module with a polarity opposite to that installed in the MCA-166

HP-200 (or HP-100)
F1011A HP-200 adapter

HP-200 - MCA-166 connection cable

4 AA alkaline batteries and 1 back-up battery.

1. PRELIMINARY CHECK

1.a. Battery check

Connect the HP-200 to the MCA-166 with the connection cable.

1.a1. MCA-166 batteries

Switch **ON** the MCA-166.
If the green power ON LED does not flash, the battery is flat.
Connect the MCA-166 to the charger:
First connect the Lemo to the MCA-166. **Then** connect the power plug to the mains.

If the orange light of the charger is
   steady: charging,
   flashing: not charging,
          (In this case, re-plug mains power with MCA-166 connected to
          the charger)
   no light: fully charged or mains power not connected.

1.a2. HP-200 batteries

Switch on the HP-200.
If the HP-200 cannot be switched on or if you see a low battery message:

"Main batteries low, press ESC" or
"Bkup battery low, press ESC", you must change the batteries.

If you can switch on the HP-200, check the battery status by pressing the menu command HP-200 battery.
The main battery should have >2.4 V, the back-up battery >2.7 V.
If this is not the case, you must change the batteries.

To do that:

Switch off the HP-200 and close the case.
Change the two alkaline AA batteries (on the back) or the back-up battery (on the right side).

1.b. Check the high voltage polarity

Connect MCA-166 and HP-200 with the connection cable.
Switch on MCA-166 and HP-200.

The main menu appears (if not, press **"CTRL" "ALT" "DEL"** simultaneously).
Press the number corresponding to the UF6 program.
Press **"Y"**, then press **any key** to reset the MCA-166.

Using the arrow keys, go to **"Setup"**.
Press **ENTER**.
Select **"Detector high voltage setup"**.
Press **ENTER**.

Read the actual polarity.
If the polarity does not correspond to that written on the detector contact E4b Luxembourg.

Switch off the instrument:
Press **ESC** twice.
Select **"File"** and press **ENTER**.
Select **"Exit"** and press **ENTER** (or press **"X"**) to return to the main menu.
A message appears: **"Attention: don't forget to turn off the MMCA"**.
FIRST press **ENTER**, *THEN* switch off the MCA-166 and the HP-200.

1.c. Check memory space and reset data and time

Switch on the HP-200.
You see the main menu.
Press **"9"** to go to DOS.
Type DIR to check the free space on drive A (one 2048 channel spectrum occupies 21 kbytes,).
Type DATE, enter the DATE or press space bar if there is no correction to be made. Press **ENTER**.
Type TIME, enter the time or press space bar if there is no correction to be made. Press **ENTER**.
Press **"CTRL" "ALT" "DEL"** simultaneously to return to the main menu.
Switch off the HP-200.

2. GAMMA-TAUCHER ASSEMBLY

Screw together tubes 5, 6, 7.

Set the cable holder bar (19) on the screw bolt of the fork (18). Screw the buoy (20) on the fork (18). The bar must stand perpendicular to the plane of the fork.

Put the cable through one of the cable rings (17) of the fork.

Fix the fishing line (23) to the other ring (17) of the fork.
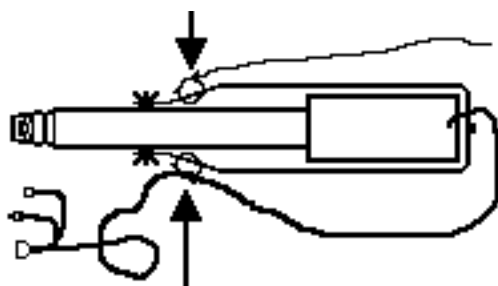
Use the following knot:

For VERTICAL operation mode:

Mount the cable holder ring (4) on the lower end tube (5) using the second grove from the end. Take the cable and the fishing line through the wire ring of the cable holder (4).
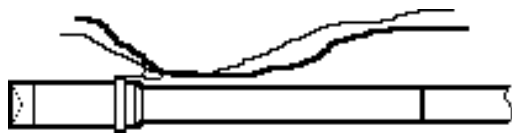
For INCLINED operation mode:

Take the cable through the wire ring at the end of the cable holder bar (19) and the fishing line through the ring at the other end.
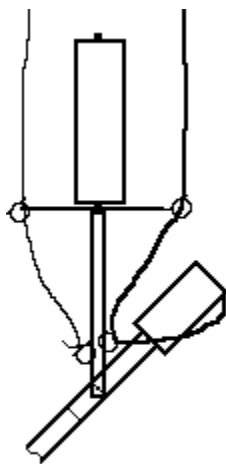
Mount a guide ring (1) or (3) on the lower end tube using the groove 3 cm from the end.
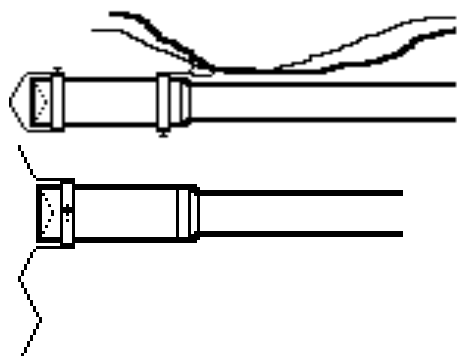
Connect cables:

Preamplifier power supply cable to MCA D9 connector **"Preamp"**, attach it with the clamps.

Signal cable to MCA-166 signal input **"IN"**.

High voltage cable to output **"HV"**.

Connection cable from MCA-166 **"PC"** to HP-200.

BEFORE LAUNCHING THE INSTRUMENT SWITCH ON AND CHECK THE ELECTRONIC CHAIN !

3. SET-UP OF THE MCA-166

3.a. Start the FP code

Switch on HP-200 and MCA-166.
The main menu appears (if not, press the
"CTRL" "ALT" "DEL" keys simultaneouly).

Press the numerical key corresponding to the FP code or go into DOS and start FP.EXE.

Press **"Y"** , then press **any key**.

Go to **"Setup"**, press ENTER.
3.b. MCA set-up with setup file

If you have no setup file see annex.

Go to **"Read setup file"**, press ENTER.

With the arrow down key select the setup file. Press **ENTER** twice.

Read the comment of the setup file.

Press **ESC**, the setup spectrum picture appears.
Press **F10** to return to the setup menu.
Select **"Detector high voltage setup"**, press **ENTER**.

Check if the polarity and the value of the HV are correct.

Switch on the high voltage by pressing **ESC**, then press **ENTER.**

3.c. Set measurement time

Select **"MCA Presets"**, press **ENTER**.

Press on the space bar to select **" Live Time (sec)"**.

With the down arrow key, go to **"Value"** and type the desired measurement live time (e.g. 100 seconds).

Press **ESC** and **ENTER** to accept the presets.

Press **ESC**.

4. TEST MEASUREMENT

Go to **"Data acquisition"**, press **ENTER**.
Select **"Measurement"**, press **ENTER**.
You see the Inspection Information 1/2.
Select **"Next screen press ENTER"**.
Press **ENTER**.
You see the inspection information 2/2.
Select **"Switch to graphic screen to measure"**
Press **ENTER**.
To start the measurement, press **F4**
Press **"Y"** to erase the previous spectrum, if necessary.

The measurement starts.

During the measurement you can:
- Check the dead time.
- Check the count rate.
- Use **F7** and **F8** to change the x scale.
- Use **F6** to change the y scale:
   aLin: linear, automatic
   mLin: linear, manual,
         use arrow up / down to change the scale
   Log: logarithmic scale
- Stop the measurement before the preset end by pressing **F5**.

Observe that there are some counts or even gamma lines in the spectrum (the environmental background) to be sure that the system works.
At the end of the measurement time (or after stopping the measurement with **F5**), you see the message **"PLEASE WAIT 15 s"**. During this time, the code evaluates the data.

5. SAVE SPECTRUM

The function **Save** will save the spectrum in a *.SPE file and, in addition, write the results into a table with the name
FP-EUxxx.REP (xxx = EURATOM inspection number).

Press **F4** , press **ENTER**
If necessary, go to **"Dir"** and write another path, e.g. a:\setup\ , press **ENTER**.

Go to **"File"**.
Write a file name with the extension   .spe.
Press **ENTER**.
Check the file name, rewrite it if necessary,
Press **ENTER**.
Type the comment, press **ESC**.
Press **ESC** 3 times to return to the FP menu.

6. SWITCHING OFF

After measuring and saving the files switch off the high voltage, the MCA-166 and the HP-200:

Select **"File"** press **ENTER**, press **"X"**.

Press **"YES"** when you see the message **" Attention: High Voltage is on! Turn off HV! "**.
Press **ENTER.**

When the HV is off, a message appears: **"Don't forget to turn off MMCA!"**. *FIRST* press **ENTER**,*THEN* switch off the MCA-166 and the HP-200.

Disconnect the cables.

7. LAUNCH AND MOVE THE GAMMA-TAUCHER

The instrument has to be switched off. Handling is easier and safer with the Gamma-Taucher disconnected from the MCA-166.

- **VERTICAL operation mode**

Lower it down using cable and fishing line, with the buoy first. After the buoy has reached the water surface, it will stay there whereas the tube will turn to the side and sink into the water. Finally, the whole instrument will go down with the lower tube ahead. Let it sink down slowly. Move it towards a fuel element to be measured. Set it down on the top of the element.

MOVE SLOWLY!
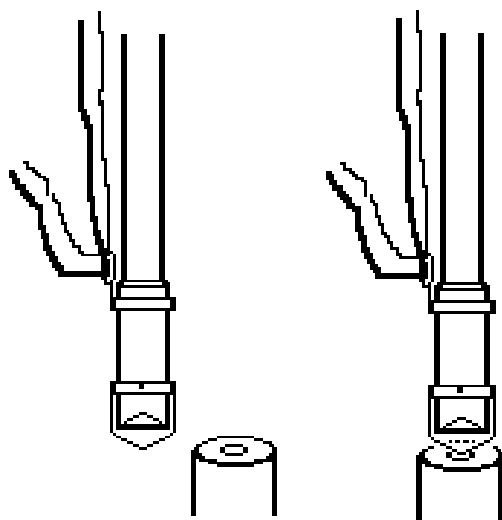
- **INCLINED operation mode**

Take the cable and fishing line out of the cable holder (4). Put them into the wire rings at the ends of the cable holder bar, see 3.6. Choose a suitable angle between the fork and the collimator tube, the fork will be approximately vertical under water (not in the air!). Lower the instrument into the water. Let it sink down slowly. Move it towards a fuel

element using cable and fishing line. Determine the horizontal direction and inclination of the tube with the cable and the fishing line. Lean it against the element.

fuel element measurement

background measurement
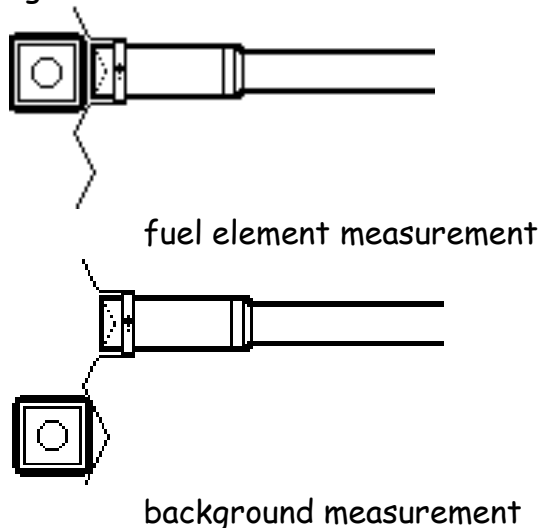
Fix the cable somewhere, e.g. with sticky tape at a handrail.

8. FIRST MEASUREMENT - RECOMMENDATION

Connect the Gamma-Taucher to the MCA-166, start FP.EXE (see 3.1.). Start the measurement series on a spent fuel element with long cooling time (more than 3 years), if possible. In this case, the spectrum will show **one** single gamma line. It is the 662 keV line of ^{137}Cs. It should be in channel 900± 15.

Often the **two** ^{60}Co peaks (1172 keV and 1332 keV) are found in the spectrum, they can be predominating. They should be in channels 1597 and 1811, respectively.

If necessary, these lines could be used to readjust the energy calibration. For pattern spectra see Annex A1 Spectra A1d.

9. INSPECTION MEASUREMENTS

Recommended measurement time: 100s.

Move the Gamma-Taucher to the element to be checked and set it on the top or lean it against it from the side, respectively.
Start a measurement (see 4.).

Save the spectrum (see 5.).

Perform a background measurement with the same measurement time close to the inspected element for later comparison!!
IN THE SAME HEIGHT. For inclined measurement mode
use guide ring (3). Check that there are no other radiation sources next to the Gamma-Taucher during the background measurements than were there during the fuel element measurement!

Save the background measurement.

END OF THE MEASUREMENTS:

Switching off (see 6.), disconnect the MCA-166 from the Gamma-Taucher and remove it.

Pull up the Gamma-Taucher slowly. While doing that, dry the cable and the fishing line.
Dry the whole instrument at the place where it is pulled out of the water.

DO NOT FORGET TO RECHARGE THE MCA-166 AS SOON AS POSSIBLE!

Annex to procedure P6

10. MCA-166 SET-UP WITHOUT SETUP FILE

10.a. HV Setup-up

Start FP.exe.
Reset to FP defaults .
Press **"Y"** , then press any key to reset MCA-166.
Select **"Setup"**, press ENTER.
Select **"Detector high voltage setup"**, press ENTER.
Check that the polarity is correct.
Type the high voltage value.
Press **ESC**, then press **ENTER** to turn on the high voltage.

10.b. Amplifier set-up

Put a ^{137}Cs (or ^{60}Co) source next to the detector.

Go to **"Amplifier setup"**, press ENTER.

Go to **"Switch to visual gain adjustment"** and press ENTER.

If no spectrum (or at least some counts) are visible, change the pulse input polarity.
To change the polarity of the input pulses: Press **ESC** and **"Y"** You see the Amplifier menu.
With the ↓ arrow key, go to the **"Input polarity"** line and with the space bar, change the polarity of the input signal.
Then, go back to **"Do visual gain adjustment"** and press **ENTER**.

Check, if the ^{137}Cs peak is in channel 900 (or if the second ^{60}Co peak is in channel 1811).
Use the cursor (arrow right and left) and the expand and compress function **F7** and **F8**.

If necessary, change the coarse gain:
To change the coarse gain:

Press **ESC** and then press **"N"**.
Go to **"Coarse gain"**. Then with the space bar, select a new coarse gain value.
Go again to **"Do to visual gain adjustment"**, press ENTER.
Repeat the adjustment of the coarse gain until the 662 keV line is close to channel 900 ± 15. Then, adjust the fine gain with the **"+"** and **"–"** keys to place the peak in the desired channel.

Press **ESC** and then press **"Y"** to save the gain.

10.c. Pole zero cancellation

Go to **"Switch to visual PZC adjustment"** and press **ENTER**.

Adjust the PZC with the **"+"** and **"–"** keys to minimise the **"Zero Offset"**.

When there is a low count rate you need to wait a minute for the indication **"Zero Offset"** (On the other hand, when there is a too high count rate the PZC adjustment will also not work, the count rate should be below 5000 cps).

When the **"Zero Offset"** is close to zero, press **ESC**, then press **"Y"** to save the value.

Check if the gain is still good, you might need to readjust the fine gain. To do that:
Go to **"Switch to visual gain adjustment"** and press **ENTER**.
Press on the **"+"** and **"–"** keys to place the 662 keV line in channel 900 ± 15.
When the adjustment is made, press **ESC** then **"Y"** to accept the settings.

Press **ESC**, press **ENTER**, press **ESC** to leave the amplifier setup menu.

Perform a spectrum measurement (see 4.) and save the spectrum as setup file :

Save the spectrum:
From the graphic screen, select **"Save"**

Press the ↑ arrow key and write A:\Setup

Press the ↓ arrow key and type the name of the spectrum.

Press **ENTER** twice.

Write the comment and then press **ESC**.

Continue with instruction 3.c.

A-

Absolute efficiency, see efficiency, absolute full energy peak

Absorption of gamma rays

Actinides

Activator

Activity of a radionuclide, definition

Activity of a radionuclide, measurement with gamma spectrometry

ADC, analog-to-digital converter

ADC, conversion gain

ADC, conversion time

ADC, resolution

ADC, specifications for MCA-166

Alpha decay

Alpha particle

Alpha radiation range, see range of particles in matter

Americium (Am)

Amplifier

Amplifier, MCA-166 specifications

Amu, see Atomic mass unit

Analog-to-digital converter, see ADC

Annihilation

Annihilation peak, see annihilation

Anti-Compton spectrometer

Area, net peak

Area, net peak area, evaluation with the MCA, SPEC and UF6 programs

Area, net peak, evaluation with U235 program

Assembly, see nuclear fuel assembly

Atom

Atomic mass

Atomic mass number

Atomic mass unit (amu)

Atomic number

Atomic weight

Attenuation

Attenuation coefficient

Attenuation coefficient tabulation, see Annex A2, Tab.8

Attenuation law

Auger electron
Autosave (SPEC program)
Avogadro number

B-

Background continuum in spectrum
Background radiation
Backscatter peak
Backscatter peak = f (Energy), tabulation, see Annex A2, Tab.7
Ballistic deficit
Band gap, see band structure in solids
Band structure in solids
Barn
Baseline
Baseline restorer (BLR)
Batemann formula
Battery for HP-200, when and how should they be changed?
Battery for MCA-166, when should the batteries be charged?
Battery life time, HP-200
Battery life time, MCA-166
Becquerel
Beta decay
Beta particle
Beta radiation range, see range of particles in matter
Binding energy, electron
Bipolar pulse
BLR, see baseline restorer
Bohr radius
Boiling Water Reactor, see reactor type
Branching
Branching ratio, see branching
Bremsstrahlung
Built-up of Pu, Am and Cm from ^{235}U and ^{238}U, see Annex A2 G5
Built-up of ^{233}U from ^{232}Th and U, see Annex A2 G6
Built-up of ^{232}U from U, see Annex A2 G7
Built-up of ^{234}U from ^{238}U in nature, see Annex A2 G8
Burn-up
BWR, see reactor type

C-

[Cable connection (detector+HP-200+MCA-166)](#)
[Cadmium filter](#)
[Cadmium filter, influence on Pu measurement](#)
[Cadmium Zinc Telluride detector (CZT)](#)
[Cadmium Zinc Telluride detector, stability of the detector response](#)
[Calibration constants for enrichment determination](#)
[Calibration Table (UF6 program)](#)
[Calorimeter](#)
[Can wall correction for enrichment determination](#)
CdZnTe, see [Cadmium Zinc Telluride detector](#)
[Centroid of the peak](#)
[Čerenkov light](#)
[Channel](#)
[Charge collection time](#)
[Cladding](#)
[Coaxial germanium detector](#)
[Coincidence](#)
[Collimator](#)
[Compton continuum](#)
[Compton edge](#)
Compton edge = f (Energy), see [Annex A2, Tab.7](#).
[Compton effect](#)
Conduction band, see [band structure of solids](#)
Conductor, see [band structure in solids](#)
[Cooling time](#)
[Count rate](#)
[Counting statistics](#)
[Critical mass](#)
[Crossover point](#)
[Cross section, nuclear](#)
[Cs ratio](#)
[Curie](#)
[Curium](#)
CZT detector, see [Cadmium Zinc Telluride detector](#)

D-

Data transfer, between two HP-200 using the infrared port
Daughter nuclide
Dead time (DT), definition
Dead time, MCA-166
Decay chain Annex A2 Graph G2, G3, G4
Decay constant λ
Decay law
Decay, radioactive
Decay scheme
Deleting spectra on the HP-200
Density for commonly used material, see Annex A2, Tab. 8
Depleted Uranium
Detector types, performance comparisons, see Annex A2, Tab. 13
Diagnostics, MCA-166
Diagnostics, batteries
Differentiator
Direct use material
Discriminator
Disintegration
Display live time/ real time, see preset counting time
Dose, energy dose
Double escape peak
DT, see dead time

E-

EC, electronic capture
Efficiency, absolute full-energy peak
Efficiency, intrinsic full-energy peak
Efficiency, relative
Efficiency, numerical values see Annex A2 Tab. T14, Annex A2 Graph G11
Electron
Electronic capture
Electronic system for gamma spectrometry
Electron volt (eV)
Energy calibration, definition
Energy calibration, with SPEC program
Energy needed to create an electron hole pair
Enriched uranium
Enrichment, calibration constants, see calibration constants for
                                         enrichment determination
Enrichment, definition
Enrichment meter principle
Enrichment techniques
Environmental ratings for the MCA-166
Equivalent dose
Escape peak, see X-ray escape peak
Excited state
Expand a spectrum

F-

Fall time
Fast Breeder Reactor, see reactor type
Fertile
Firmware
Fissile
Fission, nuclear
Fission products
Fission Product yield
Fission product yield for 235U, tabulation see Annex A2 Tab.T5
Fission, spontaneous
Fluorescence
FP program (CdZnTe detector)
Fuel, fresh
Fuel, nuclear
Fuel cycle
Fuel cycle scheme Annex A2 Graph G9
Fuel pellet
Fuel pin
Fuel reprocessing
Full-energy peak
Full-energy peak shape
FWHM, see resolution of a detector

G-

Gain, definition

Gain, adjustment with MCA, SPEC, UF6, U235 and FP programs

Gain value and gain calculation example

Gamma branching ratio

Gamma detectors and their applications, see Annex A2, Tab.13

Gammanal function

Gamma radiation path in matter, see range of particles in matter

Gamma ray (γ-ray)

Gamma spectrometer, see electronic system for γ spectrometry

Gamma Taucher

Gated integrator amplifier

Gaussian shaping

Gas centrifugation, see enrichment techniques

Gaseous diffusion, see enrichment techniques

Geiger counter

Germanium detector

Grade of Plutonium, see Plutonium, grades

Gray, see units

Ground state

H-

Half-life
Half-thickness
Half thickness of U, tabulation   Annex A2 Tab. T10
Help function
HEU
High voltage inhibit
High voltage inhibit, how to activate it?
High voltage, MCA-166 specifications
HP-200 display contrast
HP-200 hard reset
HP-200 reset
Hypermeth function

I -

IC, see internal conversion
Impedance
Infinite thickness, definition
Infinite thickness, condition, checking
Infinite thickness of uranium, numerical values   Annex A2 Tab. T9
                                                   Annex A2 Graph G1
Insulator, see band structure in solids
Integral linearity of a MCA
Integral of a ROI (Region Of Interest)
Integrator
Interaction of gamma radiation with matter
Interference of gamma rays
Internal conversion (IC)
Internal conversion coefficient
Ionization
Ionization chamber
Ionizing radiation
Isotope

K-

K-edge
K-edge densitometry
Klein-Nishina formula

L-

Laser separation, see enrichment techniques
Lead
Leakage current, see thermal generation of charge carriers in a semi-
conductor
LED
LENG program
LEU
Linear amplifier
Linear attenuation coefficient, see attenuation coefficient
Linear gate time
Live Time Clock (LTC)
Live time (LT), definition
LLD, see lower level discriminator
Logic pulse
Lower level discriminator, LLD
LTC, see Live time Clock
Luminescence

M-

Mass attenuation coefficient, see attenuation coefficient
Mass attenuation coefficient tabulation, see Annex A2 Tab.8
Mass number, see atomic mass number
Matrix
Matrix correction, for enrichment determination
MCA, see Multi Channel Analyzer
MCA-166
MCA program
MCS program
Mean Uranium dwell times at various stages of a PWR fuel cycle, see
Annex A2, Graph G 0

Measurement error
Measurement time, preset
Memory group (MCA program)
Memory space
Memory storage time
MGA software (Multi Group Analysis)
MGAU software (Multi Group Analysis for Uranium)
MGAU, sum peak effect
Minimum sample mass, U enrichment measurement
Minimum sample thickness, see infinite thickness
Move function (MCA program)
MOX (Mixed Oxide Fuel)
MOX, gamma ray spectrum
MTR (Material Testing Reactor)
MTR scanner
Multi Channel Analyser (MCA)

N-

NaI detector
NaIGEM software (NaI Gamma Enrichment Measurements)
Neptunium
Net peak area, see Area, net peak
Net peak count rate
Neutrino
Neutron
Night Vision Device
Nuclear data for selected nuclides, see Annex A2, Tab. 5
Nuclear fuel assembly
Nucleon
Nucleus
Nuclide
Nuclide chart

O-

Oscilloscope
Overshoot effect, see pole zero cancellation

P-

Pair creation

Parent nuclide

Peak position, see centroid

Peak shape, see full-energy peak shape

Peak-to-Compton ratio

Phosphorescence, see luminescence

Photocathode, see photomultiplier tube

Photoelectric effect

Photomultiplier tube

Photon

Pile-up, see pulse pile-up

Pile-up probability

Pitchblende

Planar germanium detector

Plutonium

Plutonium compounds

Plutonium gamma and X-ray lines Annex A2 Tab. T3

Plutonium, gamma ray spectrum

Plutonium, grades

Plutonium isotopes

Plutonium isotopes, half lives and decay constants

Plutonium isotopes, thermal neutron cross sections

Plutonium isotopic composition

Plutonium isotopic composition, conversion atom% to mass%

Plutonium gamma lines, see Annex A2, Tab. 3

Plutonium spectra, see Annex A1c

Pole zero cancellation (PZC)

Pole zero adjustment with the UF6, U235, MCA, SPEC and SF software

Positron

Preamplifier

Preset counting time with SPEC, UF6, FP and MCA software

Proportional counter

Proton

Pulse pile up

Pulse pile-up rejector (PUR), definition

Pulse pile-up rejector activation with MCA program

PUR, see Pulse pile up rejector
PUREX process
PUREX process scheme Annex A2 Graph G9
PWR, see reactor type
PZC, see Pole Zero Cancellation

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Q-

Quenching

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R-

Radiation protection, see Annex A4
Radiation wavelength
Radioactive decay, see decay, radioactive
Radioactivity
Radioactivity, natural
Radioelement
Radionuclide
Range of particles in matter
Rayleigh effect
Reactor type
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Re-evaluation with U235, UF6 and FP programs
Region of interest (ROI), how to mark or delete?
Relative contribution of the Rayleight, Compton and photoelectric effects
at 185.7keV

Repetitive measurements
Report of analysis (UF6 and U235 programs)
Reprocessed Uranium
Reprocessing, see PUREX process
Resolution of a detector, definition
Resolution of a detector, typical values
Resolution of a detector, graphs see Annex A1, esp. A1e
Resolution of a detector, measurement with SPEC and MCA programs
Rise time
ROI, see Region Of Interest

S-

Save a spectrum with UF6, MCA, U235, SPEC and FP programs
Scale, see expand a spectrum
Scattering of gamma radiation
Scintillation
Scintillation detector
Scintillator
Secular equilibrium
Self absorption
Self absorption factor
Semi-conductor
Semi-conductor, type n, see semi-conductor
Semi-conductor, type p, see semi-conductor
Setup file
SFAT, see spent fuel
Shaping time constant, definition
Shaping time constant setting with SPEC, MCA programs
Single channel analyzer (SCA)
Single escape peak
Smooth function
Smooth function (with MCA program)
Sodium iodide, see NaI detector
Sound velocities, Annex A2, Tab. 11
Specific activity, see activity of a radionuclide
SPEC program
Spectrum
Spectrum features
Spent fuel gamma lines Annex A2 Tab. T5
Spent fuel gamma spectrum   Annex A1d
Spent fuel, nuclear
Stability
Stable nuclide
Stabilisation with MCA, SPEC, and UF6 programs
Stabilisation, how to activate it?
Standard deviation
Strip function (MCA program)
Successive approximation ADC

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Sum peak

T-

TAC (Time-to-Amplitude Converter)
Thermal generation of charge carriers in a semi conductor
Thomson effect
Thorium 232 decay chain, see Annex A2, Graph G2
Thorium gamma and X-ray lines, see Annex A2 Tab. T4
Thorium ore spectrum, see Annex A1b , Anne   A   2, Anne   A   3
Threshold function, SPEC and MCA programs
Throughput
Transmutation
Transuranic element
Trouble shooting, see Annex A3
True time, see real time

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U-

U235 program (NaI detector)
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ULD, see Upper Level discriminator
Ultrasonic gauge
Undershoot effect, see pole zero cancellation
Unexpand a spectrum, see expand a spectrum
Unipolar pulse
Units and prefixes of ten, see Annex A2, Tab.12
Upper Level discriminator (ULD)
Uranium
Uranium 232 decay chain, see Annex A2, Graph G2
Uranium 235 decay chain, see Annex A2, Graph G3
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Uranium compounds
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Uranium gamma and X-ray lines Annex A1 Tab. T1, T2, T4(U232), T5
Uranium hexafluoride, see Uranium compounds see Enrichment techniques
Uranium isotopes, half lives and decay constants
Uranium isotopes, neutron cross sections
Uranium spectra, see Annex A1a

V-

Valence band, see band structure in solids

View report with U235 and UF6 programs, see report of analysis

Visible light, see radiation wavelength

W-

Wall thickness correction, see can wall correction
Wavelength, see radiation wavelength
Weapon grade material
Wilkinson ADC
WinSPEC

X-

X-ray
X-ray, energy and relative intensity Annex A2 Tab. T6
X-ray escape peak
X-ray fluorescence
X-ray nomenclature, see X-ray
X-ray peak
X-ray peak shape

Y

Yellow cake

Z-

Zoom, HP-200
Zero offset
Zyrcaloy

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GLOSSARY

Underlined words are defined elsewhere in the glossary. Click on them to activate the link

A-

Absolute efficiency, see efficiency, absolute full energy peak

Absorption of gamma rays
The process during which a photon disappears completely in a single interaction. In the photoelectric effect and in the pair creation the photon energy is completely transferred to an electron and an electron-positron pair respectively.

Actinides
The group of chemical elements whose atomic numbers range from 89 to 103, i.e. Actinium, Thorium, Protactinium, Uranium, Neptunium, Plutonium, Americium, Curium, Berkelium, Californium, Einsteinium, Fermium, Mendelevium, Nobelium and Lawrencium.
The Uranium mineral contains trace amounts of Ac and Pa and minute amounts of Np and Pu.
U , Pu and Th are used as nuclear fuel. U, Np, Pu, Am. and Cm occur in irradiated fuel.
All the actinide isotopes are radioactive.

Activator
In a pure inorganic scintillator, the return of the electron from the conduction band to the valence band with emission of invisible UV photon light.
Consequently, it is an inefficient process for the scintillation. This is the case with NaI and CsI crystals for example.

To obtain a visible photon, one must to add a chemical impurity called activator (for example, thallium is the activator for NaI or CsI crystals). It gives rise to extra levels within the forbidden band between the valence band and the conduction band of the pure crystal.

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The de-excitation of the activator levels leads to the emission of a visible photon and therefore serves as a basis for the scintillation process (see figure below).
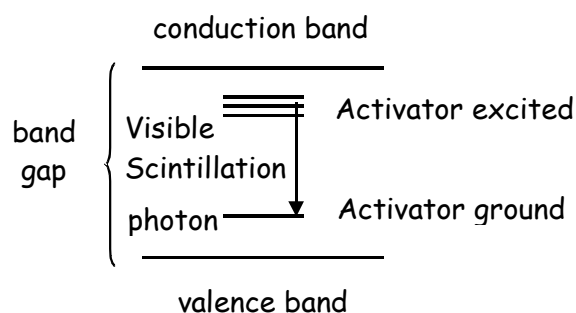
See also *scintillation*.

Activity of a radionuclide, definition
The number A of disintegrations per second in a radioactive specimen.

$$A = \lambda * N$$

where λ is the decay constant (s^{-1}) and N the number of atoms of the radioactive nuclide. The activity is expressed in Becquerel (1Bq = 1 disintegration/s) or in Curie (1Ci = $3.7*10^{10}$Bq).
The specific activity is the radioactivity of a unit weight (generally one gram) of material.

Example:

Calculation of the activity of one gram of pure ^{235}U:
One gram of ^{235}U contains:

$$N = \frac{N_A}{235}$$

atoms of ^{235}U, where $N_A = 6.023*10^{23}$ is the Avogadro number.
The decay constant is:

$$\lambda = 3.119*10^{-17} \ s^{-1}$$

The specific activity of ^{235}U is:

79 939 Bq/g

Activity of radionuclide, measurement with gamma spectrometry

The activity A of a radionuclide can be expressed as:

$$A = \frac{N}{\varepsilon_a * I_E * t * c}$$

Where:

N is the net peak area,

ε_a is the absolute efficiency of the detector (%),

I_E is the gamma branching ratio for the energy E (%),

t is the measurement live time (s),

c is the correction factor taking into account the self_absorption of
the source (equal to 1 for a point source).

ADC, Analog to Digital Converter

Electronic module which converts an analog signal (the amplifier output
signal height) to an equivalent digital number (the channel number). The
ADC is a part of the Multichannel Analyzer (MCA).

ADC conversion gain

Total number of channels used.

For the MCA-166, its value can vary from 128 to 4096 for the MCA and
SPEC programs. For the UF6 and U235 programs, its value is fixed at
4096 and 512 respectively.

To select its value with the SPEC program, go to "SETUP" and then "MCA
setup".

To select its value with the MCA program, go to "Acquire" and select
"Setup"

ADC conversion time

The time necessary to convert the analog signal into a digital number.

With the Wilkinson ADC, the conversion time is proportional to the pulse
height.

In the successive approximation ADC, the conversion time is fixed with
value ranging from 1 to 25 μs.

For the MCA-166, the sum of the conversion time and memory storage
time is less than 8 μs.

ADC, resolution
This is the total number of channels available.

ADC, specification for MCA-166
Successive approximation ADC
Resolution: 4 K
Conversion gain: 128 bytes, 256 bytes, 1Kb, 2 Kb, 4Kb
Input voltage: 3V (10V with attenuator)
Dead time: fixed and equal to 8 μs per pulse
Non-linearities :
   -Differential non-linearity (over 95%) ‹ 2%
   -Integral non-linearity (over 95%) ‹ 0.025%
Discriminator and threshold:
   -Digital LLD and ULD
   -Analog threshold (2...60% of ADC range).

Alpha decay
Radioactive decay of an unstable nucleus by emission of an alpha particle
(alpha radiation). The decay process is schematically written as:

$$\ _Z^A X \rightarrow \ _{Z-2}^{A-4} X + \alpha$$
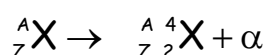
where $_Z^A X$ is a parent nucleus of atomic number Z and mass number A.
Typically the daughter nuclide $_{Z-2}^{A-4} X$ is in an excited state and decays
immediately to the ground state by emission of a gamma radiation.

Alpha particle
Helium nucleus $_2^4 He$ (2 protons, 2 neutrons).
Spontaneously emitted by some naturally radioactive isotopes, generally
those with atomic weights above 200 such as ^{238}U, ^{235}U, ^{226}Ra, ^{239}Pu, etc.

Alpha radiation range, see range of particles in matter

Americium (Am)
The third transuranic element (Z = 95). It is a product of the neutron
irradiation of Uranium or Plutonium, resp., being formed according to the
following sequence:

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$$^{238}U \quad \xrightarrow{(n,\,\gamma)} \quad ^{239}U \quad \xrightarrow{\beta^-} \quad ^{239}Np \quad \xrightarrow{\beta^-} \quad ^{239}Pu$$

$$^{239}Pu \quad \xrightarrow{(n,\,\gamma)} \quad ^{240}Pu \quad \xrightarrow{(n,\,\gamma)} \quad ^{241}Pu \quad \xrightarrow{\beta^-} \quad ^{241}Am$$
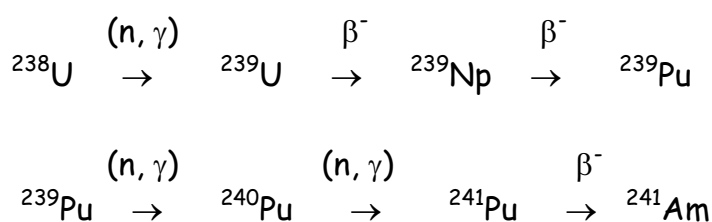
It is present in varying amounts in most irradiated Uranium fuel and built up after separation of Plutonium.
Its half-life is 432 years. It is the parent nuclide of ^{237}Np which has a half-life of approximately 2.10^6 years and decays with the emission of alpha particles.

Amplifier
Second element of the gamma electronic chain, which shapes and amplifies the preamplifier output pulse (see picture below).
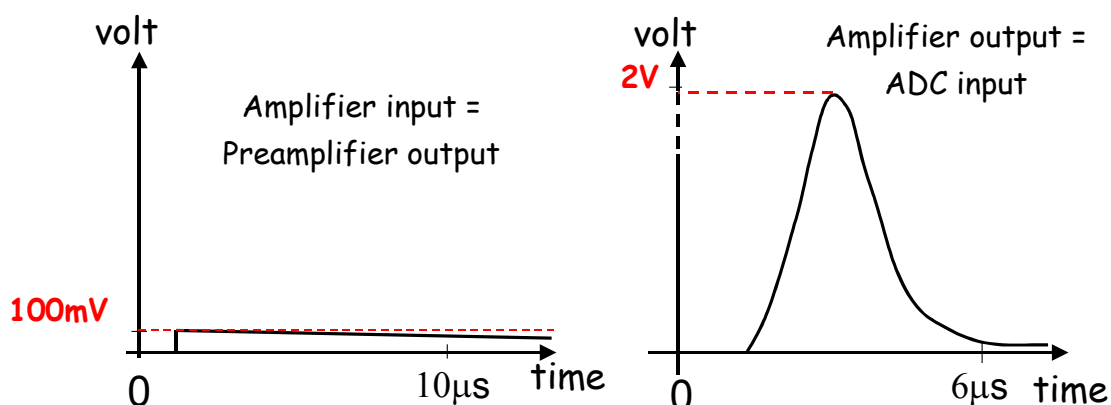
Its network comprises a single differentiator circuit followed by a single integrator circuit (see figure below).
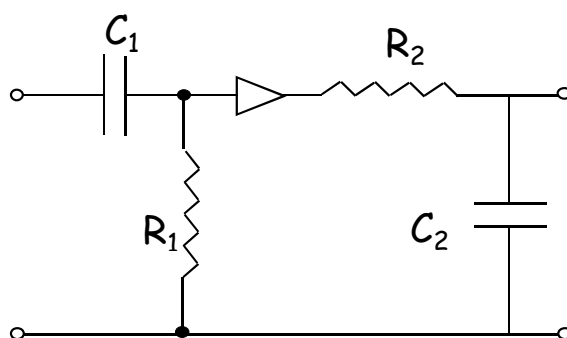
Amplifier, MCA-166 specifications
Gaussian shaping amplifier with 2 shaping time constants (1 or 2 μs),
Pile-up rejector,
Gated base line restorer,
Accepts positive or negative preamplifier signals,
Maximum input signal corresponding to full ADC scale at minimum gain +/-3V.

Amu, see Atomic mass unit

Analog-to-digital converter, see ADC

Annihilation
A positron from a β⁺ decay interacts with an electron in the radiation source. Two annihilation photons of 511 keV are created and emitted in opposite directions. The annihilation peak is caused by of one of these 511 keV photons (only one of the 511 keV photons can be detected because they are emitted in opposite directions).
The following picture shows the example of a ^{22}Na spectrum (β⁺ decay).
511 keV photons can also be observed without β⁺ decay: high-energy gamma rays from a radiation source or cosmic radiation can cause the creation of electron-positron pairs in the material around a detector (pair creation). The positron will soon slow down and annihilate with an electron emitting of two 511 keV photons which can be observed by the detector.
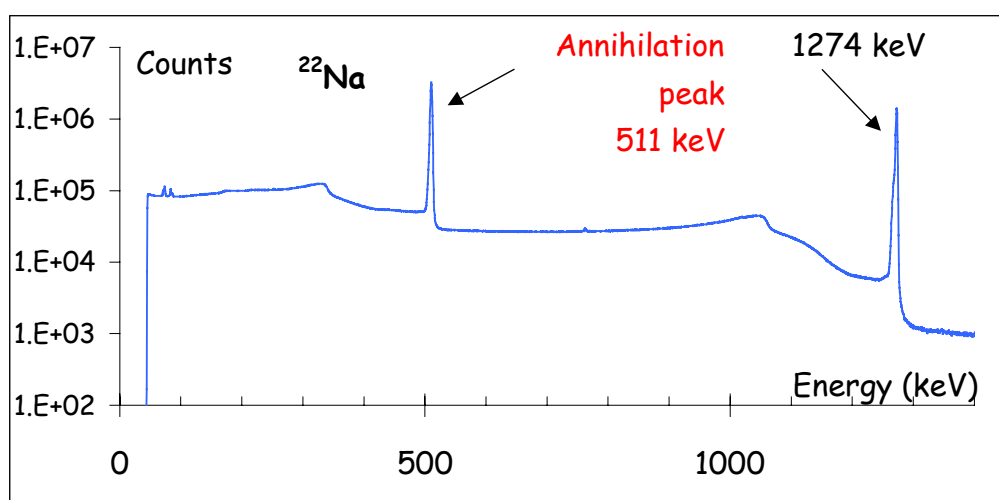
Annihilation peak, see annihilation

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Anti-Compton spectrometer
Gamma spectrometer which eliminates a part of the Compton continuum.
It is based on the rejection of each signal from the main detector when a
signal is induced by the scattered photon simultaneously in a second
detector surrounding the first one.

Area, net peak
Number of counts above the continuum level (background continuum) in a
given region.
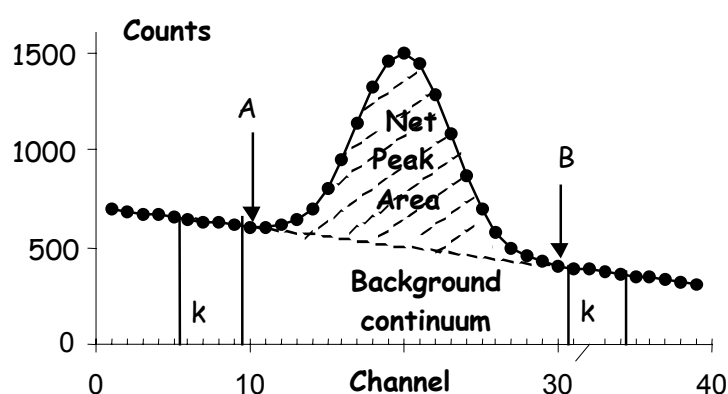
The picture above shows that the peak area is equal to the total number
of counts between channel A and B (the integral) minus the background
continuum which in this case has been estimated on the assumption of a
straight line.

$$Area = Integral - Background$$

with:

$$Integral = \sum_{A}^{B} c_i$$

$$Background = (B - A + 1) * (\sum_{A-k}^{A-1} c_i + \sum_{B+1}^{B+k} c_i)/(2 * k)$$

where:
c_i is the number of counts in channel i
A is the starting channel of the peak
B is the ending channel of the peak
k is the number of channels used to determine the background.
The statistical error on the area is:

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$$\Delta Area = \sqrt{\left(\sum_{A-k}^{A-1} c_i + \sum_{B+1}^{B+k} c_i\right) * \left(\frac{B-A+1}{2*k}\right)^2 + Integral}$$

Area, net peak area evaluation with the MCA, SPEC and UF6 programs

With these programs, the background term is the mean background term per channel estimated using upper and lower background regions 4 channels wide multiplied by the number of channels within the peak region.

Area, net peak evaluation with the U235 program

The U235 program measures the ^{235}U enrichment with a NaI or a CZT detector.

The enrichment of the sample is proportional to the net peak area of the 185.7 keV peak of ^{235}U, which in the case of a NaI detector contains all the ^{235}U peaks from 143 keV to 205 keV.

The background continuum cannot be considered as a straight line (see Area, net peak area calculation) and must be measured in a region out of the peak (ROI_2) which does not contain any peak. It is stated that the background under the peak is proportional to that in the ROI_2.

The net peak area A can then be written as follows:

$$A = ROI_1 - \beta * ROI_2$$

Where:

ROI_1 represents the total number of counts in the region of interest containing the peak,
ROI_2 the total number of counts in the region of interest taken to monitor the background continuum, β the proportionality factor.
In the U235 program, the regions of interest are set as follows:

ROI_1 = ch 261 to ch 342 (160 keV to 211 keV)
ROI_2 = ch 358 to ch 439 (220 keV to 270 keV)

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Number of counts

ROI $_1$
(261-342)

ROI $_2$
(358-439

channel
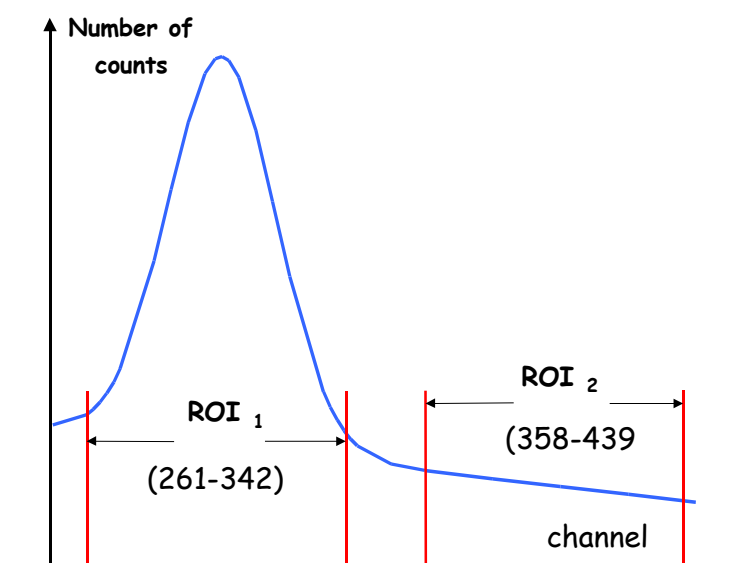
Assembly, see nuclear fuel assembly

Atom
A unit of matter consisting of a single nucleus surrounded by one or more orbital electrons.

Atomic mass
The mass of a neutral atom of a nuclide. It is usually expressed in atomic mass units (amu). The atomic masses of the different nuclides are very close to integers in value; the integer closest to the atomic mass of a given nuclide is called the atomic mass number of that nuclide, and is usually denoted by the symbol A.

Atomic mass number
The total number of protons and neutrons in a nuclide, also denoted A.

Atomic mass unit (amu)
A mass unit equal to exactly 1/12 of the mass of a carbon atom.
$1 \text{ amu} = 1.6606.10^{-24} \text{ g}$
$\qquad = 1.6606.10^{-27} \text{ kg}$
$\qquad = 931.5 \text{ MeV/c}^2$
$\qquad = 1.4924.10^{-10} \text{ J/c}^2$

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Atomic number
The number of protons in the nucleus of an atom, also called Z.

Atomic weight
The average weight of the naturally occurring isotopes of an element, based on natural isotopic abundance and using the C12 scale. The unit is g/mole.

Attenuation
The reduction of radiation intensity due to scattering and absorption as it passes through matter. The attenuation depends on the nature of the radiation (α, β, γ) and on the linear attenuation coefficient of the absorber material.

Attenuation coefficient
1. Linear attenuation coefficient
Coefficient which characterizes the attenuation by absorption and by scattering of a beam through an absorber. The unit is 1/cm. It corresponds to the probability per unit path length that the gamma-ray photon is removed from the beam and is equal to:

$$\mu = \mu(\text{photoelectric}) + \mu(\text{Compton}) + \mu(\text{pair}) + ...$$

where μ (photoelectric), μ (Compton) and μ (pair) represent the coefficients of photoelectric effect, the Compton scattering and the pair creation.
Expressed as a function of the cross sections, the linear attenuation coefficient becomes:

$$\mu = \rho * \frac{N_A}{A} * \left[\sigma(\text{photoelectric}) + \sigma(\text{Compton}) + \sigma(\text{pair}) + ...\right]$$

where σ(photoelectric), σ(Compton) and σ(pair) are the cross sections of the photoelectric effect, the Compton scattering and the pair creation, ρ the density of the material in g/cm^3, A its atomic weight (g/mol) and N_A the Avogadro number ($6.023*10^{23}$/mole).
The linear attenuation coefficient depends on the density of the absorber material.

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2. Mass attenuation coefficient
The mass attenuation coefficient is:

$$\frac{\mu}{\rho}$$

It is expressed in cm^2/g.
The mass absorption coefficient does not change with the physical state of the absorber.

For a composite material with i components, this coefficient is equal to:

$$\frac{\mu}{\rho} = \sum_i m_i * (\mu/\rho)_i$$

where :
  ρ : density of the material (g/cm^3)
  m_i : mass fraction of element i in the material (%)
  $(\mu/\rho)_i$: mass attenuation coefficient of element i (cm^2/g)

Example of linear and mass attenuation coefficient calculation for a composite material:
The material is a UO_2 powder with a density of 2 g/cm^3 and the calculations are performed for the energy E = 200 keV.

1. Mass attenuation coefficient calculation:

For E = 200 keV, table T8 (Annex A2) gives:
μ_U = 1.2980 cm^2/g and μ_O = 0.1237 cm^2/g

The mass fractions are:
    m_U = 238/(238+2*16)= 0.88 and m_O = 2*16/(238+2*16) = 0.12

The mass attenuation coefficient is equal to:

  μ/ρ = [0.88*1.2980+0.12*0.1237] = 1.1571 cm^2/g

2. Linear attenuation coefficient calculation:

  μ = ρ * μ/ρ = 2 g/cm^3 * 1.1571 cm^2/g = 2.3142 cm^{-1}

Attenuation coefficient tabulation, see Annex A2, Tab. T8

Attenuation law
The intensity attenuation factor I/I_0 of monoenergetic radiation under narrow beam condition passing through an absorber of thickness x having a linear attenuation coefficient μ is an exponential process and may be expressed as:

$$\frac{I}{I_0} = \exp(-\mu x)$$

where:

      I_0 is the incident intensity

      I is the intensity after passing through the absorber.

The attenuation law is not valid for radioprotection.

Auger electron
When an atom is in an excited state (for example, an atom with a vacancy on an inner shell), the excitation energy may be transferred directly to an outer electron, which is ejected from the atomic shell: this is the Auger electron.

Autosave (SPEC program)
To save the spectra automatically with the SPEC program:

Select "File", then "AutoSave". Press ENTER.
Toggle "Yes" in front of "AutoSave".
Toggle "Yes" in front of "prompt before overwrite".
Press ESC, then ENTER to accept the setting.
Select "Save".
Input the file name with the following format:
xxxx0001.spe. Press ENTER twice.
Write a comment and press ESC.
Now the number of the file name will be increased by one each time a spectrum is saved.

Avogadro number
Number of atoms or molecules in 1 mole.
$N_A = 6.023 * 10^{23}$/mole.

B-

Background continuum in spectrum

Baseline on which the peaks are superimposed in a gamma ray spectrum.

Background radiation

Radiation from other sources than the object to be measured. The background radiation may come from:

- radioactive sources in the vicinity,
- natural radioactivity in the material surrounding the detector (collimator, support), in the wall of the room or in the detection chain components,
- cosmic radiation.

The most common lines observed in a background spectrum are 511 keV (annihilation radiation), 662 keV (^{137}Cs), 1460 keV (^{40}K), 2614 keV (^{208}Tl, ^{232}Th series).

Characteristic lead X-rays (at around 74 keV and 85 keV) are present when a lead collimator is used.

If a tungsten collimator is used, the X-ray at 59.3 keV (Kα_1) is visible.

Backscatter peak

The peak produced by the photons of the source, which were first scattered by Compton effect in the materials surrounding the detector.
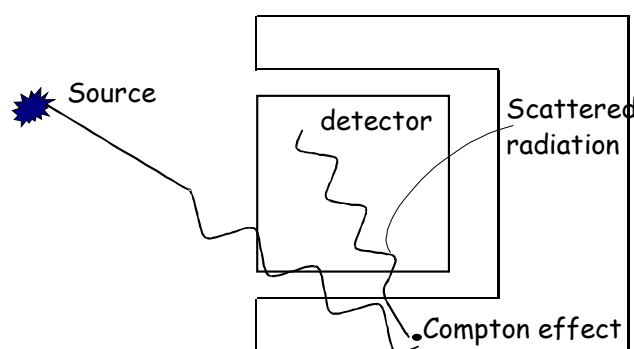
If the scattering angle is between 110° and 180°, the energy E' of the scattered photon is close to:

$$E' = \frac{E}{(1 + 2 * E / 511)}$$

where E is the energy of the incident photon expressed in keV.

Some backscatter peak values of are given in Annex A2, Tab. T5 or typical radionuclides while the backscatter peak values are given as a function of the photon Annex A2, Tab. T7.
See spectrum features to display the example of the backscatter peak of the 1273.6 keV line of the ^{22}Na.

Backscatter peak = f (Energy), see Annex A2, Tab. T7

Ballistic deficit
Difference in amplifier output signal height corresponding to a pulse shaped with a time constant comparable to the pulse rise time and the same pulse shaped with an infinite time constant (see figure below).
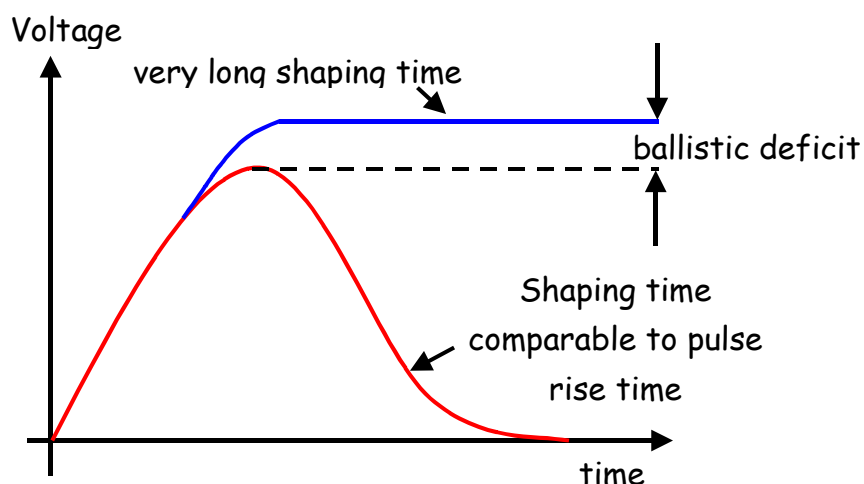
The ballistic deficit contributes to the degradation of the resolution.

Band gap, see band structure in solids

Band structure in solids
In a solid, the electrons only have available discrete bands of energy.
The uppermost-occupied energy band is called the valence band. It contains the electrons that are bound to specific lattice sites within the solid. The next available energy level is called the conduction band and contains the electrons that have jumped from the valence band They are free to migrate within the solid and contribute to the conductivity of the material.

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These two energy bands may be separated by a forbidden energy gap, the size of which determines whether the material is classified as an insulator or a semi- conductor. In a pure material, the forbidden band gap is empty.
In the case of conductors, there is an overlapping of the valence band and
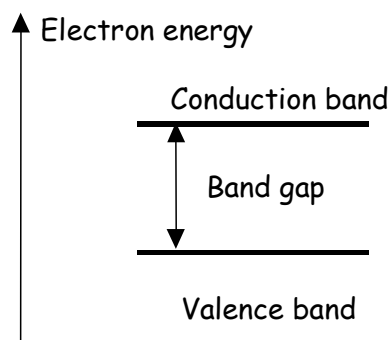
the conduction band.
The band gap value is :
-in the order of 10 eV, for an insulator
-in the order of 1 eV, for a semi- conductor with:
    for Ge at 77 K: 0.74 eV
    for CdTe at 300 K 1.47 eV
    for Si at 300 K 1.12 eV

Barn
The unit of cross section for interactions between target objects (nuclei, atoms and electrons,) and radiation particles (photon, nucleons...) at a particular energy.
1 barn = $1*10^{-24}$ cm^2
(See also cross section).

Baseline
A reference voltage from which a pulse excursion varies. Usually zero volts.

Baseline restorer (BLR)
Circuit which allows the return to true zero of the baseline between pulses in as short a time as possible.

Batemann formula

If we consider the following decay sequence:

$$X_1 \xrightarrow{\lambda_1} X_2 \xrightarrow{\lambda_2} \ldots X_{n-1} \xrightarrow{\lambda_{n-1}} X_n \xrightarrow{\lambda_n} \ldots$$
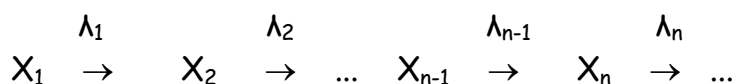
where:

λ_i are the decay constants associated to the nuclides i, the number N_n of atoms of a given nuclide X_n of the chain at a certain time t is given by the Batemann formula:

$$N_n = N_{1,0} * \prod_{i=1}^{n-1} \lambda_i \sum_{i=1}^{n} \left[\frac{e^{(-\lambda_i * t)}}{\prod_{j=1, j \neq i}^{n} (\lambda_j - \lambda_i)} \right]$$

where $N_{1,0}$ is the number of atoms of the radionuclide X_1 at the time t = 0.

Batteries for HP-200, when and how should they be changed?

The HP-200 contains:

The main battery: two 1.5V AA Alkaline batteries (or two Nickel-cadmium rechargeable batteries)

The back-up battery: A 3-volt CR2032 lithium coin cell. This battery prevents data loss when the main batteries are flat.

All the batteries must be replaced if:

- the HP-200 beeps and turns off immediately after you turn it on (the main batteries are flat),

or,

- if you see a low-battery message in the display for the main or back-up batteries.

To change the batteries:

warning: Do not remove both the main batteries and the back-up battery at the same moment to avoid losing the complete memory. Change the back-up battery first.

To change the back up battery:

Remove the back-up battery cover (on the right side) and pull out the battery tray.

Remove the old battery and insert a new one. The + on the battery faces down in the tray.

To change the main batteries:

Close all open applications before changing batteries, Switch the HP-200 off and close it.

Remove the battery cover and the old batteries

Install the new batteries as shown in the battery compartment and replace the cover.

To charge the main batteries:

From the MCA-166 main menu:

Press the number corresponding to "return to DOS".

Press 100 for the HP-100 and 200 for the HP-200.

Press ENTER.

Press the blue key &, select "Setup" and press ENTER.

Press the ALT key, select "Options", press ENTER.

Select "Battery", press ENTER.

With the down arrow key, select Nickel Cadmium (rechargeable).

Press the E key to enable recharging and then press the F10 key.

Press "ALT", "CTRL""DEL" simultaneously to return to the MCA-166 main menu.

Battery for MCA-166, when should the battery be charged?

The MCA-166 contains a rechargeable Li battery with no memory effect.

If the green power ON LED does not flash after switching on the MCA-166, the battery is flat.

In this case connect the MCA-166 to the charger:

First connect the Lemo to the MCA-166 and then connect the power plug to the mains.

If the orange light of the charger is:

  - constant: it is charging

  - flashing: it is not charging (in this case re-connect to
    mains power with the MCA-166 connected to the
    charger).

If there is no light, it is fully charged or the mains power is not connected.
(see also diagnostics, MCA-166 and diagnostics batteries).

Battery life-time, HP-200
Fresh alkaline batteries: 2 to 8 weeks

Battery life-time, MCA-166
no detector : 16 hours
NaI : about 14 hours
CdTe: about 12 hours
HPGe: about 6 hours

Becquerel
Legal unit of activity since 1975.

   1 Bq = 1 disintegration/s
   1 Ci = $3.7*10^{10}$ Bq.
(See also Annex A2, Tab. T12)

Beta decay
The transformation of nuclei either by the spontaneous emission of electrons or positrons, or by electronic capture from the K-shell, is known as beta decay.
For the three processes the mass number of the nucleus does not change. The reaction sequences for the three processes, positron emission (β^+), electron emission (β^-) and electronic capture (EC) are:

$$_Z^A X \rightarrow {}_{Z-1}^A X + e^+ + \nu_{e+} \qquad (\beta^+)$$

$$_Z^A X \rightarrow {}_{Z+1}^A X + e^- + \nu_{e-} \qquad (\beta^-)$$

$$_Z^A X + e^- \rightarrow {}_{Z-1}^A X + \nu_{e+} \qquad (EC)$$
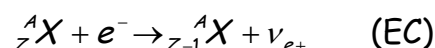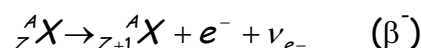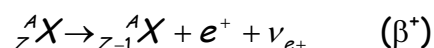
where $_Z^A X$ represents a nucleus of atomic number Z and mass number A and ν_{e+} and ν_{e-} the neutrino and anti neutrino respectively.
β^+ decay occurs with proton rich nuclei, β^- decay with neutron rich nuclei.

Beta particle

Particle emitted by β^- or β^+ decay, electron or proton (see beta decay).

Beta radiation range, see range of particles in matter

Binding energy, electron

The energy required to remove an electron from an atom or molecule completely. The electrons in an atom are arranged in shells and sub-shells, each of which is associated with a defined binding energy .The binding energy is greatest for the innermost shells and least for the outermost shells.

For example, the binding energies for the Uranium atom are:

        level K: 115.6   keV
        level L_I: 21.76   keV
        level L_{II}:   20.95   keV
        level L_{III}:   17.17   keV
        level M: 5.5 keV (M_I) to 3.5 keV(M_{IV})
        level N: 1.4 keV (N_I) to 0.4 keV (N_{VII})

Bipolar pulse

A pulse that has successive excursions in both the positive and the negative direction from the baseline.
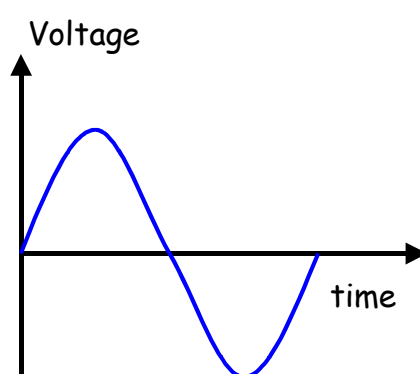
BLR, see baseline restorer

Bohr radius

The radius of the electron orbit of lowest energy in the Bohr model of the hydrogen atom. It is equal to:

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$$a_0 = 0.52917*10^{-10} \text{ m.}$$

It is the typical size of an atom.

Boiling Water Reactor, see reactor type

Branching
There exist competing modes of radioactive decay of a particular nuclide. For example ^{137}Cs may decay in either of two modes (see picture below), a direct β^- emission of energy 1.17 MeV to ^{137}Ba or a β^- emission of energy 0.51 MeV to an excited state of ^{137}Ba followed by its decay to the ground state accompanied by the emission of the γ-ray of 0.662 MeV. The first process occurs in 6.5 percent of disintegrations, the second in 93.5 percent. These quantities are known as the branching fractions for the two modes. The branching ratio is the ratio of the branching fractions for any two modes of disintegrations.
In this example, the gamma branching ratio I_γ represents the probability of emission of a gamma of 0.662 MeV during the disintegration of ^{137} Cs. It is equal to the probability of reaching the excited level of the ^{137}Ba by beta decay multiplied by $1-\alpha$, the probability that the excited ^{137}Ba nucleus will return to the ground state by emission of a 0.662 MeV gamma ray (α is the internal conversion coefficient, equal to 8.94% in the case of ^{137}Ba).
The numerical value is:

$$I_\gamma = 0.935*(1-0.0894) = 85\%$$

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30.0 y

$_{55}$ **Cs** ^{137}

93.50%

6.50%

85%   15%   0.6616

γ   Internal conversion

0

$_{55}$ **Ba** ^{137}
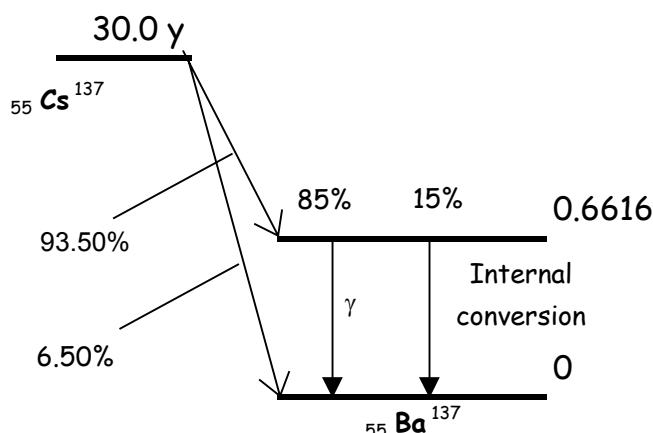
Branching ratio, see branching

Bremsstrahlung
(From German "slowing-down radiation")
Radiation produced by the interaction of fast electrons with the Coulomb field of a nucleus.
For monoenergetic electrons that slow down and stop in a given material, the bremsstrahlung energy spectrum is a continuum with photon energies that extend as high as the electron energy itself.
This process becomes important for electrons whose energy exceeds 5 MeV.

Burn-up
A measure of the consumption of nuclear fuel, U or MOX, in a reactor, and hence of the cumulative radiation dose to which the material has been exposed. The unit is MWd/tU, a typical value is 40000 MWd/t for light water reactor spent fuel.

BWR, see reactor type

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C-

Cable connection (detector+MCA-166+HP-200)
Connect cables from the detector:

1. preamplifier power supply cable to DB9 connector of the adapter cable and attach it with the clamps. Then, the adapter cable to the MCA-166 DB9 connector.

2. signal cable to MCA-166 signal input "IN".

3. high voltage cable to high voltage output "HV".

4. connection cable from MCA-166 "PC" to HP-200.

5. HV inhibit cable to adapter cable.
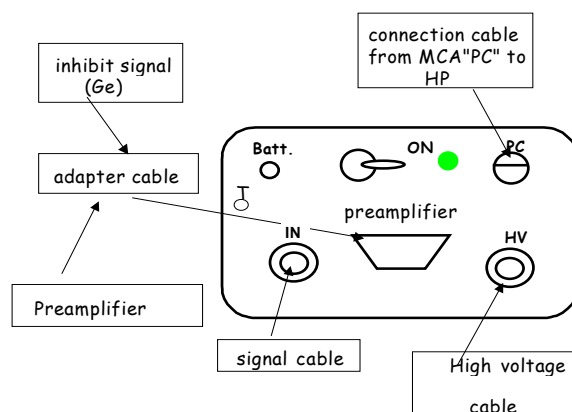
Cadmium filter
A thin layer of Cadmium interposed between the source and the detector to reduce the count rate or / and the intensity of the low energy gamma lines and X-rays.

Cadmium filter, influence on Pu measurement
The MGA code requires that the 59.6 keV line of ^{241}Am and the 208 keV line of the ^{241}Pu are approximately equal in intensity. The Cd filter can to decrease the ^{241}Am/^{241}Pu line height ratio to satisfy this requirement.

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The following pictures show examples of Pu spectra in different experimental situations.

Pu spectrum for MGA
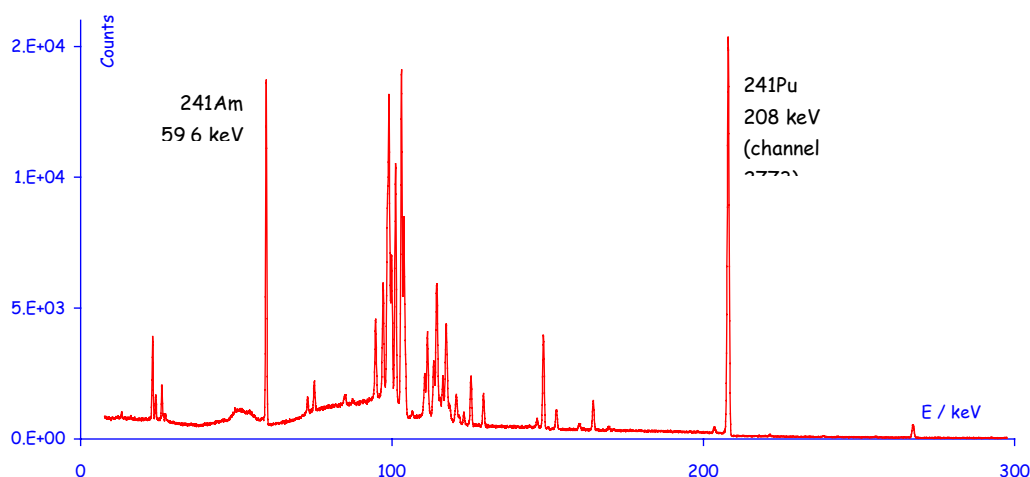
The peak height ratios in this Pu gamma ray spectrum fulfill the requirements of the MGA code.

Pu spectrum for MGA, Add Cd filter for MGA
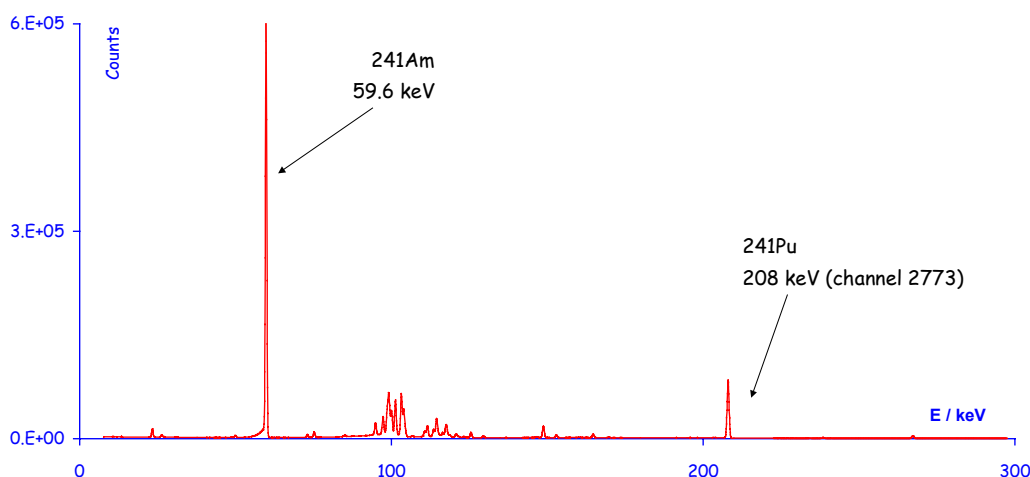
Pu spectrum measured with a too thin Cd filter

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Pu spectrum for MGA, remove Cd filter
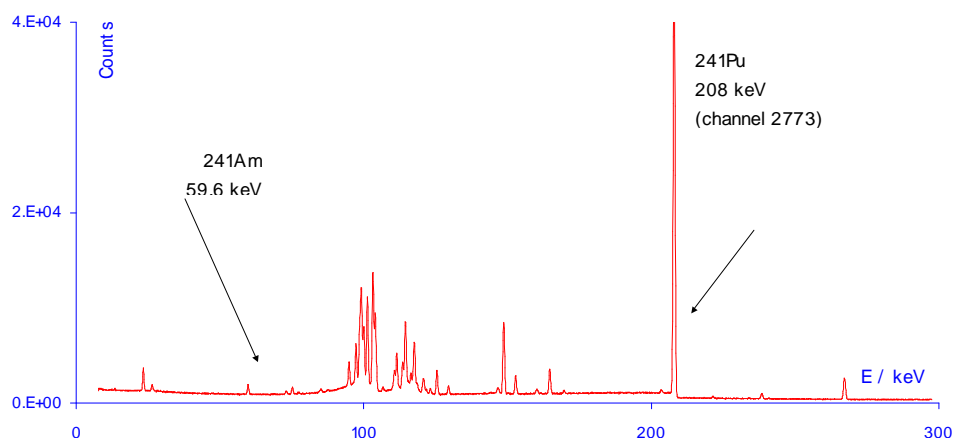
Pu spectrum measured with a too thick Cd filter (or the container wall is rather thick).

Cadmium Zinc Telluride detector (CZT)
A semi-conductor detector working at room temperature. These detectors have a high attenuation coefficient and a large band gap (E_g = 1.5 ... 1.7 eV), but suffer from poor hole transport properties. Their spectrum is less well resolved than a germanium detector spectrum but much better than a NaI detector spectrum (see resolution of a detector). Choosing hemispherical crystal geometry optimizes the resolution of the CZT detectors (only the electrons are collected). The following picture shows the structure of such a detector with a positive contact at the
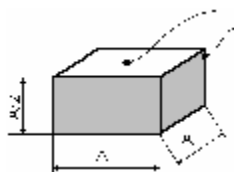
centre of the flat surface and the outer spherical surface grounded.
For a CZT/500, A=10 mm and for CZT/60, A=5 mm.
See Annex A2, table 13 for CZT detector applications and NIM A 556 (2006) 219-227 for enrichment determination with CZT/1500.

Cadmium Zinc Telluride detector, stability of the detector response
Stability tests performed during 900 hours with a uranium source on a CZT/1500 showed the following results:

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- without any electronic stabilisation of the peak position The shift of the 185.7 keV photo peak is than 0.5 % or 0.7 keV,

- the FHWM of the 186 keV peak deviates by as much as 86 % to 106 % from its initial. However, in spite of this large variation, the net peak area stays in a rather narrow band, from 97 % to 104 % of its initial value.

Calibration constants for enrichment determination
1. With germanium detector (UF6 program):
The calibration constant is determined by the measurement of at least one standard of reference.
The calibration constant for a single standard is calculated as:

$$\frac{e_1}{CR_1}$$

where e_1 is the enrichment of standard 1 and CR_1 the count rate in the 185.7 keV peak.

2. With NaI detector (U235 program):
In this case, the enrichment is expressed as:

$$e_x = A * R_{1x} + B * R_{2x} \ ,$$

where A and B are the two calibration constants determined by two standards of reference. R_{1x} and R_{2x} are the count rate of the regions of interest corresponding to the peak and background region of the sample x respectively.
The calibration constants are given by:

$$A = (e_1 * R_{22} - e_2 * R_{21}) / (R_{11} * R_{22} - R_{12} * R_{21})$$

$$B = (-e_1 * R_{12} + e_2 * R_{11}) / (R_{11} * R_{22} - R_{12} * R_{21})$$

3. With NaI detector (NaI GEM software):
The calibration constant is determined by the measurement of one standard of reference and is equal to:

$$\frac{e_s}{CR_s}$$

where e_s is the enrichment of the standard and CR_s the count rate in the 185.7 keV peak.

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Calibration Table (UF6 program)
This table contains all the information concerning the calibration constant (value, number of standards used, file name and enrichment value of the reference standards) and can add or suppress standards of reference.
To access this table, from the UF6 menu,
Select" Data acquisition" and then "Calib.Table", press ENTER.

To clean the table completely,
select "Clear Calib.table", press ENTER and YES.

To add a reference spectrum,
select " Add Entry (read file),
select the spectrum to be added with the ↓ arrow key, press ENTER twice.
Press ESC, then you see the comment and then press the F10 key to return to the calibration menu.

To suppress a reference spectrum, select "Edit entries",and press ENTER,
Type the measurement number you want to suppress, with the ↓ arrow key, go to the status bar and with the space bar, toggle "Remove this entry" and press "YES".

Calorimeter
A calorimeter is a device which measures of the heat output of samples. The release of decay heat of radioactive substances is proportional to the quantity of radioactive matter in the calorimeter.
The calorimetry is insensitive to disturbing parameters such as geometry, *matrix*, humidity, etc…It measures the plutonium mass of a sample with an high accuracy. Unfortunately, it takes hours to measure each sample.

Can wall correction for enrichment determination
Photon attenuation through the sample container wall must be corrected for if the canning material and/or thickness are different from those of the calibration standard.
The correction to be applied to the enrichment is:

$$\frac{\exp(-\mu_c * x_c * K_{wtc,c})}{\exp(-\mu_s * x_s * K_{wtc,s})}$$

where x_s , μ_s represent the thickness and [linear absorption](#) coefficient of the sample container and x_c and μ_c the thickness and linear [absorption coefficient](#) of the calibration standard container. The factor $K_{wtc,p}$ is the geometrical factor describing the effective mean path length $x_{eff,p}$ of radiation passing trough an absorber layer p of thickness x_p as follow: $x_{eff,p} = K_{wtc} * x_p$.

The wall thickness correction is automatically performed by the [UF6](#) ([Ge detector](#)) and [NaI GEM](#) ([NaI detector](#)) codes. For the [UF6](#) code, $K_{wtc,c} = K_{wtc,s} = 1$ whereas for [NaI GEM](#), the algorithm calculates an approximate K_{wtc} factor applicable for collimator diameter/thickness ratios lower than 1.7.

During the calibration and the measurement of the unknown sample, the operator inputs the container wall thickness and material type.

For more details about the calculation of K_{wtc} with a NaI detector, see [NIM A 550 (2005) 675-690](#).

CdZnTe, see [Cadmium Zinc Telluride detector](#)

Centroid of a peak
Geometric centre of a peak calculated as follows:

$$Centroid = \frac{\sum c_i * i}{\sum c_i}$$

where c_i is the content of the [channel](#) i.

Čerenkov light
Visible light, emitted when charged particles pass through a transparent medium (water, e.g.) with a velocity exceeding the velocity of light in the medium.
The beta radiation of [spent fuel](#) with a [cooling time](#) not longer than 2 years produces [Čerenkov](#) light in the surrounding water. The light can be used for attribute tests with a [night vision device](#).

Channel
The smallest energy or time slot used in the [MCA](#).

Charge collection time
The time for a charge carrier to reach its destination.

For example, in a CZT detector, the electron collection time is less than 0.5μs for an electron and 5 μs for a hole.

Cladding

The metal surrounding the nuclear fuel. For PWR fuel, the cladding consists of long tubes of a zirconium alloy. In MTR fuel, aluminum is used.

Coaxial germanium detector

A type of germanium detector with a cylindrical geometry (see drawing) and a large active volume (20 to 60 cm^3). Typical dimensions are:

   diameter: 4.5 cm

   length: between 3 and 4 cm

P-type   N-type
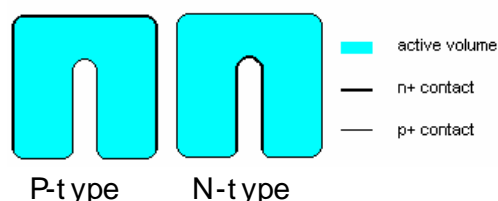
Their intrinsic detection efficiency is higher than that of a Germanium planar detector.

Typical values for the resolution are 0.8 keV at 122 keV (^{57}Co) and 1.8 keV at 1332 keV (^{60}Co).

Coincidence

The occurrence of two or more events in one or more detectors within a predetermined time interval.

Collimator

A device, usually a set of diaphragms, which collimates a beam of radiation.

Compton continuum

The continuous background observed in the spectrum and corresponding to the continuous distribution of the Compton electron energies E_e ranging from zero to the Compton edge. Associated with the energies E_e, the Compton scattering also leads to a continuous distribution of the energy E' of the scattered photons from E'= E down to the value of the backscatter peak.

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Compton edge
Pattern in a gamma spectrum:
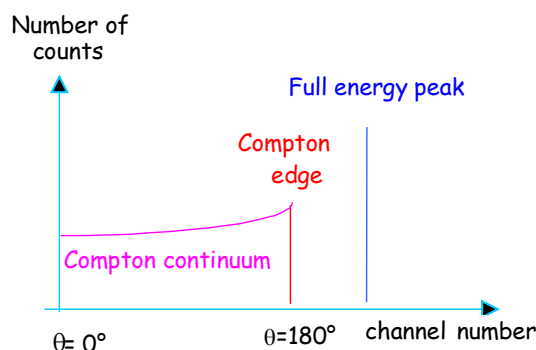
Maximum energy value for Compton electrons created by a Compton scattering in the detector, achieved when the scattering angle is θ = 180°. This energy is equal to:

$$E_{ComptonEdge} = E * (1 - \frac{1}{1 + 2 * E/511})$$

where E (in keV) is the energy of the incident photon.
Numerical values of the Compton edge energy are given in Annex A2, Tab. T5 and Tab. T7.
See also spectrum features.

Compton edge = f (Energy), see Annex A2, Tab. T7.

Compton effect
Interaction of a gamma quantum with a "free" electron. The incoming gamma quantum transmits a fraction of its energy to the electron, is scattered with an angle θ and leaves with energy E'.
The kinematics of the Compton effect is shown in the diagram:
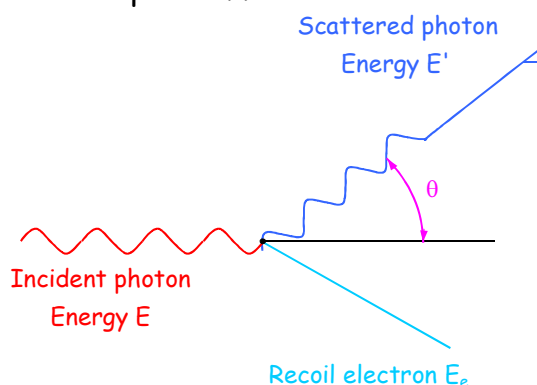
From the conservation of energy and momentum with the scattering, we obtain the relationships:

$$E_e = E - E'$$

$$E' = \frac{E}{(1 + \frac{E}{511} * (1 - \cos\theta))}$$

where:
E is the energy (in keV) of the incident <u>photon</u> and E_e is the energy of the recoil <u>electron</u>.

After a <u>Compton effect</u>, the scattered <u>photon</u> can once again interact in the crystal by <u>Compton effect</u> or by <u>photoelectric effect</u> or it can escape. This whole process (including possible sequences of interactions after a <u>Compton effect</u>) is shown in the following diagram:
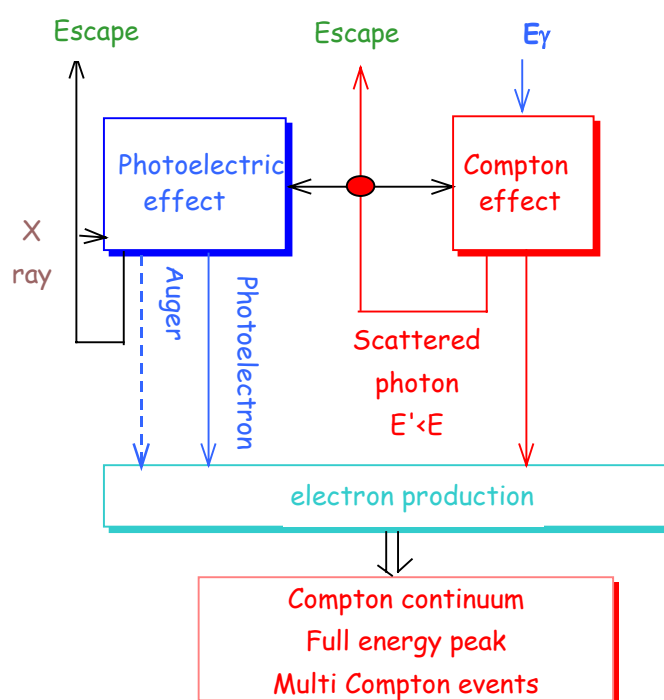
Conduction band, see <u>band structure in solids</u>

Conductor, see <u>band structure in solids</u>

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Cooling time
Time span since the end of the irradiation of nuclear <u>fuel.</u>

Count rate
Number of counts divided per unit time. It is expressed in counts per second (cps).

Counting Statistics
The <u>radioactive decay</u> is a random process. For this reason a measured (total) number of counts N from a certain radioactive sample has a statistical error ΔN:

$$\Delta N = \sqrt{N}$$

If these N counts were collected in a time t, the <u>count rate</u> n and its statistical error are:

$$n = N / t$$
$$\Delta n = \sqrt{N} / t$$

Measurement with <u>background radiation</u>:
if the measurement of the N counts of the sample is disturbed by B counts from other origins (sources, environment), the measurement will give D counts in a time t_D:

$$D = N + B$$

To correct for the <u>background radiation</u>, it must be measured without of the radioactive sample. This background measurement gives B counts in a time t_B.
The number of counts from the sample is:

$$N = D - B * \frac{t_D}{t_B}$$

The statistical error of N is:

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Caution! Do not forget other additional sources of measurement errors. (see also Net Peak Area).

Critical mass
A sufficiently high mass of a given fissile material to achieve a self-sustaining chain reaction. The amount depends on the fissile species involved, its concentration and purity, the geometry of the assembly, and the matter surrounding it.

Examples of critical masses:
Bare sphere:
^{233}U: 15kg ^{235}U: 50kg
^{239}Pu: 10kg ^{239}Pu in water: 5.4kg ^{239}Pu with 4.5% of ^{240}Pu: 16kg
^{237}Np: 60kg ^{237}Np: 60kg
^{241}Am: 60-100 kg ^{242m}Am: 8-18 kg ^{243}Am: 50-150 kg

in a metal structure:
^{235}U: 23kg ^{237}Np: 65kg ^{239}Pu: 5kg ^{237}Np: 30kg

Crossover point
The time at which the bipolar pulse passes through a designed level: the base line.

Cross section, nuclear
The effective total area of the target (nucleus, electron,...) exposed to bombardment by particles (neutrons, alpha particles, photons, etc.), used to express the probability of a particular nuclear process or reaction. The cross section σ is given by:

$$\sigma = \frac{a}{(b * c)}$$

where a is the number of processes occurring per cm^2, b the number of incident particles (per cm^2) and c the number of target nuclei (per cm^2).

The linear absorption coefficient μ is related to the cross section per atom σ by the equation:

$$\mu = N * \sigma$$

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The linear attenuation coefficient μ is related to the cross section per atom σ by the equation:

$$\mu = N * \sigma$$

where N is the number of atoms per unit volume of absorber.

The unit of cross section is the *barn* ($1b = 10^{-24} cm^2$).

Cs ratio
The ratio of the fission products ^{134}Cs and ^{137}Cs is approximately proportional to the burn-up of spent nuclear fuel at the end of the irradiation. The proportionality constant depends on the fuel type, the initial enrichment, the irradiation history and the material surrounding the fuel during the operation in the reactor.

Curie
The old unit of measurement of radioactivity. It corresponds to $3.7*10^{10}$ disintegrations per second.
(see also Annex A2, Tab. T12)

Curium
(Cm) Element 96 of the periodic classification, fourth element of the group of transuranic elements. It is produced artificially in nuclear reactors through successive neutron captures by plutonium and americium isotopes and beta decay.
Curium is an intense neutron source in spent nuclear fuel.
See also built up scheme of transuranic elements.
See spent fuel, nuclear

CZT detector, see Cadmium Zinc Telluride detector

D-

Data transfer between two HP-200 using the infrared port
1.
Configure each computer for IR communication:
From the general menu, press the number corresponding to "Exit to DOS".
Type "200" (for HP-200) or "100" (for HP-100), press ENTER.
Press the blue key "&..".
With the arrow key, go to "Filer" and press ENTER.
Press the black "MENU" key.
With the → arrow key, select " Communications" and press ENTER.
With the ↓ arrow key, select "Remote Settings" and press ENTER
With the 'TAB" and arrow keys, set:
     the Baud rate to 57600,
     the interface to Infrared,
     the server mode to Enable and press F10.

2. Position the two computers for the IR communication:

15 cm
maximum
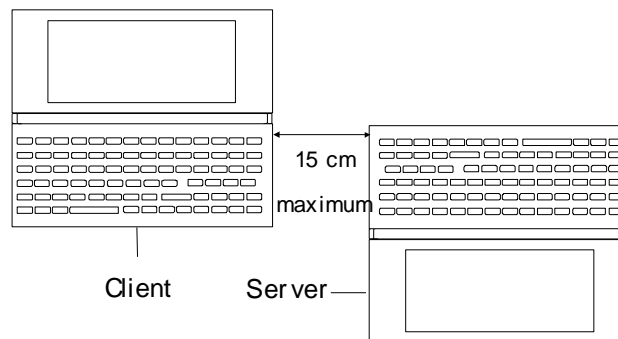
Client   Server

3.
Establish IR communication for file and directory transfer:
Press F6 on the client to establish the communication.
The left window (remove) shows the server directory.
The right window ("local") shows the client directory (the one you are working with).
Use the arrow keys and Filer functions (last line of the Filer menu) to transfer your data.
Press F10 to break the IR connection.
Press "MENU" key, then press ENTER and then "Q" to quit.

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Press F10 to break the IR connection.
Press "MENU" key, then press ENTER and then "Q" to quit.

Daughter nuclide
The product nucleus of a radioactive decay of a nuclide (called the parent nuclide).

Dead time (DT), definition
The time during which the ADC is busy and not ready to accept another pulse.

It is due to:

- the pulse pile-up
- the linear gate time
- the ADC conversion time
- the memory storage time

Dead time, MCA –166
The dead time is fixed for each pulse and is less than 8 μs (conversion time + memory storage time).
The dead time should not exceed a value of 40% for precise U measurement, 15..20% for Pu.

$$DT = \frac{(real\ time\ -\ live\ time)}{real\ time} * 100\ \%$$

Decay chain see Annex A2 Graphs G2, G3, G4

Decay constant λ
The probability per second that the nucleus will decay:

$$\lambda = \frac{\ln(2)}{T_{1/2}}$$

where $T_{1/2}$ is the half- life time of the radionuclide.

If the nucleus has several modes of decay characterized by the decay constants λ_1, λ_2...λ_n then:

$$\lambda = \sum_{i}^{n} \lambda_i$$

Example of decay constant calculation:

The half life of ^{235}U is $7.037*10^8$ years, the decay constant is:

$$\lambda = 3.12*10^{-17}\ s^{-1}$$

See also, Uranium isotopes, half lives and decay constants
and Plutonium isotopes, half-lives and decay constants

Decay law
Law which gives the number of radioactive atoms as a function of time t:

$$N = N_0 * \exp(-\lambda * t)$$
$$N = N_0 * \exp(-\ln(2) * t / T_{1/2})$$

Where: N   = atoms at time t
         No   = atoms at time t=0
         $T_{1/2}$ = time of half-life
         λ = decay constant

The picture below shows ratio N/N_0 as a function of the time:
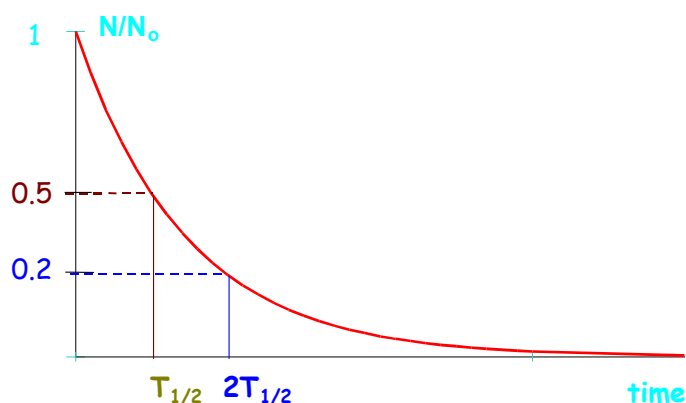
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Decay, radioactive
The gradual diminishing of the quantity of a radioactive substance due to spontaneous disintegration of nuclei by the emission of α or β particles or by spontaneous fission.

Decay scheme
The graph, diagram or table showing the transformation of a radioisotope into another radioisotope.

Example:
simplified decay scheme of ^{137}Cs:
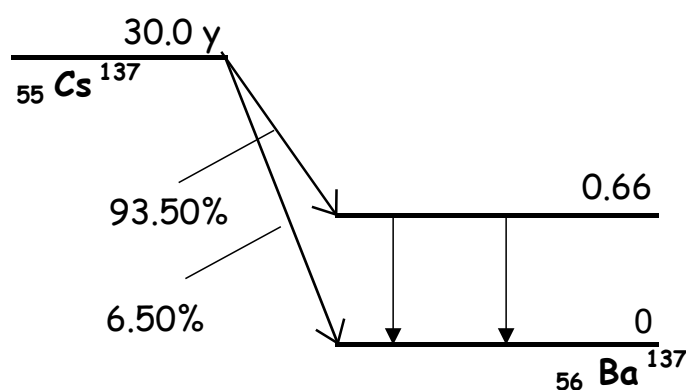
In 93.5% of the β^- decays, the ^{137}Cs leaves the ^{137}Ba (daughter) in an *excited state*. The excitation energy lost by emission of gamma rays of 661.62 keV. 6.5 % of the disintegrations of the ^{137}Cs leaves the ^{137}Ba in the ground state.

Deleting spectra on the HP-200
From the general menu, press the key corresponding to "Exit to DOS".
Type 200 for HP-200 or type 100 for HP-100 resp.
Press ENTER.
Press the blue key: ⌨
With the "TAB" and arrow keys, select the file to delete.
Press "DEL" and then F10 to confirm.
Press "MENU" and "Q" to quit the DOS.
Type "ALT","CTRL", "DEL" simultaneously to return to the general menu.

Density for commonly used material, see Annex A2, Tab.8

Depleted Uranium

Uranium in which the proportion of ^{235}U has been reduced below natural concentration (0.71%) by burn up in nuclear reactors or in the enrichment process.

Detector types, performance comparisons, see Annex A2, Tab. T13.

Diagnostics, MCA-166

The diagnostics menu of the MCA-166 software presents information on the MCA-166 used such as:

- serial number SN#
- hardware version HW#
- firmware version FW#
-the actual battery outlet currents (on the 6 ... 8V level)
  supplying the MCA and the preamplifier with +-12V and +-
  24V,
- the actual battery outlet current (on the 6 ... 8V level)
  supplying the HV module,
- the battery voltage and the actual battery outlet current,
- the charger current.

Caution! The indication "-24V 62mA" means a current from 62mA out of the battery to provide -24V to the preamplifier. The preamplifier current on the -24V level depends on the actual battery voltage (7.2V e.g.). The preamplifier current on the -24V level of this example can be estimated as follows:

$$I_{24V} = 0.8 * 62mA * 7.2V / 24V$$
$$I_{24V} = 14.9 \ mA$$

The factor 0.8 is the efficiency of the voltage transformation.

If the total power consumption is above about. 2 W, a warning appears:

"MCA Power Fail! Go to Diagnostics!"

In the Diagnostics menu, the relevant current indication flashes. This warning may appear for old (but still good!) Ge detectors whose preamplifiers have a higher power consumption. Despite of the warning the MCA-166 might still work correctly: this must be observed during the measurements. The battery will discharge in a shorter time.

If there is a short circuit, the instrument will switch off.

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Diagnostics, batteries

If the MCA-166 battery voltage is below 5.6V, the green light will flash irregularly and a warning will appear on the computer screen. The measurement will be stopped automatically and the HV and the preamplifier supply will be switched off. The user can now still transfer the spectra.

If the user does not react and the battery voltage falls below 5.4V, the MCA-166 will switch off completely. The spectrum stays in the memory of the MCA-166 and can be read out later. The battery must be recharged as soon as possible.

Differentiator

A pulse shaping network using a capacitor in series and a resistor to ground.
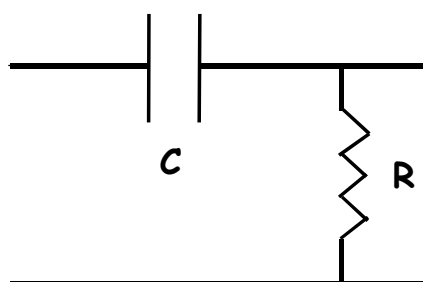
It allows high frequency inputs to pass but attenuates the low frequency input.

(See also integrator).

Direct use material

Material which can be used to manufacture a nuclear weapon without further enrichment or irradiation in a reactor.

See also, weapon grade material

Discriminator

A device that generates a logic pulse when the input signal exceeds a preset threshold level.

(See also Lower Level Discriminator and Upper Level Discriminator).

Disintegration
A process resulting in the change of a radioactive nuclide through the emission of alpha or beta particles producing a change in the atomic number of the element.

Display live time/ real time, see preset counting time

Dose, energy dose
The mean value of ionization energy deposited in matter per unit of mass. It is expressed in Gray, 1Gy = 1 J/kg (see units).

Double escape peak
With a pair production process in a detector, the annihilation of the positron leads to the production of 2 gamma photons of 511 keV. The escape of these two photons from the detector gives rise to a double escape peak at the energy $E\gamma$-1022 keV where $E\gamma$ is the energy of the incident photon (see picture below).
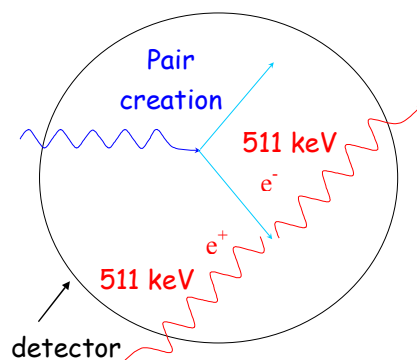
For example, on the ^{22}Na spectrum (see spectrum features), it is possible to see the double escape peak corresponding to the energy E equal to:

$$1274 - 1022 = 252 \text{ keV}$$

DT, see dead time

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E-

EC, see electronic capture.

Efficiency, absolute full-energy peak
Equal to:

$$\varepsilon_a = \frac{\text{Net peak area}}{\text{number of gamma quanta emitted}}$$

The absolute efficiency depends on the geometrical arrangement of source and detector. The self-absorption factor is assumed to be 1 (i.e. no self absorption in the source), see Annex A1e, Annex A2 Tab. 14, Annex A2 Graph G

Efficiency, intrinsic full energy peak
Equal to:

$$\varepsilon_i = \frac{\text{Net peak area}}{\text{number of gamma quanta striking the detector}}$$

For a point source:

$$\varepsilon_i = \frac{Net\ peak\ area}{a * I_\gamma * \frac{A}{4\Pi r^2}}$$

where:

a is the activity of the point source
I_γ is the gamma branching ratio
A is the detector surface (seen from the source)
r is the distance source – detector
(see Annex A1e, Annex A2 Tab. 14, Annex A2 Graph G)

Efficiency, relative
Characterizes the efficiency of the detector compared to a NaI detector of 76 mm diameter and 76 mm length

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It is equal to:

$$\varepsilon_r = \frac{\text{efficiency of a detector at 1332 keV with 25 cm source distance}}{\text{efficiency of a 76*76mm NaI(Tl) detector at 1332 keV with 25 cm source distance}}$$

(see Annex A1e, Annex A2 Tab. 14, Annex A2 Graph G)

Electron
An elementary particle carrying one unit of negative electrical charge.
The electrons determine the chemical behavior of elements.
The mass m_e of the electron is:
  m_e = 9.108*10^{-31} kg
     = 1/1836 of proton mass.

Electronic capture
A process in which the excited nucleus of an atom captures a K electron
following the nuclear reaction:

$$e^- + p \rightarrow n + \nu_e$$
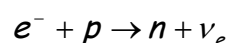
The reaction sequence is:

$$^A_Z X + e^- \rightarrow ^A_{Z-1} X + \nu_{e+}$$
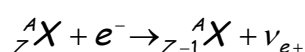
where $^A_Z X$ represents a nucleus of atomic number Z and mass number A
and ν_{e+} the neutrino .
The electron vacancy leads to the rearrangement of the atom shell with
X-rays or / and Auger electron emission.

Electronic system for gamma spectrometry
The different modules of the electronic system for gamma spectrometry
are illustrated in the following diagram.

```
        ┌──────────────┐
        │ Low voltage  │
        │   Supply     │
        └──────┬───────┘
               │
┌──────────┐   ▼   ┌──────────────┐   ┌───────────┐   ┌───────────────┐
│ Detector │──►│ Preamplifier │──►│ Amplifier │──►│ Multichannel  │
└──────────┘   └──────┬───────┘   └───────────┘   │   analyser    │
               ▲                                    └───────────────┘
        ┌──────┴───────┐
        │ Detector bias│
        │   Supply     │
        └──────────────┘
```
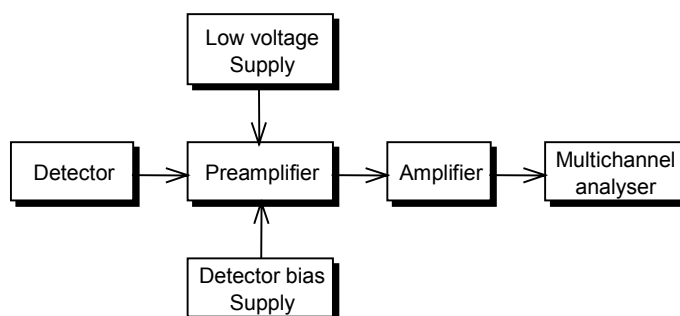
Electron volt (eV)

Amount of energy gained by an electron (or any particle with 1 elementary charge) as it passes through a potential difference of 1Volt.
(See also Annex A2, Tab. T12)

Energy calibration, definition

The energy calibration converts the x-axis channel number into energy values expressed in keV following the formula:

$$E = a * channel + b$$

Where a is the slope, b the zero offset.

Energy calibration, with SPEC program

From the SPEC menu, select "Data acquisition", then "Energy calibration".
Use the space bar to turn the Energy calibration "on"
with the arrow and numeric keys, enter the 2 energy values and then there are three calibration possibilities:
1.You know the peak positions:
Toggle "manual input" for the peak position, press ENTER and type the values for channel 1 and 2.
Press ENTER. The "actual calibration" gives the equation of the energy calibration
Press ESC and ENTER to return to the menu.
2. You want to define the peak positions looking at the spectrum:
Toggle "cursor" for the peak- position, press ENTER, select "Do visual calibration".

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Follow the instructions on the screen (use F7 to expand the spectrum
and F8 to unexpand) and then press "Y" to store the calibration
The "actual calibration" gives the equation of the energy calibration.
Press ESC and ENTER to return to the menu.

3. The peaks are in two predefined regions of interest:
Toggle "centroid" for peak position and select "Do visual calibration",
press ENTER
Follow the instructions on the screen (use F7 to expand the spectrum and
F8 to unexpand).
Press "Y" to store the calibration
The "actual calibration" gives the equation of the energy calibration.
Press ESC and ENTER to return to the menu

Energy needed to create an electron-hole pair

Material	Energy (eV)
Ge	2.96 (77° K)
NaI	20 (300° K)
CdTe	4.43 (300° K)

Enriched Uranium

Uranium containing more than the natural abundance (0.71%) of the
isotope ^{235}U.

Enrichment, calibration constants, see calibration constants for
enrichment determination.

Enrichment, definition:
Relative to weight:

$$e_{wt\%} = \frac{^{235}U \text{ mass}}{\text{Total mass of U}} * 100 \ [wt\%]$$

Relative to atom number:

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$$e_{at\%} = \frac{\text{number of } ^{235}\text{U atoms}}{\text{number of U atoms}} *100 \ [at\%]$$

The relationships between $e_{wt\%}$ and $e_{at\%}$ are:

$$e_{at\%} = 238 / (235/e_{wt\%} + 3/100)$$

$$e_{wt\%} = 235 / (238/e_{at\%} - 3/100)$$

Enrichment meter principle
One of the techniques used to determine the Uranium enrichment.
It consists in establishing the proportionality relation of count rate (at 185.7 keV) and enrichment between a calibration standard (reference) and an unknown sample.
It is expressed by:

$$\frac{e_{us}}{e_{st}} = \frac{CR_{us}}{CR_{st}}$$

Where:

e_{us} is the unknown sample enrichment
e_{st} is the standard enrichment
CR_{us} is the unknown sample count rate
CR_{st} is the standard count rate

The enrichment meter principle can be applied only to infinitely thick material (see infinite thickness).
The codes U235, UF6, NaIGEM and the "Enrichment meter" mode of the MGAU code apply the enrichment meter principle.

Enrichment techniques
There are several possible enrichment methods, but the only two that are used on a large scale are gaseous diffusion and gas centrifuging. Laser diffusion is also used on an industrial scale.

Gaseous diffusion:

This consists in passing gaseous Uranium hexafluoride UF_6 (made in conversion plants) through walls (diffusion membranes) with countless tiny pores. The molecules of $^{235}UF_6$ diffuse more rapidly than those of $^{238}UF_6$, and a small separation is achieved. Little by little the mixture is enriched leaving depleted Uranium. Some thousands of stages are therefore needed in the plant to produce a substantial enrichment.

Gas centrifugation:

It consists in using a mixture of gaseous molecules (UF_6) at high speed in a specially designed closed container. The heaviest species $^{238}UF_6$ concentrates near the outer walls and is thus separated from the lightest $^{235}UF_6$ which remains near the axis.

Laser separation, SILVA process (French acronym for Separation

Isotopique par Laser de la Vapeur Atomique d'Uranium):

The process is based on the selective absorption of photons by gases of Uranium hexafluoride (UF_6) molecules or Uranium atoms.

The first stage consists in evaporating metallic Uranium at 3000 °C with an electron beam.

The Uranium vapour is then bombarded with laser photons tuned to a specific wavelength to excite ^{235}U selectively.

During this stage only the ^{235}U atoms are ionized and the ions are separated by an electric field and received on dedicated collectors. This last operation is performed at 1200°C.

Environmental ratings for the MCA-166

Storage temperature range:

-20 to +60 degrees C

Operational temperature range:

0 to 50 degrees C

Humidity range:

up to 90%, non-condensing

Equivalent dose

Parameter which quantifies the effect produced by irradiation. It is expressed as a function of the type of radiation, the irradiation conditions and the type of tissue irradiated.

The unit is Sievert (see Annex A4 and also Annex A2, Tab. T12).

Excited state

If the internal energy of an atom, molecule or nucleus exceeds the minimum possible value, it is said to be in an excited state.

Normally, the excited states have an extremely short half life and decay to the ground state by emission of gamma quanta.

Example: the following diagram shows excited states of ^{231}Th.
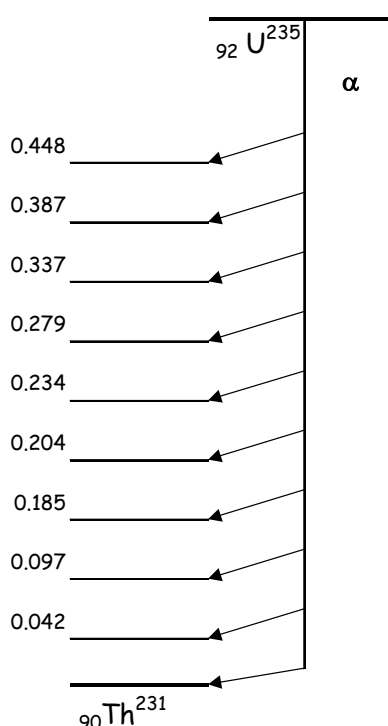
Expand a spectrum

Press F6 to change the Y scale: automatic linear mode, manual linear mode and log scale.

In the linear mode the ↓ and ↑ arrow keys can be used to change the Y scale.

To expand the X scale, first move the cursor to the desired region and then press F7. To unexpand the spectrum, press F8.

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F-

Fall time
The time required for the pulse to fall from 90% of its maximum to 10% of its maximum.

Fast breeder reactor, see reactor type

Fertile
Any nucleus which is not fissionable by thermal neutrons and which can capture a neutron to become fissile is called a fertile nuclide. The most common example is ^{238}U, which can capture a neutron to yield ^{239}U which decays to ^{239}Np and then into fissile ^{239}Pu:

$$^{238}U + n \rightarrow {}^{239}U + \gamma$$

$$^{239}U \xrightarrow{\beta^-} {}^{239}Np + \gamma$$

$$^{239}Np \xrightarrow{\beta^-} {}^{239}Pu + \gamma$$
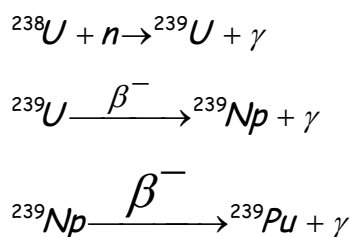
Firmware
Device specific piece of software to implement a special interface on the device, which can only be used but not changed by the routine user.

Fissile
The term is applied to any nucleus which can be caused to undergo nuclear fission by neutron bombardment. The principal fissile materials are ^{235}U, ^{233}U and ^{239}Pu, the last two being artificially produced from the fertile materials ^{232}Th and ^{238}U, respectively.

Fission, nuclear
The splitting of an atomic nucleus into two fission fragments. It can be a spontaneous process (spontaneous fission, a type of radioactivity) or the result of the irradiation with neutrons (induced fission).

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Fission products
Any of the primary fragments resulting from the fission of heavy nuclei, together with their radioactive decay products. About 200 different stable and radionuclides have been identified as fission products. These range in mass from 72 to about 160 and represent variant forms (isotopes) of some 35 different chemical elements, ranging from atomic number 30 (Zinc) to 74 (Gadolinium).

Fission product yield
The fission product yield of a fission product nuclide is the probability to receive this nuclide with a fission of a fissile nuclide. It depends on the fissile nucleus. It may be slightly different for spontaneous and induced fission. For induced fission, it depends on the neutron energy. The sum of all fission product yields for one fissile nuclide is 200% (1 fissile nucleus gives 2 fission product nuclei.) Table T2 in Annex A2 gives fission product yields for ^{235}U for induced fission with thermal neutrons.

Fission product yield for 235U   see Annex A2 Tab. T5

Fission, spontaneous
Some of the nuclei of high mass are unstable against break-up into two fission product nuclei. This process is called spontaneous fission.

Fluorescence
Light emission of some substances under the influence of radiation. It is the prompt emission of visible light from the substance (contradistinction to phosphorescence which is the slow component).
See also scintillator, luminescence and NaI detector.

FP program (CdZnTe detector)
Program which allows the verification of the presence of ^{137}Cs, ^{134}Cs and ^{60}Co gamma lines in spectra of spent nuclear fuel. The spectra are measured under water in a spent fuel pond with a *SFAT* (Gamma-Taucher, e.g.), which is equipped with a CdZnTe detector. The code informs already during the measurement if there are ^{137}Cs or ^{60}Co gamma lines. In case of doubt it writes "trace" to tell that probably, after a longer measurement time, there will be a line. At the end of the measurement there will be also a search for ^{134}Cs lines.

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Fuel, fresh
Nuclear fuel before its use in a reactor. It is fissile material and emits gamma radiation from U isotopes (or both U and Pu isotopes in the case of MOX). The gamma radiation makes it possible to non-destructively determine the enrichment of ^{235}U or the isotopic composition of Pu. There is also a neutron emission from Pu.

Fuel, nuclear
Technical structures containing fissile material such as U metal, UO_2 or MOX.
Examples:
Fuel rods or pins: Metal tubes of about 10 mm diameter and 1...4 m length containing UO_2 or MOX pellets. Bundles of about. 200 rods (fuel elements) are used in power reactors.
Fuel plates: Stacks of metal plates of about.2 * 100 * 800 mm^3 containing UO_2, used in MTR (material test reactors).

Fuel cycle
All the stages involving the nuclear fuel from the Uranium mining and making yellow cake to the fuelling of a reactor, fuel reprocessing and waste management. A simplified scheme of the fuel cycle is given the following diagram:
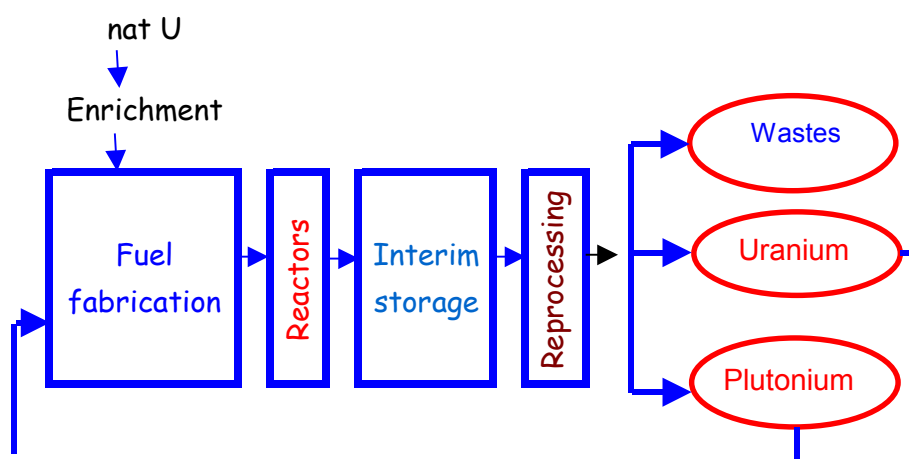
See also Annex A2, Graphs G9 and G10

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Fuel pellet
Sintered UO_2 or MOX cylinder, smallest individual fuel component in a fuel rod, typically up to about 1.5 cm long and 1 cm thick. One pellet contains more energy than one ton of coal.

Fuel pin
Metal tube filled with pellets.

Fuel reprocessing
The chemical or metallurgical treatment of irradiated reactor fuel for the purpose of recovering and decontaminating the fissionable and/or fertile materials that it contains.
A diagram of the PUREX fuel reprocessing is given in Graph G9 (Annex A2).

Full-energy peak
The peak which is caused by the photoelectric effect or by a sequence of interactions with complete energy release in the active detector volume, e.g. Compton effect + Photoelectric effect, etc…

Full-energy peak shape
A full-energy peak can be represented by a Gaussian function:

$$G(i) = H_g * \exp(-(i - i_o)^2 / (2\sigma^2))$$

where H_g is the height of the Gaussian, i the channel number, i_0 the centroid, and σ the standard deviation related to the resolution FWHM (Full Width at Half Maximum) by:

$$FWHM = 2.35 * \sigma$$

Alternatively, this expression can be written as:

$$G(i) = \frac{A}{\sigma\sqrt{2\pi}} \exp(-(i - i_o)^2 / (2\sigma^2))$$

where A is the *net* peak area.

FWHM

Full Width at Half Maximum, see resolution of a detector

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G-

Gain, definition
Ratio of the amplifier's output signal to its input signal.
The gain of the amplifier is the product of the coarse gain (switched gain factor) times the fine gain (continuous gain control).

Gain, adjustment with MCA, SPEC, UF6, U235 and FP programs
Some spectrum evaluation codes need to find special gamma ray lines in certain channels.

For example, for the enrichment determination, the 185,7 keV line of ^{235}U must be in channel 300 of 512 for the 235U code and in channel 3321 of 4096 for the UF6 code.
For the FP program, the 662 keV line of ^{137}Cs must be in channel 900.
For MGA, the 208 keV line of ^{241}Pu must be in channel 2773 of 4096.

For all the codes,
go to "Setup", press ENTER
select "Amplifier setup", press ENTER
Toggle the value of the coarse gain with the space bar
Press the down arrow key and type the value of the fine gain.
Then select "switch to visual gain adjustment", press ENTER.
You see the spectrum.
Press "+" or "-" to adjust the fine gain and if it is necessary to adjust the coarse gain, press ESC and "N".
When the adjustment is correct, press ESC and ENTER to accept the settings.

Gain value and gain calculation example
The following table gives the values of the gain that brings 2 MeV into the last channel of the spectrum for a series of typical detectors for a shaping time of 2µs (for 1 µs, the gain values are practically identical).

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Detector type	Gain for 2 MeV full range
CdTeZn SDP/Z/60-Ritec	54.74
CdTeZn SDP/Z/20-Ritec	88.06
CdTeZn CZT500-Ritec	105
Ge Planar-GIO210R-7905SL-7.6	3.22
Ge coaxial-GEM-25185-S	19.12
NaI S-1203 teledyne	25.92

Example of gain calculation:
Data:
Detector used: germanium coaxial detector (type GEM-25185-S).
Number of channels used: 4096.
The user wants to adjust the gain so as to place the 185.7 keV line of ^{235}U in channel 3321. It corresponds to:
187.5 / 3321 = 0.0559 keV/channel.

Calculation:
The table gives a gain of 19.12 for a 2 MeV full range.
For 4096 channels, this gain corresponds to:
        2000 / 4096 = 0.488 keV/channel

To obtain 0.0559 keV/channel, the gain must be equal to:
        (0.488 / 0.0559) * 19.12 = 166.91
Since 166.91 = 200 * 0.8346, the coarse gain must be equal to 200 and the fine gain to 0.8346.

Gamma branching ratio
The ratio of the branching fractions for any gamma mode of *disintegration* of a particular nuclide. See also branching.

Gamma detectors and their applications, see Annex A2, Tab. T13

Gammanal function
Name of the analytical peak-shape function used in the MGA program.

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The peak is describe with an exponential and a short term tailing function T_1 and a long-term tailing function T_2:

$$y_i = y_0 * (\exp(\alpha(x_i - x_o)^2 + T1(x_i) + T2(xi)$$

where

y_I is the net counts in channel xi
y_0 is the peak height at the peak position x
x_o is the peak position
α is the peak width parameter $\alpha = -1/2\,\sigma_s^2 = -2.7726/(FHWM)^2$
The tailing functions are given by:

$$T_1(x_i) = A.\exp(B(x_i - x_o)) * [1 - \exp(E*\alpha*(x_i - x_o)^2]$$
$$T_2(x_i) = C.\exp(D(x_i - x_o)) * [1 - \exp(E*\alpha*(x_i - x_o)^2)]$$

The parameters A and C represents the tailing height whereas B and D are the two tailing decay constants. E is the truncation parameter that usually has a value of 0.4 for Ge detector and O.6 for CZT detector.

Gamma radiation path in matter, see range of particles

Gamma ray (γ-ray)
Electromagnetic radiation of nuclear origin, of very short wavelength, emitted by the nuclei of certain atoms in the course of their radioactive decay. Gamma rays are not composed of particles, but consist of high-energy photons; they have the speed of light, have no electric charge and no rest mass.

Gamma spectrometer, see electronic system for γ spectrometry.

Gamma-Taucher
Under-water measurement head for the measurement of gamma radiation emission of nuclear spent fuel with cooling times longer than 1 … 2 years. It is equipped with a CZT detector. The spectra show gamma lines of fission products (^{134}Cs, ^{137}Cs, …) or activation products (^{60}Co). The spectrum measurement can be performed with the MCA-166 using the FP code.

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Gated integrator amplifier

Type of amplifier which can minimize the pulse amplitude loss caused by the ballistic deficit by integration of the shaped pulse.

Gaussian shaping

A common method of processing a signal in an amplifier so that the shape of the output pulse can be approximately described by a gaussian distribution.
The MCA-166 uses a gaussian shaping.

Gas centrifugation, see enrichment techniques

Gaseous diffusion, see enrichment techniques

Geiger counter

A radiation detector which has been in widespread use for many years. It is usually a gas filled cylindrical metal tube having a central anode of tungsten wire. The field strength applied is such that the gas multiplication is very high and the output pulse height is independent of the primary ionization and hence the type and energy of the radiation which is being detected. Thus the Geiger counter cannot be used to measure energy or distinguish between various particles (e.g. alpha and beta particles).

Germanium detector

A semi-conductor detector which consists of a high purity Germanium crystal which is placed between two electrodes P and N themselves connected to a voltage generator (see figure below). The Ge crystal is an intrinsic region.
Under reverse bias (reverse because the positive voltage is connected to the N electrode), an electric field extends across the intrinsic region.
The interaction of ionizing radiation with the crystal produces "hole-electron" pairs that are swept by the electric field to the N and P electrodes.
The charge collected is proportional to the energy deposited by the incoming photon.

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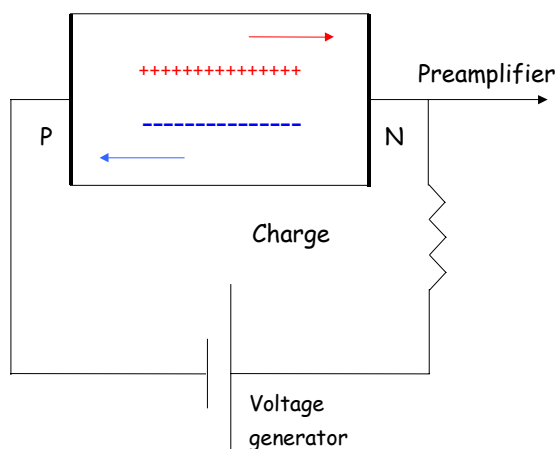
Two structures are possible:
-the planar geometry
-the coaxial geometry.

The advantage of the germanium detectors is their excellent energy
resolution.
Their disadvantage is that they need to be cooled down with liquid
nitrogen.(see thermal generation of charge carriers).

Grade of Plutonium, see Plutonium grades

Gray, see units

Ground state
The state of an atom, molecule or nucleus for which the internal energy
has the minimum possible value.

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H-

Half-life
The time T required for a source to lose 50% of its activity.
See decay law.

Half-thickness
The thickness of material which will reduce the intensity of a given monoenergetic gamma radiation to one-half. This thickness x can be related to the linear attenuation coefficient μ by the equation:

$$x = 0.693 / \mu$$

(See attenuation law).
The Table T10 in Annex A2 gives the values (in cm) for different absorbers and energies.

Help function
Press F1 on the HP-200.

HEU
High Enriched Uranium. An HEU sample has an enrichment of more than 20% ^{235}U.

High voltage inhibit
Germanium detectors are equipped with an internal temperature sensor and associated circuitry which can be used to disable the bias supply in the case of accidental warm-up of the detector.
The polarity of the high voltage can only be inverted by changing the HV module inside the MCA-166 box.

High voltage inhibit, how to activate it?
It is possible to activate the HV inhibit with the programs UF6, SPEC, FP, MCS and RATE.
For all programs,
Select "SETUP", press ENTER
With the space bar, select the type of detector to be used on the line "HV Inhibit signal "

Press ESC and Y to return to the program used.

High Voltage, MCA-166 specifications
Positive or negative, 0 to 3000 V, with remote shutdown.

HP-200 display contrast
To darken: Press "ON" and "+" key,
To lighten: Press "ON" and "-" key.

HP-200 hard reset
On the HP-200, press "CTRL","ALT","ON" simultaneously.
then press "N" and "ENTER". Check date, time and battery charging.
(See also HP-200 reset)
Attention! A hard reset will:
- reset all HP-200 settings made with the Setup Utility (e.g. battery charging, date, time) at the default state and
- cause danger of data loss!

HP-200 reset
If the HP-200 no longer reacts to any key or behaves unusually, try a system reset with "CTRL" "ALT" "DEL" simultaneously. The HP-200 will restart and present the user program menu.
If the HP-200 does not react to a system reset by pressing "CTRL" "ALT" "DEL" simultaneously, you can attempt a hard reset.

Hypermeth function
Name of a mathematical model used to describe a gamma peak shape. It combines the following components:

      A Gaussian $G(i)$
      A step-like function $S(i)$ whose intensity is zero to the far right of the peak
      A low-energy tails $D(i)$

For a single peak, the response $F(i)$ is:
      $F(i) = G(i) + S(i) + D(i)$,
      where i is the channel number,
with

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$G(i) = H_g * \exp(-(i-i_0)^2/(2\sigma^2))$,

    where H_g is the height of the Gaussian,
    i_0 the centroid: $i_0 = A_1 + A_2 * E_{peak}$
    σ the standard deviation:

$$\sigma^2 = A_3 + A_4 * E_{peak} \ ,$$

$S(i) = H_s * H_g * \mathrm{erfc}((i-i_0)/(\sigma*2^{1/2}))$,

    where H_s is the step height expressed as a fraction of the parent
    gaussian height,

$D(i) = H_t * H_g * \exp((i-i_0)/(T_s*\sigma)) * \mathrm{erfc}((i-i_0)/(\sigma*2^{1/2}) + 1/(T_s*2^{1/2}))$,

    where H_t is the tail height expressed as a fraction of the parent
    gaussian height ,
    T_s the inverse slope of the exponential tail and erfc, the
    complementary error function.

I -

IC, see internal conversion

Impedance
In an alternating current mode, measure of the total resistance that a circuit or a part of a circuit such a resistor presents to electrical current flow.

Infinite thickness, definition
Remember that the intensity attenuation I/I_o of a beam passing through an absorber of thickness x (cm) and with a linear attenuation coefficient μ (cm^{-1}) is:

$$\frac{I}{I_0} = \exp(-\mu x)$$

Sample layers with a thickness dx in a depth x below the sample surface contribute to the radiation emission out of the surface with an intensity:

$$dI = \exp(-\mu x).dx$$

The practically infinite thickness IT is achieved, if :

$$\int_{x=0}^{IT} e^{-\mu x}\,dx \geq 0.999 * \int_{x=0}^{\infty} e^{-\mu x}\,dx$$

Resolving this equation gives:

$$IT \geq \frac{6.91}{\mu} = 10 * \text{half thickness}$$

Table T9 (Annex A2) gives the values of the infinite thickness for typical Uranium materials.

Example of a cylindrical geometry:
The figure below represents a cylindrical sample with varying filling height. The next figure gives the
number of counts detected by the detector as a function of the filling height. For a height IT, the infinite thickness, the number of emitted counts N is equal to 99.9 % * N_{max}.

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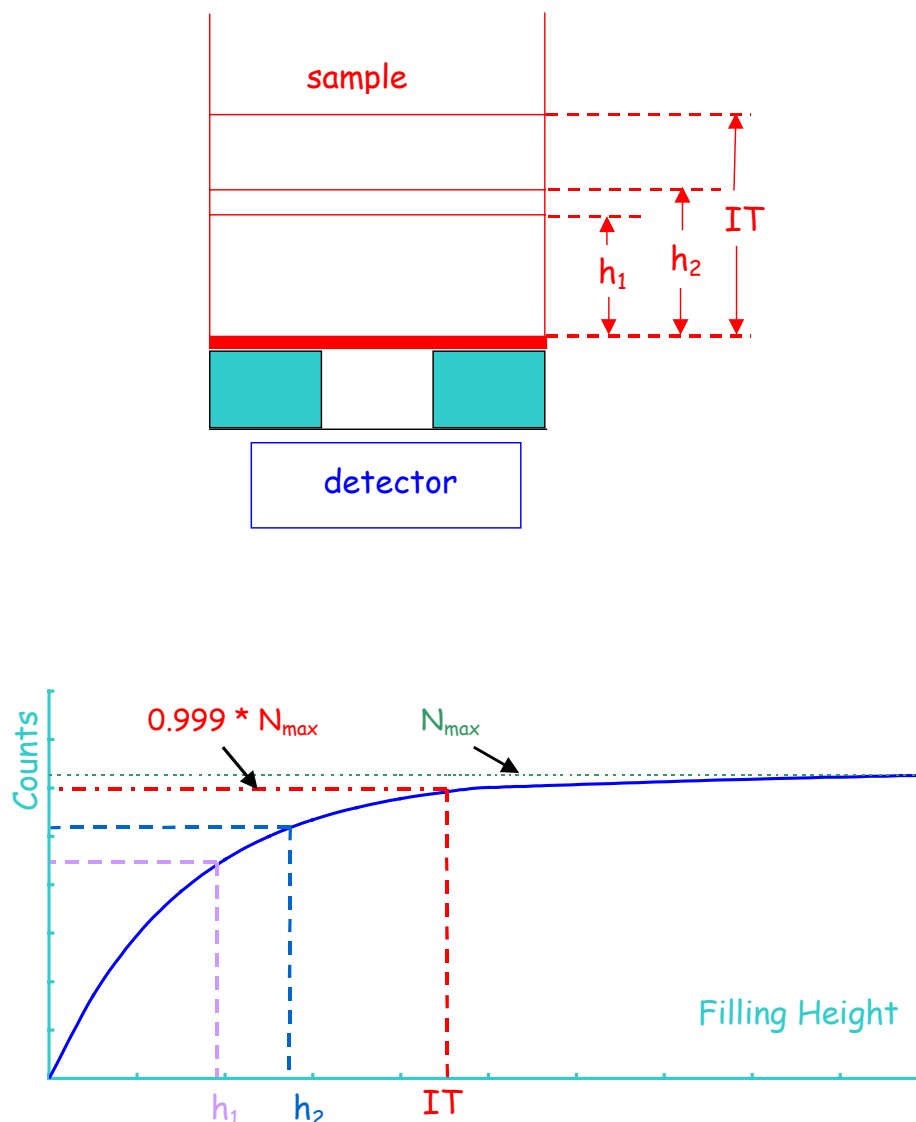
Infinite thickness condition, checking

We consider a cylindrical sample.
To check the infinite thickness condition, it is necessary to:

1.
calculate the minimum sample mass m_{min}:

$$m_{min} = SD^2 * \frac{5.42}{(\frac{\mu}{\rho})}$$

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where SD is the sample diameter and (μ/ρ) is
the mass attenuation coefficient (cm^2/g) of the matrix.
The Graph G1 (Annex A2) give the values of the minimum sample mass for
different matrices.

If the mass of the sample is lower than m_{min}, the enrichment meter
principle cannot be applied. If you try to apply it, the read-out
enrichment will be under-estimated.

2.
if the sample mass is higher than m_{min}, check that the infinite thickness
condition is fulfilled in all the directions of the viewing angle (see figure
below):
calculate the infinite thickness IT:

$$IT = \frac{6.91}{\mu}$$

and then, with a sketch (see figure below), check that the infinite
thickness condition is fulfilled in alldirections "seen" by the detector. If
it is not fulfilled, you cannot apply the enrichment principle meter.
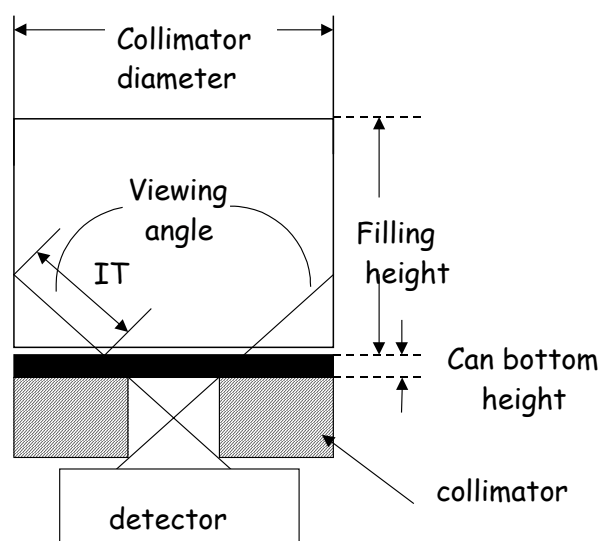
Infinite thickness of Uranium, numerical values, see Annex A2 Tab.T9,
Annex A2 Graph G1

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Insulator, see band structure in solids

Integral linearity of a MCA
The integral linearity is the maximum deviation of the measured curve pulse height versus channel number from a best-fit straight line. It is conventionally quoted as a percentage. Nonlinearities are most often observed at either pulse height extreme and typical values are less than 1% for well-designed analyzers.

Integral, of a ROI (Region of Interest)
Total number of counts in the ROI (including the background).

Integrator
Pulse shaping network using a resistor in series and a capacitor to ground (see figure below).
The low frequency inputs are transmitted to the output without attenuation and the high frequency inputs are blocked by the network. (see also, differentiator).
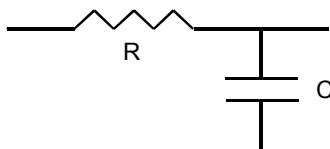
Interaction of gamma radiation with matter
Gamma radiation interacts with matter, producing energetic charged particles. The three main interactions by which the photon energy is transferred partially or completely to electron energy are the:

        photoelectric effect
        Compton effect
        pair creation.

The whole mechanism of interactions (including possible sequences of interactions as first a Compton effect and then a photoelectric effect) is shown in the following diagram:
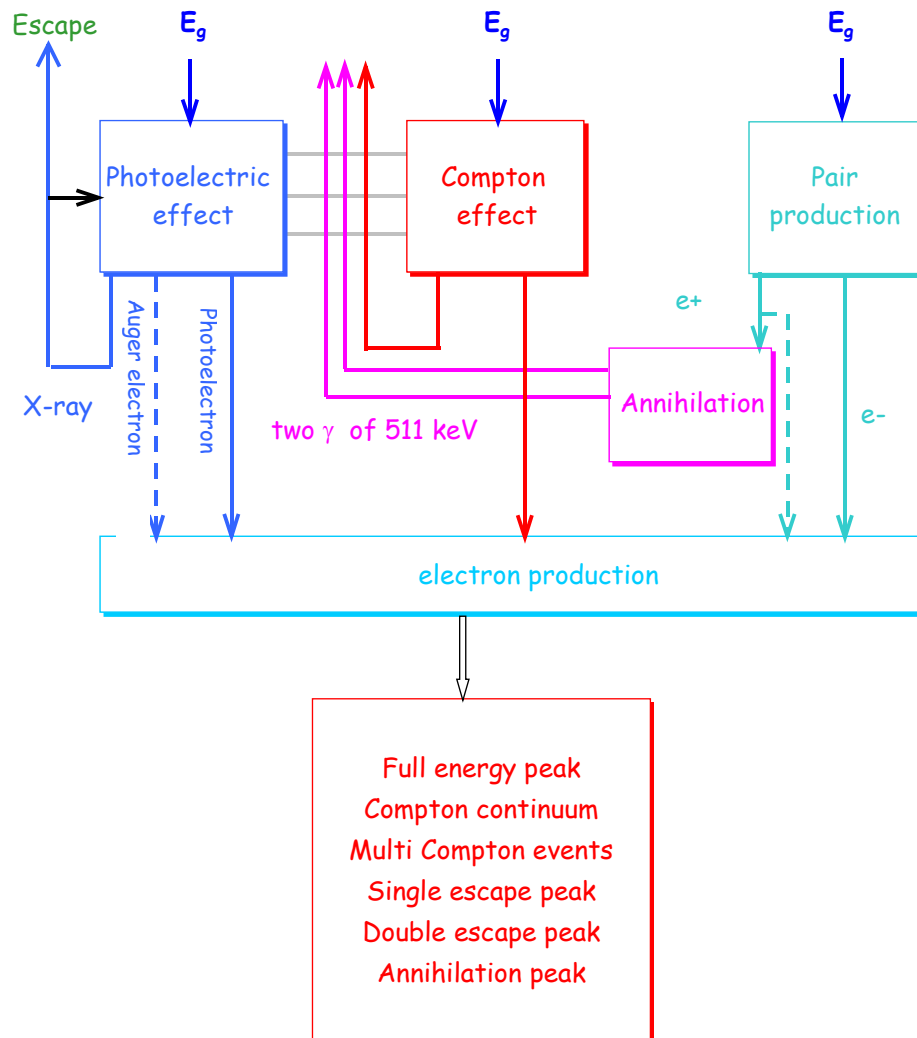
At low energy (<100 keV), the photoelectric effect in heavy elements is the most probable way of interaction. Between 100 keV and 1MeV, either the photoelectric effect or the Compton effect is the most dominant process in heavy elements. Above 1 MeV the Compton effect is the major process, but the probability of a pair production effect increases rapidly in heavy elements and becomes dominant at 10 MeV.

Interference of gamma rays
Overlapping of gamma rays which are so close that they cannot be resolved by the detector.

The diagram below shows U spectra taken with a NaI detector and with a Ge detector.
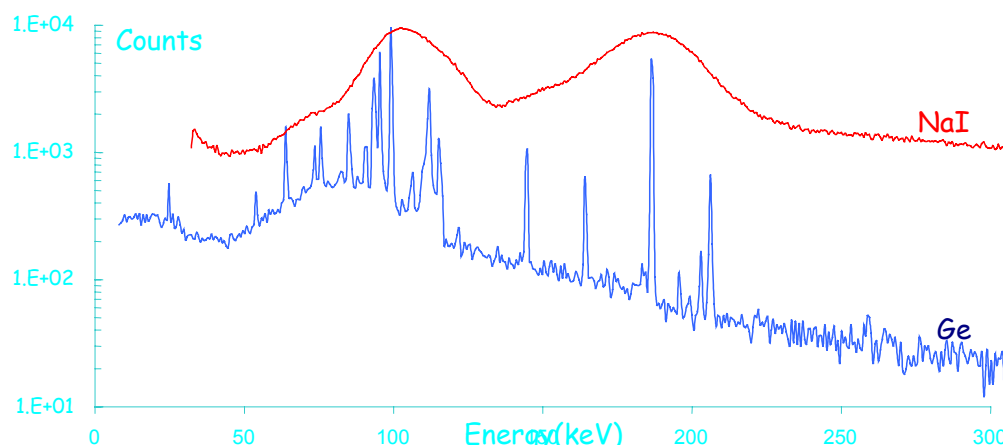
Between 120 keV and 250 keV, we see 6 well isolated lines in the case of a Ge detector whereas there is one peak only in the case of NaI: the 6 lines interfere.

Significant interference is expected when measuring the enrichment from reprocessed Uranium.

In particular, the interference due to ^{232}U and its decay products may cause biases when measuring enrichment with a NaI detector and performing the evaluation of the enrichment with a code which does not take interference into account.

To measure reprocessed Uranium, it is therefore advisable to use either a NaI detector with a code taking interference into account (NaIGEM code) or a Ge detector.

Internal conversion (IC)

Nuclear process by which the gamma emission is inhibited and the nuclear excitation energy is transferred directly to an atom electron After ejection of the electron from the atom, there is a rearrangement of the atom shell with X radiation and / or Auger electron emission.

Internal conversion coefficient

Internal conversion is a competing process to gamma ray de-excitation of the nuclear states. The ratio of the two is the internal conversion coefficient,

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$$\alpha = \frac{\text{number of IC electrons emitted}}{\text{number of gamma rays emitted}}$$

For example, the excited state of the ^{137}Ba has an internal conversion coefficient α = 8.94 %. It means that 8.94 % of the excited ^{137}Ba atoms will decay via internal conversion and 91.06 % via gamma ray emission.

Ionization
A process by which an atom (electrically neutral) becomes electrically charged, due to losing or gaining one or more electrons.

Ionization chamber
A piece of apparatus for measuring the amount of ionization produced by radioactivity in air or some other gaseous medium. It consists of an enclosure filled with air or some other gas, and containing two oppositely charged electrodes. When the air or gas is ionized by a radioactive emission or X-rays, the resulting ions are attracted to the electrodes, and the ionization current is measured.
The current measured is proportional to the energy of the incident particles and to their number.

Ionizing radiation
Radiation that causes ionization, either directly or through secondary effects. The ionizing radiation of nuclear origin includes gamma rays, alpha particles, beta particles, neutrons and fission fragments.

Isotope
Isotopes are atoms of the same element and hence have the same number of protons but different numbers of neutrons and therefore different atomic weights.

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K-

K-edge
Step in the function describing the energy dependence of the attenuation coefficients. Photons with an energy below the binding energy of the K-shell electrons cannot be absorbed by the photoelectric effect with K electrons and consequently the attenuation coefficient for their energy is smaller than for photons with energies above the K shell binding energy.
Numerical values of K-edge are given in the Annex A2, Tab6

K-edge densitometry
A non-destructive technique which determines the Uranium or Plutonium concentration of liquid samples.
This method is based on the different absorption coefficients directly below and above the K-edge.

Klein-Nishina Formula
A formula which describes the cross-section of an unbound electron for scattering of a photon by Compton effect as a function of the energy of the photon. The term usually refers to the integral Klein-Nishina formula, which gives the total cross section of the process. The differential Klein-Nishina formula gives the differential cross section for scattering at a given angle.
The differential Klein-Nishina cross section per electron is given by:

$$\frac{d\sigma_{KN}(\theta)}{d\Omega} = \frac{r_e^2}{2} * [\frac{1}{(1+\gamma)-\gamma\cos\theta}]^2 [\frac{1}{(1+\gamma)-\gamma\cos\theta} + (1+\gamma) - \gamma\cos\theta - \sin^2\theta]$$

where r_e is the classical radius of the electron, the θ scattering angle and γ the photon energy measured in units of the electron rest energy.

L-

Lanthanium Bromide detector (LaBr$_3$)
Scintillator detector with a light output of 60 photons per keV (38 for NaI (Tl)) when doped with Cerium (concentration< 0.5%). Its decay time constant is less than 25 ns and its energy resolution is 3.2 % at 662 keV and at room temperature. The non-proportionality in light yield is about 6% over the energy range from 60 to 1275keV (20% for NaI over the same energy range).

Laser separation, see enrichment techniques

Lead
Element with atomic number 82 (Symbol Pb) commonly used as radiation shield because of its high density, high mass attenuation coefficient and relatively low cost. The naturally occurring stable element consists of four isotopes: ^{204}Pb (1.37%), ^{206}Pb (26.26%), ^{207}Pb (20.82%), ^{208}Pb (51.55%). The lead ore can contain some traces of ^{210}Pb (decay product of ^{238}Uranium) which produces a low background due to its 46 keV gamma line.

Leakage current, see thermal generation of charge carriers in a semi-conductor.

LED
The abbreviation of " Light–Emitting Diode".
An opto-electronic device containing a diode emitting visible light with a direct polarization.

LENG program
A program which supports the semi-automated active length measurement of a nuclear fuel element using a NaI or CZT detector.

LEU
Low Enriched Uranium. A LEU sample has an enrichment below 20%.

Linear amplifier

A pulse amplifier for which the output pulse height is proportional to the
input pulse height.

Linear attenuation coefficient, see attenuation coefficient

Linear gate time

Time when the ADC reads the pulse height and where the LLD and ULD
are set to restrict the range of the pulse height being processed.

Live Time Clock (LTC)

Clock in the MCA which is stopped during the processing of a pulse.

Live time (LT), definition

The time during which the system is ready to accept pulses and to
process them.

LLD, see Lower level discriminator.

Logic pulse

A standard rectangular pulse with a height ranging from 2.5 to 5 Volts
and a width of a few microseconds.

Lower level discriminator (LLD)

Voltage level which defines the minimum height that a signal must have to
be analyzed by the ADC.
For example, on the picture below, pulse 1 is ignored by the ADC whereas
pulse 2 is analyzed. The LLD distinguishes between electronic noise and
small pulses.
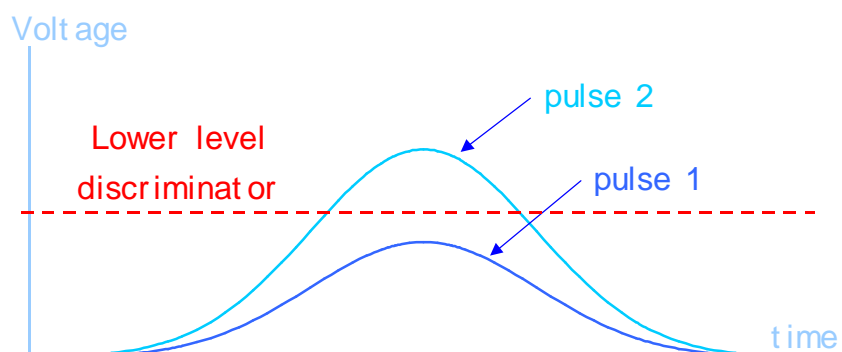
LTC, see Live Time Clock

Luminescence

Emission of radiation in the form of light by substances suitably excited by X-rays, alpha, beta or gamma rays, etc.

The absorption of the incident radiation produces excited states of the molecules of the luminescent substances, which is relieved by light emission. Return to the ground state may take place quickly or slowly. If the return is so rapid (in the order of a few nanoseconds in most organic scintillators) that when the exciting radiation ceases the luminescence decays very rapidly, the process is known as fluorescence. If the return is slower, phosphorescence (0.15 s for a NaI scintillator) is said to occur.

M-

Mass attenuation coefficient, see attenuation coefficient

Mass attenuation coefficient tabulation, see Annex A2, Tab. T8

Mass number, see atomic mass number

Matrix
The chemical composition of a material.

Matrix correction, for enrichment determination
Photon attenuation in the sample must be corrected for if the matrix is different from that of the calibration standard.
Remember that:

$$CR = \alpha * [U] * e / \mu$$

where : CR is the count rate
             [U] is the Uranium concentration factor
             e is the enrichment
             μ is the mass attenuation coefficient

If the calibration is performed with a standard with a matrix c ($[U]_c$, μ_c) and the measurement with the sample s ($[U]_s$, μ_s), the correction factor to apply to the enrichment is:

$$\frac{[U]_c}{[U]_s} * \frac{\mu_s}{\mu_c}$$

The matrix correction is automatically performed by the UF6 and NaIGEM codes when the operator declares the matrix of the standards and samples.

MCA, see Multi Channel Analyser

MCA-166
The MCA-166 comprises a Multi Channel Analyzer (MCA), an amplifier, a preamplifier power supply and a detector power supply.

MCA program
A general multi-channel analysis program for the MCA-166 (see also SPEC program).

MCS program
Automated measurements of count rates in a certain number of consecutive time intervals.
During an acquisition with the MCS program two spectra are collected. The first one gives the count rate as a function of time. The second spectrum represents the number of counts as a function of the energy, collected during all the time intervals.

Mean Uranium dwell times at various stages of a PWR fuel cycle, **see** Annex A2, Graph G 0.

Measurement error
Measurement errors are caused by:
-user (incorrect use of instrument or methods)
-instrument (technical failures)
-violation of method application limits
-counting statistics (see net peak area) .

Measurement time, preset
From the UF6 or FP program:
select "Setup", and then "MCA presets"
From the U235 and SPEC program:
Select "Setup" and then "Presets"
From the MCA program,
Select "Acquire" and then "Setup"
(Normally, "Live time " is used)

Memory group (MCA program)
The MCA program contains 3 memory groups in which the spectrum can be collected. Group 1 is selected by default. These memory groups keep spectra during other measurements (a background spectrum e.g.) and are used by the " Strip" and "Move" functions.

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Memory space
Flash disk: 20Mb or 10Mb or 5Mb
HP: 1Mb, 2Mb or 4Mb including 640 kB of RAM memory.

Memory storage time
Time necessary to store the pulse in the proper position in the memory of a MCA. It ranges from 0.5 to 2µs.

MGA software (Multi Group Analysis)
Computer code written and developed by R. Gunnink for the unfolding of Plutonium *gamma ray spectra* measured with high resolution planar *Germanium* detectors. The code calculates the isotopic composition of Plutonium. The application of the MGA code does not require any efficiency calibration of the detector and there are no assumptions about the shape or size of the sample.
To apply the MGA code, the measurement must be performed according to the following points:
- measurement with a planar Ge detector (with a resolution smaller than 720 eV at 208 keV).
- number of *channels*: 4096
- energy calibration: 0.075keV/channel (208 keV line in channel 2773 ± 40, see Plutonium, *gamma ray spectrum*)
- the peak height of ^{241}Am 59.5 keV is comparable to the peak of ^{241}Pu at 208 keV. (see Cadmium filter, influence on Pu measurement).
- the count rate is between 15 000 and 20 000 cps approximately (with a dead time below 20%).
- the total number of counts should be in the order of 10^7 counts in the total spectrum.

MGAU software (Multi Group Analysis for Uranium)
Code written and developed by Ray Gunnink.
A computerized analysis method for determining ^{235}U enrichment in Uranium items without reference standards.
It is based on the analysis of the 84 to 130 keV region in a Uranium spectrum measured with a planar Ge detector. The net peak areas are determined by using peak-fitting techniques. Sets of points of the energy-efficiency relation for the ^{235}U and ^{238}U are combined into one

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smooth function and from this relative efficiency curve the enrichment can be derived.

Unlike to the U enrichment determination with the enrichment meter, the MGAU code does not require any calibration of the detector and there are no assumptions about the shape, size or container wall of the sample.

The optimum accuracy is in the 3-20% range of enrichment.

This method cannot be applied to:

- Uranium samples for which secular equilibrium is not reached ($\approx$6 months after chemical separation), unless the date of complete Th-U separation is known,

- UF$_6$ cylinders containing deposits on the wall of the container (retention of ^{234}Th daughter products)

- Sample containers with more than 8...10 mm Fe wall thickness.

If any of these conditions prevails, the "Enrichment meter" mode of the MGAU code must be used to analyse samples, i.e. the infinite thickness condition must be fulfilled. In this case the detector / system must be calibrated for a given measurement configuration (see enrichment meter principle).

To apply the MGAU code, use a planar detector with a resolution smaller than 650 keV at 122 keV.

The recommended gain is 0.075keV/channel (185.7 keV line in channel 2476).

MGAU, sum peak effect

When measuring samples placed closed to the detector, the enrichment determination with MGAU may be underestimated.

This underestimation is caused by true coincidences between Th K alpha X ray (γ transition of Th231 are strongly converted) and gamma occurring in the U235 decay scheme (see figure below). These coincidences result in a decrease of the intensity of the Th K alpha lines used to determine the intrinsic efficiency curve.

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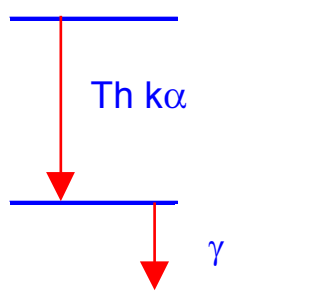
The figure below shows an example of a set of pellets measured at different distance d from the detector. With the pellets on the detector cap, the relative bias of the measured 235U abundance is about 1% (the value [declared enrichment –measured enrichment] is equal to 5*sigma). Such a dependence on the sample to detector distance is typical for the measurements of sources emitting cascade radiation with true coincidence summing effect. The further the source is from the detector, the less likely it is that the probability that the two radiation in coincidence will be detected together. The probability for true coincidence is also reduced by absorbers between source and detector.
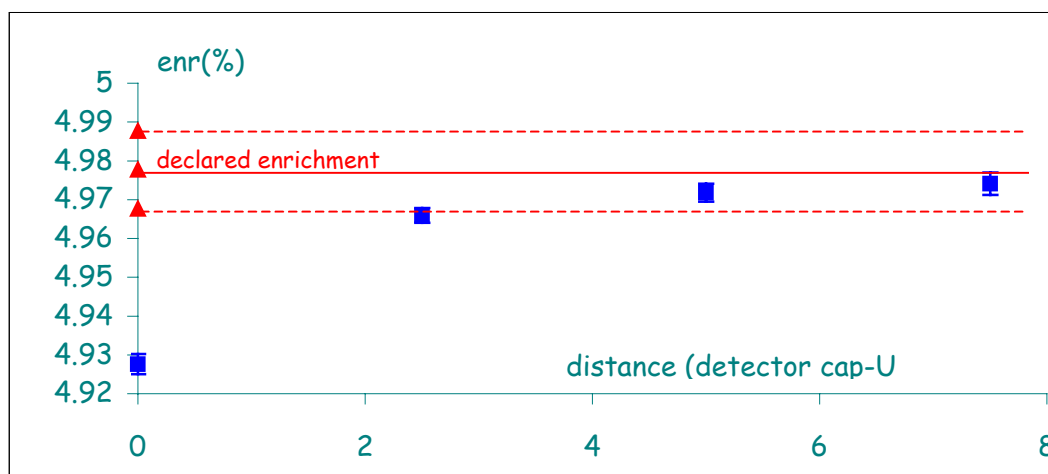
Minimum sample mass, U enrichment measurement
It is the minimum mass that a U sample must contain to fulfill the condition of infinite thickness (see infinite thickness condition).
See Annex A2, Graph G1.

Minimum sample thickness, see infinite thickness

Move function (MCA program)
Function which transfers a spectrum from one memory group to another.
From the MCA menu, select "Analysis", press ENTER
Select "Move", press ENTER
With the space bar, input the number corresponding to the origin group
and to the destination group.
Press ESC and ENTER to validate the choice.

MOX (Mixed Oxide Fuel)
Reactor fuel consisting of Plutonium oxide (about 5%) separated from
spent fuel by chemical reprocessing, mixed with natural or depleted
Uranium oxide (about 95%) .

MOX, gamma ray spectrum
A gamma ray spectrum of MOX measured according to the requirements
of the MGA code is presented below.
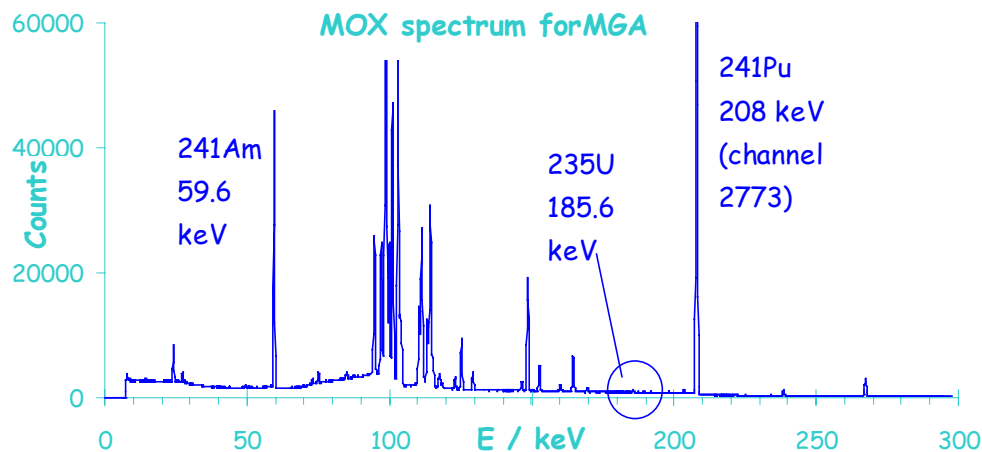
The second figure shows the 185.7 keV line of ^{235}U. It is very small
compared to the intense Pu lines.

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MOX- and Pu spectra

241Pu
208 keV

MOX with
185.7 keV
line of 235U

Pu,
no line

8000

4000

0

Counts

150   170   E / keV   190   210
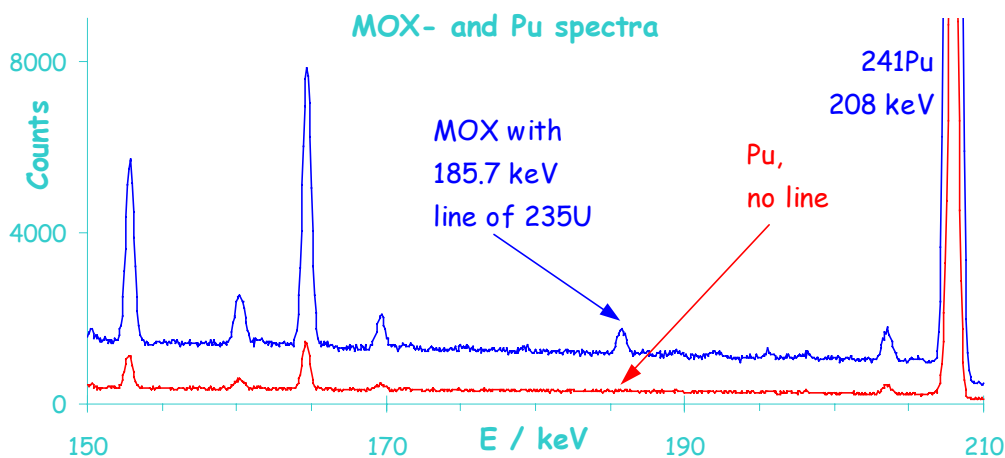
MTR (Material Testing reactor)

A large general purpose test reactor to study the effects of radiation on
fuel, moderator and structural material of interest for power reactor
designers.

MTR scanner

Gamma spectrometric device which measures the ^{235}U gamma radiation
emitted from fresh MTR fuel plates and assemblies. An additional
transmission measurement determines the number of plates in an
assembly.

Multi-channel analyser (MCA)

The Multi-channel analyser consists of an ADC and the memory.

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N-

NaI detector
The most commonly used scintillation detector. To enhance the probability of visible light emission during the de-excitation process, it is doped with small amounts of impurities (thallium) called activator.
It is characterized by its high scintillation efficiency (about 12%): absorption of 1 MeV of energy yields about $1.2.10^5$ eV in total light (the rest of the energy is retained as lattice vibrations or heat). It has the most intense light output of all inorganic scintillators. Coupled to a standard photomultiplier it also has the best energy resolution of all the scintillators (about 46 keV or 7% at 661 keV for a 3-inch diameter by 3 inch thick).
NaI(Tl) has several drawbacks:
- its light decay time constant is about 0.25μsec, consequently, it is not well-suited for high count rate applications.
- it is hydroscopic and will deteriorate due to water absorption.
- it is fragile and sensitive to thermal gradients and thermal shock.
- the relationship Channel number versus Energy is not linear. The two following graphs illustrate the dependency relation between the channel number and the energy of a NaI detector and the deviation of the energy
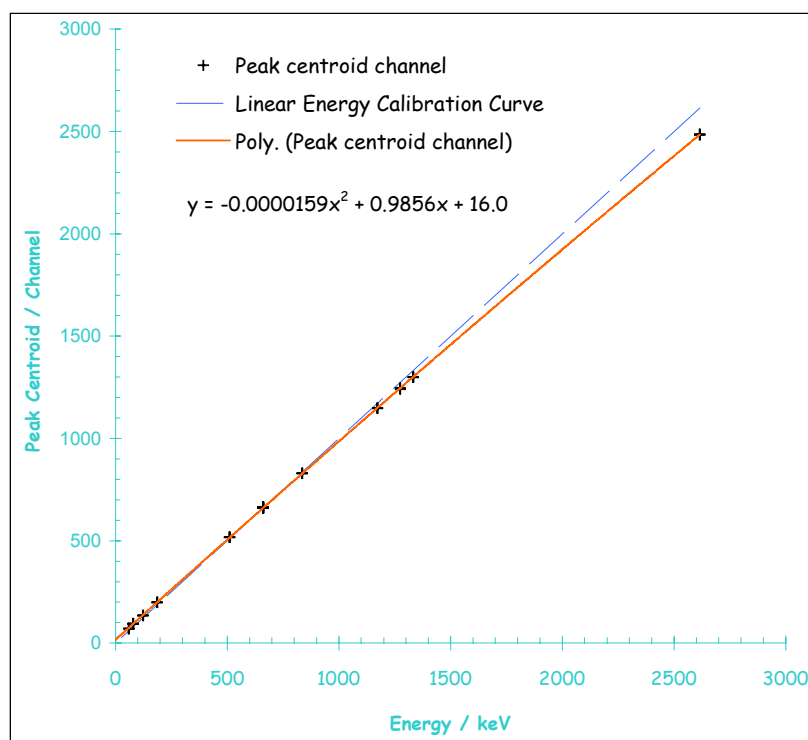
y = -0.0000159x² + 0.9856x + 16.0

Calibration curve from an ideal curve (the 662 keV line is brought into channel 662).
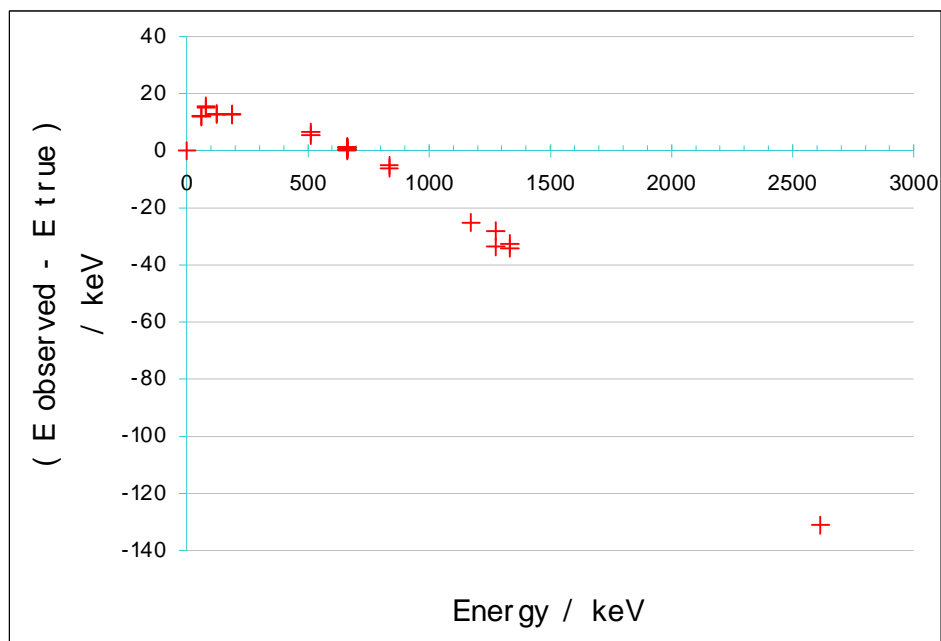
NaI GEM software (NaI Gamma Enrichment Measurements)
Computer code developed by R. Gunnink for the unfolding of U gamma spectra measured with NaI detectors. The code calculates the ^{235}U enrichment by using a peak-fitting technique. Here also, the infinite thickness condition must be fulfilled. The application of the code requires one-time calibration and unlike to the U235 program, it allows can wall thickness and matrix corrections. In addition, it takes interference from foreign activities (e. g. Th) into account.
To apply the NaI GEM code, the recommended settings are:
- number of channels: 511
- energy calibration: 0.6 keV/channel (the 185 keV peak in channel 300 ± 5).
- the collimator diameter-to-height ratio must not exceed a value of 2.
Test measurements are reported in the article NIM A 530 (2004) 559-567.

Neptunium
(Np) Element 93 of the periodic classification, first element of the group of transuranic elements. It is produced from Uranium by neutron irradiation and beta decay in a nuclear reactor. Neptunium is fissile and

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may potentially used as nuclear explosive.
See also built up scheme of transuranium elements.
See spent fuel, nuclear

Net peak area, see Area, net peak

Net peak count rate
Number of counts in the net peak area per time unit.

Neutrino
A neutral elementary particle with a rest mass of less than a thousandth of that of the electron and possibly zero. A neutrino is thought to be emitted in every beta decay process, taking away part of the decay energy.

Neutron
An elementary particle slightly heavier than a *proton* and with no electric charge Its mass m_n is:

$$m_n = 1.00866 \text{ amu (atomic mass unit)}$$

Night Vision Device
Light amplification device for the visual observation of weak Čerenkov light around spent nuclear fuel. It is used as attribute test for the presence of spent fuel with maximum two years cooling time in storage ponds.

Nuclear data for selected nuclides, see Annex A2, Tab. T5

Nuclear fuel assembly
In power reactors, a group of long tubes (fuel rods or pins) filled with fuel, usually assembled into arrays of up to 300 to be used in a reactor.
A typical pressurized water reactor core contains about two hundred fuel assemblies.
In Material Test Reactors (MTR), the fuel elements often consist of 1.5 mm thick Aluminium plates with UO_2 inside.

Nucleon
A constituent particle of the atomic nucleus, i.e. either a proton or a neutron.

Nucleus
The system of protons and neutrons forming the positively charged centre of the atom. The nucleus contains Z protons and (A-Z) neutrons.

Nuclide
A particular species of atom, identified by the characteristics of its nucleus, i.e., by its atomic number Z and mass number A. The isotopes of a given chemical element are different nuclides, therefore there are as many different nuclides as chemical elements including all their isotopes.

Nuclide chart
Diagram showing all nuclides, sorted by number of neutrons (abscissa) and number of protons (ordinate).
All the isotopes of an element are on the same row.

O-

Oscilloscope

Electrical measurement instrument which shows on a graphic screen electrical signals as a function of time, e.g. the output voltage of a preamplifier or an amplifier.

In case of disturbances of a gamma spectrometric measurement chain, the oscilloscope allows to check the electronic signals.

Check preamplifier output signal:
Connect the signal cable which comes from the preamplifier to the input connector of the oscilloscope (BNC connector).
Check, if there are signals at all.
A good preamplifier output signal looks like in the following picture (positive polarity):
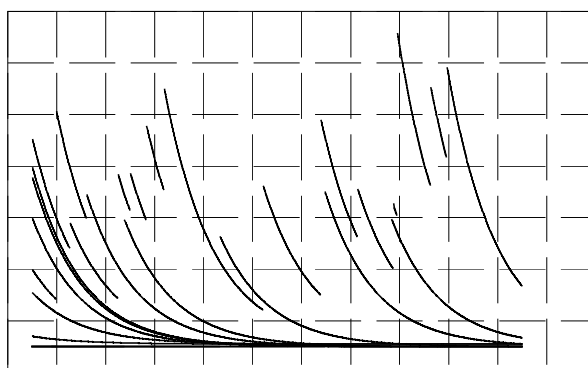
x-axis: time, 50 μs per division
y-axis: output voltage, 0.1 V per division

A low frequency disturbance (microphony effect, mechanical swingig) becomes visible if the x-axis is compessed (10 ms per division, e.g.). Often it does not decrease the spectrum quality.

High frequency disturbances, also small ones, result normally in reduced spectrum quality. They become visible after expansion of the x-axis. An example is shown in the following picture:

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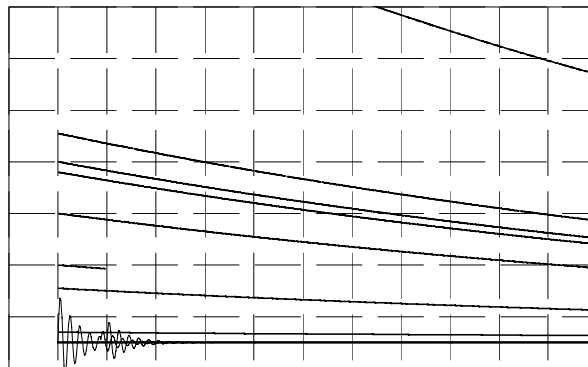
x-axis: time, 5 μs per division
y-axis: output voltage, 0.1 V per division

Check main amplifier output signal:
With the measurement probe of the oscilloscope, connect the input connector of the oscilloscope (BNC connector) with the green measurement point of the MCA-166 and the mass cable of the probe to the instrument mass of the MCA-166.

Check, if there are signals at all.
Check the polarity of the signal.
A good amplifier output signal looks like in the following picture (positive polarity):
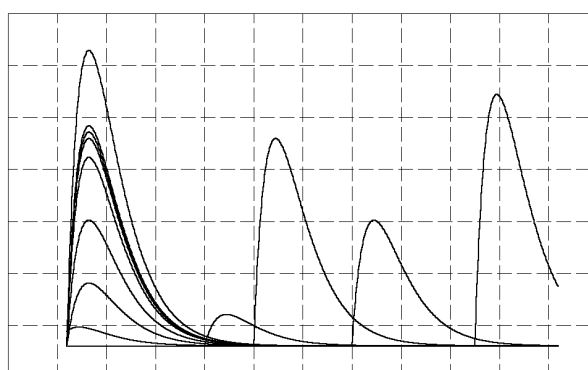
x-axis: time, 1 μs per division
y-axis: output voltage, 0.5 V per division

An amplifier output signal with low frequency disturbance is shown in the next picture, here the x-axis is compressed:
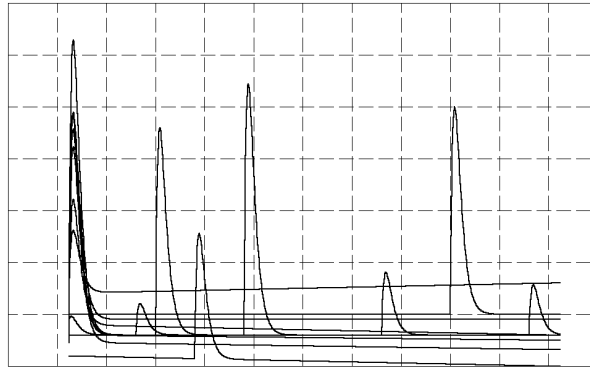
x-axis: time, 5 μs per division
y-axis: output voltage, 0.5 V per division

Overshoot effect, see pole zero cancellation

P-

Pair creation

Interaction during which a gamma quantum is absorbed in the electrical field of a charged particle, or of the nucleus or of an electron and is replaced by a (electron-positron) pair. This process is energetically possible if the gamma ray energy exceeds twice the rest mass of an electron (1.02 MeV). Then the positron slows down and annihilates with an electron producing two directly opposed 511 keV photons known as an annihilation pair.

The whole pair creation process (including possible sequences of interactions after a pair creation) is schematized in the following diagram:
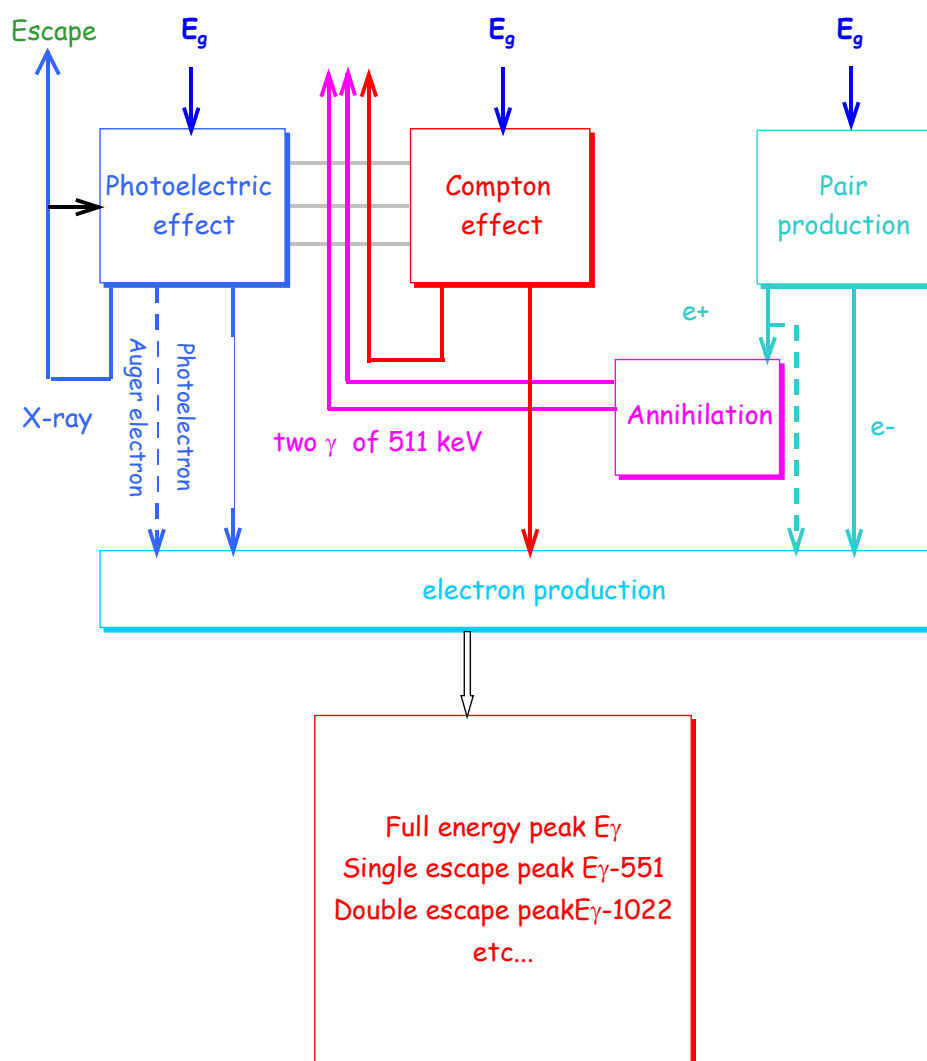
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Parent nuclide
A nuclide which produces another nuclide, whether by spontaneous *radioactive* decay or as target nuclide in an irradiation, is called the parent of the newly produced nuclide (which is called the daughter nuclide).

Peak position, see centroid

Peak shape, see full-energy peak shape

Peak-to-Compton ratio
It is the ratio of the counts in the highest full energy peak channel to the counts in a typical channel of the Compton continuum associated with that peak.
This ratio is conventionally measured from the 1332 keV line from the ^{60}Co. Typical values range from 30 to 60 for a coaxial Ge detector, and 3 to 4 for CdZnTe detectors (SDP310/60, CZT/500).

Phosphorescence, see luminescence

Photocathode, see photomultiplier tube

Photoelectric effect
Interaction during which a photon is completely absorbed by an atom. A photoelectron is ejected from the atom and there is a rearrangement of the atom shell with emission of X radiation and / or Auger electron.
The following diagram schematizes the whole photoelectric process:

Escape E_γ

Absorption   → Photoelectric effect

Auger electron   Photoelectron

X-ray

electron production

Full energy peak E_γ

X-ray escape peak $E_\gamma - E_x$
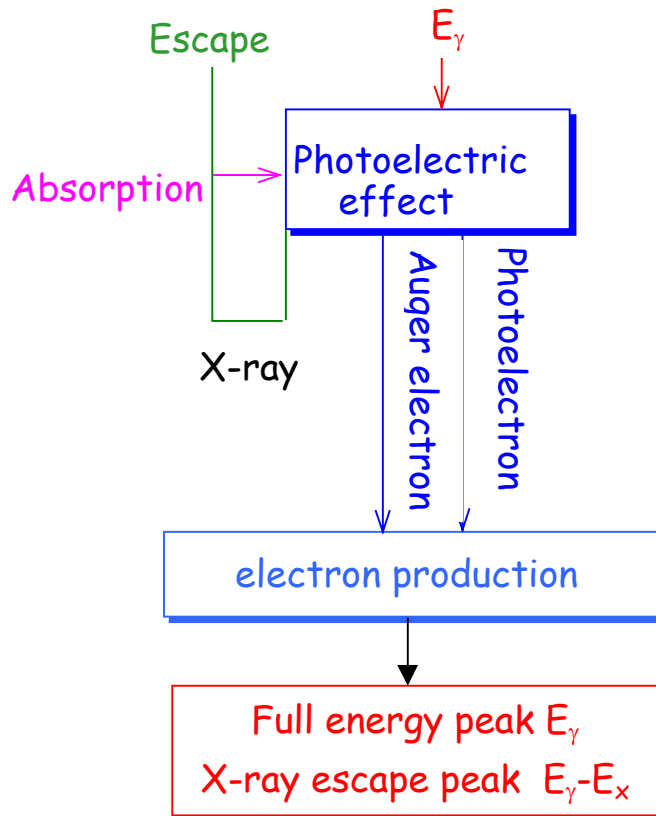
Photomultiplier tube

The module which converts the light emitted by the <u>scintillator</u> into a usable current pulse. It consists of two major elements: the <u>photocathode</u> and the multiplier structure (see figure below).

The photocathode is a photosensitive surface consisting of a semi-transparent or opaque layer which converts the incident light into low energy <u>electrons</u> according to the <u>photoelectric effect</u>.

The multiplier structure consists in a series of electrodes (called dynodes). The <u>electrons</u> leaving the photocathode are accelerated and hit the surface of the first dynode. This emits more <u>electrons</u> than it receives thus amplifying the signal. The multiplier structure is arranged so that <u>electrons</u> emitted from one dynode are focused onto the next. The <u>electrons</u> from the first dynode are multiplied at the second dynode and again at the third, all the way down the chain. The total charge is then collected at the anode and transferred out to the measurement circuits.

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γ-ray Photon — Reflector and light — Photocathode — Dynode — Light shield — Scintillator — Electrical connector — Particle track — Light Photon — Photelectron — Anode — Focussing — Detector | Photomultiplier tube (PMT)
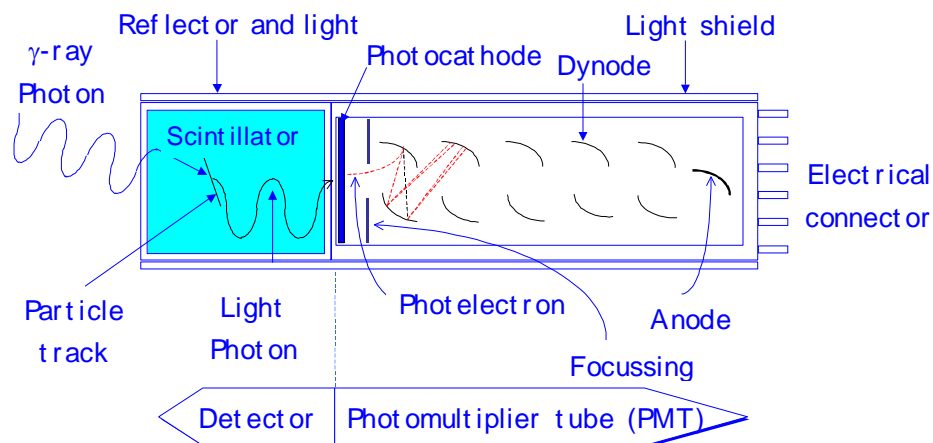
Photon

A quantum or unit of visible light, and in general of all electromagnetic radiation, which may be regarded either as a wave or as a particle having the energetic mass of $h\nu/c^2$, where h is the Planck constant, ν the frequency of the vibration and c the speed of light in a vacuum.

Photons are never at rest, they have no electric charge, no magnetic momentum, but have a spin moment of $h/2\pi$, i.e. a spin quantum number of 1.

Pile-up, see pulse pile-up.

Pile up probability

The probability to have a pile up event during a time constant $6*\tau$ is equal to:

$$P = (1-\exp(-6*CR*\tau))$$

where CR is the count rate of the source.
For example, for a count rate = 4000 counts/second, P=2.37% for τ = 1 μsec and P = 4.7% for τ = 2 μsec.

Pitchblende

A mineral containing some Uranium. See also, Uranium ore spectra, Annex A1a11.

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Planar germanium detector
Type of germanium detector having the structure of a thick disk with a diameter of a few centimetres and a depth of 1 to 2 cm.
They are characterized by their excellent resolution (about 0.55 keV at 122 keV) at low energy and as a consequence are well adapted to the measurement of Plutonium isotopic composition.

Plutonium
Element 94 of the periodic classification, second element of the group of transuranic elements. It is produced from Uranium by neutron irradiation in a nuclear reactor and occurs in nature in minute traces (about 1 part in 10^{14}) in pitchblende and carnotite, where it forms apparently due to accidental absorption of neutrons by ^{238}U nuclei contained in these ores.
See also, Plutonium isotopes.

Plutonium compounds
The important Plutonium compounds and their use are given in the table below:

Compound	Uses
Oxides	PuO_2, can be mixed with Uranium dioxide (UO_2) for use as reactor fuel (*MOX*).
Carbides	PuC, PuC_2, Pu_2C_3 All three carbides can potentially be used as fuel in gas cooled reactors.
Fluorides	PuF_3, PuF_4 Both fluorides are intermediate compounds in the production of Plutonium metal.
Nitrates	$Pu(NO_3)_4$ and $Pu(NO_3)_3$ Intermediate product during *reprocessing*.

Plutonium gamma and X-rays lines
see Annex A2 Tab. T3

Plutonium, gamma ray spectrum
A gamma ray spectrum of Pu measured with a planar Ge detector and

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according to the requirements of the MGA code is presented below.

Pu spectrum for MGA
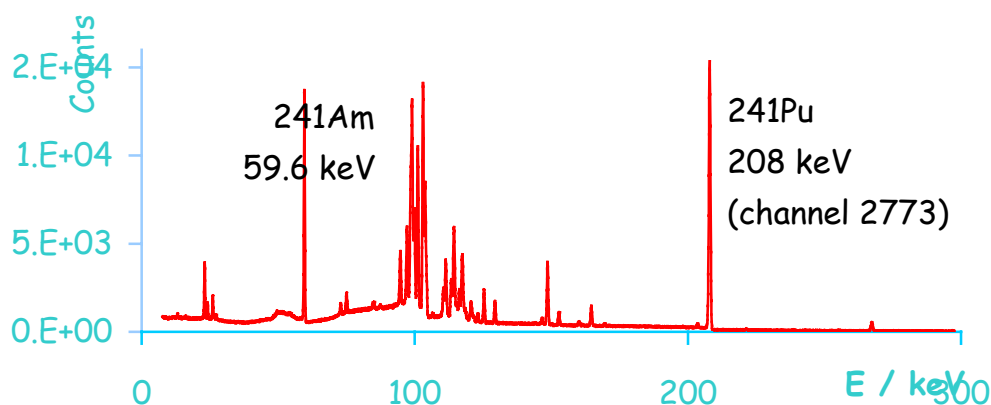
Plutonium, grades
Plutonium is classified by the US Department of Energy with respect to the ^{240}Pu content (disturbing for the fabrication of nuclear weapons due to the high emission of spontaneous fission neutrons.

Grades	^{240}Pu content
Super grade	2-3 %
Weapon grade	< 7 %
Fuel grade	7-19 %
Reactor grade	> 19 %

Plutonium isotopes
Plutonium has 16 known isotopes, from ^{232}Pu to ^{247}Pu.
The basic reactions to obtain the important Pu isotopes are:
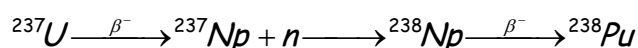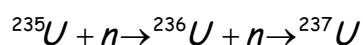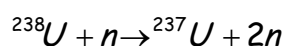
$$^{238}U + n \rightarrow ^{237}U + 2n$$

$$^{235}U + n \rightarrow ^{236}U + n \rightarrow ^{237}U$$

$$^{237}U \xrightarrow{\beta^-} ^{237}Np + n \longrightarrow ^{238}Np \xrightarrow{\beta^-} ^{238}Pu$$

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$$^{238}U + n \rightarrow {}^{239}U \xrightarrow{\beta^-} {}^{239}Np \xrightarrow{\beta^-} {}^{239}Pu$$

$$^{239}Pu + n \rightarrow {}^{240}Pu$$

$$^{240}Pu + n \rightarrow {}^{241}Pu$$

$$^{241}Pu + n \rightarrow {}^{242}Pu$$
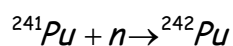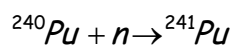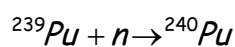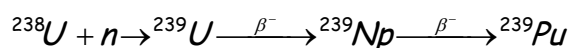
See nuclide chart, Annex 5

Plutonium isotopes, half lives and decay constants

Isotope	$T_{1/2}$ (years)	Decay constant (s^{-1})
^{238}Pu	87.74	$2.503 \cdot 10^{-10}$
^{239}Pu	24110	$9.112 \cdot 10^{-13}$
^{240}Pu	6563	$3.348 \cdot 10^{-12}$
^{241}Pu	14.35	$1.525 \cdot 10^{-9}$
^{242}Pu	373000	$5.856 \cdot 10^{-14}$
^{241}Am	432.7	$5.075 \cdot 10^{-11}$

Plutonium isotopes, neutron cross sections

	Thermal neutron cross sections for capture and fission		Effective neutron cross sections for capture and fission in a PWR*	
	$\sigma_{th,cap}$ / barn	$\sigma_{th,fiss}$ / barn	$\sigma_{eff,cap}$ / barn	$\sigma_{eff,fiss}$ / barn
^{238}Pu	540	18		
^{239}Pu	270	748	423	799
^{240}Pu	290	0	1120	0
^{241}Pu	358	1011	333	939
^{242}Pu	18	0		
^{241}Am	533	0		

*) WWER-440, initial enrichment = 3.6%

Plutonium, isotopic composition

The isotopic composition of Pu depends on the reactor type, the irradiation history, and the burn-up of the nuclear fuel in which the Pu was produced. The following graph shows the build-up the Pu isotopes during the fuel irradiation in the reactor.
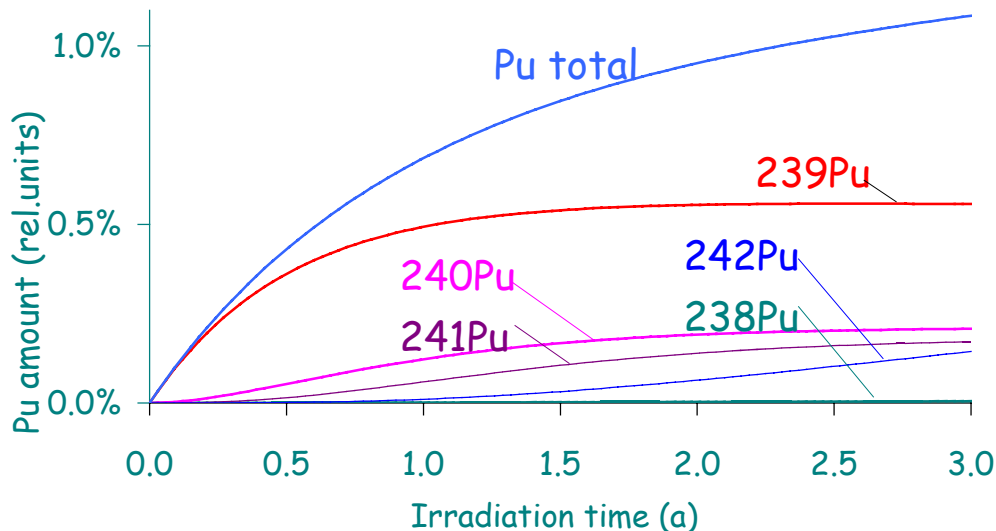
The isotopic composition changes during the irradiation. In the first months in the reactor, it is weapon grade material (see graph below).

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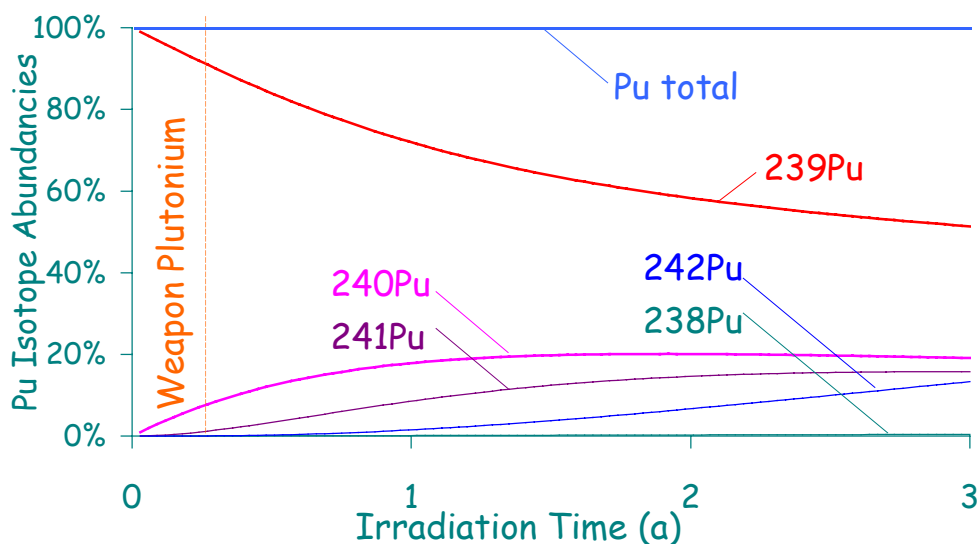
The table gives examples of the plutonium isotopic composition as a function of the irradiation time or of the burn-up for different fuel types:

	PWR High burn-up* wt%	PWR Low burn-up** wt%	FBR*** wt%	Weapon grade**** wt%
^{238}Pu	1.721	0.199	0.1	0.000117
^{239}Pu	58.096	70.955	71.7	93.412
^{240}Pu	24.768	24.583	24.1	6.313
^{241}Pu	9.771	3.288	2.7	0.002235
^{242}Pu	5.645	0.975	1.30	0.000395
^{241}Am	1.424	1.021	-----	0.001047

*   about. 30000 MWd/tU, 2.8 years after purification
**   about. 7000   MWd/tU, 5.6 years after purification
***   about 80000 MWd/tU
****   about 1500 MWd/tU, 8.0 years after purification

After irradiation, the amount of ^{241}Pu significantly decreases with time due to its decay (half-life of 14.4 years) into ^{241}Am. Consequently, its percentage in the total Pu amount decreases whereas the percentages of the other Pu isotopes increase (in spite of the fact that they also decay slowly). Mainly because of the ^{241}Pu decay the total amount of Pu also decreases.

Immediately after chemical separation the Pu does not contain ^{241}Am. Then, the ratio between the elements Am and Pu changes due to the increase of ^{241}Am and the decrease of Pu (see figure below).

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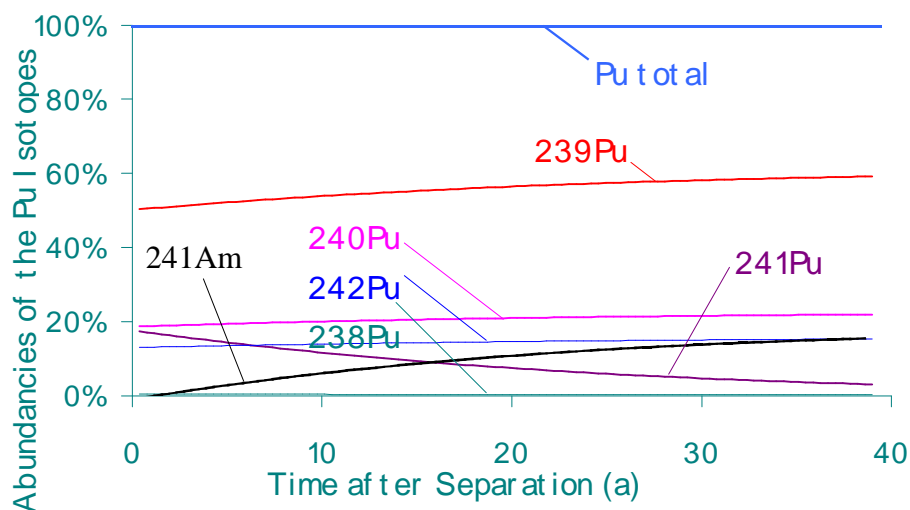
Plutonium Isotopic composition, conversion atom % to mass %

Calculation of atom percentages $at_i\%$ of the Pu isotope i from mass percentages $wt_i\%$.

$$at_i\% = \frac{\left(wt\%_i \,/\, i\right)}{\sum\limits_{j=238}^{242}\left(wt\%_j \,/\, j\right)}$$

Calculation of mass percentages $wt_i\%$ of the Pu isotope i from atom percentages $at_i\%$.

$$wt_i\% = \frac{\left(i * at_i\%\right)}{\sum\limits_{j=238}^{242} j * at_j\%}$$

With :

i: atomic mass of the isotope i,
$wt_i\%$: mass percentage of the isotope i,
$at_i\%$: atom percentage of the isotope i,

Plutonium gamma lines, see Annex A2 Tab. T3

Plutonium spectra, see Annex A1c

Pole zero cancellation (PZC)

A technique in which the amplifier network is modified to restore the zero crossover (over/under shoot effect) of the amplifier output signal again.

To adjust the pole zero, the source strength must be between 3000 and 30000 counts per second and the spectrum must reach at least 50 % of the MCA range. A bad adjustment of the pole zero (overshoot or undershoot effect) leads to the degradation of the peak resolution on the spectrum.
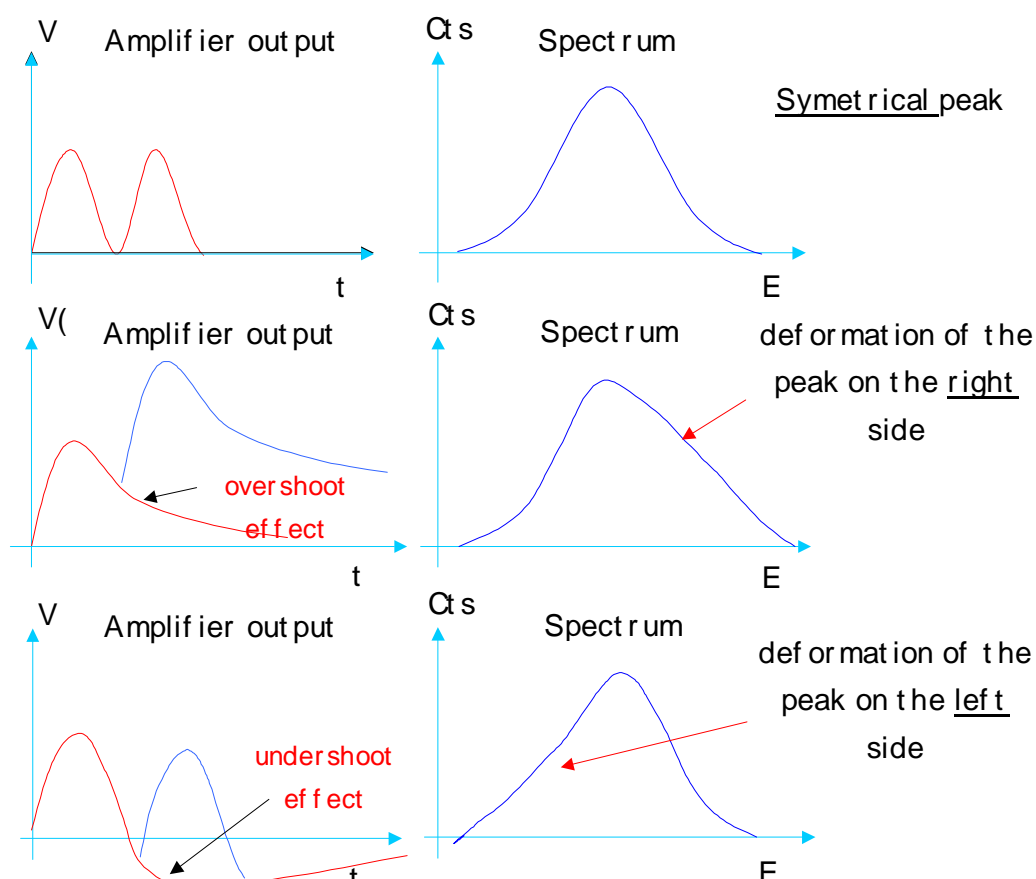
The following diagrams illustrate the effect of the adjustment of the pole zero on the spectrum.

Pole zero adjustment with the UF6, U235, MCA, SPEC and FP software:

From the menu of each program, go to the "Setup" menu, select "Amplifier setup", press ENTER

Move on to "switch to visual PZC adjustment" (for UF6, FP, U235 and SPEC programs) or "Do PZC" (MCA program) and press ENTER.

Press "+" or "-" to minimize the zero offset. Once the adjustment is done, press ESC and "Y".

Positron
An elementary particle similar to the electron but positively charged (anti-particle of the electron).

Preamplifier
First element of the electronic chain of a gamma spectrometer.
It is an impedance adapter between the detector and the amplifier which converts the charge into a voltage and amplifies and shapes the pulse.
Normally, the preamplifier is in the same housing as the detector.

Preset counting time with SPEC, UF6, FP and MCA software
From the SPEC menu, select "Setup", press ENTER, select "preset", press ENTER and with the space bar select the option real time or live time. Press the down arrow key and type the counting time. Press ESC and ENTER to validate.

From the UF6 and FP menu, select "Setup", press ENTER, select "MCA presets", press ENTER and with the space bar select the option real time or live time. Press the down arrow key and type the counting time. Press ESC and ENTER to validate.

From the MCA program, select "Acquire", press ENTER, select "Setup", press ENTER and with the space bar select the option real time or live time. Press the down arrow key and type the counting time. Press ESC and ENTER to validate.

Proportional counter
The proportional counter is a type of nuclear detector similar in many respects to the ionization chamber but where the voltage applied between the electrodes is such that gas multiplication takes place. The particle with a given energy has a larger pulse amplitude with a

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proportional counter than with an ionization chamber. The pulse amplitude is proportional to the energy released in the counter gas.

Proton
An elementary particle with a positive electric charge and a mass m_p that is slightly below the neutron mass:

$$m_p=1.007276 \text{ amu (atomic mass number)}.$$

Pulse Pile-up
Interference between pulses due to superposition of pulses:
on long-duration tail (tail pile-up) or
- on the pulse itself (pulse pile-up).
In both cases, the pile-up pulse height is overestimated. The picture below shows an example of pulse pile-up.
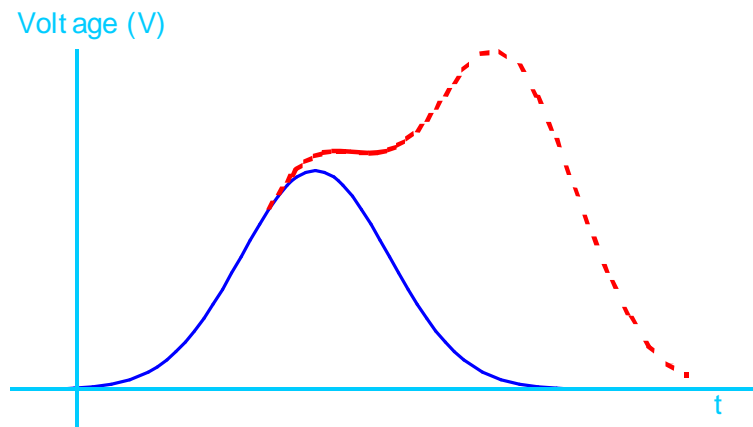
Pulse Pile-up rejector (PUR), definition
Electronic circuit which rejects the piled-up pulses.
The working principle consists in feeding the preamplifier output signal in two parallel branches:
 - a fast shaping amplifier which delivers a logic pulse triggering a time period
 - and a normal pulse shaping circuit
If a second pulse is triggered in the fast amplifier during the time period, both pulses will be ignored by the ADC.

Pulse pile-up rejector activation with MCA program
From the MCA menu, go to "Setup", press ENTER

Select "Amplifier setup", press ENTER
With the down arrow key, select the line corresponding to the Pile-up
rejector and with the space bar, select "on",
then press ESC and ENTER to accept the settings.

PUR, see pulse pile up rejector

PUREX process
(Plutonium Uranium Refining by EXtraction)
A solvent extraction process used in the fuel reprocessing of irradiated
fuel elements made of natural or low enriched uranium.
The organic solvent employed is a kerosene or a hexane solution of
tributyl phosphate (TBP). The salting agent is nitric acid.
Uranium and Plutonium are recovered in the form of uranyl and Plutonium
nitrate solutions essentially free of fission product contamination.
An overview of the PUREX process operations is shown in Annex A2,
Graph G9.

PWR, see reactor type

PZC, see pole zero cancellation

Q-

Quenching
Processes which represent the radiationless transitions in a crystal and loss mechanisms in the conversion of the particle energy into scintillation light.

R-

Radiation protection, see Annex A4

Radiation wavelength
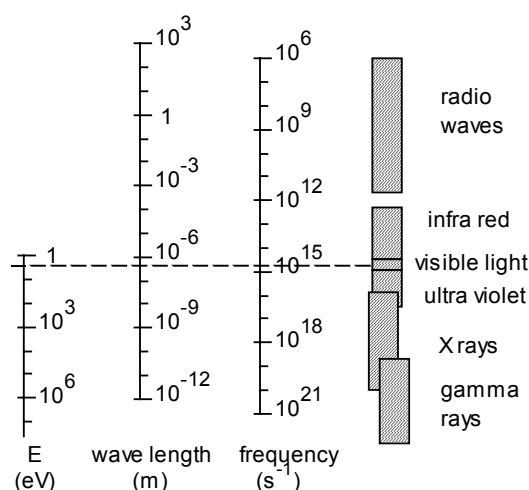
Radioactive decay, see decay, radioactive

Radioactivity
The emission of radiation (alpha, beta or gamma) by certain nuclei, resulting in the spontaneous transmutation of the nucleus into another nucleus.

Radioactivity, natural
The natural radioactivity is that exhibited by naturally occurring substances.
The natural species fall into two broad classes:
- those which have very long half-lives, comparable with the estimated age of the earth (e.g. ^{238}U, ^{235}U, ^{232}Th, ^{40}K), of the order of 10^9 years, or which result from the *decay* of such long-lived isotopes(^{234}U, ^{226}Ra, ^{222}Rn…);
- those which are continuously being produced in nature by the action of cosmic radiation (e.g. ^3H, ^7Be, ^{10}Bi and ^{14}C).

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Radioelement
Element all isotopes of which are radioactive. There are 9 natural radioelements and 19 artificial radioelements.
A radionuclide is a radioactive isotope of an element. By extension, a radionuclide is very often inappropriately called radioelement.

Radionuclide
A synonym for radioactive nuclide.

Range of particles in matter
The distance that the particles are able to travel in matter. It depends on the particle energy.
The alpha particles are limited in range, up to about 8.6 cm in air and they are stopped by a sheet of paper. The beta particles are more penetrating than alpha rays. Their range is several meters in the air and they are stopped by a sheet of Aluminum. The range of gamma rays is far greater than that of both alpha and beta rays. Low energy gamma will penetrate up to about 12 mm of lead and high energy gamma rays can be stopped by several centimeters of lead only.(see also half-thickness, attenuation law).

Rayleigh effect
Scattering of a photon on a electron bound to an atom. It involves the cooperative effect of all electrons, and its differential cross section is given by:

$$\frac{d\sigma_R(\theta)}{d\Omega} = \frac{r_e^2}{2} * (1 + \cos^2\theta) * [f(x,Z)]^2$$

where r_e is the classical radius of the electron, $d\Omega$ the differential solid angle, θ is the scattering angle, .and $f(x,Z)$ is the atomic form factor.

Reactor type
Nuclear reactors can be classified using different criteria:
neutron spectrum (thermal or fast neutrons),
cooling medium (water , gas or liquid metal),
moderator (light water, heavy water, graphite),

reactor power (zero power systems, research reactors, power reactors)..... .

PWR - Pressurized water reactor: Thermal neutron spectrum, UO$_2$ or MOX fuel, moderator and coolant light water, the water does not boil in the reactor due to the high pressure of around 160 bar.

BWR - Boiling water reactor: Thermal neutron spectrum, UO$_2$ or MOX fuel, moderator and coolant light water, the water boils in the reactor and steam goes directly to the turbine.

FBR - Fast breeder reactor: Fast neutron spectrum, U, Pu and Th *fuel*, liquid metal cooling (Na), can transform non-fissile isotopes into fissile - it "breeds" fissile material
For example ^{238}U is transformed into ^{239}Pu and ^{232}Th into ^{232}U.

Real time or true time
Normal time as recorded on a watch.

Re-evaluation with U235, UF6 or FP programs
Option which reads a file:
  - to re-calibrate the detector or
  - to re-evaluate a spectrum or,
   - to re-evaluate a spectrum using another calibration.

1.With the U235 program,
Select "Data acquisition", press ENTER
With the space bar select "Standard1" or "Standard2", if you want to recalculate the calibration coefficient using others samples as standards or, select "Unknown", to reevaluate a spectrum.
If necessary, type the new enrichment value using the arrow and numerical keys.
Then go to "File selection", press ENTER
With the down arrow key, select the file, press ENTER twice.
Now you can see the spectrum.

2.With the UF6 program:
   See instruction 7 of procedure P1.

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3. With the FP program:
Go to " Data acquisition", press ENTER
Selct "Re-evaluation", press ENTER
Select the spectrum and press ENTER twice.
You see the graphic screen with the results.

Region of interest (ROI), how to mark or to delete?
From the display, bring the cursor to the beginning of the region to mark.
Then while holding down the shift and → keys move to the end of the
region. The ROI corresponds to the highlighted region.
To delete a ROI, place the cursor in the ROI and then press DEL.

Relative contribution of the Rayleight, Compton and photoelectric effects at 185.7keV

Detector type	Coherent Effect (Rayleight)	Incoherent effect (Compton)	photoelectric effect
NaI	7.97%	26.74%	65.29%
Ge	. 8.83%	58.73%	32.44%

Repetitive Measurements
With the MCA-166, automated repetitive measurements can be made
using the MCA program (versions 1.51, 1.60, and 1.61) in the following way:
- Perform a complete set-up for one measurement.
- Go to Acquire, Setup, Repeat and type the number of repeated
measurements.
- Go to File, Save, Save and choose a directory (A:\DATA\   e.g.) and give
a name for the files. It must consist of three letters followed by the
number of the first measurement with five decimal positions and the
extension .SPE, for example: ABC00200.SPE
- Write a comment and press ESC to save this information.
-   Start a measurement (Acquire, Start)

Report of analysis (UF6, U235 and FP programs)
To visualize a report file, select "File", press ENTER.
For the UF6 program: Go to "Report", press ENTER.
For the U235 program: Go to "Report", select "View report".
With the ↓ arrow key, select the report file by pressing ENTER twice.
Use the arrow down key to scroll through the text
At the end, press ESC.
Select Yes to add a comment, then ESC
or NO, then ESC to return to the menu.

Reprocessed Uranium
Uranium from reprocessing. It contains all the isotopes of Uranium in particular ^{232}U and ^{236}U.
A spectrum of reprocessed Uranium is characterized by an intense line at 238 keV (^{212}Pb, decay product of ^{232}U). See Annex A1a.
Interference due to the decay products of ^{232}U may distort the result of enrichment determination with a NaI detector if not taken into account by the evaluation code.

Reprocessing, see PUREX process.

Resolution of a detector, definition
The resolution is the Full Width at Half Maximum of the full-energy peak (FWHM). See figure below.
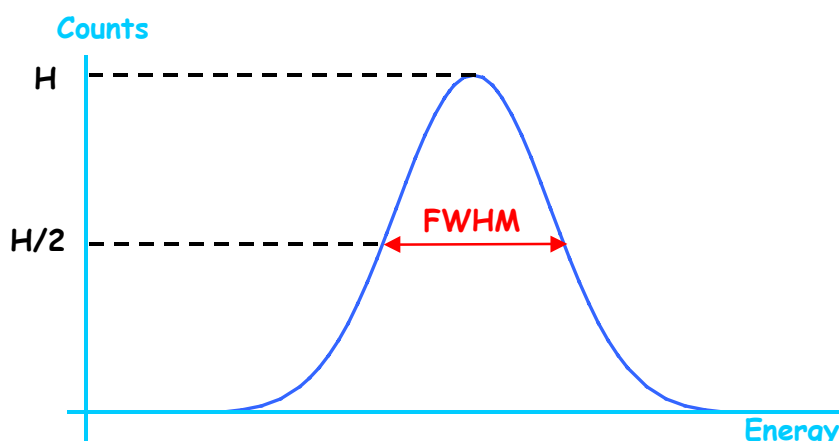
The resolution is a function of the energy and of the type of detector used (for instance, see ^{232}Th spectra taken with planar Ge, CZT and NaI detectors in Annex A1b or Uranium spectra taken with naI, CZT or Ge

detectors, Annex A1 a9). It is expressed in keV or as a percentage of the energy at that point. For a Gaussian peak shape, the FWHM is equal to 2.35σ, where σ is the standard deviation of the Gaussian.

The main factors contributing to the resolution detector are:

for a NaI :

    the statistical fluctuations,

    the electronic noise

    the energy drift,

for semi-conductor detectors:

    the statistical fluctuations,

    the incomplete charge collection

    the electronic noise

Resolution of a detector, typical values

Detector type	Resolution (keV) at:		
	122 keV	662keV	1332 keV
planar-Ge	0.6	1.2	1.8
coaxial-Ge	0.8	1.5	1.8
NaI (79mm*19mm)	23 (19%)	56 (8%)	70 (5.2%)
SDP310/60S (Ritec)		11..15	
CZT/500 (Ritec)	12	18 …25	35
CZT/1500 (Ritec)	8	11 ... 14	18
LaBr3		21	

See also spectrum pictures Annex A1e.

Resolution of the detector, measurement with SPEC or MCA programs
From the graphic screen, define a region of interest where the peak is. At the end of the measurement the peak resolution can be read if the cursor is in the ROI .

Rise time
The time required for the pulse to rise from 10% of its maximum to 90% of its maximum.

ROI, see Region Of Interest

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S-

Save a spectrum with UF6, MCA, U235 , SPEC and FP programs
Go to "File", press ENTER
Select "Save", press ENTER
Type the name of the directory and subdirectory
Press the ↓ arrow key
Type the name of the spectrum (8 characters maximum) with the extension .spe
Press ENTER twice
Write the comment and then press ESC.

Scale, see expand a spectrum

Scattering of gamma radiation
Process during which the photon can transfer a part of its energy to an atom or an electron and undergoes a change of direction and possibly an increase in wavelength.

Scintillation
The flash of light caused by a photon, an alpha particle, a beta particle or a proton moving at high speed and striking a fluorescent material in the dark.
The different stages of the scintillation process are:
-absorption of the gamma ray and formation of primary electrons,
-creation of electron-hole pairs
-migration of the electron to the conduction band
-migration of the electron to the excited level of the activator
-de-excitation of the activator levels with emission of a visible light
-light collection.

Scintillation detector
An instrument that detects and measures the ionizing radiation by means of light flashes induced in a certain material called scintillator.
A scintillation detector consists of a scintillator and a photomultiplier tube. By absorption of the radiation, the crystal emits light which is converted by the photomultiplier into an electric charge proportional to the energy of the incident radiation.

Scintillator

A crystal which emits fluorescent or phosphorescent light after absorption of ionizing radiation.

There are the inorganic crystals like sodium iodide (NaI), caesium iodide (CsI), calcium fluoride (CaF_2) and bismuth germanate (BGO). These materials are used for the detection of gamma radiation. There are also organic-based liquid and plastic scintillators. They have a low efficiency for gamma radiation and they are used for the detection of charged particles.

Secular equilibrium

We consider the decay sequence of two radioactive substances A and B:

$$A \xrightarrow{\lambda_A} B \xrightarrow{\lambda_B} C$$
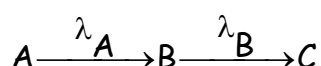
where λ_A and λ_B are the decay constants of A and B respectively.

The activity of B, A_B is given by:

$$\frac{A_B}{A_A} = \frac{T_A}{T_B} * (1 - e^{-(\ln 2 / T_B - \ln 2 / T_A) * t})$$

Where T_A and T_B are the times of half-life of A and B and A_A the activity of A.

If $T_A \gg T_B$ and if $t > 7 * T_B$, then:

$$A_B \cong A_A \text{ at } 99\%$$

It is the secular equilibrium.

Example 1: ^{235}U chain

$$^{235}U \rightarrow ^{231}Th \rightarrow ^{231}Pa \rightarrow ...$$
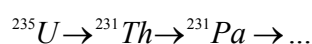
$T_{1/2,}$ ^{235}U = $7.037*10^8$ a ,, $T_{1/2,}$ ^{231}Th = 1.0633 d

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After 8 days: $A^{231}_{Th} \cong A^{235}_{U}$

Example 2: ^{238}U chain

$$^{238}U \rightarrow ^{234}Th \rightarrow ^{234}Pa \rightarrow ...$$
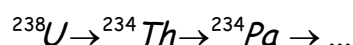
$T_{1/2,}{}^{238}{}_{U}$ = 4.468*10^9 a , $T_{1/2,}{}^{234}{}_{Th}$ = 24.1 d

After 169 days:

$$A^{234}_{Th} \cong A^{238}_{U}$$

Self absorption
The absorption of radiation in the emitting substance itself.

Self absorption factor
Ratio of the number of photons which can be detected outside a radiation
source to the number of photons which would be detected if there was no
absorption of radiation in the source material itself.

Example 1: Self absorption in a UO_2 pellet
pellet diameter: 1.06 cm
pellet height: 1.22 cm
UO_2 density: 10.6 g/cm^3
no cladding
μ/ρ at 186 keV: 1.384   cm^2/g
μ/ρ at 1001 keV: 0.0771 cm^2/g
detector position: lateral, middle height,
          5 cm distance from pellet axis

Self absorption factor for 186 keV photons: **0.074**
        (92.6 % of the photons are absorbed inside the pellet)
Self absorption factor for 1001 keV photons: **0.704**
        (29.6 % of the photons are absorbed inside the pellet)

Example 2: Self absorption in a MTR element
MTR element PERLA1:
Stack of 21 plates,

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plate structure: 0.038 cm Al - 0.061 cm fuel - 0.038 cm Al,
fuel region in the plate: 60 cm * 6.27 cm,
plate spacing: 0.23 ... 0.28 cm
U content: 61 g per plate = 1281 g total
Detector position:
1 to 10 cm above the middle of the top plate

Self absorption factor for 186 keV photons: **0.150** ± 0.005
     (85.0 % of the photons are absorbed inside the pellet)
Self absorption factor for 1001 keV photons: **0.70** ± 0.02
     (30 % of the photons are absorbed inside the pellet)

Semi-conductor
A material such as Ge, Si, CdTe or CdZnTe which contains electrons in a loosely bound condition so that the electron bonds may be rather easily broken. Their conductivity is between that of the metals and insulators, and it can be increased by an increase in temperature or by the presence of impurities. These impurities may provide excess free electrons (n-type conduction) or else they may be deficient in electrons, in which case conduction occurs by diffusion of positive holes (p-type conduction).
(see band structure in solids).

Semi-conductor, type n, see semi-conductor.

Semi-conductor, type p, see semi-conductor.

Setup file
A file of the format *.SPE for the specific program (MCA, SPEC, UF6, U235 and FP) which contains for a specific application all the setting parameters of:
- the detector (value and polarity of the HV),

- amplifier (gain, pole zero adjustment, input signal polarity)
- the MCA (number of channel, threshold, LLD, ULD and ADC input) if not predefined by the program used (for the UF6 program, the number of channels is fixed at 4096 and for the U235 program at 512),
-and possibly, the enrichment calibration constants for a given geometry.

The users should obtain a setup file (for a given detector and application) when they pick up the instrument. When a setup file (or another *.SPE file) is opened, all its parameters become operative in the MCA-166, except the detector high voltage which must be switched on by the user.

SFAT, see spent fuel

Shaping time constant, definition
The time constant of the amplifier which determines the width of the output pulse.
For MCA-166, there are two possible values: 1 or 2 μs for the SPEC and MCA programs.
For the UF6 , U235 and FP programs, the shaping time constant is fixed and equal to 1μs.

Shaping time constant setting with SPEC, MCA programs
For each program,
Select "Setup", press ENTER.
Select "Amplifier setup".
Press 3 times the arrow down key.
With the space bar, select the shaping time.
Press ESC and ENTER to accept the setting.
For high count rates (>10000 counts per second), choose 1μs. For low count rates, the energy resolution may be better with 2 μs time constant.

Single channel analyzer (SCA)
A device which counts only the amplifier output pulses with a height between two voltage levels (LLD - Lower level discriminator and ULD - Upper level discriminator).

Single escape peak
After a pair production process in a detector, the annihilation of the positron leads to the production of 2 photons of 511 keV. There is a reasonable probability that one of the 2 photons escapes from the detector whilst the other is completely absorbed. On the spectrum, we obtain a single escape peak at the energy E_γ-511 keV where E_γ is the energy of the incident photon.
See double escape peak, spectrum features

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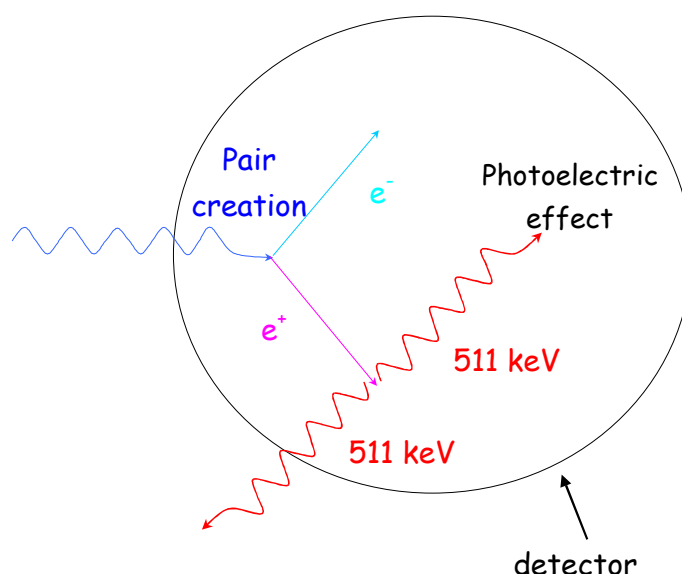
Smooth function

Function where the content c_i of each channel i of a spectrum is replaced by a weighted average over a number of adjacent channels to reduce random fluctuations in the spectrum.

If the smoothing is based on 3 points, the content of each channel is:

$$c_i = \frac{c_{i-1} + 2 * c_i + c_{i+1}}{4}$$

Based on 5 points, it becomes:

$$c_i = \frac{c_{i-2} + 4 * c_{i-1} + 6 * c_i + 4 * c_{i+1} + c_{i+2}}{16}$$

Smooth function (with MCA program)

This function smooths a spectrum using a binomial formula with 3 or 5 points.
The original data is overwritten.
To smooth a spectrum, from the MCA menu,
Select "aNalysis", press ENTER
Go to "Smooth", press ENTER
With the space bar, select the type of smoothing (3 points or 5 points).
Press ESC and then ENTER to validate.

On the MCA evaluation screen, you can see the smoothed spectrum.

Sodium iodide, see NaI detector

Sound velocity, see Annex A2, Tab. 11

Specific activity, see activity of a radionuclide

SPEC program
The general program to control measurements with the MCA-166. It can be used for measurements of gamma spectra performed with NaI, CdZnTe or Ge detectors.
The differences with the MCA program are:
- the autosave function (for semi-automated measurement series)
- the pile up rejector is always ON
- there is no Smooth, Move and Strip functions,
- there is no possibility of repeated measurements.
- there is no automatically repeated measurement mode.

Spectrum
A distribution of radiation intensity as a function of energy.

Spectrum features
The components of a spectrum are:
- the full energy peak
- the X-ray escape peak
- the X-ray peak
- the Compton continuum
- the Compton edge
- the backscatter peak
- the single escape peak
- the double escape peak
- the annihilation peak
- the sum peak
- the pile-up peak

The shape of the spectrum depends on the type of detector used.

The following diagrams give examples of ^{22}Na spectrum with a certain number of spectral components.
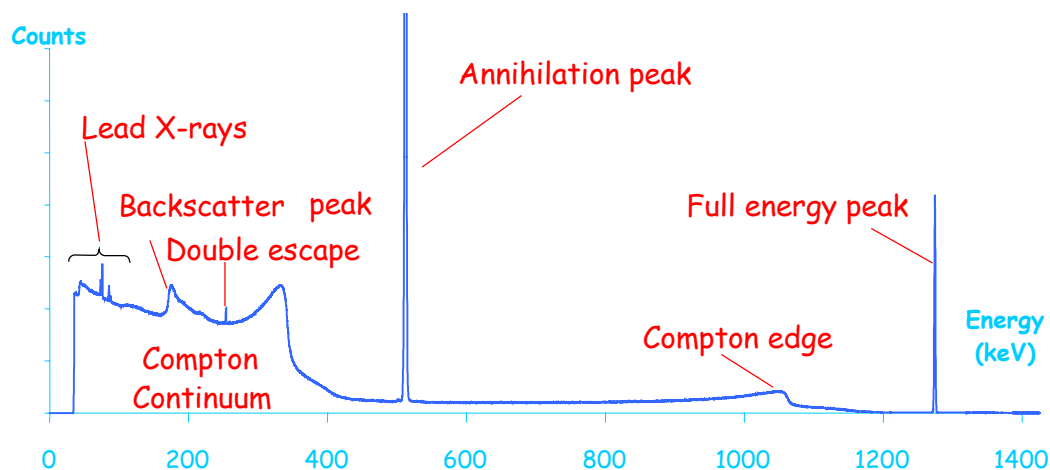
Spectrum obtained with a planar Ge detector
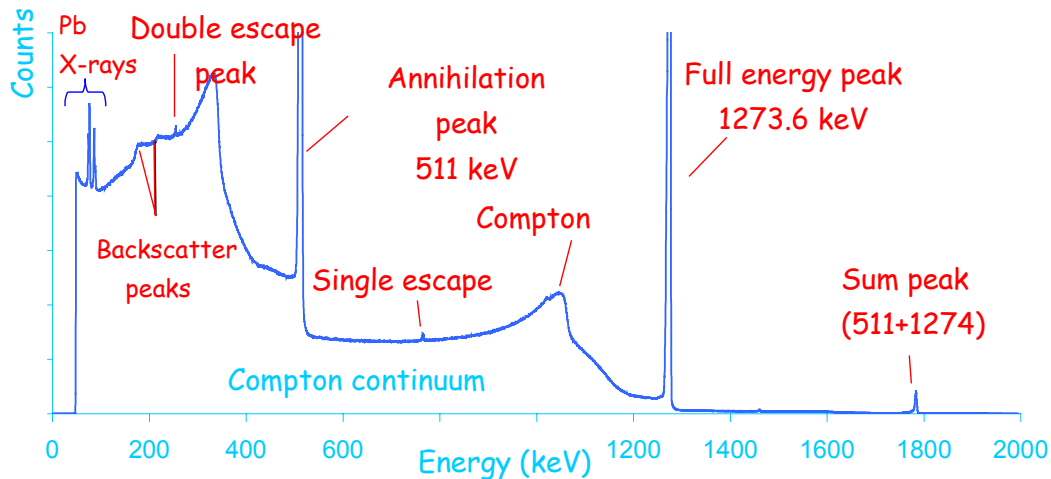
Spectrum obtained with a coaxial Ge detector

Spent fuel gamma lines Annex A2 Tab. T5

Spent fuel gamma spectrum Annex A1d

Spent fuel, nuclear

Nuclear fuel after its use in the reactor. It is highly radioactive and produces decay heat. It emits fission product gamma radiation and spontaneous fission neutrons from heavy elements.

The intense beta radiation causes visible Cerenkov light in the water around the fuel for up to about two years. This can be observed with a Night Vision Device and counts for an attribute of spent fuel.

Caution: Cerenkov light also appears around highly active objects like control rods which do not contain fission products or U or Pu.

For cooling times longer than two years, spent fuel gamma spectra can be measured with a Spent Fuel Attribute Tester SFAT, the Gamma-Taucher, e.g., which is equipped with a CdZnTe detector. This gamma spectrum measurement can prove the presence of fission products. The spectra given in Annex A1d show gamma lines of the most important gamma radiation emitting isotopes ^{137}Cs and ^{134}Cs and the activation product ^{60}Co for different cooling times and different burn-up values for MTR fuel. For special cases, the ratio of the Cs isotopes might be used to give an indication about the fuel burn-up. The sketch below illustrates the characteristics of LWR irradiated fuel.

See AnnexA2 Tab T15

Characteristics of a LWR irradiated fuel
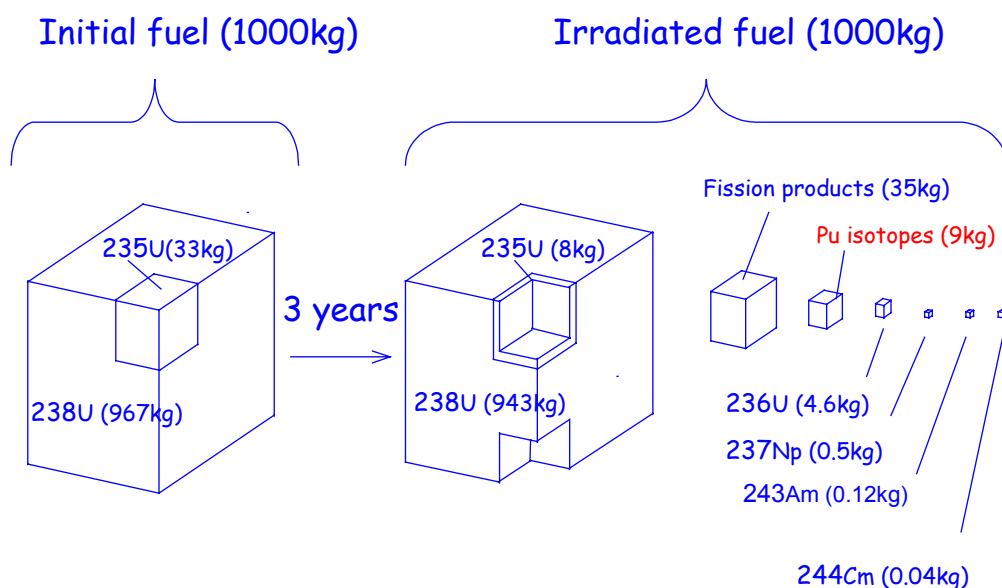
Initial fuel (1000kg)   Irradiated fuel (1000kg)

235U(33kg)

238U (967kg)

3 years

235U (8kg)

238U (943kg)

Fission products (35kg)

Pu isotopes (9kg)

236U (4.6kg)

237Np (0.5kg)

243Am (0.12kg)

244Cm (0.04kg)

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Stability
Invariance (within specified limits) of amplitude and/or timing of an output with reference to the same input repeated over a significant period of time.

Stable nuclide
A nuclide is said to be stable if it does not change its composition without the introduction of energy to the system. That is, it does not lose electrons, protons or neutrons or split into two nuclei spontaneously, as is the case for radioactive nuclides.

Stabilization with MCA, SPEC, U235, and UF6 programs
Function which prevents gain drift during the measurement.
The stabilizer calculates the peak centroid in a defined stabilisation ROI, and compares it to a target value given by the program or the operator. If the calculated value and the reference are not equal, an error signal is generated and the gain is readjusted to restore the peak in the position defined by the reference.
For the UF6 and U235 programs, the ROI and reference are predefined and the stabilization is turned on automatically.
For the SPEC program, the user defines the ROI and reference value; with the automatic mode, the position of the centroid at the beginning will be taken as target value.
For the MCA program, the user defines only the ROI (the reference corresponds to the middle of the ROI).

Stabilization, how to activate it?
Select "Setup", press ENTER
Go to "Stabilization", press ENTER
Use the space bar to activate the calibration, then
for the MCA program,
Press ESC and follow the instructions on the screen, to mark the ROI for the SPEC program,
Select the ↓ arrow key "Do visual Stab.Setup", press ENTER and follow the instructions on the screen to mark the ROI and the reference for the UF6 and U235 programs,
Press ESC and ENTER to validate

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Standard deviation

The standard deviation s_x is a measure of the mean deviation of data x_i from the mean value $\overline{x}$

$$\overline{x} = \sum_{i=1}^{n} x_i / n$$

$$s_x = \sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 / (n-1)}$$

or

$$s_x = \sqrt{(\overline{x^2} - \overline{x}^2) * n / (n-1)}$$

$$\text{where} \quad \overline{x^2} = \sum_{i=1}^{n} x_i^2 / n$$

(see also Gaussian distribution)

Strip function (MCA program)

This function adds or subtracts two spectra. The original data (memory 1) is overwritten. For instance, it can be used to subtract a background spectrum from another spectrum.
If you want to subtract / add the spectrum 2 to spectrum 1:
Open spectrum 1, select memory 1 (go to "acquire", select " Active group" and with the space bar, select memory group 1, press ESC and ENTER to validate).
Open spectrum 2, select memory 2.
Go to "aNalysis" and select "sTrip".
With the space bar, select the sign of the strip factor S and then input its value.
Press ESC and then ENTER to validate.
The MCA-evaluation screen now shows:
     spectrum 1 - S * spectrum 2.

Successive approximation ADC

Type of fast ADC. The processing time does not depend on the pulse height.

Sum peak

Peak due to photons that dump their energies into the crystal at the same time. When such a time coincidence takes place, the recorded pulse represents the sum of the energies of the individual photons. The event results in loss of counts from the full-energy gamma ray peaks and a loss of efficiency. Time coincidence can occur if photons from different decays coincide accidentally in time (accidental coincidence) or if photons are emitted one after the other in the decay of a single nucleus (true coincidence). Accidental coincidences will be easily observed with strong sources (see also pile-up) and can be rejected by pile-up rejector circuitry whereas the electronic pulses of true coincidences are not misshapen. The probability to detect true coincidence depends on the geometry of measurement (especially on the distance between the source and the detector).

See also, MGAU, sum peak effect and spectrum features.

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T-

TAC (Time-to-Amplitude converter)
A device that measures the time interval between two signal pulses, and represents the quantity as an analog voltage pulse with an amplitude proportional to the input time difference.

Thermal generation of charge carriers in a semi-conductor
At any non-zero temperature, it is possible for a valence electron to gain sufficient thermal energy to be elevated across the band gap into the conduction band.
The probability of thermal excitation depends on the ratio of the band energy to the absolute temperature.
In the case of germanium, sufficient thermal excitation will cause a high conductivity (the leakage current) at room temperature.

Thomson effect
Elastic scattering of photons with free electrons.
The Thomson differential cross section per electron is given by:

$$\frac{d\sigma_T(\theta)}{d\Omega} = \frac{r_e^2}{2} * (1 + \cos^2 \theta)$$

where r_e is the classical radius of the electron, $d\Omega$ the differential solid angle, and θ is the scattering angle.

Thorium 232 decay chain, see Annex A2, Graph G2

Thorium gamma and X-ray lines see Annex A2 Tab. T4

Thorium ore spectra, see Annex A1b

Threshold function, SPEC and MCA programs
Function which sets a value between 2% and 60% of the current MCA energy scale. This is an analog threshold which suppresses the pulses before they reach the ADC. Setting the threshold high removes unwanted pulses and reduces the dead time of the ADC.
The threshold can be used to cut off electronic noise coming from the detector or from the preamplifier.

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Throughput
The capability of processing data in a specified time.

Transmutation
Process of transforming one chemical element into another. The term is usually used in reference to nuclear reactions involving one or more small step changes in atomic number.

Transuranic elements
The elements beyond Uranium in the periodic table, i.e., elements with atomic number Z greater than 92. All the transuranic elements are radioactive and do not occur in nature except for very small amounts of Plutonium which result from the interaction of cosmic radiation neutrons with Uranium. Transuranic nuclides are produced in nuclear reactors as the result of successive neutron capture by Uranium or Plutonium.

Trouble shooting, see Annex A3

True time, see real time

U-

U235 program (NaI detector)
Program which allows the determination of the U enrichment with a NaI detector by application of the enrichment meter principle. The program can evaluate gamma spectra measured on infinitely thick samples of Uranium. It needs a calibration with 2 samples of different enrichment and identical matrix composition and wall container (material and thickness). Unlike to the NaIGEM code, the program does not allow matrix correction and wall thickness correction.

UF6 program (Germanium detector)
Program which allows the determination of the U enrichment with a Ge detector by application of the enrichment meter principle. The program can evaluate gamma spectra measured on infinitely thick samples. It requires a calibration performed with a minimum of one standard of reference.
The matrix and the wall container of the sample to be measured can be different from those of the calibration standards and wall thickness correction and matrix correction are performed automatically.

ULD, see Upper Level Discriminator

Ultrasonic gauge
System which allows the accurate determination of the wall thickness of different materials.
The measurement principle consists in measuring the time interval from sound emission to reception of the echo and multiplying this interval by the material specific sound propagation velocity:

thickness = sound velocity * time interval.

Caution: In the case of double walls (double containers), the ultrasonic gauge measures the thickness of the outer wall only. See Annex A2, Tab. 11 for the numerical values of sound velocities.

Undershoot effect, see pole zero cancellation

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Unexpand a spectrum, see expand a spectrum

Unipolar pulse
A pulse which has an excursion in only one direction from the baseline. It can be either positive or negative.

Units and prefixes of ten, see Annex A2, Tab.12

Upper level discriminator (ULD)
Voltage level which defines the maximum height that a signal must have to be analyzed by the system. On the following picture, pulse 2 is ignored by the system whereas pulse 1 is analyzed.
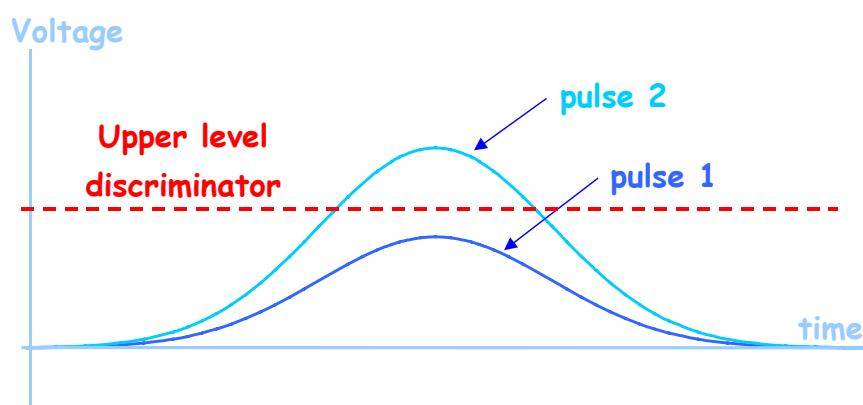
Uranium
Element 92 of the periodic classification. All Uranium isotopes are radioactive. The three natural *isotopes* are ^{234}U, ^{235}U and ^{238}U. The other isotopes are produced artificially.

Uranium 232 decay chain, see Annex A2, Graph G2

Uranium 235 decay chain, see Annex A2, Graph G3

Uranium 238 decay chain, see Annex A2, Graph G4

Uranium compounds
Uranium forms a large number of compounds, of which only the most common with their principal chemical properties are mentioned here.

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U oxides (UO_2, U_3O_8):
- used in fuel element
- high melting temperature
- good chemical inertia
- good behaviour with respect to radiation

UO_2 is soluble in water, U_3O_8 not. This property is important for the storage of reprocessed Uranium

U carbides (UC, UC_2, U_2C_3):
- not very stable, but very oxidizable
- pyrophoric at room temperature

U fluorides (UF_4, UF_6):
UF_6 is the only compound which can be used for enrichment on the industrial scale because it is gaseous at low temperature and fluorine has only one stable *isotope*. For this reason, the whole molecules $^{235}UF_6$ and $^{238}UF_6$ have different atomic weights. In the solid state, it can be transported in pressure steel containers. In the liquid state, it boils immediately at room temperature and with athmospheric pressure and is transformed into heavy vapours. When it is a vapour, in contact with moisture, it gives the following reaction:

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$
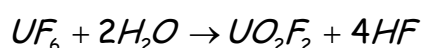
If the concentration is in the order of $1g/cm^3$, the visibility is only about ten centimeters. If there is considerable leakage, the principal risk comes from the HF concentration, and the radioactive or chemical noxiousness of the U compound is of secondary importance.

U metal:
- decomposes the water
- is oxidized in the open air
- is attacked by acid
- has bad mechanical properties (brittle)

Uranium concentration factor
This is the ratio of the total mass of Uranium to the total mass of the matrix.

Example:
Calculation of the Uranium concentration factor for an UO_2 matrix:
Molar mass of natural UO_2:   238 + 2 * 16 = 270g
U concentration factor: 238 / 270 = 88.15%

Uranium gamma and X-ray lines see Annex A1 Tab. T1, T2, T4(U232), T5

Uranium hexafluoride, see Uranium compounds
                              see Enrichment techniques

Uranium isotopes, half lives and decay constants
Uranium has 22 *isotopes* (from ^{218}U to ^{242}U). All are radioactive
Natural Uranium has three isotopes:
^{238}U (99.28 wt%), ^{235}U (0.718wt%), ^{234}U (0.0056wt%)
Reprocessed Uranium contains all the isotopes from ^{232}U to ^{238}U.

Isotope	$T_{1/2}$	Decay constant (s^{-1})
^{232}U	69.8 a	$3.137*10^{-10}$
^{233}U	$1.592.10^5$ a	$1.379*10^{-13}$
^{234}U	$2.457.10^5$ a	$8.938*10^{-14}$
^{235}U	$7.037.10^8$ a	$3.119*10^{-17}$
^{236}U	$2.342.10^7$ a	$9.377*10^{-16}$
^{237}U	6.75.d	$1.188*10^{-6}$
^{238}U	$4.468.10^9$ a	$4.913*10^{-18}$
^{239}U	23.5 min	$4.916*10^{-4}$

Uranium isotopes, neutron cross sections

	Thermal neutron cross sections for capture and fission		Effective neutron cross sections for capture and fission in a PWR*	
	$\sigma_{th,cap}$ / barn	$\sigma_{th,fiss}$ / barn	$\sigma_{eff,cap}$ / barn	$\sigma_{eff,fiss}$ / barn
^{233}U	45.5	529		
^{234}U	99.8	0		
^{235}U	98.3	582	83	360
^{236}U	5.2	0		
^{238}U	2.7	0	7.3	0.7

*) WWER-440, initial enrichment = 3.6%

Uranium spectra, see Annex A1a

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V-

Valence band, see band structure in solids

View report with U235 and UF6 programs, see report of analysis

W-

Wall thickness correction, see can wall correction

Wavelength, see radiation wavelength

Weapon grade material
Material which can be used for preparing nuclear material explosive without further enrichment (of Uranium e.g) or transmutation (of LEU to Pu)
See also Plutonium, grades
        Plutonium, isotopic composition
        Direct used material

Wilkinson ADC
Type of ADC for which the processing time is proportional to the height of the pulse.

WINSPEC
Windows version of SPEC program.
The new features of WINSPEC compared to the DOS version are:
-Automatic control of the pole zero
-Automatic adjustment of peak centroid within ROI
-Software such as MGAU, MGA and Cs ratio are integrated

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X-

X-ray

An electromagnetic radiation similar to light but of much shorter wavelength. It has two origins:
- the slowing-down of fast electrons in matter (see Bremsstrahlung)
- the rearrangement of the electronic shell after ionization caused by electron capture, by internal conversion or photoelectric effect. The X-ray energy is given by the energy difference between the initial and final states. It goes up to 120 keV. For example, if a vacancy is temporarily created in the K-shell of an atom and if this vacancy is filled by an electron coming from the L shell, then the energy of the X-ray is equal to the binding energy of a K-electron K minus the binding energy of the L-electron.
The nomenclature for the most intense transition is given in the following table:

Nomenclature	Transition
K_{α_1}	$K\text{-}L_{III}$
K_{α_2}	$K\text{-}L_{II}$
K_{β_1}	$K\text{-}M_{III}$
$K_{\beta_{21}}$	$K\text{-}N_{II}$
$K_{\beta_{22}}$	$K\text{-}N_{III}$
K_{β_3}	$K\text{-}M_{II}$
K_{β_4}	$K\text{-}N_{IV,V}$
K_{β_5}	$K\text{-}M_{IV,V}$
KO	$K\text{-}O_2O_3$
KP	$K\text{-}P_2P_3$

Group designations: $K_{\beta_1'} = K_{\beta_1} + K_{\beta_3} + K_{\beta_5}$
$K_{\beta_2'} = K_{\beta_2} + K_{\beta_4} + KO + KP$

The Pb X-rays are often present in U or Pu spectra (see Uranium spectrum) because Pb is used as collimator material. Too intense Pb X-rays disturb the MGA code.
See also Annex A2, Tab 6.

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X-ray energy and relative intensty see Annex A2 Tab. T6

X-ray escape peak
During the photoelectric process, a characteristic X-ray is emitted by the absorber atom. If this effect takes place near the surface of a detector, the X-ray may escape from the detector. A new peak will appear on the spectrum at an energy corresponding to the energy of the incident photon minus the energy of the X-ray.
The spectrum below shows the escape peak for a spectrum taken with a CZT detector (60mm^3).

counts

X escape peaks :
Energy = 511-23.17
        = 487.83 keV (E_{Ka1}Cd)
Energy =511-27.3
        = 483.7 keV (E_{Ka1}Te)

511 keV

Energy (keV)

460   470   480   490   500   510   520   530
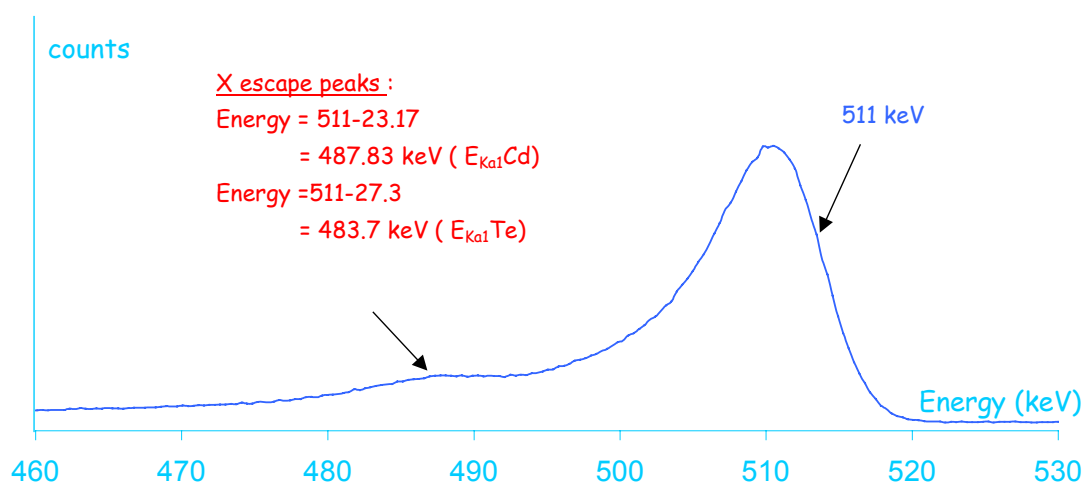
X-ray fluorescence
Emission of X-rays from a material. The X-ray emission, in particular the K-line, is a unique property of an element. Observation of a K line of an element in the X-ray emission from a material proves the presence of this element in the material, independent of the state of chemical composition of the element. This property is used for surface analysis (PIXE).

X-ray nomenclature, see X-ray

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X-ray peak
When a photoelectric effect takes place in the shielding surrounding the detector, there is a significant probability that the emitted X-ray may escape the shielding and the detector will detect it. A new peak appears in the spectrum at the energy of the X-ray of the surrounding material. See spectrum feature to visualize the X-rays of lead.
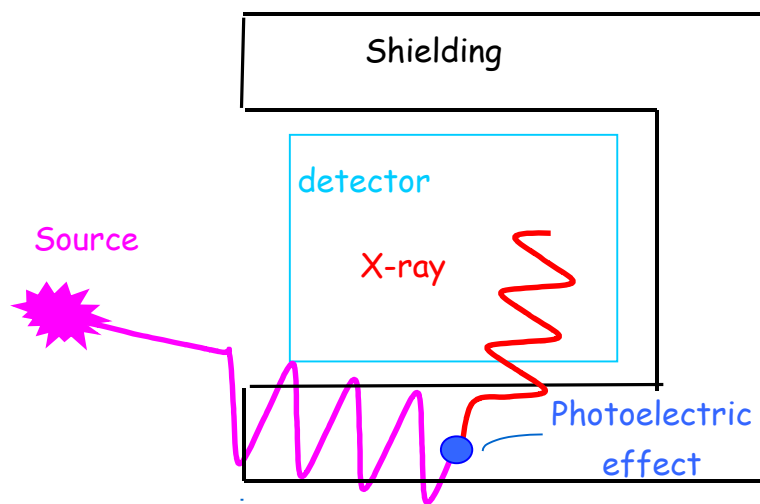
X-ray peak shape
A X-ray peak can be represented by a Lorentzian function:

$$L(i) = \frac{\Gamma/2\pi}{(i - i_o)^2 + (\Gamma/2)^2}$$

Where i is the channel number, i_o the centroid and Γ the line width expressed in channels.

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Y-

Yellow cake
A term applied to certain Uranium concentrates produced by Uranium mills: specifically, those in which Uranium is mainly in the form of ammonium diuranate $(NH_4)_2U_2O_7$ or sodium diuranate $(Na_2U_2O_7)$. It contains some 75% of Uranium and looks like a yellow powder or paste, hence the name "yellow cake".

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Z-

Zoom, HP-200
Press the FN key and space bar key simultaneously.

Zero offset
Shift at the origin such that a non-zero amplitude is required for storage in the first channel.

Zircaloy
Alloy of zirconium, used as reactor fuel cladding material. It is characterized by its high resistance to corrosion, its low neutron absorption cross section, its good behavior at high temperature and its ductility.
The table below presents typical compositions for commercial zirconium alloys used in nuclear applications (wt %)

Element	Zircaloy-2	Zircaloy-4
Tin	1.5	1.5
Iron	0.1	0.2
Chromium	0.1	0.1
Nickel	0.1	0.1
Oxygen	1400 ppm max.	1400 ppm max.
Zr+ impurities	98.2	98.1

ANNEX A1   SPECTRA

ANNEX A2   TABLES AND GRAPHS

ANNEX A3   TROUBLE SHOOTING

ANNEX A4   RADIATION PROTECTION

ANNEX A5   NUCLIDE CHART

ANNEX A1

SPECTRA

A1a   Uranium spectra

A1a1   with planar Ge detector, 80 to 105 keV
A1a2   with planar Ge detector, 100 to 220 keV
A1a3   with NaI detector, LEU
A1a4   with NaI detector, HEU
A1a5   with CZT/500 detector, LEU
A1a6   with CZT/500 detector, HEU
A1a7   with planar Ge detector, reprocessed U
A1a8   with planar Ge detector, reprocessed U, 140..250 keV
A1a9   with Ge, NaI, CZT detector, 20 to 300 keV
A1a10   with planar Ge and NaI detector, 20 to 1600 keV
A1a11   with planar Ge, U ore, 50 to 3000 keV

A1b   Thorium spectrum

A1b1   with planar Ge detector
A1b2   with CZT/500 detector
A1b3   with NaI detector

A1c   Plutonium spectra

A1c1   with planar Ge detector, 90 to 120 keV
A1c2   with planar Ge detector, 120 to 195 keV
A1c3   with planar Ge detector, 190 to 300 keV

A1d   Spent fuel spectra with CdZnTe detector

A1d1   Gamma spectra of PWR spent fuel with different cooling times
A1d2   Gamma spectra of MTR spent fuel with different burn-up

A1e   Detector Efficiency

A1e   Spectra of ^{152}Eu (740 kBq) and ^{154}Eu (100 kBq) with Different Detector Types

Uranium Spectra with Planar Ge Detector, 80 keV to 105 keV
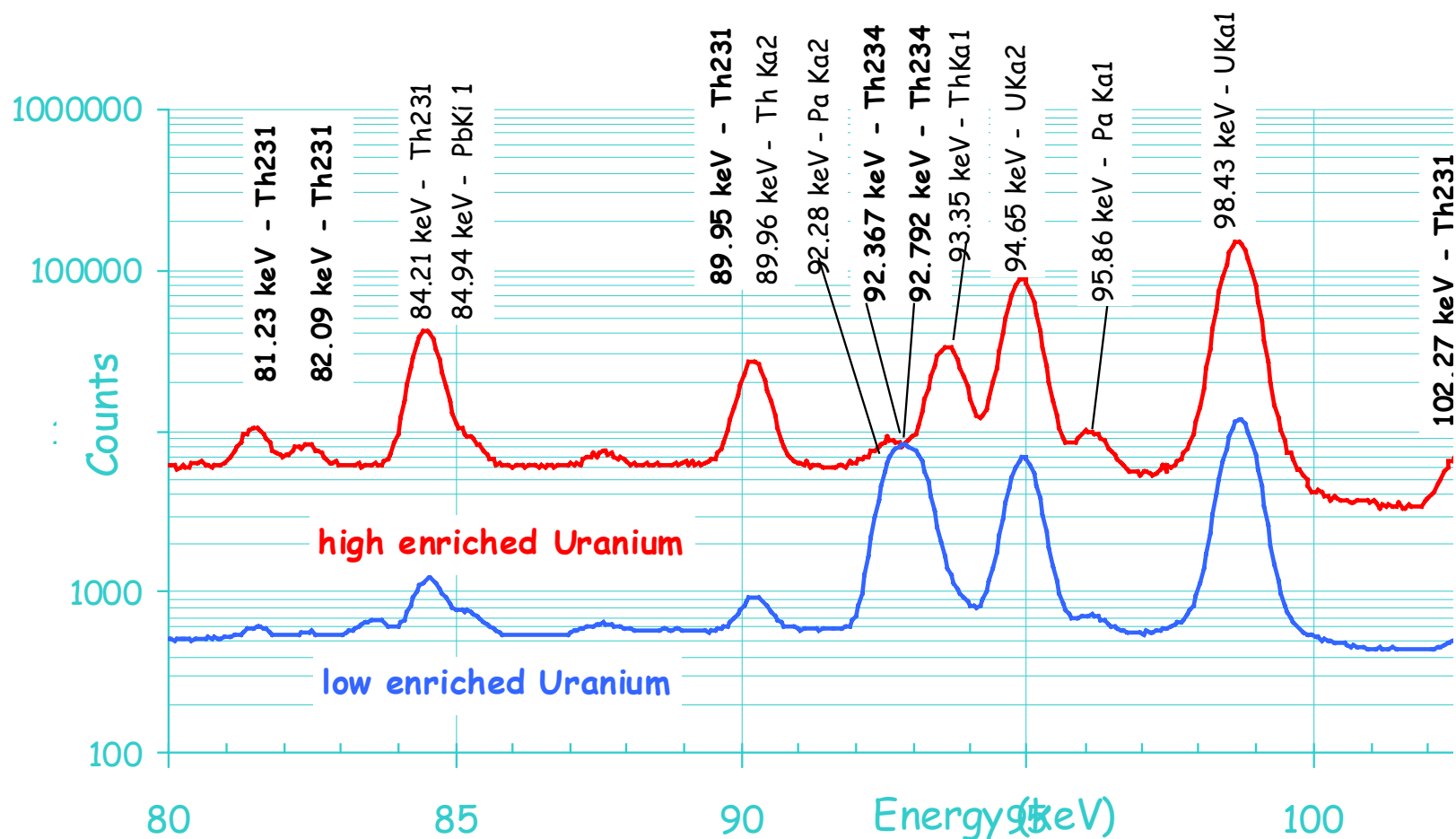
Uranium Spectra with Planar Ge Detector, 100 keV to 220 keV
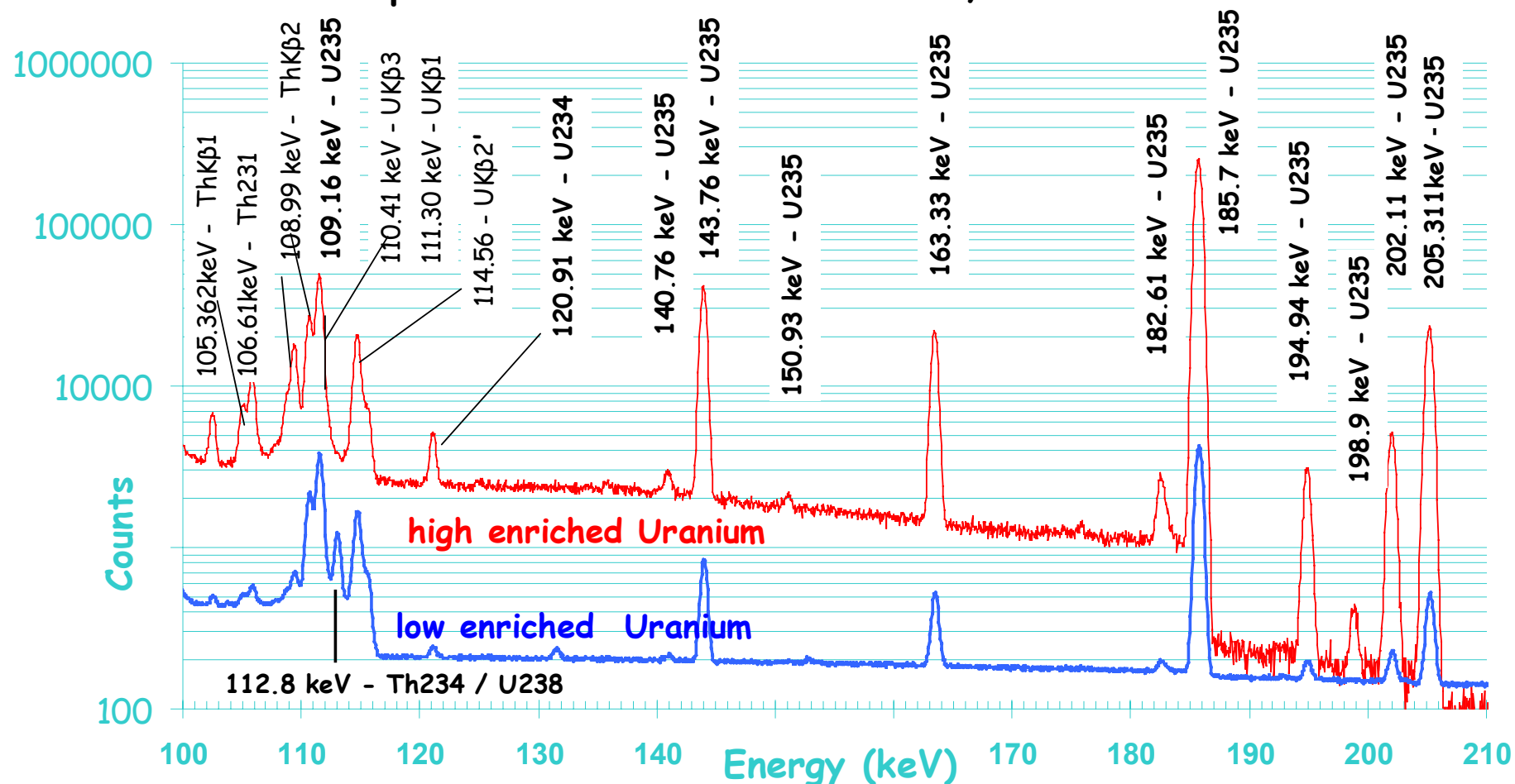
Uranium Spectra with NaI Detector - Low Enriched Uranium
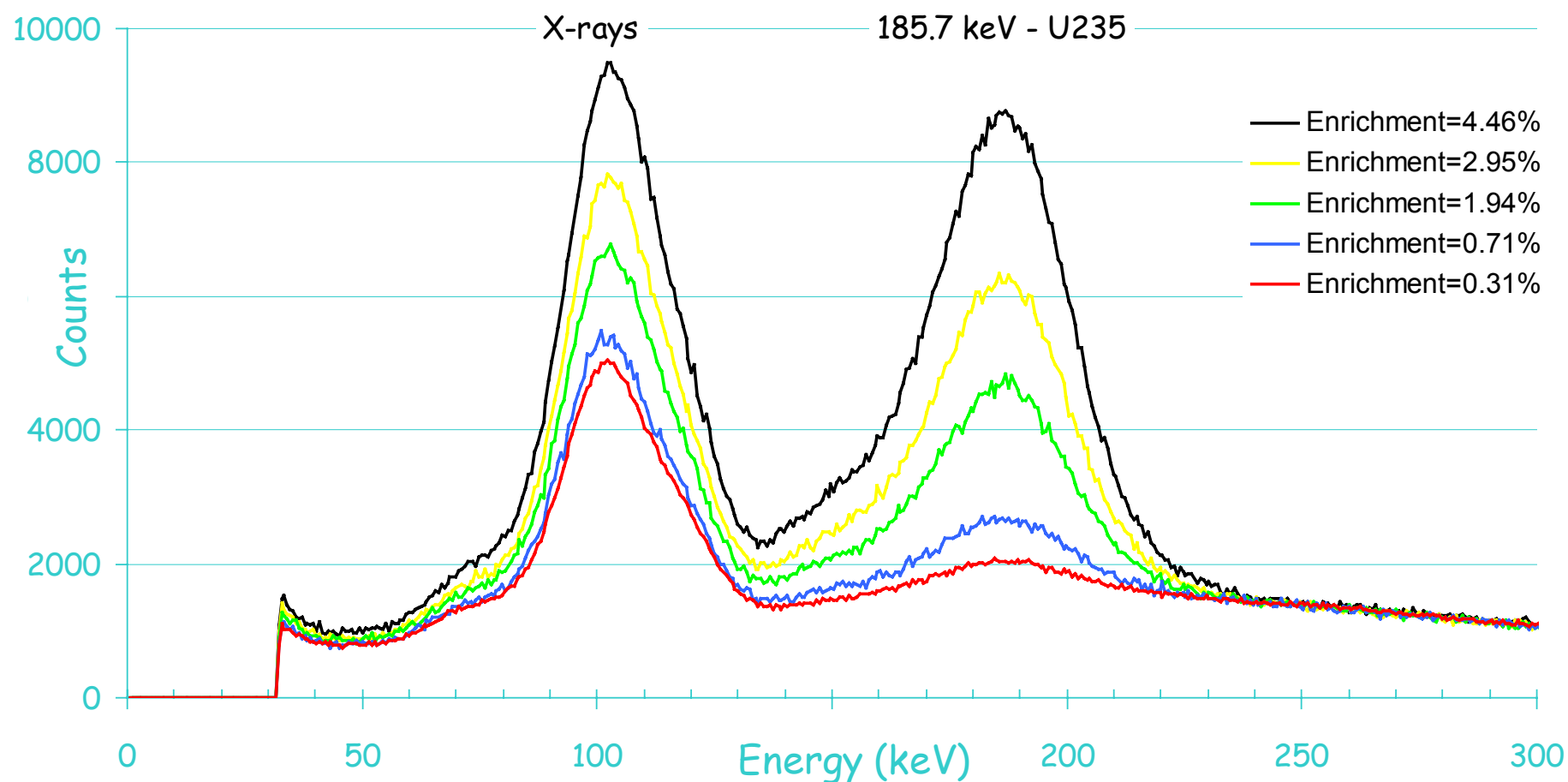
Uranium Spectra with NaI Detector - High Enriched Uranium
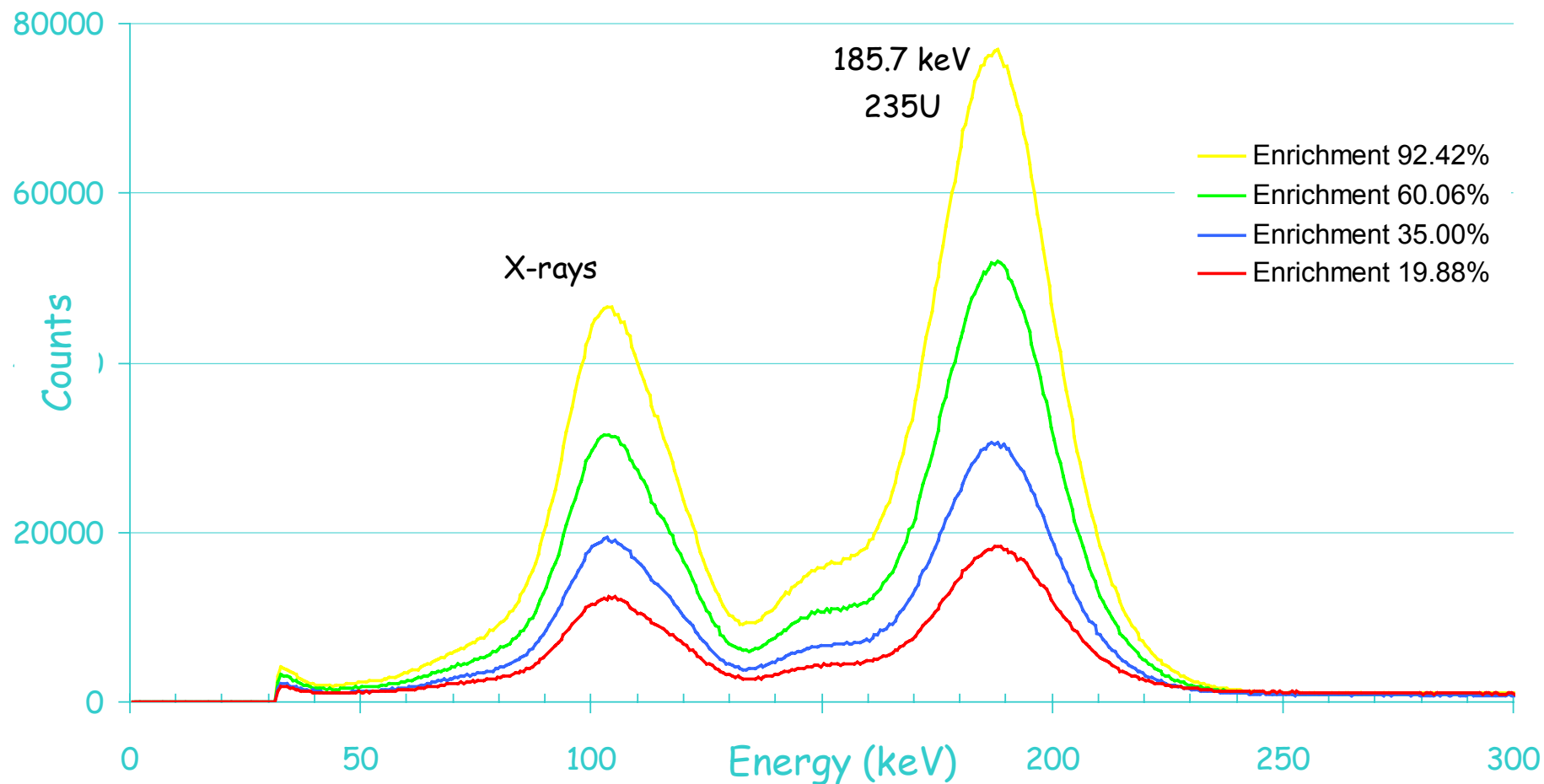
Uranium Spectra, CZT/500 Detector - Low Enriched Uranium
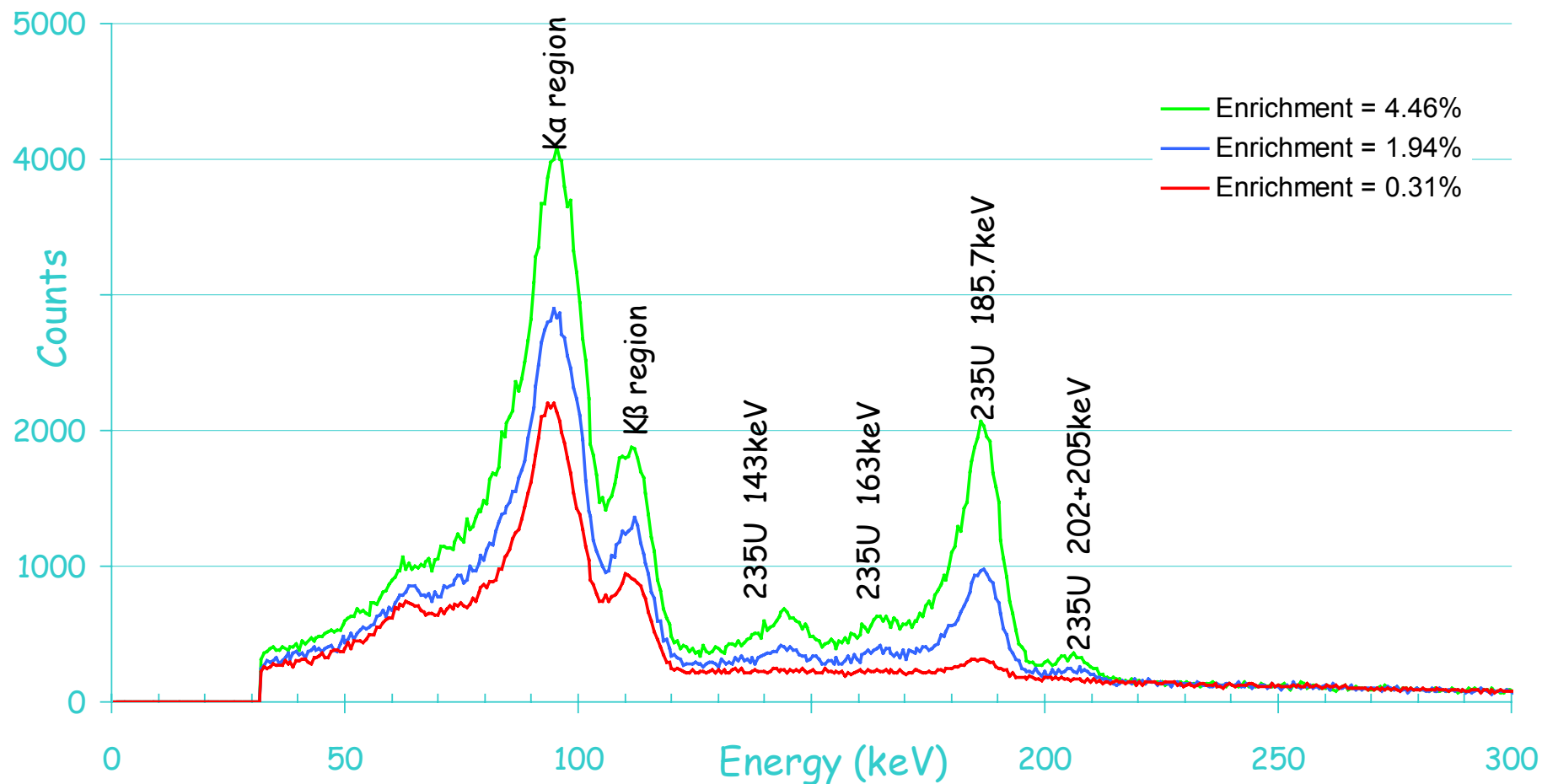
Uranium Spectra, CZT/500 Detector - High Enriched Uranium
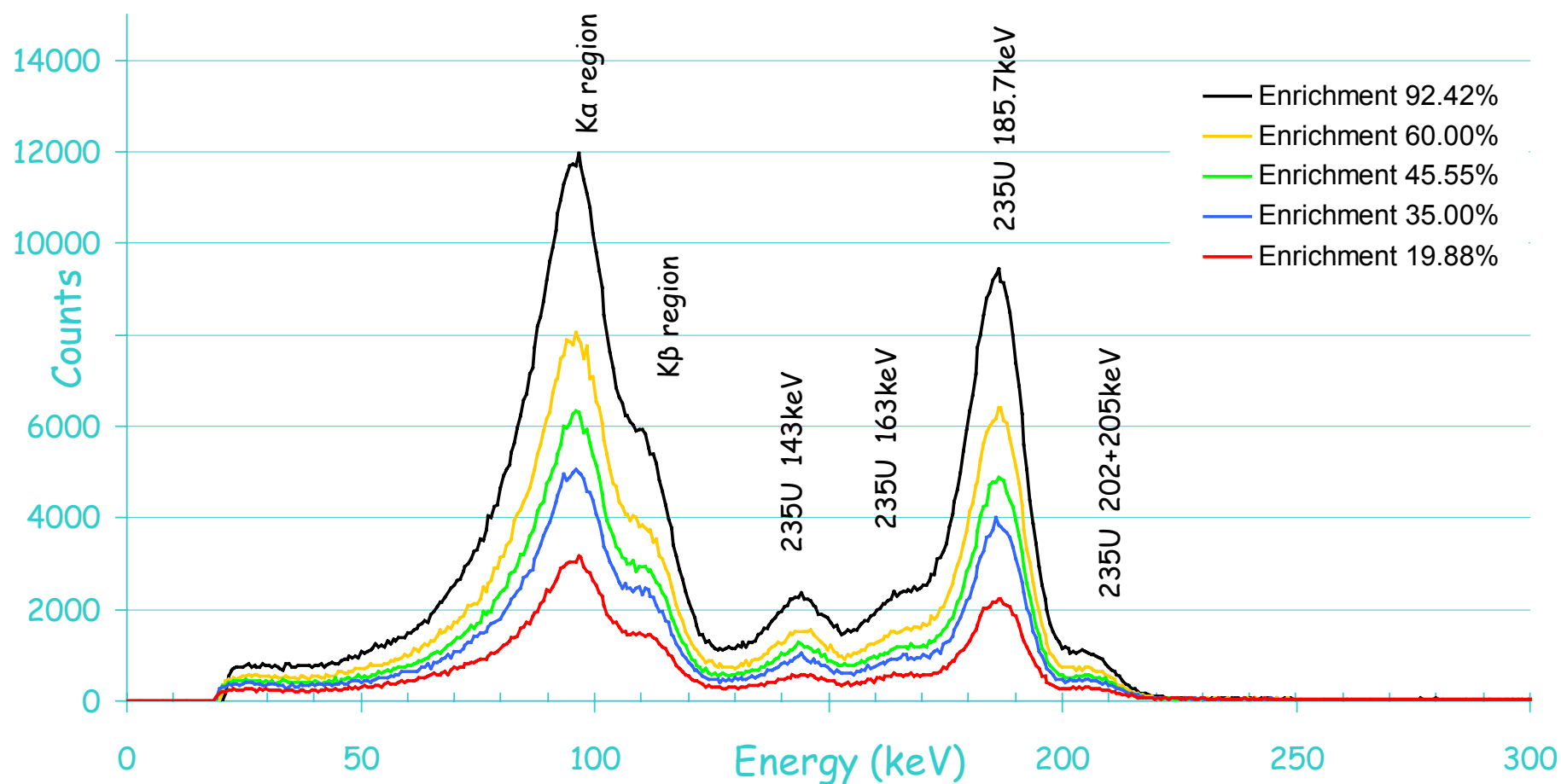
Reprocessed Uranium with Planar Ge Detector
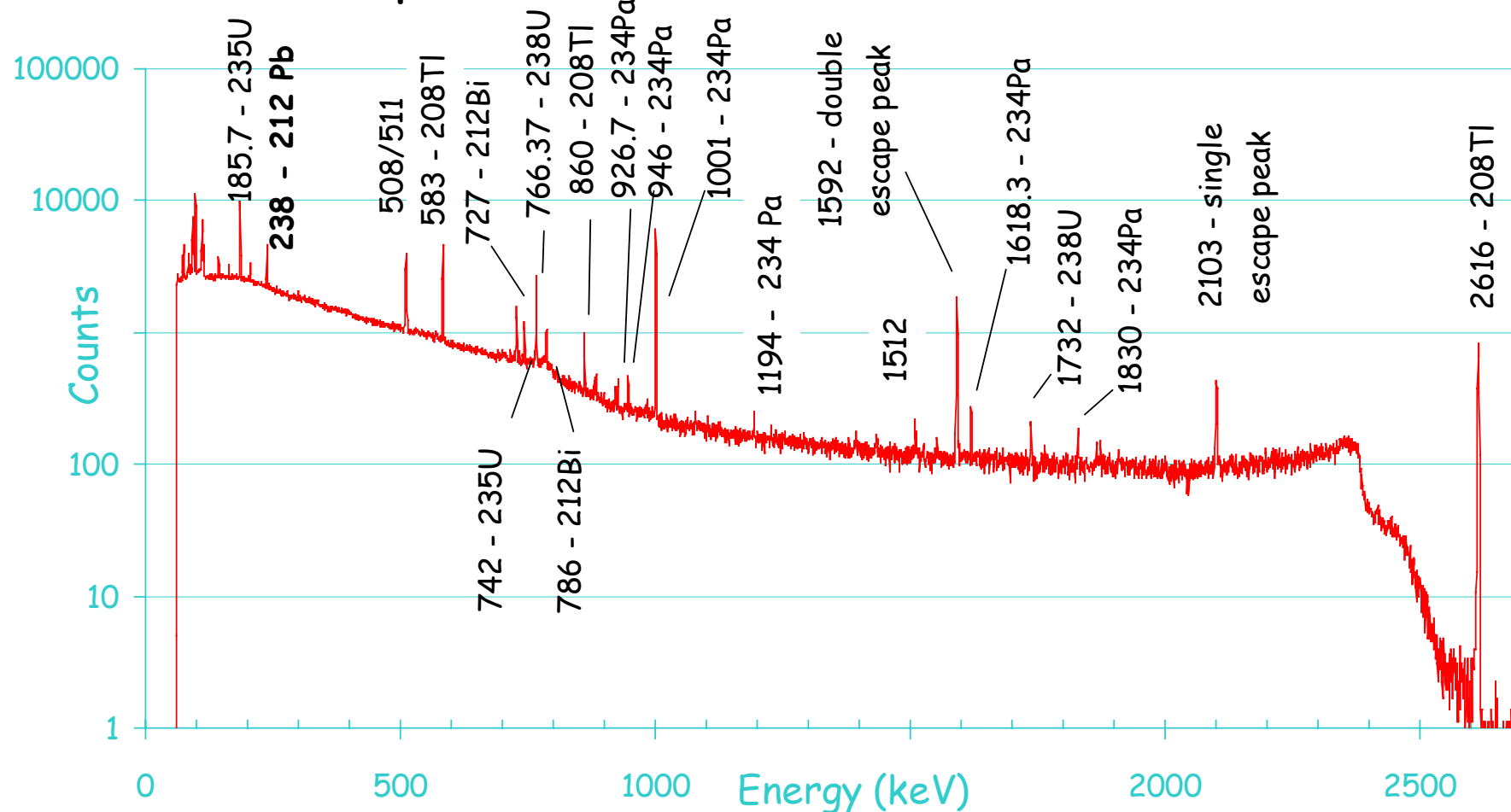
Uranium from Reprocessing and with Natural Origin, Planar Ge Detector

U spectra taken with NaI, CZT or Ge detectors

143.76 keV - U235

163.33 keV - U235

185.715 keV - U235

205.31 keV - U235
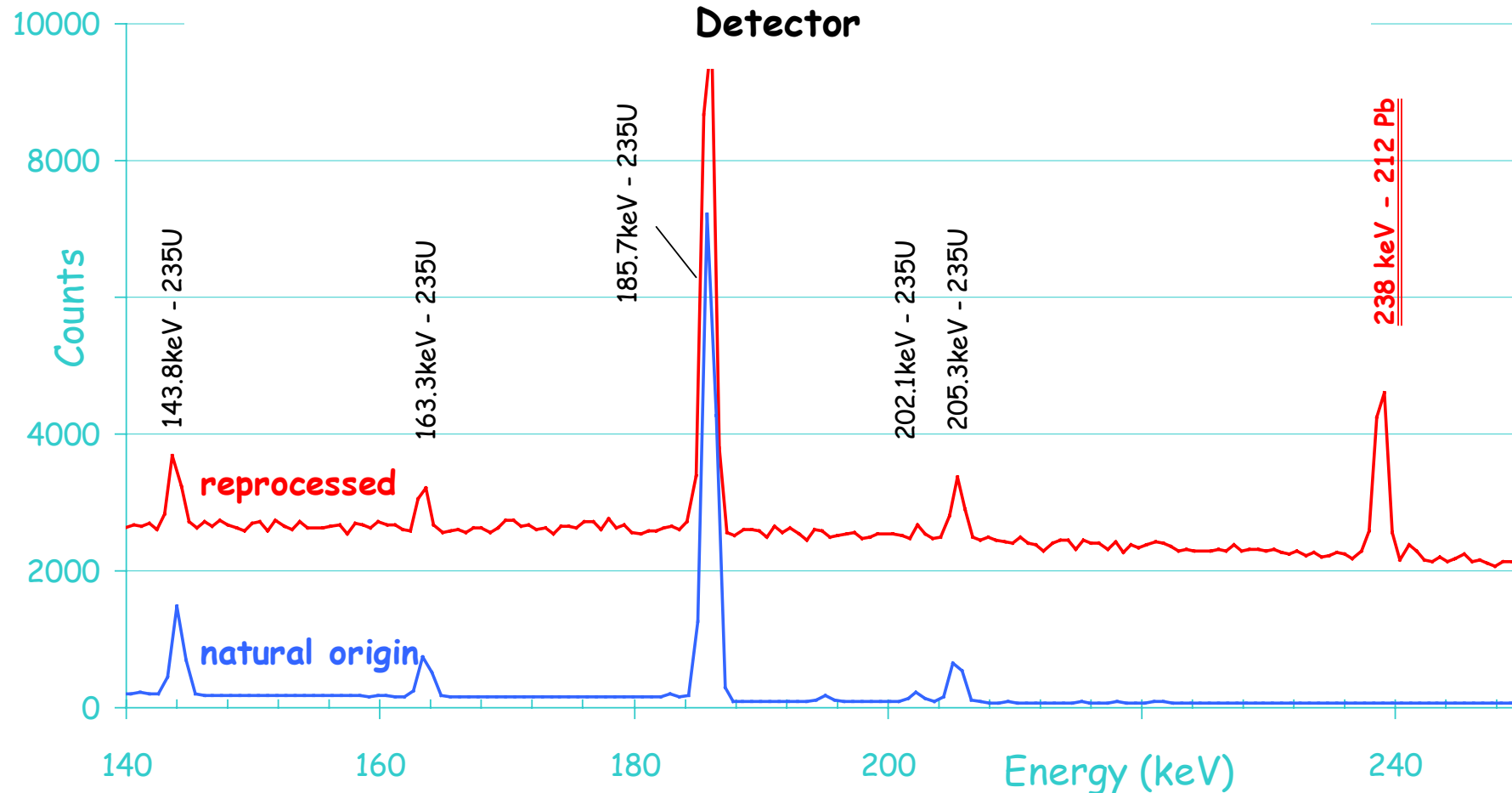
Uranium spectra with Ge and NaI detectors
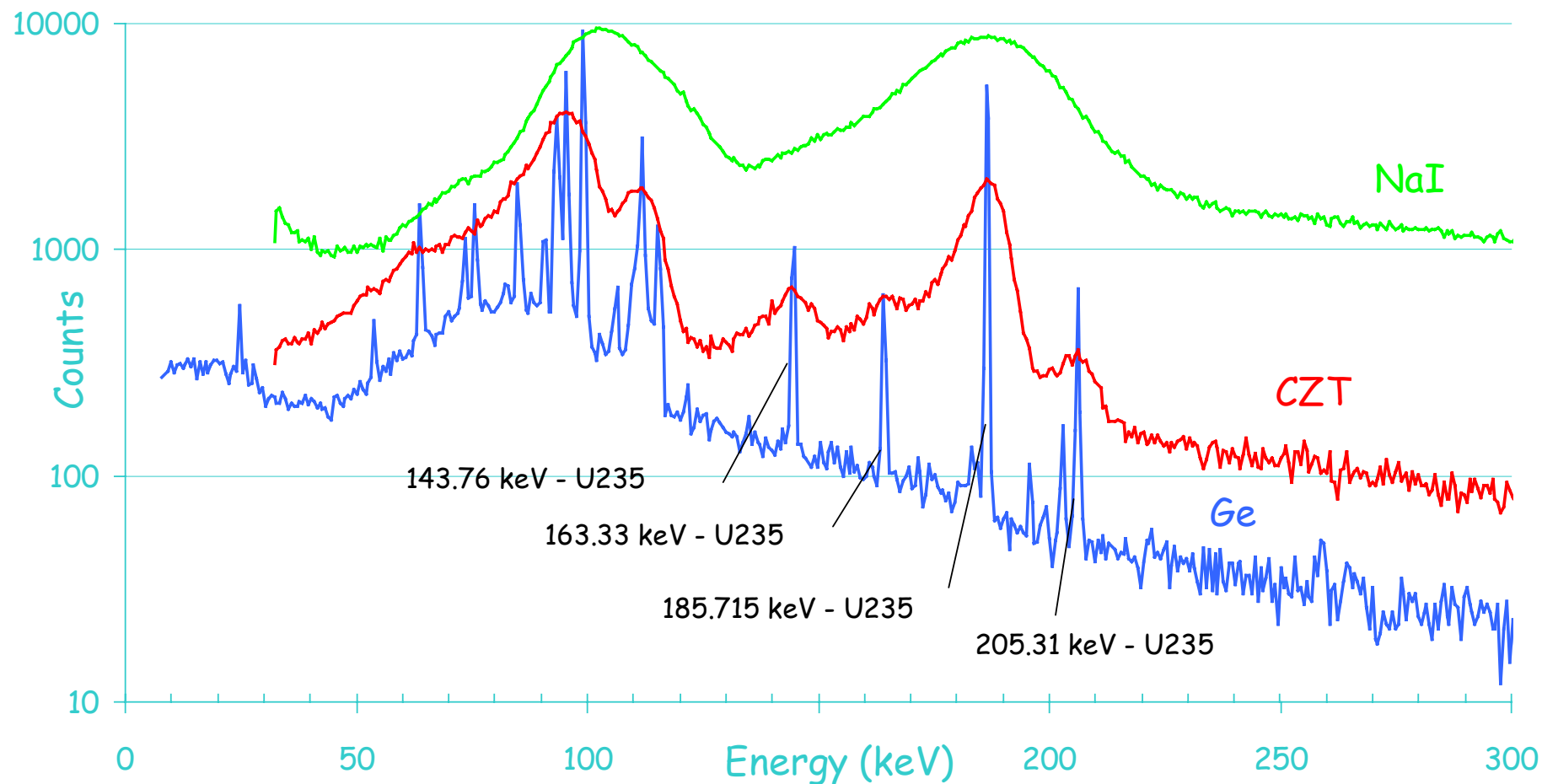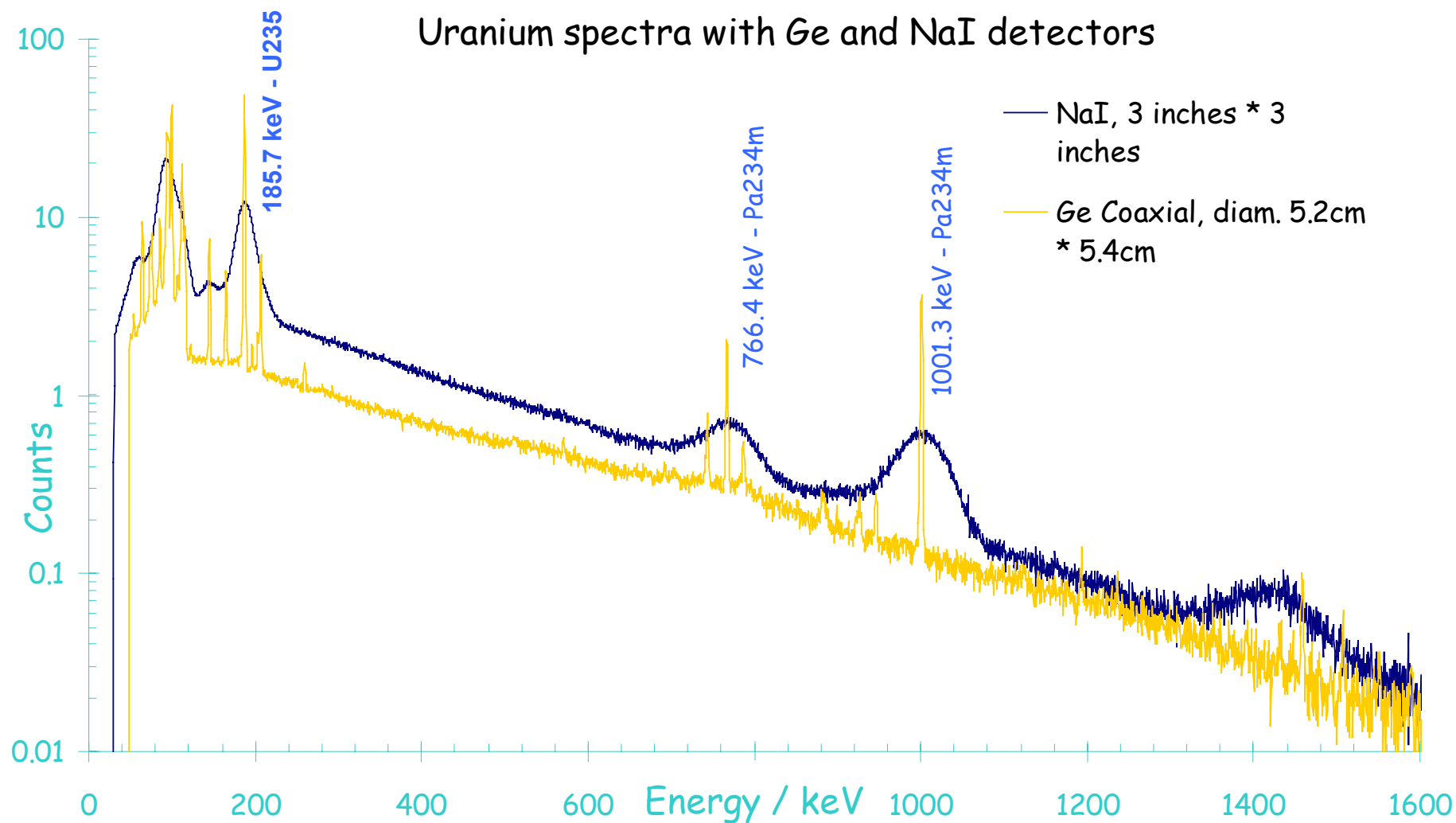
U ore spectrum, Planar Ge detector
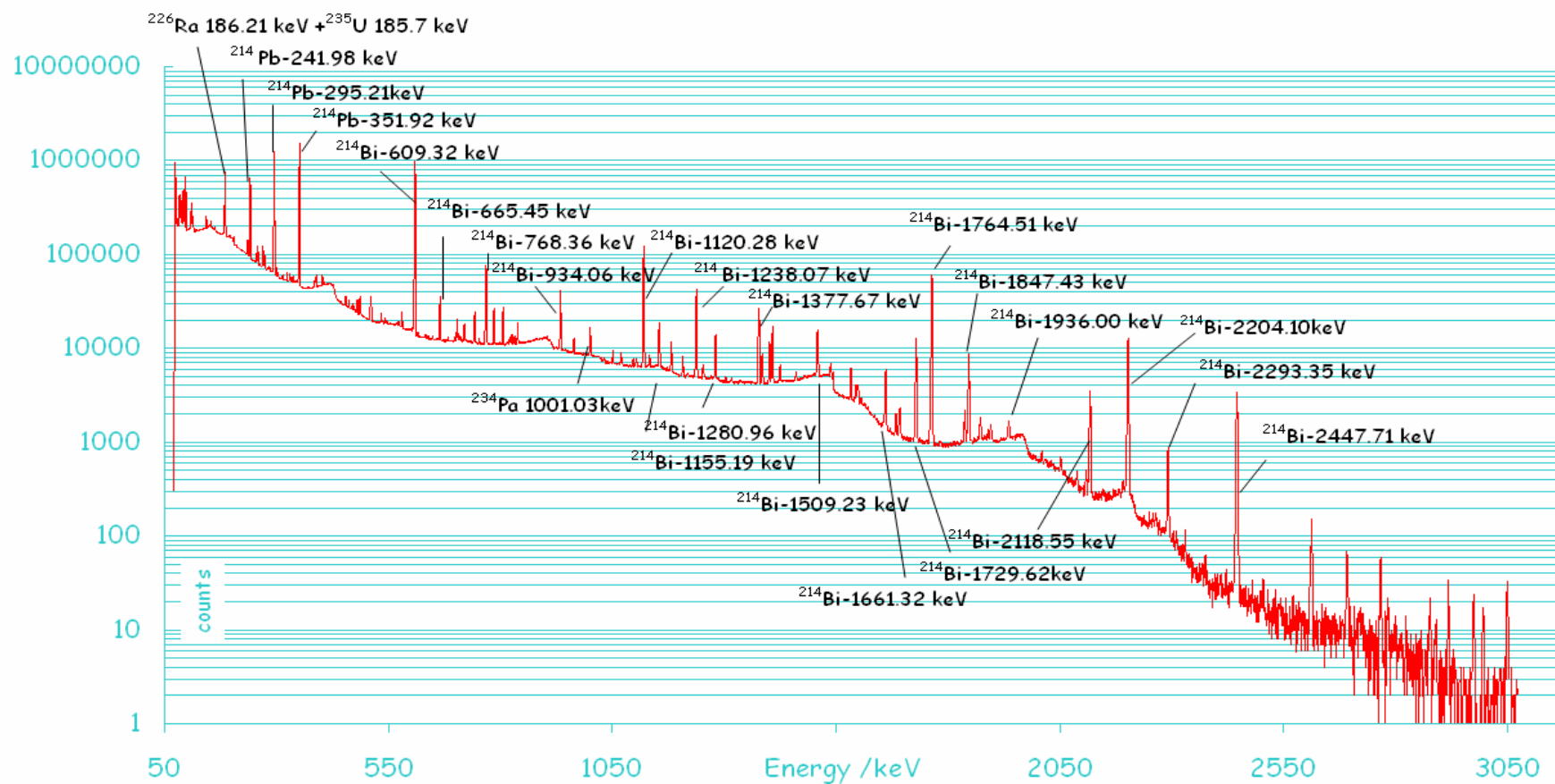
232Th Spectrum with Planar Ge Detector
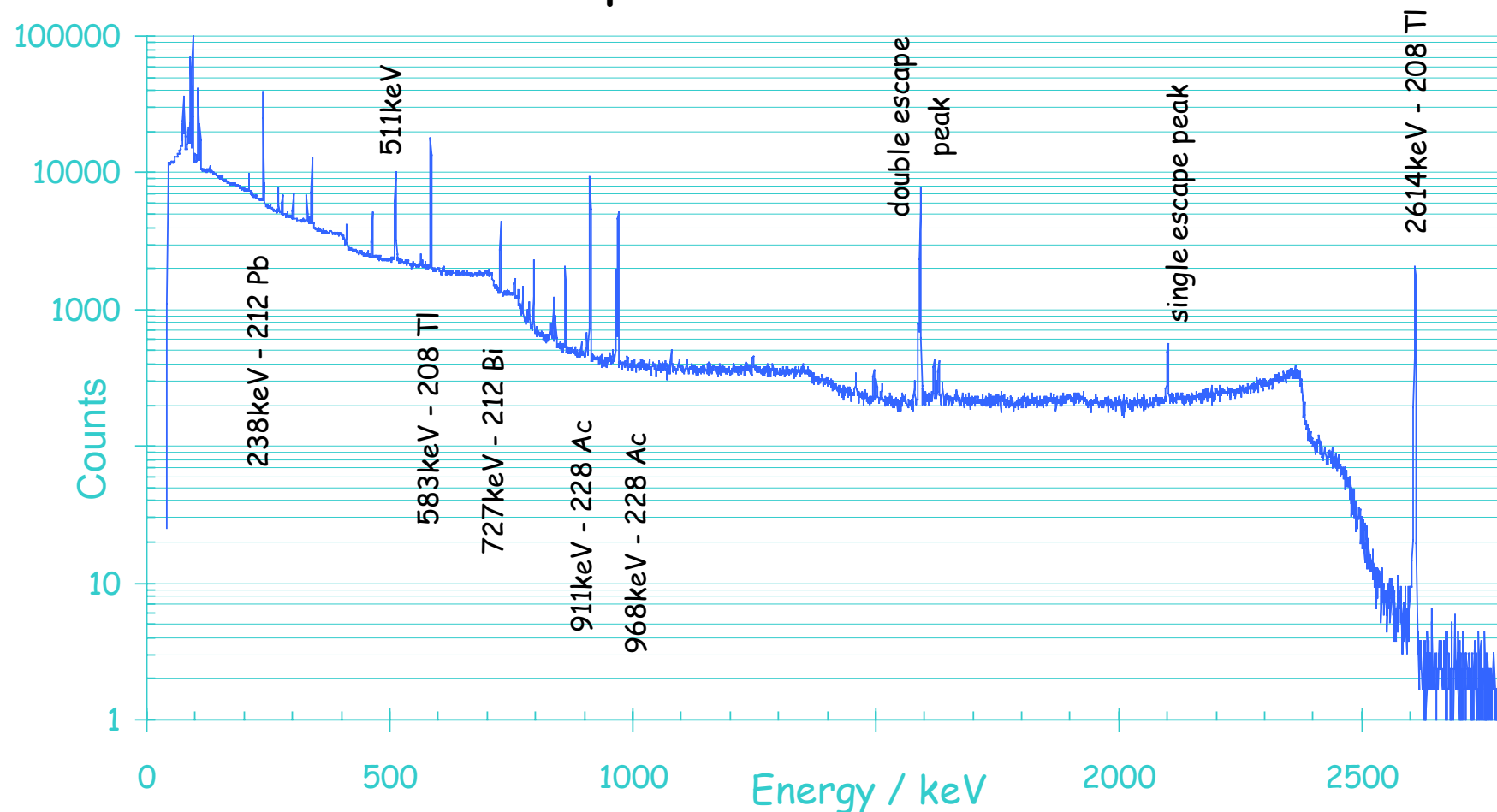
232Th Spectrum with CZT/500 Detector
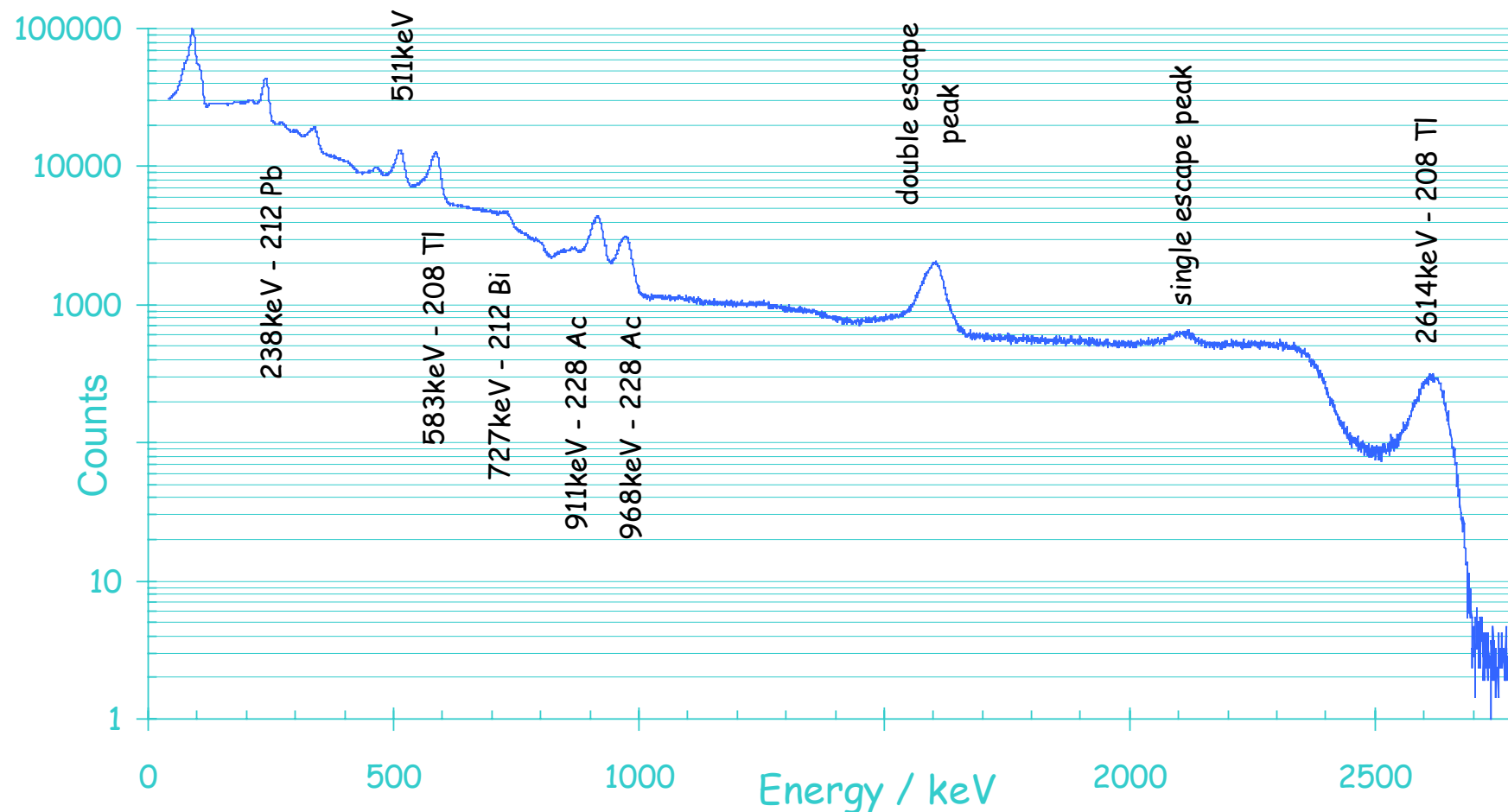
232Th Spectrum with NaI Detector
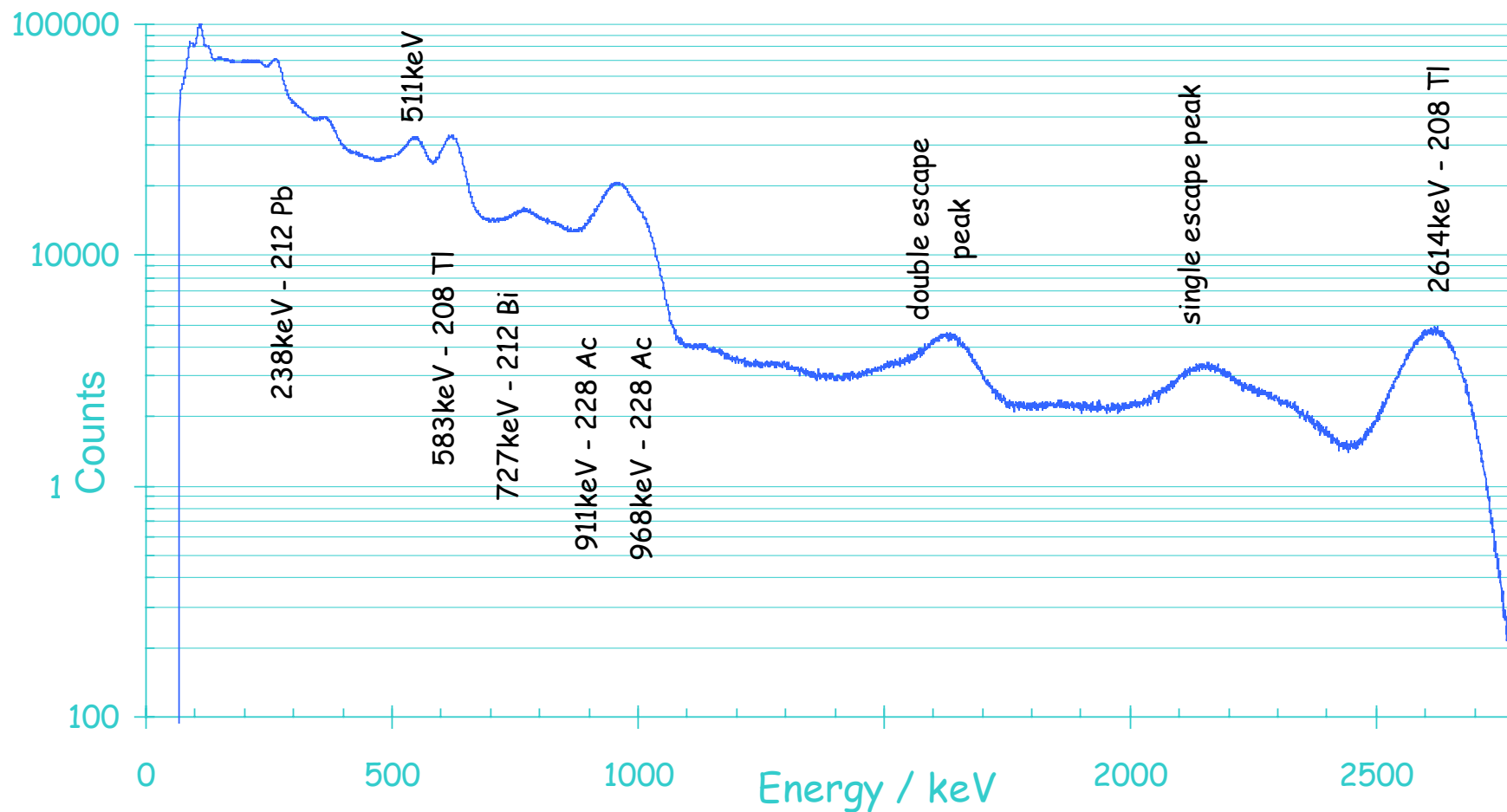
Plutonium Spectrum, Planar Ge Detector, 90keV to 120keV

CBNM93,   0.01% 238Pu, 93.5% 239Pu,   6.3% 240Pu, 0.1% 241Pu, 0.2% 241Am
CBNM61,   1.1% 238Pu, 64.9% 239Pu, 26.8% 240Pu, 3.9% 241Pu, 4.5% 241Am
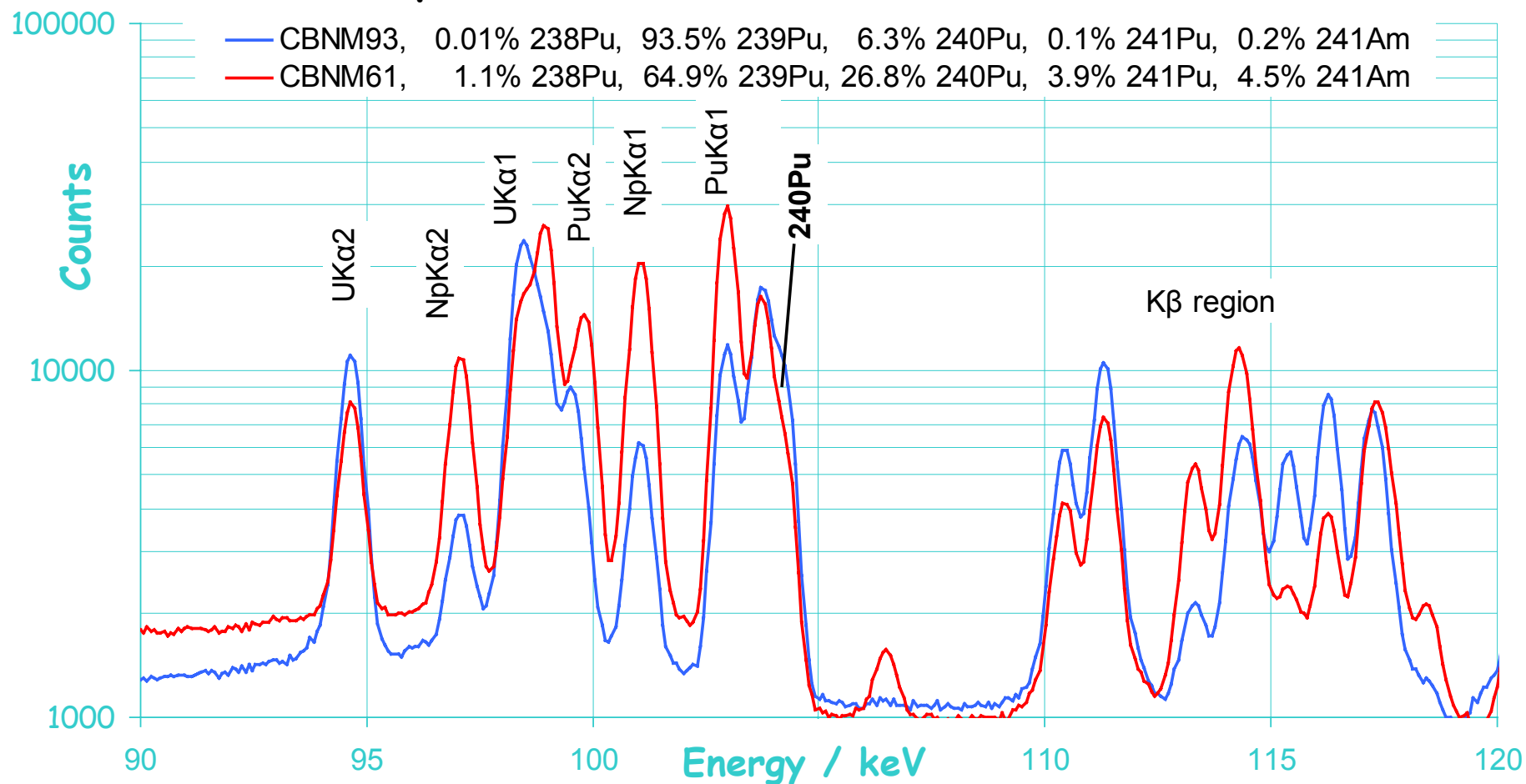
Plutonium Spectrum, Planar Ge Detector, 120keV to 195keV

— CBNM93,   0.01% 238Pu, 93.5% 239Pu,   6.3% 240Pu, 0.1% 241Pu, 0.2% 241Am
— CBNM61,   1.1% 238Pu, 64.9% 239Pu, 26.8% 240Pu, 3.9% 241Pu, 4.5% 241Am
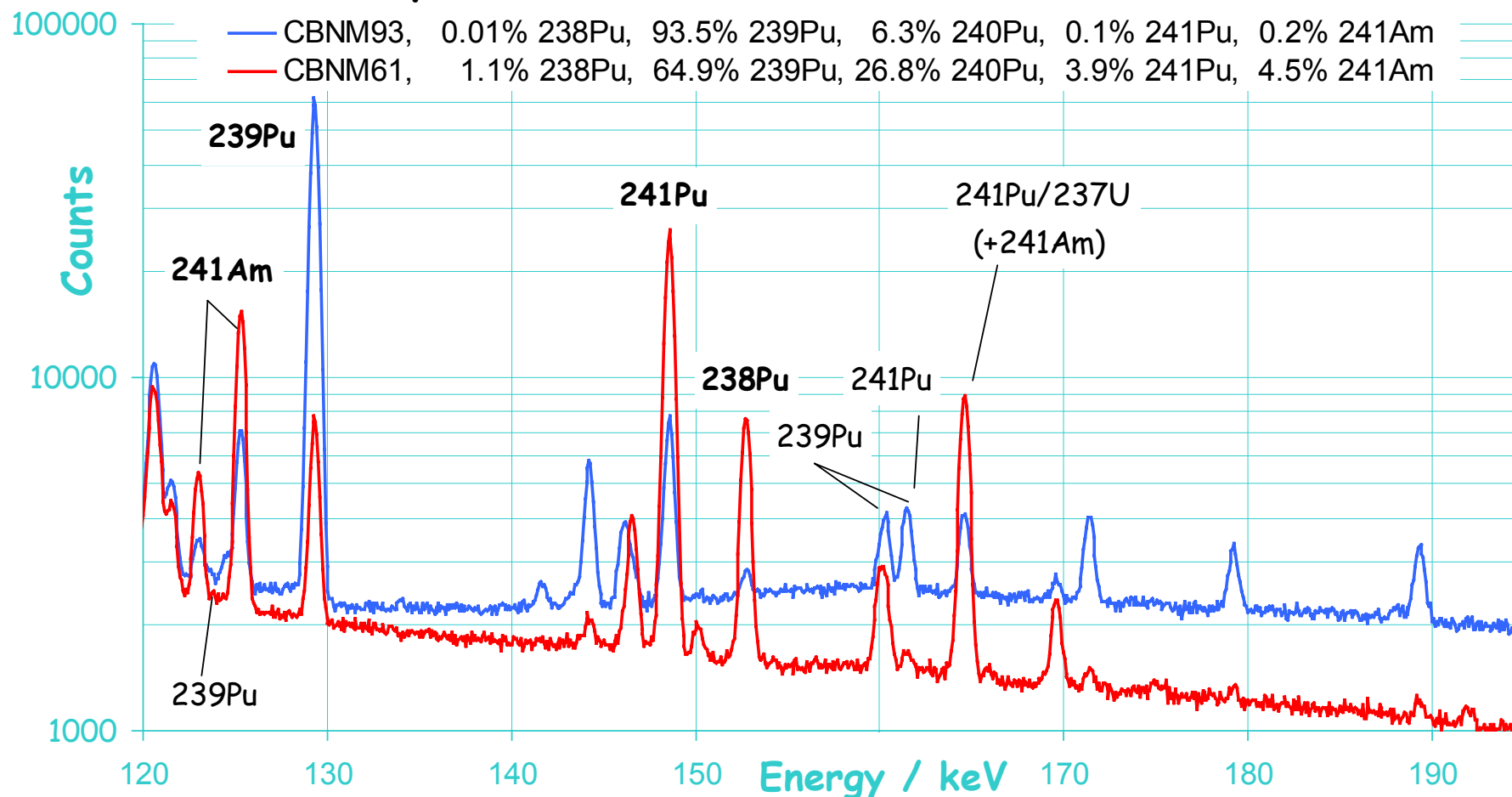
Plutonium Spectrum, Planar Ge Detector, 190keV to 300keV

CBNM93, 0.01% 238Pu, 93.5% 239Pu,
6.3% 240Pu, 0.1% 241Pu, 0.2% 241Am

CBNM61,   1.1% 238Pu, 64.9% 239Pu,
26.8% 240Pu, 3.9% 241Pu, 4.5% 241Am

239Pu

241Pu/237U
(+241Am)

241Pu/237U
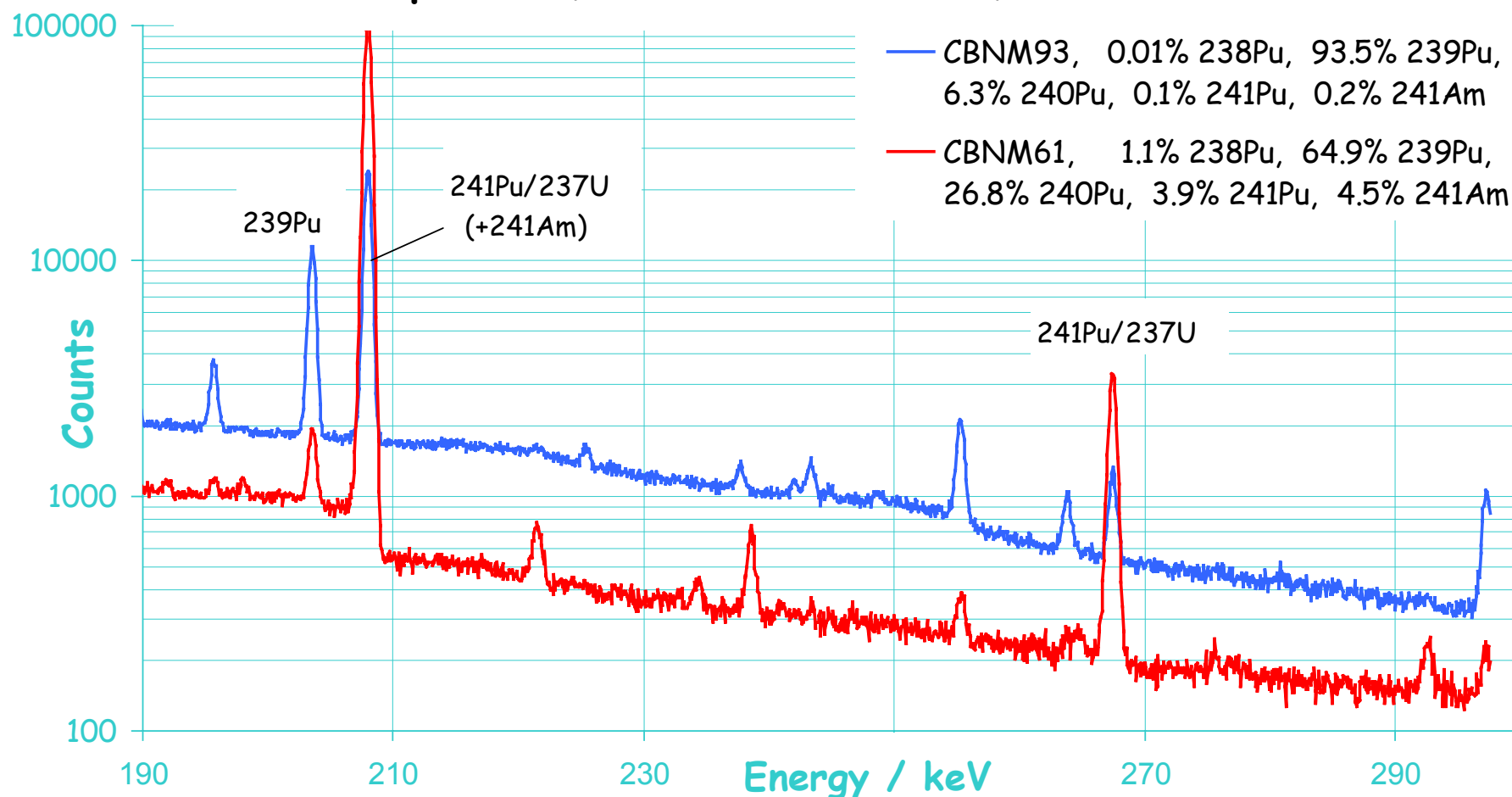
Gamma spectra of PWR spent fuel with final burn-up. Cooling times of 1.3 to 5.3 year with 3.6% initial enrichment, fuel rods with ZrNb cladding(WWER-440 fuel of Loviisa NPS)

Spent Fuel Spectra with CdZnTe Detector
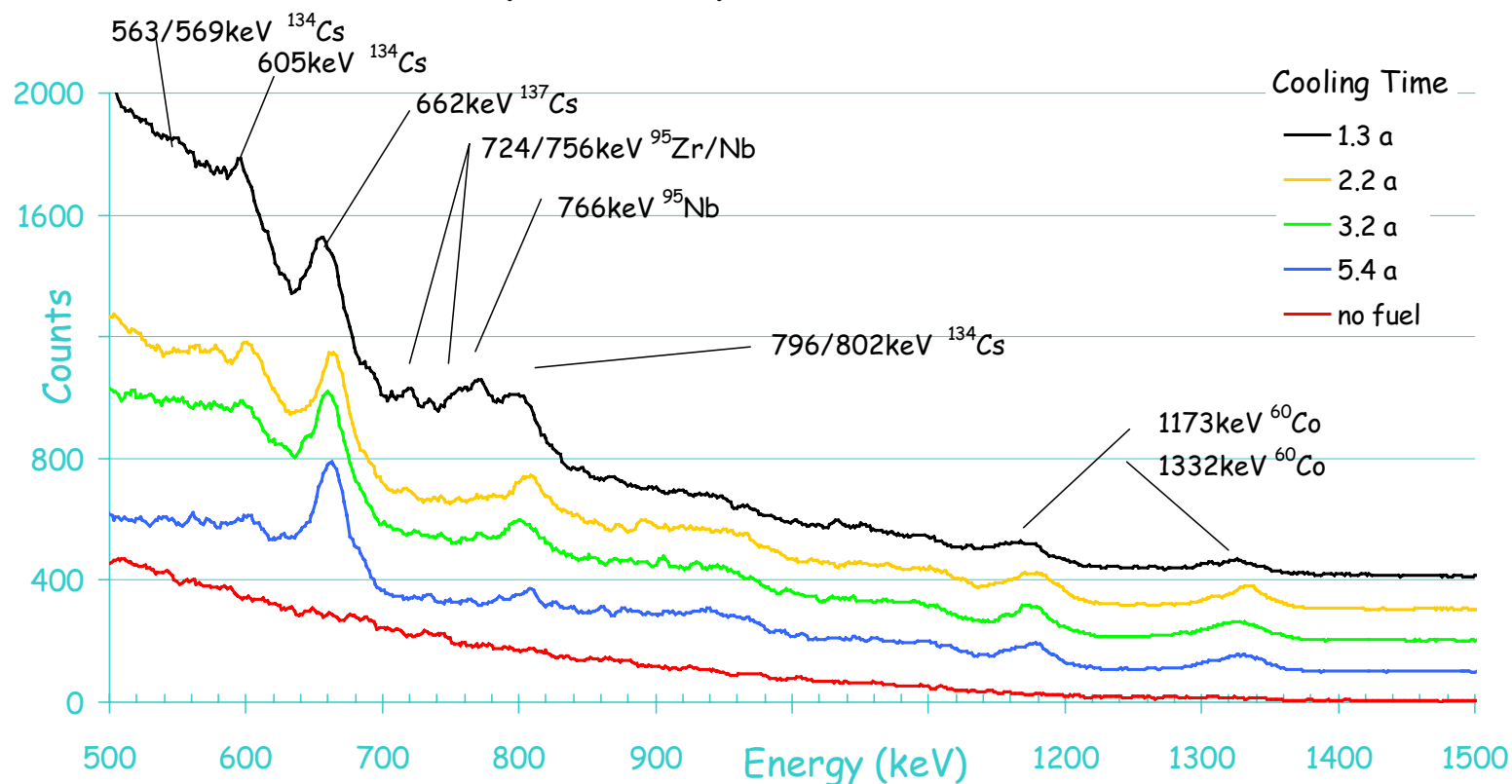
Gamma spectra of MTR spent fuel after 3 years cooling time. Burn-up from1500 to 96000MWd/t. MRT fuel with 36% initial enrichment, fuel tubes Al cladding (Rossendorf Research Reactor, WWR-M element)

Spent Fuel Spectra with CdZnTe Detector
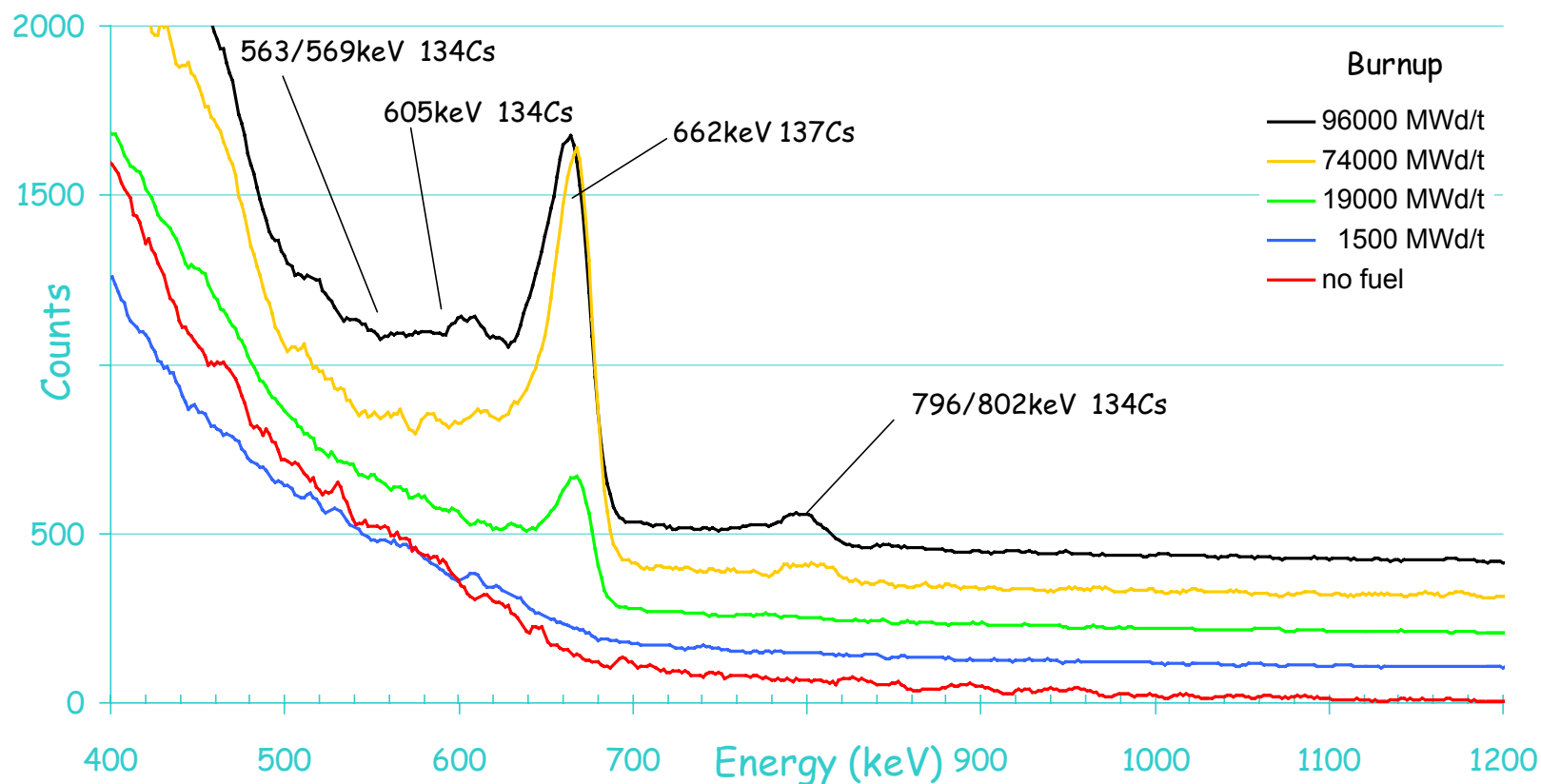
Detector efficiency – Spectra of 152Eu(695 kBq) and 154Eu(~90kBq) with different detectors (25 cm distance 0.1cm Cd Filter) see Annex A2Tab.14, Annex A2 Graph G11

ANNEX A2

TABLES AND GRAPHS

Tab.1: Gamma and X-rays of ^{235}U and its Decay Products

The absolute branching ratios are valid when ^{235}U (7.1*10^{8}a) and ^{231}Th (25.5 h) are in secular equilibrium.

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
231Th	**25.64**	**14.5**	U K$_{\alpha1}$	98.43	*)
235U	31.60	0.016	231Th	99.28	0.12
235U	34.70	0.037	231Th	102.27	0.41
235U	41.40	0.03	Th K$_{\beta1}$	105.36	1.98
235U	41.96	0.06	231Th	106.61	0.017
231Th	42.86	0.058	Pa K$_{\beta1}$	108.17	0.228
231Th	44.08	0.0007	Th K$_{\beta2}$	108.99	0.66
235U	51.22	0.02	235U	109.16	1.54
235U	54.10	0.002	Uk$_{\beta3}$	110.41	*)
235U	54.25	0.03	U K$_{\beta1}$	111.30	*)
231Th	58.57	0.48	Pa K$_{\beta2}$	111.90	0.076
231Th	63.86	0.023	U K$_{\beta2'}$	114.56	*)**)
231Th	68.50	0.0057	235U	115.45	0.07
235U	72.70	0.11	231Th	115.63	0.001
231Th	72.75	0.251	231Th	116.82	0.0207
235U	73.72	0.01	235U	120.35	0.026
235U	75.02	0.06	231Th	124.91	0.056
231Th	77.80		231Th	134.03	0.024
231Th	81.23	0.89	231Th	135.66	0.078
231Th	82.09	0.4	235U	136.55	0.012
231Th	**84.21**	**6.6**	231Th	136.75	0.0042
231Th	89.95	0.94	231Th	140.54	0.00071
Th K$_{\alpha2}$	89.96	3.36	235U	140.76	0.22
Pa K$_{\alpha2}$	92.28	0.39	235U	142.40	0.005
231Th	93.02	0.045	**235U**	**143.76**	**10.96**
Th K$_{\alpha1}$	93.35	5.5	231Th	145.06	0.0058
U K$_{\alpha2}$	94.65	*)	231Th	145.94	0.032
235U	95.70		235U	147.00	
Pa K$_{\alpha1}$	95.86	0.63	235U	150.93	0.076
235U	96.09	0.086	231Th	163.11	0.155

*) produced by self-excitation in the sample
**) UK$_{\beta2'}$ = UK$_{\beta21}$+UK$_{\beta22}$+UK$_{\beta4}$ + UKO+ UKP

Tab. 1 *(cont.)*: **Gamma and X-rays of ²³⁵U and its Decay Products**

Isotope	E (keV)	$I_{\gamma abs.}$ (%)	Isotope	E (keV)	$I_{\gamma, abs.}$ (%)
235U	**163.33**	**5.08**	**235U**	**279.50**	**0.27**
231Th	165.00	0.0039	235U	281.42	0.006
231Th	169.66	0.0012	235U	282.92	0.005
235U	173.30	0.01	231Pa	283.69	
231Th	174.15	0.0181	235U	289.56	0.007
235U	182.10		235U	291.20	
235U	182.61	0.34	**235U**	**291.65**	**0.038**
235U	**185.72**	**57.2**	231Pa	300.07	
231Th	188.76	0.0032	235U	301.70	0.005
235U	194.94	0.63	231Pa	302.67	
235U	198.90	0.042	231Th	308.78	0.00039
235U	**202.11**	**1.08**	235U	310.69	0.004
235U	**205.31**	**5.01**	231Th	311.00	0.0029
235U	215.28	0.027	235U	317.10	0.001
231Th	217.94	0.04	231Th	317.87	0.00008
235U	221.38	0.12	231Th	320.15	0.00011
235U	228.78	0.008	235U	325.80	0.0004
235U	233.50	0.029	231Pa	330.06	
231Th	236.01	0.0092	235U	343.50	0.003
231Th	240.27	0.00028	235U	345.90	0.038
235U	240.87	0.075	231Th	351.80	0.00007
231Th	242.50	0.00084	235U	356.03	0.005
235U	246.84	0.053	235U	387.82	0.038
231Th	249.60	0.00078	235U	390.30	0.04
231Th	250.45	0.00065	235U	410.29	0.003
235U	251.50	0.04	235U	433.00	0.004
235U	266.45	0.006	235U	448.40	0.001
231Th	267.62	0.00116	235U	455.10	0.008
231Th	274.10	0.00003	235U	517.20	0.0004
235U	**275.13**	**0.042**	235U	742.50	0.0004
235U	275.43	0.007	235U	794.70	0.0006

<u>Reference</u>: 2001 ENSDF data base (files:AR231TH.ENS, AR231PA.ENS, AR227AC.ENS)

Tab.2: Gamma and X-rays of ^{238}U and its Decay Products

The absolute branching ratios are valid when ^{238}U (4.51*10^{9}a), ^{234}Th (24.1 d), ^{234m}Pa (1.17 m) and ^{234}Pa (6.7 h) are in secular equilibrium.

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
238U	49.6	0.064	**234mPa**	**786.3**	**0.0485**
234Th	**63.3**	**4.84**	234mPa	805.7	0.0043
234Th	**92.4**	**2.81**	234Pa	805.8	0.00392
234Th	92.8	2.77	234mPa	808.2	0.003
U K α_2	94.7	*)	234Pa	825.1	0.002928
U K α_1	98.4	*)	234mPa	825.6	0.0014
U K β_1	111.3	*)	234Pa	831.5	0.006432
U K $\beta_{2'}$	114.6	*) **)	234mPa	851.6	0.0062
238U	113.5	0.0102	234Pa	876.0	0.00392
234Pa	131.3	0.028	234Pa	880.5	0.01616
234Pa	186.2	0.002736	234mPa	880.9	0.0038
234Pa	226.5	0.00656	234mPa	883.2	0.0018
234Pa	227.3	0.00896	234mPa	883.2	0.0017
234mPa	**258.3**	**0.0728**	234Pa	883.2	0.014976
234mPa	387.6	0.001	234mPa	887.3	0.0071
234mPa	387.6	0.0005	234Pa	898.7	0.00504
234Pa	568.9	0.005664	234Pa	921.7	0.00002032
234Pa	569.5	0.012928	234Pa	925.0	0.01224
234mPa	691.0	0.0078	234Pa	926.0	0.002736
234Pa	699.0	0.005632	234Pa	926.7	0.011344
234mPa	702.1	0.0071	234mPa	926.6	0.00123
234mPa	702.9	0.004	234mPa	936.3	0.0018
234Pa	705.9	0.00352	**234Pa**	**946.0**	**0.0208**
234Pa	733.4	0.010784	234Pa	980.3	0.00272
234mPa	740.0	0.0117	234Pa	980.3	0.00416
234mPa	**742.8**	**0.08**	234Pa	984.2	0.002512
234Pa	742.8	0.003216	234mPa	996.1	0.0041
234Pa	755.0	0.001952	**234mPa**	**1001.3**	**0.837**
234mPa	**766.4**	**0.294**	234Pa	1028.7	0.0008848
234mPa	781.4	0.0078	234mPa	1041.7	0.0012

*) produced by self-excitation in the sample
**) $UK_{\beta2'} = UK_{\beta21} + UK_{\beta22} + UK_{\beta4} + UKO + UKP$

Tab. 2 *(cont.)*: **Gamma and X-rays of ^{238}U and its Decay Products**

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
234mPa	1061.8	0.0023	234mPa	1667.6	0.0008
234Pa	1083.2	0.0007888	234Pa	1668.4	0.001192
234mPa	1125.7	0.0035	234Pa	1685.7	0.0004832
234mPa	**1193.8**	**0.0135**	234Pa	1693.8	0.0010832
234mPa	1220.4	0.0009	234mPa	1694.1	0.0005
234mPa	1237.2	0.0053	234mPa	1732.2	0.0018
234Pa	1292.8	0.0007248	**234mPa**	**1737.7**	**0.0211**
234Pa	1352.9	0.0018	234mPa	1759.8	0.0014
234mPa	1392.7	0.0034	234mPa	1765.4	0.0087
234Pa	1393.9	0.003216	234mPa	1796.2	0.0003
234Pa	1400.3	0.0002752	234mPa	1809.0	0.0037
234mPa	1413.9	0.0029	234mPa	1819.7	0.0009
234Pa	1426.9	0.0002592	234mPa	1819.8	0.0041
234mPa	1434.1	0.0097	**234mPa**	**1831.3**	**0.0172**
234Pa	1445.4	0.0005008	234mPa	1863.1	0.0012
234Pa	1452.7	0.001248	234mPa	1867.7	0.0092
234mPa	**1510.2**	**0.0129**	234mPa	1874.9	0.0082
234mPa	1527.3	0.0024	234mPa	1893.5	0.0022
234mPa	1550.0	0.0018	234mPa	1911.2	0.0063
234mPa	1553.7	0.0081	234mPa	1926.5	0.0004
234mPa	1570.7	0.0011	234mPa	1937.0	0.0029
234mPa	1593.9	0.0027	234mPa	1970.0	0.0006

Reference: 2001 ENSDF Data base (files: AR234TH.ENS,
AR234PA.ENS, AR234U.ENS)

Tab. 3: Gamma and X rays of Pu and ^{241}Am and their Decay Products

(The half lives are given in A2T5)

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
241Am	43.4	7.30E-02	241Am	146.6	4.61E-04
241Am	57.9	5.20E-03	**241Pu**	**148.6**	**1.86E-04**
241Am	**59.5**	**3.59E+01**	238Pu	152.7	9.37E-04
UK$_{\alpha 2}$	94.65		241Pu	159.9	6.54E-06
NpK$_{\alpha 2}$	97.07		239Pu	160.2	6.20E-06
UK$_{\alpha 1}$	98.43		240Pu	160.3	4.02E-04
PuK$_{\alpha 2}$	99.53		239Pu	161.5	1.23E-04
238Pu	99.9	7.35E-03	**241Pu/7U**	**164.6**	**4.53E-05**
NpK$_{\alpha 1}$	101.059		241Am	164.6	6.67E-05
241Pu	103.7	1.02E-04	241Am	169.6	1.73E-04
PuK$_{\alpha 1}$	103.73		239Pu	171.4	1.10E-04
240Pu	**104.2**	**7.08E-03**	241Am	175.1	1.82E-05
UK$_{\beta 3}$	110.4		239Pu	179.2	6.60E-05
UK$_{\beta 1}$	111.3		239Pu	189.4	8.30E-05
NpK$_{\beta 3}$	113.31		241Am	192.0	2.16E-05
241Pu	114.0	6.13E-06	239Pu	195.7	1.07E-04
NpK$_{\beta 1}$	114.24		238Pu	201.0	3.90E-06
UK$_{\beta 22}$	114.4		239Pu	203.5	5.69E-04
UK$_{\beta 21}$	114.6		**241Pu/7U**	**208.0**	**5.10E-04**
239Pu	115.4	4.62E-04	241Am	208.0	7.91E-04
239Pu	116.3	5.97E-04	240Pu	212.5	2.90E-05
NpK$_{\beta 22}$	117.35		241Am	221.5	4.24E-05
NpK$_{\beta 21}$	117.59		238Pu	235.9	1.00E-10
241Pu	121.2	6.86E-07	239Pu	237.8	1.44E-05
239Pu	122.0	3.00E-06	239Pu	255.4	8.00E-05
239Pu	123.6	1.97E-05	239Pu	264.0	2.65E-05
241Am	123.0	1.00E-03	241Pu/7U	267.5	1.72E-05
239Pu	124.5	6.13E-05	**241Am**	**267.6**	**2.63E-05**
239Pu	125.2	7.11E-05	239Pu	297.5	4.98E-05
241Am	**125.3**	**4.08E-03**	239Pu	311.8	2.58E-05
239Pu	**129.3**	**6.31E-03**	239Pu	320.9	5.42E-05
239Pu	144.2	2.83E-04	241Am	322.5	1.52E-04
239Pu	146.1	1.19E-04	241Am	332.4	1.49E-04

Tab. 3 *(cont.)*: **Gamma and X rays of Pu and** ^{241}**Am and their Decay Products**

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
241Pu/7U	**332.4**	**2.89E-05**	239Pu	640.0	8.70E-06
239Pu	332.8	4.94E-04	240Pu	642.4	1.30E-05
241Am	**335.4**	**4.96E-04**	239Pu	645.9	1.52E-05
241Pu/7U	335.4	1.08E-06	239Pu	652.1	6.60E-06
239Pu	336.1	1.12E-04	241Am	653.0	3.77E-05
239Pu	341.5	6.62E-05	239Pu	658.9	9.70E-06
239Pu	345.0	5.56E-04	**241Am**	**662.4**	**3.64E-04**
239Pu	361.9	1.22E-05	241Am	680.0	3.13E-06
239u	367.0	8.90E-05	240Pu	687.6	3.50E-06
241Am	368.6	2.17E-04	239Pu	688.1	1.11E-07
239Pu	368.6	8.80E-05	241Am	688.7	3.25E-05
241Pu/7U	368.6	9.00E-07	239Pu	693.2	3.00E-08
241Pu/7U	370.9	2.60E-06	241Am	696.6	5.34E-06
241Am	370.9	5.23E-05	239Pu	703.7	3.95E-06
239Pu	**375.0**	**1.55E-03**	238Pu	708.4	4.10E-07
241Am	376.6	1.38E-04	241Am	709.5	6.41E-06
239Pu	380.2	3.05E-04	**241Am**	**722.0**	**1.96E-04**
239Pu	382.8	2.59E-04	239Pu	727.9	1.24E-07
241Am	383.8	2.82E-05	241Am	737.3	8.00E-06
239Pu	392.5	2.05E-04	239Pu	742.7	5.20E-06
239Pu	**413.7**	**1.47E-03**	241Am	755.9	7.60E-06
241Am	419.3	2.87E-05	239Pu	756.4	3.47E-06
239Pu	422.6	1.22E-04	238Pu	766.4	2.20E-05
241Am	426.5	2.46E-05	239Pu	766.5	1.30E-07
239Pu	426.7	2.33E-05	241Am	767.0	5.00E-06
239Pu	451.5	1.89E-04	239Pu	767.3	1.40E-07
239Pu	582.9	6.15E-07	239Pu	769.2	5.10E-06
239Pu	596.0	3.90E-08	239Pu	769.4	6.80E-06
239Pu	618.3	2.04E-06	241Am	770.6	4.74E-06
241Am	619.0	5.94E-05	238Pu	786.3	3.25E-06
239Pu	619.2	1.21E-06	239Pu	786.9	8.60E-08
239Pu	637.8	1.92E-06			

Reference: 2001 ENSDF Data base (Files: AR234U.ENS, AR235U.ENS, AR236U.ENS, AR237NP.ENS)

Tab. 4: Gamma Lines of Th Ore (^{232}Th and Decay Products)

The absolute branching ratios are when each daughter nuclide of the chain is in secular equilibrium with its parent nuclide (the half-life values are given in A2G2). *Attention! Th ore normally contains U.*

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
Bi $K_{\alpha2}$	74.81	10.5	228Ac	503.82	0.182
Bi $K_{\alpha1}$	77.11	17.76	228Ac	508.96	0.45
Bi $K_{\beta1}$	86.83	6.27	208Tl	510.77	22.60
Th $K_{\alpha2}$	89.96	3.40	228Ac	520.15	0.067
Bi $K_{\beta2'}$	90.128	1.86	228Ac	523.13	0.103
T $K_{(1}$	93.35	5.60	228Ac	546.47	0.201
U $K_{(1}$	98.44		228Ac	562.50	0.87
Th $K_{\beta1}$	105.36	2.00	**208Tl**	**583.17**	**84.42**
Th $K_{\beta2}$	108.99	0.67	*214Bi*	*609.31*	*46.10*
212Pb	115.18	0.592	228Ac	616.22	0.08
228Ac	129.06	2.42	228Ac	620.38	0.08
228Ac	153.98	0.72	228Ac	640.34	0.054
235U	185.7		228Ac	651.51	0.09
226Rn	186.21		*214Bi*	*665.45*	*1.46*
228Ac	209.25	3.89	228Ac	701.75	0.173
228Th	215.75	0.207	228Ac	707.42	0.155
212Pb	**238.62**	**43.3**	228Ac	726.86	0.62
224Ra	240.99	3.90	212Bi	727.33	6.58
208Tl	252.61	0.69	228Ac	755.32	1
228Ac	270.24	3.46	208Tl	763.13	1.81
208Tl	277.36	6.30	*214Bi*	*768.36*	*4.94*
214Pb	*295.22*	*19.30*	228Ac	772.29	1.49
212Pb	300.09	3.27	228Ac	782.14	0.485
228Ac	321.65	0.226	212Bi	785.37	1.102
228Ac	328.00	2.95	228Ac	794.95	4.25
228Ac	332.37	0.40	*214Bi*	*806.17*	*1.22*
228Ac	338.30	11.27	228Ac	830.49	0.54
228Ac	340.96	0.369	228Ac	835.00	1.61
214Pb	*351.93*	*37.6*	228Ac	840.00	0.91
228Ac	409.46	1.92	208Tl	860.56	12.42
228Ac	463.20	4.40	212Bi	893.41	0.378
228Ac	478.33	0.21	228Ac	904.20	0.77

Tab. 4 (cont.): Gamma Lines of Th Ore (^{232}Th and Decay Products)

Isotope	E (keV)	$I_{\gamma,abs.}$ (%)	Isotope	E (keV)	$I_{\gamma,abs.}$ (%)
228Ac	**911.18**	**25.8**	214Bi	1401.50	1.272
208Tl	927.60	0.131	214Bi	1407.98	2.155
214Bi	934.06	3.03	228Ac	1459.14	0.83
228Ac	944.20	0.095	228Ac	1495.91	0.86
228Ac	947.98	0.106	228Ac	1501.57	0.46
212Bi	952.12	0.166	214Bi	1509.23	2.114
228Ac	958.00	0.28	212Bi	1512.70	0.288
228Ac	964.77	4.99	228Ac	1529.05	0.057
228Ac	**968.94**	**15.8**	214Bi	1538.50	0.376
228Ac	975.00	0.05	228Ac	1557.11	0.178
208Tl	982.70	0.203	228Ac	1580.53	0.60
228Ac	987.71	0.077	228Ac	1588.20	3.22
228Ac	988.63	0.077	**Dbl.esc.**	**1592.00**	
234mPa	1001.00		214Bi	1594.73	0.254
228Ac	1033.00	0.201	214Bi	1599.31	0.236
228Ac	1065.00	0.132	212Bi	1620.50	1.486
212Bi	1078.62	0.564	228Ac	1625.06	0.25
208Tl	1093.90	0.397	228Ac	1630.63	1.51
228Ac	1095.68	0.129	228Ac	1638.28	0.47
228Ac	1110.61	0.304	228Ac	1666.52	0.178
214Bi	1120.29	15.12	Sum peak	1666.28	
214Bi	1133.66	0.248	212Bi	1679.70	0.057
228Ac	1153.52	0.139	228Ac	1686.09	0.095
214Bi	1155.19	1.632	214Bi	1729.59	2.92
228Ac	1164.50	0.065	214Bi	1764.51	15.42
214Bi	1238.11	5.798	212Bi	1806.00	0.09
228Ac	1245.05	0.09	214Bi	1847.42	2.113
228Ac	1247.08	0.50	228Ac	1887.10	0.090
214Bi	1280.96	1.43	Singl. esc.	2103.00	
228Ac	1287.00	0.08	214Bi	2118.55	1.14
214Bi	1377.67	4.00	214Bi	2204.21	5.084
214Bi	1385.31	0.757	214Bi	2447.86	1.572
			208Tl	**2614.48**	**99.16**

Reference: 2001 ENSDF data base
(files: AR208PB.ENS, AR228RA.ENS, AR224RA.ENS,
    AR214BI.ENS, AR212PO.ENS, AR214PO.ENS)

Tab. 5: Nuclear Data for Selected Nuclides

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
7Be	53.2 d	477.6	10.4	310.9	166.4
22Na	2.6 a	511.0	180.5	340.6	170.3
		1274.5	99.9	1059.6	214.0
40K ***)	1.26*10^{9}a	1460.8	10.7	1243.3	217.5
51Cr	27.7 d	320.1	9.9	178.7	142.3
54Mn	312.2 d	834.8	100.0	639.4	195.6
59Fe	44.5 d	142.6	1.0	51.1	91.5
		192.3	2.9	82.6	109.7
		1099.2	56.1	891.9	207.3
		1291.6	43.6	1078.3	213.3
57Co	271.7 d	122.1	85.7	39.4	82.6
		136.5	10.7	47.5	89.0
60Co	5.27 a	1173.2	100.0	962.9	209.8
		1332.5	100.0	1118.1	214.4
65Zn	243.9 d	511.0	2.9	340.7	170.3
		1115.5	50.8	907.6	207.9
88Y	106.6 d	898.0	94.1	699.1	198.0
		1836.1	99.4	1611.7	198.9
95Zr 6.54%*)	64.0 d	724.2	44.1	535.3	188.9
		756.7	54.5	565.5	191.0
95Zr/95Nb	35.0 d	765.8	99.8	574.2	191.2
103Ru 3.02%*)	39.2 d	497.1	89.5	328.3	168.8
		610.3	5.6	430.0	180.1
106Ru/ 0.41%*)	372.6 d	511.9	20.5	341.4	170.7
106Rh 4.3%**)		616.2	0.7	435.6	180.6
		621.8	9.9	441.0	181.1
		1050.4	1.5	844.5	205.5
		1128.1	0.38	919.7	208.3
109Cd	462.6 d	88.0	3.65	22.5	65.5
110mAg	249.8 d	446.8	3.7	284.3	162.5
		620.4	2.8	439.4	181.0
		657.8	94.4	474.0	183.8
		677.6	10.5	492.2	185.6
		687.0	6.4	500.8	186.2

*)   Fission product yield for thermal fission of 235U

**)   Fission product yield for thermal fission of 239Pu

***) Natural K contains 0.0117 % of the isotope 40K

Tab. 5*(cont.)*: Nuclear Data for Selected Nuclides

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
110mAg *(cont.)*		706.7	16.7	519	187.7
		744.3	4.7	554.1	190.2
		763.9	22.5	572.4	191.5
		818.0	7.3	623.3	194.7
		884.7	72.7	686.5	198.2
		937.5	34.3	736.7	200.8
		1384.3	24.2	1168.6	215.7
		1475.8	4.0	1258	217.8
		1505.0	13.1	1286.6	218.4
		1562.3	1.2	1342.7	219.6
114mIn	49.5 d	190.3	15.4	81.2	109.1
131I 2.88%*)	8.02 d	80.2	2.6	19.2	61.0
		284.3	6.2	149.7	134.6
		364.5	81.6	214.3	150.2
		637.0	7.1	454.6	182.4
		722.9	1.8	535.1	188.8
133Ba 6.61%*)	10.5 a	79.6	34.1	18.9	62.1
		276.4	7.2	143.6	132.8
		302.9	18.3	164.3	138.6
		356.0	62.0	207.3	148.7
		383.9	8.9	230.5	153.4
134Cs **)	2.07 a	475.3	1.5	309.1	166.2
		563.2	8.4	363.2	173.0
		569.3	15.4	392.9	176.4
		604.7	97.6	425.1	179.6
		795.8	85.5	602.4	193.4
		801.9	8.7	608.1	193.8
		1038.6	1.0	833.5	205.1
		1167.9	1.8	958.3	209.6
		1365.2	3.0	1150	215.2
137Cs 6.24%*	30.1 a	661.6	85.2	477.4	184.2
140Ba 6.27%*)	12.8 d	328.8	20.6	185.0	143.8
140La		487.0	43.8	319.4	167.6
		537.3	24.0	364.1	173.2
		751.6	5.1	560.9	190.7

*) Fission product yield for thermal fission of 235U

**)134Cs is built up by neutron capture from the fission prod. 133Cs

Tab. 5*(cont.)*: Nuclear Data for Selected Nuclides

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
140Ba/La		815.8	27.3	621.2	194.6
(cont.)		867.8	6.4	670.4	197.4
		919.6	3.1	719.7	199.9
		925.2	8.1	725.0	200.2
		1596.2	100.8	1376.0	220.2
141Ce 5.84%*)	32.5 d	145.5	48.5	52.8	92.7
144Ce/5.46%*)	285.1 d	133.5	11.1	45.8	87.7
144Pr3.8%**)		696.5	1.3	509.6	186.9
		2185.7	0.7	1956.9	228.8
152Eu 0.26%*)	13.53 a	121.8	28.4	36.3	82.5
		244.7	7.5	119.7	125.0
		295.9	0.44	158.8	137.1
		344.3	26.5	197.6	146.7
		367.8	0.8	217.0	150.8
		411.1	2.2	253.5	157.6
		444.0	3.1	281.8	162.2
		503.4	0.16	333.9	169.5
		719.4	0.33	530.9	188.5
		778.9	12.9	586.5	192.4
		867.4	4.2	670.0	197.4
		964.1	14.6	761.6	201.9
		1085.8	10.1	879.0	206.8
		1089.7	1.7	882.7	207.0
		1112.1	13.5	904.3	207.8
		1212.9	1.4	1001.9	211.0
		1299.1	1.6	1085.6	213.5
		1457.6	0.5	1240.2	217.4
154Eu ***)	8.6 a	123.1	40.5	40.0	83.1
		247.9	6.6	122.2	125.8
		591.7	4.8	413.3	178.4
		723.3	19.7	534.5	188.8
		756.9	4.3	565.9	191.0
		873.2	11.5	675.5	197.7

*)   Fission product yield for thermal fission of 235U
**)   Fission product yield for thermal fission of 239Pu
***) Built up from several primary fission products

Tab. 5(cont.)**: Nuclear Data for Selected Nuclides**

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
140Ba/La (cont.)		815.8	27.3	621.2	194.6
		867.8	6.4	670.4	197.4
		919.6	3.1	719.7	199.9
		925.2	8.1	725.0	200.2
		1596.2	100.8	1376.0	220.2
141Ce 5.84%*)	32.5 d	145.5	48.5	52.8	92.7
144Ce 5.46%*)	285.1 d	133.5	11.1	45.8	87.7
144Pr 3.8%**)		696.5	1.3	509.6	186.9
		2185.7	0.7	1956.9	228.8
152Eu 0.26%*)	13.53 a	121.8	28.4	36.3	82.5
		244.7	7.5	119.7	125.0
		295.9	0.44	158.8	137.1
		344.3	26.5	197.6	146.7
		367.8	0.8	17.0	150.8
		411.1	2.2	253.5	157.6
		444.0	3.1	281.8	162.2
		503.4	0.16	333.9	169.5
		719.4	0.33	530.9	188.5
		778.9	12.9	586.5	192.4
		867.4	4.2	670.0	197.4
		964.1	14.6	761.6	201.9
		1085.8	10.1	879.0	206.8
		1089.7	1.7	882.7	207.0
		1112.1	13.5	904.3	207.8
		1212.9	1.4	1001.9	211.0
		1299.1	1.6	1085.6	213.5
		1408.0	20.8	1191.7	216.3
		1457.6	0.5	1240.2	217.4
154Eu ***)	8.6 a	123.1	40.5	40.0	83.1
		247.9	6.6	122.2	125.8
		591.7	4.8	413.3	178.4
		723.3	19.7	534.5	188.8
		756.9	4.3	565.9	191.0
		873.2	11.5	675.5	197.7

*)   Fission product yield for thermal fission of 235U
**)   Fission product yield for thermal fission of 239Pu
***) Built up from several primary fission products

Tab. 5 *(cont.)*:   Nuclear Data for Selected Nuclides

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
154Eu		996.3	10.3	92.9	203.4
(cont.)		1004.8	17.9	801.1	203.7
		1274.4	35.5	1061.6	212.8
198Au	2.695 d	411.8	95.6	254.1	157.7
203Hg	46.6 d	279.2	81.6	145.8	133.4
207Bi	32.8 a	570.0	97.7	393.9	176.4
		1063.6	74.0	857.6	206.0
		1770.2	6.9	1546.9	223.3
212Pb	10.6 h	238.6	43.3	115.2	123.4
231Th	25.52 h	84.2	6.7	20.9	63.3
234Th	24.1 d	92.4	2.8	24.5	67.8
		92.8	2.8	24.7	68.1
231Pa	32760 a	283.7	1.6	149.3	134.4
		300.1	2.4	162.1	138.0
		302.7	2.5	164.1	138.5
234Pa	6.7 h	131.3	17.5	44.6	86.7
		880.5	10.1	672.5	198.0
		946.0	13.0	744.8	201.1
234mPa	1.17 m	766.4	0.294	574.8	191.6
		1001.0	0.837	797.5	203.5
232U	69.8 a	42.5	0.06	6.1	36.4
233U	$1.592*10^5$ a	54.7	0.014	9.6	45.1
234U	$2.457*10^5$ a	53.2	0.123	9.2	44.0
235U	$7.037*10^8$ a	143.7	10.96	51.8	92.0
		150.9	0.076	56.0	94.9
		163.3	5.08	63.7	99.6
		182.6	0.34	75.8	106.3
		185.7	57.20	78.2	107.5
		194.9	0.63	84.4	110.6
		198.9	0.042	87.1	111.8
		202.1	1.08	89.3	112.8
		205.3	5.01	91.5	113.8
236U	$2.34*10^7$ a	49.4	0.08	8.0	41.4
		112.7	0.02	34.5	78.2
237U	6.75 d	59.5	33.5	11.2	48.3
		208.0	21.7	93.3	114.7

Tab. 5 _(cont.)_: Nuclear Data for Selected Nuclides

Nuclide	Half life	Gamma line (keV)	Absolute Intensity (keV)	Compton edge (keV)	Backscatter peak (%)
238U	4.468*10^9 a	49.6	0.064	8.0	41.5
		113.5	0.0102	34.9	78.6
238Pu	87.74 a	99.9	7.35E-03	28.1	71.8
		152.7	9.37E-04	57.1	95.6
		742.8	5.20E-06	552.7	190.1
		766.4	2.20E-05	574.8	191.6
		786.3	3.25E-06	593.5	192.8
239Pu	24110 a	129.3	6.31E-03	43.4	85.9
		203.5	5.69E-04	90.2	113.3
		332.8	4.94E-04	188.3	144.5
		345.0	5.56E-04	198.2	146.8
		375.0	1.55E-03	223.0	152.0
		413.7	1.47E-03	255.7	158.0
		451.5	1.89E-04	288.3	163.2
		640.0	8.70E-06	457.5	182.6
		645.9	1.52E-05	462.0	183.0
		658.9	9.70E-06	474.8	184.1
		718.0	2.80E-06	529.6	188.4
		769.4	1.19E-05	577.6	191.8
240Pu	6563 a	45.2	450E-02	6.8	38.4
		104.2	7.08E-03	30.2	74.0
241Pu	14.35 a	148.6	1.86E-04	54.6	94.0
		159.9	6.58E-06	61.6	98.3
242Pu	3.73*10^5 a	44.9	3.73E-02	6.7	38.2
241Am	432.7 a	59.5	35.9	11.2	48.3
		125.3	4.08E-03	41.2	84.1
		146.6	4.61E-04	53.4	93.2
		164.6	6.67E-05	64.5	100.1
		169.6	1.73E-04	67.7	101.9
		208.0	7.91E-04	93.3	114.7
		322.5	1.52E-04	179.9	142.6
		332.4	1.49E-04	187.9	144.4
		335.4	4.96E-04	190.4	145.0
		368.6	2.17E-04	217.7	150.9
		662.4	3.64E-04	478.0	184.4

Tab. 6: Energies and Relative Intensities of X-rays

X-ray energy (keV)
Relative Intensity (%)

Element Z	K_{α_1}	K_{α_2}	$\Sigma K_{\beta 1'}$	$\Sigma K_{\beta 2'}$	K edge
Fe 26	6.40	6.39	7.06		7.11
	100	*51.1*	*21.0*		
Cu 29	8.05	8.03	8.90		8.98
	100	*51.3*	*20.9*		
Ge 32	9.89	9.86	10.98	11.10	11.10
	100	*51.5*	*22.3*	*0.5*	
Cd 48	23.17	22.98	26.10	26.64	26.71
	100	*53.2*	*28.0*	*5.1*	
Te 52	27.47	27.20	31.00	31.70	31.81
	100	*53.7*	*29.1*	*6.3*	
I 53	28.61	28.32	32.29	33.04	33.17
	100	*53.8*	*29.3*	*6.6*	
Cs 55	30.97	30.63	34.99	35.82	35.96
	100	*54.1*	*29.7*	*7.3*	
W 74	59.32	57.98	67.24	69.10	69.52
	100	*57.6*	*33.4*	*9.1*	
Pb 82	74.97	72.80	84.94	87.36	88.01
	100	*59.5*	*34.6*	*10.4*	
Th 90	93.35	89.96	105.61	108.68	109.65
	100	*61.8*	*35.8*	*12.1*	
Pa 91	95.86	92.28	108.42	111.59	112.58
	100	*62.1*	*35.9*	*12.2*	
U 92	98.43	94.65	111.30	114.56	115.60
	100	*62.5*	*36.1*	*12.3*	
Np 93	101.06	97.07	114.23	117.58	118.62
	100	*62.8*	*36.2*	*12.5*	
Pu 94	103.73	99.53	117.23	120.67	121.76
	100	*63.2*	*36.4*	*12.6*	

$*\Sigma K_{\beta 1'} = I(K-M_{III}) + I(K-M_{II}) + I(K-M_{IV+V})$
        1   ~0.5   <0.05

$**\Sigma K_{\beta 2'} = I(K-N_{III}) + I(K-N_{II}) + I(K-N_{IV+V}) + K(K-O+)$
    1   ~0.5   <0.05   ~0.2-0.4
                                         (Z~50-111)

Table 7: Compton edge and backscatter Peak = f(Energy)

E (keV)	Back scatter Peak	Compton Edge	E (keV)	Back scatter Peak	Compton Edge	E (keV)	Back scatter Peak	Compton Edge
60	48.6	11.4	250	126.4	123.6	440	161.6	278.4
65	51.8	13.2	255	127.6	127.4	445	162.3	282.7
70	54.9	15.1	260	128.9	131.1	450	163.0	287.0
75	58.0	17.0	265	130.1	134.9	455	163.6	291.4
80	60.9	19.1	270	131.3	138.7	460	164.3	295.7
85	63.8	21.2	275	132.4	142.6	465	164.9	300.1
90	66.6	23.4	280	133.6	146.4	470	165.5	304.5
95	69.3	25.7	285	134.7	150.3	475	166.1	308.9
100	71.9	28.1	290	135.8	154.2	480	166.7	313.3
105	74.4	30.6	295	136.9	158.1	485	167.3	317.7
110	76.9	33.1	300	138.0	162.0	490	167.9	322.1
115	79.3	35.7	305	139.0	166.0	495	168.5	326.5
120	81.7	38.3	310	140.1	169.9	500	169.1	330.9
125	83.9	41.1	315	141.1	173.9	505	169.7	335.3
130	86.2	43.8	320	142.1	177.9	510	170.2	339.8
135	88.3	46.7	325	143.0	182.0	515	170.8	344.2
140	90.4	49.6	330	144.0	186.0	520	171.3	348.7
145	92.5	52.5	335	144.9	190.1	525	171.9	353.1
150	94.5	55.5	340	145.9	194.1	530	172.4	357.6
155	96.5	58.5	345	146.8	198.2	535	172.9	362.1
160	98.4	61.6	350	147.7	202.3	540	173.4	366.6
165	100.3	64.7	355	148.6	206.4	545	174.0	371.0
170	102.1	67.9	360	149.4	210.6	550	174.5	375.5
175	103.9	71.1	365	150.3	214.7	555	175.0	380.0
180	105.6	74.4	370	151.1	218.9	560	175.5	384.5
185	107.3	77.7	375	152.0	223.0	565	175.9	389.1
190	109.0	81.0	380	152.8	227.2	570	176.4	393.6
195	110.6	84.4	385	153.6	231.4	575	176.9	398.1
200	112.2	87.8	390	154.4	235.6	580	177.4	402.6
205	113.7	91.3	395	155.1	239.9	585	177.8	407.2
210	115.3	94.7	400	155.9	244.1	590	178.3	411.7
215	116.8	98.2	405	156.7	248.3	595	178.7	416.3
220	118.2	101.8	410	157.4	252.6	600	179.2	420.8
225	119.6	105.4	415	158.1	256.9	605	179.6	425.4
230	121.0	109.0	420	158.9	261.1	610	180.1	429.9
235	122.4	112.6	425	159.6	265.4	615	180.5	434.5
240	123.8	116.2	430	160.3	269.7	620	180.9	439.1
245	125.1	119.9	435	161.0	274.0	625	181.4	443.6

Table 7(cont.): Compton edge and backscatter Peak = f(Energy)

E (keV)	Back scatter Peak	Comp- ton Edge	E (keV)	Back scatter Peak	Comp- ton Edge	E (keV)	Back scatter Peak	Comp- ton Edge
630	181.8	448.2	820	194.8	625.2	1010	203.9	806.1
635	182.2	452.8	825	195.1	629.9	1015	204.1	810.9
640	182.6	457.4	830	195.4	634.6	1020	204.3	815.7
645	183.0	462.0	835	195.6	639.4	1025	204.5	820.5
650	183.4	466.6	840	195.9	644.1	1030	204.7	825.3
655	183.8	471.2	845	196.2	648.8	1035	204.9	830.1
660	184.2	475.8	850	196.4	653.6	1040	205.1	834.9
665	184.6	480.4	855	196.7	658.3	1045	205.3	839.7
670	185.0	485.0	860	197.0	663.0	1050	205.5	844.5
675	185.3	489.7	865	197.2	667.8	1055	205.7	849.3
680	185.7	494.3	870	197.5	672.5	1060	205.9	854.1
685	186.1	498.9	875	197.8	677.2	1065	206.1	858.9
690	186.5	503.5	880	198.0	682.0	1070	206.3	863.7
695	186.8	508.2	885	198.3	686.7	1075	206.4	868.6
700	187.2	512.8	890	198.5	691.5	1080	206.6	873.4
705	187.5	517.5	895	198.8	696.2	1085	206.8	878.2
710	187.9	522.1	900	199.0	701.0	1090	207.0	883.0
715	188.2	526.8	905	199.2	705.8	1095	207.2	887.8
720	188.6	531.4	910	199.5	710.5	1100	207.3	892.7
725	188.9	536.1	915	199.7	715.3	1105	207.5	897.5
730	189.3	540.7	920	200.0	720.0	1110	207.7	902.3
735	189.6	545.4	925	200.2	724.8	1115	207.9	907.1
740	189.9	550.1	930	200.4	729.6	1120	208.0	912.0
745	190.3	554.7	935	200.7	734.3	1125	208.2	916.8
750	190.6	559.4	940	200.9	739.1	1130	208.4	921.6
755	190.9	564.1	945	201.1	743.9	1135	208.6	926.4
760	191.2	568.8	950	201.3	748.7	1140	208.7	931.3
765	191.5	573.5	955	201.6	753.4	1145	208.9	936.1
770	191.8	578.2	960	201.8	758.2	1150	209.1	940.9
775	192.2	582.8	965	202.0	763.0	1155	209.2	945.8
780	192.5	587.5	970	202.2	767.8	1160	209.4	950.6
785	192.8	592.2	975	202.4	772.6	1165	209.5	955.5
790	193.1	596.9	980	202.7	777.3	1170	209.7	960.3
795	193.4	601.6	985	202.9	782.1	1175	209.9	965.1
800	193.7	606.3	990	203.1	786.9	1180	210.0	970.0
805	193.9	611.1	995	203.3	791.7	1185	210.2	974.8
810	194.2	615.8	1000	203.5	796.5	1190	210.3	979.7
815	194.5	620.5	1005	203.7	801.3	1195	210.5	984.5

Table 7(cont.): Compton edge and backscatter Peak = f(Energy)

E (keV)	Back scatter Peak	Comp- ton Edge	E (keV)	Back scatter Peak	Comp- ton Edge	E (keV)	Back scatter Peak	Comp- ton Edge
1200	210.6	989.4	1390	215.8	1174.2	1770	223.3	1546.7
1205	210.8	994.2	1400	216.1	1183.9	1780	223.4	1556.6
1210	211.0	999.0	1410	216.3	1193.7	1790	223.6	1566.4
1215	211.1	1003.9	1420	216.5	1203.5	1800	223.7	1576.3
1220	211.3	1008.7	1430	216.8	1213.2	1810	223.9	1586.1
1225	211.4	1013.6	1440	217.0	1223.0	1820	224.0	1596.0
1230	211.6	1018.4	1450	217.2	1232.8	1830	224.2	1605.8
1235	211.7	1023.3	1460	217.4	1242.6	1840	224.3	1615.7
1240	211.8	1028.2	1470	217.7	1252.3	1850	224.5	1625.5
1245	212.0	1033.0	1480	217.9	1262.1	1860	224.6	1635.4
1250	212.1	1037.9	1490	218.1	1271.9	1870	224.8	1645.2
1255	212.3	1042.7	1500	218.3	1281.7	1880	224.9	1655.1
1260	212.4	1047.6	1510	218.5	1291.5	1890	225.1	1664.9
1265	212.6	1052.4	1520	218.7	1301.3	1900	225.2	1674.8
1270	212.7	1057.3	1530	218.9	1311.1	1910	225.4	1684.6
1275	212.8	1062.2	1540	219.1	1320.9	1920	225.5	1694.5
1280	213.0	1067.0	1550	219.3	1330.7	1930	225.6	1704.4
1285	213.1	1071.9	1560	219.5	1340.5	1940	225.8	1714.2
1290	213.3	1076.7	1570	219.7	1350.3	1950	225.9	1724.1
1295	213.4	1081.6	1580	219.9	1360.1	1960	226.0	1734.0
1300	213.5	1086.5	1590	220.1	1369.9	1970	226.2	1743.8
1305	213.7	1091.3	1600	220.3	1379.7	1980	226.3	1753.7
1310	213.8	1096.2	1610	220.5	1389.5	1990	226.4	1763.6
1315	213.9	1101.1	1620	220.7	1399.3	2000	226.6	1773.4
1320	214.1	1105.9	1630	220.9	1409.1	2010	226.7	1783.3
1325	214.2	1110.8	1640	221.1	1418.9	2020	226.8	1793.2
1330	214.3	1115.7	1650	221.2	1428.8	2030	226.9	1803.1
1335	214.5	1120.5	1660	221.4	1438.6	2040	227.1	1812.9
1340	214.6	1125.4	1670	221.6	1448.4	2050	227.2	1822.8
1345	214.7	1130.3	1680	221.8	1458.2	2060	227.3	1832.7
1350	214.8	1135.2	1690	221.9	1468.1	2070	227.4	1842.6
1355	215.0	1140.0	1700	222.1	1477.9	2080	227.5	1852.5
1360	215.1	1144.9	1710	222.3	1487.7	2090	227.7	1862.3
1365	215.2	1149.8	1720	222.5	1497.5	2100	227.8	1872.2
1370	215.3	1154.7	1730	222.6	1507.4	2110	227.9	1882.1
1375	215.5	1159.5	1740	222.8	1517.2	2120	228.0	1892.0
1380	215.6	1164.4	1750	222.9	1527.1	2130	228.1	1901.9
1385	215.7	1169.3	1760	223.1	1536.9	2140	228.2	1911.8

Table 7(cont.): Compton edge and backscatter Peak = f(Energy)

E (keV)	Back scatter Peak	Compton Edge	E (keV)	Back scatter Peak	Compton Edge	E (keV)	Back scatter Peak	Compton Edge
2150	228.4	1921.6	2530	232.1	2297.9	2910	234.9	2675.1
2160	228.5	1931.5	2540	232.1	2307.9	2920	234.9	2685.1
2170	228.6	1941.4	2550	232.2	2317.8	2930	235.0	2695.0
2180	228.7	1951.3	2560	232.3	2327.7	2940	235.1	2704.9
2190	228.8	1961.2	2570	232.4	2337.6	2950	235.1	2714.9
2200	228.9	1971.1	2580	232.5	2347.5	2960	235.2	2724.8
2210	229.0	1981.0	2590	232.6	2357.4	2970	235.3	2734.7
2220	229.1	1990.9	2600	232.6	2367.4	2980	235.3	2744.7
2230	229.2	2000.8	2610	232.7	2377.3	2990	235.4	2754.6
2240	229.3	2010.7	2620	232.8	2387.2	3000	235.4	2764.6
2250	229.4	2020.6	2630	232.9	2397.1	3010	235.5	2774.5
2260	229.5	2030.5	2640	233.0	2407.0	3020	235.6	2784.4
2270	229.7	2040.3	2650	233.0	2417.0	3030	235.6	2794.4
2280	229.8	2050.2	2660	233.1	2426.9	3040	235.7	2804.3
2290	229.9	2060.1	2670	233.2	2436.8	3050	235.8	2814.2
2300	230.0	2070.0	2680	233.3	2446.7	3060	235.8	2824.2
2310	230.1	2079.9	2690	233.3	2456.7	3070	235.9	2834.1
2320	230.2	2089.8	2700	233.4	2466.6	3080	235.9	2844.1
2330	230.3	2099.7	2710	233.5	2476.5	3090	236.0	2854.0
2340	230.3	2109.7	2720	233.6	2486.4	3100	236.0	2864.0
2350	230.4	2119.6	2730	233.6	2496.4	3110	236.1	2873.9
2360	230.5	2129.5	2740	233.7	2506.3	3120	236.2	2883.8
2370	230.6	2139.4	2750	233.8	2516.2	3130	236.2	2893.8
2380	230.7	2149.3	2760	233.9	2526.1	3140	236.3	2903.7
2390	230.8	2159.2	2770	233.9	2536.1	3150	236.3	2913.7
2400	230.9	2169.1	2780	234.0	2546.0	3160	236.4	2923.6
2410	231.0	2179.0	2790	234.1	2555.9	3170	236.4	2933.6
2420	231.1	2188.9	2800	234.1	2565.9	3180	236.5	2943.5
2430	231.2	2198.8	2810	234.2	2575.8	3190	236.6	2953.4
2440	231.3	2208.7	2820	234.3	2585.7	3200	236.6	2963.4
2450	231.4	2218.6	2830	234.3	2595.7	3210	236.7	2973.3
2460	231.5	2228.5	2840	234.4	2605.6	3220	236.7	2983.3
2470	231.5	2238.5	2850	234.5	2615.5	3230	236.8	2993.2
2480	231.6	2248.4	2860	234.5	2625.5	3240	236.8	3003.2
2490	231.7	2258.3	2870	234.6	2635.4	3250	236.9	3013.1
2500	231.8	2268.2	2880	234.7	2645.3	3260	236.9	3023.1
2510	231.9	2278.1	2890	234.7	2655.3	3270	237.0	3033.0
2520	232.0	2288.0	2900	234.8	2665.2	3280	237.0	3043.0

Tab. 8: Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)

Energy (keV)	Hydrogen 1 H	Lithium 3 Li	Beryllium 4 Be	Boron 5 B	Carbon 6 C	Nitrogen 7 N	Oxygen 8 O	Fluorine 9 F	Sodium 11 Na
10	0.3854	0.3294	0.6233	1.2100	2.2980	3.7790	5.8320	8.0310	15.3000
15	0.3765	0.2150	0.3010	0.4709	0.7869	1.2070	1.7980	2.4430	4.6170
20	0.3695	0.1846	0.2228	0.2968	0.4340	0.6083	0.8495	1.1130	2.0260
30	0.3571	0.1641	0.1786	0.2052	0.2541	0.3035	0.3736	0.4434	0.7111
40	0.3458	0.1550	0.1637	0.1789	0.2069	0.2276	0.2568	0.2807	0.3935
50	0.3355	0.1488	0.1553	0.1663	0.1867	0.1974	0.2124	0.2204	0.2787
60	0.3260	0.1438	0.1492	0.1582	0.1751	0.1814	0.1903	0.1914	0.2258
80	0.3091	0.1356	0.1400	0.1472	0.1609	0.1638	0.1677	0.1637	0.1793
100	0.2944	0.1288	0.1328	0.1391	0.1513	0.1529	0.1551	0.1495	0.1583
150	0.2651	0.1157	0.1190	0.1243	0.1347	0.1353	0.1360	0.1298	0.1335
186	**0.2485**	**0.1084**	**0.1114**	**0.1163**	**0.1259**	**0.1263**	**0.1268**	**0.1207**	**0.1233**
200	0.2429	0.1060	0.1089	0.1136	0.1229	0.1233	0.1237	0.1176	0.1199
300	0.2112	0.0920	0.0946	0.0965	0.1066	0.1068	0.1070	0.1015	0.1029
400	0.1893	0.0825	0.0847	0.0883	0.0955	0.0956	0.0957	0.0907	0.0919
500	0.1729	0.0753	0.0774	0.0807	0.0871	0.0872	0.0873	0.0828	0.0837
600	0.1599	0.0697	0.0716	0.0746	0.0806	0.0806	0.0807	0.0765	0.0774
662	**0.1530**	**0.0667**	**0.0685**	**0.0714**	**0.0771**	**0.0772**	**0.0772**	**0.0732**	**0.0740**
800	0.1405	0.0612	0.0629	0.0655	0.0708	0.0708	0.0709	0.0672	0.0679
1000	0.1263	0.0550	0.0565	0.0589	0.0636	0.0637	0.0637	0.0603	0.0610
1173	**0.1164**	**0.0507**	**0.0521**	**0.0543**	**0.0587**	**0.0587**	**0.0587**	**0.0556**	**0.0563**
1333	**0.1091**	**0.0475**	**0.0488**	**0.0509**	**0.0550**	**0.0550**	**0.0551**	**0.0522**	**0.0527**
1500	0.1027	0.0448	0.0460	0.0479	0.0518	0.0518	0.0519	0.0492	0.0497
2000	0.0877	0.0388	0.0394	0.0411	0.0444	0.0445	0.0446	0.0423	0.0428
3000	0.0692	0.0304	0.0314	0.0328	0.0356	0.0358	0.0360	0.0342	0.0349
density (g/cm3)	0.090 g/l	0.534	1.850	2.340	1.9 - 2.3 (cryst.)	1.251 graphit	1.429 g/l	1.696 g/l	0.971 g/l

Tab. 8 *(cont.)*: **Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)**

Energy (keV)	Magnesium 12 Mg	Aluminium 13 Al	Silicon 14 Si	Phosphorus 15 P	Sulfur 16 S	Chlorine 17 Cl	Potassium 19 K	Calcium 20 Ca	Iron 26Fe
10	20.7100	25.8200	33.3900	39.7900	49.4700	56.520	78.150	93.020	16.900
15	6.2580	7.8360	10.1900	12.2200	15.3100	17.630	27.450	29.860	56.560
20	2.7220	3.3920	4.4040	5.2830	6.6270	7.6490	10.8100	13.0200	25.4600
30	0.9292	1.1150	1.4190	1.6800	2.0900	2.3990	3.3790	4.0650	8.1090
40	0.4835	0.5630	0.6943	0.8018	0.9778	1.1060	1.5270	1.8250	3.6010
50	0.3270	0.3655	0.4351	0.4878	0.5803	0.6431	0.8609	1.0230	1.9440
60	0.2558	0.2763	0.3188	0.3473	0.4027	0.4365	0.5639	0.6606	1.1970
80	0.1946	0.2012	0.2220	0.2315	0.2576	0.2684	0.3235	0.3655	0.5918
100	0.1684	0.1701	0.1832	0.1861	0.2015	0.2044	0.2337	0.2577	0.3701
150	0.1393	0.1378	0.1447	0.1431	0.1505	0.1479	0.1579	0.1674	0.1960
186	**0.1282**	**0.1261**	**0.1318**	**0.1295**	**0.1351**	**0.1317**	**0.1381**	**0.1446**	**0.1574**
200	0.1245	0.1223	0.1275	0.1250	0.1301	0.1265	0.1318	0.1374	0.1458
300	0.1065	0.1042	0.1082	0.1055	0.1091	0.1053	0.1079	0.1115	0.1098
400	0.0949	0.0928	0.0961	0.0936	0.0967	0.0931	0.0949	0.0976	0.0940
500	0.0865	0.0845	0.0875	0.0851	0.0878	0.0845	0.0860	0.0883	0.0841
600	0.0799	0.0780	0.0808	0.0786	0.0810	0.0780	0.0792	0.0813	0.0770
662	**0.0764**	**0.0746**	**0.0772**	**0.0751**	**0.0775**	**0.0745**	**0.0757**	**0.0777**	**0.0735**
800	0.0701	0.0684	0.0708	0.0688	0.0710	0.0683	0.0693	0.0711	0.0670
1000	0.0630	0.0615	0.0636	0.0618	0.0637	0.0613	0.0622	0.0638	0.0599
1173	**0.0581**	**0.0567**	**0.0587**	**0.0570**	**0.0588**	**0.0565**	**0.0574**	**0.0588**	**0.0553**
1333	**0.0545**	**0.0532**	**0.0550**	**0.0535**	**0.0551**	**0.0530**	**0.0538**	**0.0551**	**0.0518**
1500	0.0513	0.0501	0.0518	0.0504	0.0520	0.0499	0.0507	0.0519	0.0488
2000	0.0443	0.0422	0.0448	0.0436	0.0450	0.0433	0.0440	0.0452	0.0427
3000	0.0361	0.0354	0.0368	0.0359	0.0372	0.0359	0.0367	0.0377	0.0362
density (g/cm3)	1.740	2.699	2.330	white 1.82 red 2.2	2.070 1.960	3.214 g/l	0.860	1.550	7.784

Tab. 8 *(cont.)*: **Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)**

Energy (keV)	Copper 29 Cu	Zinc 30 Zn	Gallium 31 Ga	Germanium 32 Ge	Zirconium 40 Zr	Niobium 41 Nb	Cadmium 48 Cd	Tellurium 52 Te	Iodine 53 I
10	21.400	23.110	33.260	36.400	73.750	80.380	121.300	150.100	15.850
15	73.430	80.510	84.670	90.810	24.420	26.720	40.840	50.780	53.890
20	33.5200	36.9000	38.9700	41.9000	71.9500	77.1200	18.8100	23.4300	24.9000
30	10.8300	11.9800	12.7100	13.7500	24.8400	26.6600	37.4000	7.8780	8.4060
40	4.8280	5.3460	5.6860	6.1650	11.4200	12.2300	17.6700	20.6400	21.9600
50	2.5910	2.8730	3.0550	3.3140	6.1540	6.6440	9.7220	11.4500	12.2500
60	1.5830	1.7490	1.8560	2.0110	3.7550	4.0320	5.9410	7.0410	7.5360
80	0.7587	0.8319	0.8773	0.9451	1.7280	1.8520	2.7360	3.2550	3.4910
100	0.4563	0.4950	0.5172	0.5525	0.9688	1.0370	1.5160	1.8010	1.9320
150	0.2221	0.2335	0.2380	0.2484	0.3808	0.4023	0.5570	0.6492	0.6948
186	**0.1707**	**0.1777**	**0.1788**	**0.1842**	**0.2578**	**0.2697**	**0.3548**	**0.4047**	**0.4314**
200	0.1557	0.1615	0.1617	0.1658	0.2248	0.2344	0.3029	0.3429	0.3650
300	0.1118	0.1141	0.1122	0.1130	0.1322	0.1357	0.1568	0.1679	0.1768
400	0.0941	0.0954	0.0932	0.0933	0.1016	0.1040	0.1127	0.1163	0.1215
500	0.0836	0.0845	0.0823	0.0821	0.0867	0.0883	0.0924	0.0933	0.0969
600	0.0762	0.0769	0.0749	0.0745	0.0774	0.0785	0.0806	0.0802	0.0830
662	**0.0726**	**0.0732**	**0.0712**	**0.0709**	**0.0731**	**0.0742**	**0.0756**	**0.0748**	**0.0774**
800	0.0661	0.0666	0.0647	0.0643	0.0656	0.0664	0.0667	0.0654	0.0674
1000	0.0590	0.0594	0.0577	0.0573	0.0580	0.0587	0.0583	0.0567	0.0584
1173	**0.0544**	**0.0548**	**0.0532**	**0.0528**	**0.0533**	**0.0539**	**0.0534**	**0.0518**	**0.0534**
1333	**0.0510**	**0.0514**	**0.0498**	**0.0495**	**0.0498**	**0.0505**	**0.0498**	**0.0483**	**0.0497**
1500	0.0480	0.0484	0.0469	0.0466	0.0468	0.0474	0.0467	0.0452	0.0465
2000	0.0420	0.0424	0.0411	0.0409	0.0414	0.0419	0.0414	0.0401	0.0412
3000	0.0360	0.0364	0.0354	0.0353	0.0363	0.0369	0.0370	0.0361	0.0372
density (g/cm3)	8.960	7.133	5.900	5.323	6.506	8.570	8.650	6.240	4.930

Tab. 8 *(cont.)*: **Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)**

Energy	Barium	Tungsten	Mercury	Lead	Uranium	Plutonium	UO2	UO3	U3O8
(keV)	56 Ba	74 W	80 Hg	82 Pb	92 U	94 Pu	88.1wt%U	83.2wt%U	84.8wt%U
10	18.600	96.920	122.100	130.600	17.910	-	16.473	15.881	16.074
15	63.470	138.900	168.100	111.600	65.270	-	57.717	54.607	55.622
20	29.2800	65.7300	81.2300	86.3600	71.0600	-	62.7050	59.2646	60.3880
30	9.9040	22.7300	28.4100	30.3200	41.2800	-	36.4121	34.4077	35.0622
40	24.5700	10.6700	13.4200	14.3600	19.8300	-	17.5008	16.5417	16.8549
50	13.7900	5.9490	7.5040	8.0410	11.2100	12.5000	9.9013	9.3624	9.5384
60	8.5110	3.7120	4.6840	5.0200	7.0340	7.8895	6.2196	5.8843	5.9938
80	3.9630	7.8090	2.2590	2.4190	3.3950	3.8166	3.0110	2.8528	2.9045
100	2.1960	4.4380	5.2790	5.5500	1.9540	2.1730	1.7399	1.6518	1.6806
150	0.7827	1.5810	1.9090	2.0140	2.5910	2.7621	2.2989	2.1786	2.2178
186	**0.4802**	**0.9410**	**1.1349**	**1.1981**	**1.5533**	**1.6302**	**1.3840**	**1.3143**	**1.3370**
200	0.4045	0.7844	0.9456	0.9985	1.2980	1.3549	1.1583	1.1007	1.1195
300	0.1891	0.3238	0.3834	0.4026	0.5191	0.5362	0.4701	0.4499	0.4565
400	0.1265	0.1925	0.2225	0.2323	0.2922	0.3075	0.2688	0.2592	0.2623
500	0.0992	0.1378	0.1555	0.1613	0.1976	0.2100	0.1845	0.1791	0.1808
600	0.0841	0.1093	0.1210	0.1248	0.1490	0.1589	0.1409	0.1375	0.1386
662	**0.0780**	**0.0986**	**0.1081**	**0.1111**	**0.1308**	**0.1396**	**0.1245**	**0.1219**	**0.1228**
800	0.0674	0.0807	0.0868	0.0887	0.1016	0.1086	0.0979	0.0964	0.0969
1000	0.0580	0.0662	0.0699	0.0710	0.0789	0.0850	0.0771	0.0764	0.0766
1173	**0.0529**	**0.0592**	**0.0621**	**0.0629**	**0.0689**	**0.0745**	**0.0677**	**0.0672**	**0.0674**
1333	**0.0492**	**0.0543**	**0.0565**	**0.0571**	**0.0618**	**0.0671**	**0.0610**	**0.0607**	**0.0608**
1500	0.0459	0.0500	0.0518	0.0522	0.0559	0.0609	0.0554	0.0552	0.0553
2000	0.0408	0.0443	0.0458	0.0461	0.0488	0.0525	0.0483	0.0481	0.0481
3000	0.0369	0.0408	0.0421	0.0423	0.0445	0.0482	0.0434	0.0430	0.0432
density (g/cm3)	3.500	19.300	13.530	11.350	18.950	19.8400			

Tab. 8 *(cont.)*: **Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)**

Energy (keV)	UF4 75.8wt%U	UF6 67.6wt%U	PuO2 88 wt%Pu	NaI	CsI	CdTe	Cd0.9 Zn0.1 Te1	Water H2O	Tissue soft
10	14.987	13.997	-	136.500	16.910	134.600	134.189	5.2230	4.8350
15	49.910	44.705	-	46.330	57.550	45.520	47.348	1.6390	1.5270
20	54.0691	48.3118	-	21.3900	26.6000	21.0000	21.8252	0.7958	0.7485
30	31.3807	28.0263	-	7.2260	8.9690	21.6300	20.6578	0.3718	0.3568
40	15.0933	13.4883	-	18.6500	22.9100	19.1800	18.9376	0.2668	0.2595
50	8.5486	7.6468	11.0257	10.4100	12.8400	10.6000	10.4685	0.2262	0.2216
60	5.3778	4.8166	6.9656	6.4150	7.9000	6.5040	6.4209	0.2055	0.2021
80	2.6140	2.3494	3.3788	2.9830	3.6670	3.0020	2.9645	0.1835	0.1811
100	1.5187	1.3712	1.9309	1.6600	2.0300	1.6630	1.6422	0.1707	0.1687
150	1.9969	1.7956	2.4469	0.6087	0.7276	0.6046	0.5980	0.1504	0.1489
186	**1.2090**	**1.0923**	**1.4503**	**0.3846**	**0.4498**	**0.3806**	**0.3770**	**0.1404**	**0.1406**
200	1.0138	0.9175	1.2071	0.3274	0.3799	0.3235	0.3207	0.1370	0.1357
300	0.4194	0.3856	0.4847	0.1655	0.1816	0.1625	0.1616	0.1187	0.1175
400	0.2446	0.2285	0.282	0.1170	0.1236	0.1145	0.1142	0.1061	0.1051
500	0.1709	0.1619	0.1953	0.0949	0.0980	0.0928	0.0927	0.0969	0.0959
600	0.1325	0.1269	0.1495	0.0822	0.0837	0.0803	0.0803	0.0896	0.0887
662	**0.1180**	**0.1136**	**0.1322**	**0.0769**	**0.0779**	**0.0751**	**0.0751**	**0.0857**	**0.0849**
800	0.0942	0.0916	0.1041	0.0675	0.0677	0.0660	0.0660	0.0787	0.0779
1000	0.0753	0.0740	0.0824	0.0588	0.0595	0.0574	0.0574	0.0707	0.0700
1173	**0.0665**	**0.0656**	**0.0727**	**0.0538**	**0.0539**	**0.0526**	**0.0526**	**0.0673**	**0.0646**
1333	**0.0602**	**0.0596**	**0.0657**	**0.0501**	**0.0499**	**0.0490**	**0.0490**	**0.0643**	**0.0605**
1500	0.0549	0.0546	0.0598	0.0470	0.0464	0.0459	0.0459	0.0576	0.0570
2000	0.0477	0.0474	0.0516	0.0415	0.0412	0.0407	0.0407	0.0494	0.0489
3000	0.0424	0.0417	0.0467	0.0368	0.0372	0.0365	0.0365	0.0397	0.0393
density (g/cm3)				3.667	4.510	6.060	5.8 - 5.9	1.000	1.000

Tab. 8 *(cont.)*: **Photon Mass Attenuation Coefficients (cm^2/g) and Material densities (g/cm^3)**

Energy (keV)	Concrete	Steel CrNiTi 18/10/0.7%	Lead glass	Glass pyrex	Mylar (C8H10O4)n	Polyethylen (C2H4)n	Bitumen 80/100	REI-RTD	Teflon (C2F4)n
10	26.1900	37.4860	102.800	16.780	3.3950	2.0230	2.3541	5.3017	6.6540
15	8.1850	55.6430	85.570	5.1360	1.1060	0.7279	0.8166	1.6958	2.0450
20	3.6050	25.0510	65.870	2.2640	0.5697	0.4247	0.4566	0.8228	0.9499
30	1.2020	7.9816	23.050	0.7893	0.2982	0.2689	0.2728	0.3754	0.3979
40	0.6070	3.5464	10.930	0.4304	0.2293	0.2269	0.2243	0.2635	0.2630
50	0.3918	1.9154	6.134	0.3004	0.2015	0.2081	0.2034	0.2204	0.2123
60	0.2943	1.1753	3.8420	0.2407	0.1865	0.1968	0.1913	0.1986	0.1875
80	0.2119	0.5846	1.8690	0.1886	0.1894	0.1822	0.1762	0.1761	0.1630
100	0.1781	0.3662	4.2160	0.1656	0.1586	0.1719	0.1659	0.1633	0.1499
150	0.1433	0.1947	1.5490	0.1388	0.1406	0.1534	0.1478	0.1437	0.1310
186	**0.1310**	**0.1566**	**0.9339**	**0.1281**	**0.1313**	**0.1434**	**0.1382**	**0.1340**	**0.1219**
200	0.1270	0.1451	0.7820	0.1246	0.1282	0.1401	0.1350	0.1308	0.1189
300	0.1082	0.1094	0.3294	0.1070	0.1111	0.1216	0.1103	0.1130	0.1027
400	0.0963	0.0937	0.1984	0.0954	0.0995	0.1089	0.1049	0.1013	0.0919
500	0.0877	0.0839	0.1429	0.0870	0.0908	0.0995	0.0957	0.0924	0.0838
600	0.0810	0.0768	0.1138	0.0804	0.0840	0.0920	0.0885	0.0855	0.0775
662	**0.0775**	**0.0732**	**0.1027**	**0.0769**	**0.0800**	**0.0880**	**0.0847**	**0.0818**	**0.0741**
800	0.0710	0.0668	0.0842	0.0705	0.0727	0.0808	0.0778	0.0751	0.0680
1000	0.0638	0.0598	0.0692	0.0634	0.0663	0.0726	0.0699	0.0675	0.0611
1173	**0.0589**	**0.0551**	**0.0618**	**0.0584**	**0.0611**	**0.0670**	**0.0644**	**0.0622**	**0.0564**
1333	**0.0552**	**0.0517**	**0.0566**	**0.0548**	**0.0573**	**0.0628**	**0.0604**	**0.0583**	**0.0529**
1500	0.0520	0.0487	0.0521	0.0516	0.0539	0.0591	0.0569	0.0549	0.0498
2000	0.0448	0.0425	0.0457	0.0445	0.0463	0.0506	0.0488	0.0471	0.0428
3000	0.0365	0.0361	0.0408	0.0361	0.0372	0.0405	0.0390	0.0378	0.0346
density (g/cm3)	1.8 - 2.4	7.8		2.6 ...		0.92 ... ... 0.97			2.200

Tab. 9: Infinite Thickness (IT) for Typical Uranium Materials for E =186 keV

Matrix type	$\mu(cm^2/g)$ at 185.7 keV	density (g/cm^3)	IT (cm)
U metal	1.553	19	0.2
UO_2	1.384	1	5.0
powder		2	2.3
pellet		11	0.4
U_3O_8 powder	1.337	1	5.2
powder		2.3	2.2
pellet		8.3	0.6
UF_6 gas	1.0923	1	6.3
solid		4.7	1.3
$(NH4)_2U_2O_7$	1.2172	1	5.7
		2	2.8
$UO_2(NO_3)_2, 6H_2O$	0.796	1	8.7
		2.8	3.1

Tab. 10: Half-Thickness for Different Absorbers and Energies

Absorber type	air	water	ordinary concrete	lead glass	lead
density (g/cm^3)	0.0013	1	2.35	6.2	11.34
Energy (keV)	Half-thickness (cm)				
50	3711	4.42	1.09	0.03	0.01
100	4992	5.86	2.39	0.04	0.02
186	6081	7.12	3.25	0.17	0.08
200	6234	7.30	3.35	0.21	0.09
300	7271	8.42	3.93	0.49	0.22
500	8832	10.32	4.85	1.13	0.55
662	9977	11.67	5.49	1.57	0.82
1000	12095	14.14	6.67	2.33	1.27
1332	13986	16.37	7.71	2.85	1.56

Tab. 11: Sound velocities

Material	Velocity [m/s]	Material	Velocity [m/s]
Air	330	Neoprene	1600
Aluminium	6300	Nickel	5600
Aluminium oxide	8700	Nylon,6-6	2600
Berillium	12900	Plexiglas	2700
Boron carbide	11000	Polystyrene	2400
Brass	3800	Polyethylene	2400
Cadmium	2800	Polyurethane	1900
Copper	4700	Quartz	2400
Glas	5100	Butyl (rubber)	5800
Glycerin	1900	Silver	1800
Gold	3200	Steel (mild)	3600
Ice	4000	Steel(stainless)	5900
Inconel	5700	Teflon	5800
Iron	5900	Tin	1400
Iron (cast)	4600	Titanium	3300
Lead	2200	Tungsten	6100
Magnesium	5800	Uranium	5200
Molybdenum	6300	Water	3400
Monel	5400	Zinc	1500

Table T12- Units and prefixes for powers of ten

Activity:

1 Bq (Becquerel) = 1 decay per second

old: 1Ci (Curie) = $3.7*10^{10}$ Bq = 37 GBq

Radiation energy dose:

1 Gy (Gray) = 1 J/kg

old: 1 Gy = 100 rd (rad)

Equivalent dose:

1 Sv (Sievert)

old: 1 Sv = 100 rem

Atomic mass unit: u = $1.660431*10^{-24}$ g

1 u = 931 MeV

Avogadro constant: N_A = $6.023*10^{23}$

Electron charge: e = $1.602*10^{-19}$ C

Light velocity: c = $3*10^8$ m/s

Nuclear radius unit: R = $A^{1/3} * 1.5*10^{-15}$ m

A = mass number

Electron radius: r_e = $2.818*10^{-15}$ m

1 eV = $1.602*10^{-19}$ J

1 Fermi = 10^{-15} m = 10^{-5} Å (Ångström)

1 b (barn) = 10^{-24} cm^2

1 d (day) = 86 400 s

1 a = 1 y (year) = $\pi * 10^7$ s

Prefixes for power of then

E	exa	10^{18}	c	centi	10^{-2}
P	peta	10^{15}	m	milli	10^{-3}
T	tera	10^{12}	μ	micro	10^{-6}
G	giga	10^9	n	nano	10^{-9}
M	mega	10^6	p	pico	10^{-12}
k	kilo	10^3	f	fempto	10^{-15}
			a	atto	10^{-18}

Tab. 13: Gamma Radiation Detectors and Their Applications

Detector type	Resolution	Efficiency	Application	Codes	Remarks
NaI	low	very high		U235	Calibration requires two standards. Wall thickness correction not allowed.
				NaIGEM	Calibration with one standard. Wall tickness correction possible.
			attribute test	SPEC, MCA	
Ge planar	very high	low	U enrichment	UF6	calibration with at least one standard
				MGAU	no calibration required
			Pu isotopic composition	MGA	no calibration
Ge coaxial	high	high	attribute test	SPEC, MCA	
			U enrichment	UF6	calibration with at least one standard
CdZnTe	medium or high	very low	U enrichment	U235	Calibration requires two standards. Wall thickness correction not allowed.
				MGAU	no calibration required
			attribute test on spent fuel	FP	

Tab. 14:. Efficiencies of different detector Types (see AnnexA1e,
　　　　　and Annex A2 Graph G11)

Absolute Full-Energy Peak Efficiency
(in Counts per emitted Photon, 25 cm distance)
Intrinsic Efficiency
(in Counts per Photon entering the detector)
Relative Efficiency
(in comparision to a NaI diam. 7.6 cm x 7.6 cm)

	E(keV)	Abs. Full-E peak eff.	Intrinsic Eff.	relative Eff.
NaI	122	0.0049	0.84833795	100%
diam 7.6cm	244	0.00448	0.775623269	100%
x 7,6cm	344	0.00395	0.683864266	100%
	779	0.00177	0.306440443	100%
	1086	0.00125	0.216412742	100%
	1408	0.00092	0.159279778	100%
NaI	122	0.00486	0.841412742	99,1%
diam 7.6cm	244	0.00238	0.412049861	53,1%
x 1,9cm	344	0.00155	0.268351801	39,2%
	779	0.0006	0.103878116	34,0%
	1086	0.00038	0.065789474	29,9%
	1408	0.00023	0.039819945	25,5%
Ge coax	122	0.0024	0.887573964	49,0%
diam 5.2cm	244	0.00131	0.484467456	29,3%
x 5.4cm	344	0.00094	0.347633136	23,7%
	779	0.00044	0.162721893	24,9%
	1086	0.00033	0.12204142	26,5%
	1408	0.00027	0.099852071	29,3%
Ge planar	122	0.001025	0.790895062	20,9%
diam 3.6cm	244	0.000348	0.268518519	7,8%
x 2cm	344	0.0002	0.154320988	5,1%
	779	0.000061	0.047067901	3,5%
	1086	0.000042	0.032407407	3,3%
	1408	0.00003	0.023148148	3,3%

Tab. 14 *(cont)*: Efficiencies of different detectors

Ge planar	122	0.0001699	0.663671875	3,47%
diam 1.6cm	244	0.0000391	0.152734375	0,87%
x 1cm	344	0.0000182	0.07109375	0,46%
	779	0.000004	0.015625	0,23%
	1086	0.0000026	0.01015625	0,21%
	1408	0.0000017	0.006640625	0,18%
CZT/1500	122	0.0001714	0.598281222	3,50%
1.5 x 1.5	244	0.0000503	0.175574944	1,12%
x 0.75 cm3	344	0.0000294	0.102622333	0,74%
	779	0.000005	0.017452778	0,28%
	1086	0.0000033	0.011518833	0,26%
	1408	0.0000023	0.008028278	0,25%
CZT/500 (56)	122	0.0001055	0.828595062	2,15%
1 x 1	244	0.0000243	0.190851754	0,54%
x 0,5 cm3	344	0.000013	0.102101761	0,33%
	779	0.0000022	0.01727876	0,13%
	1086	0.0000011	0.00863938	0,09%
	1408	0.0000007	0.005497787	0,08%
CZT/500 (13)	122	0.0000866	0.68015481	1,77%
1 x 1	244	0.0000205	0.161006623	0,46%
x 0.5 cm3	344	0.0000109	0.0856084	0,28%
	779	0.0000014	0.010995574	0,08%
	1086	0.0000007	0.005497787	0,06%
	1408	0.0000005	0.003926991	0,06%
SDP310	122	0.00000436	0.13697344	0,089%
0.5 x 0.5	244	0.00000139	0.043668138	0,031%
x 0.25 cm3	344	0.00000081	0.0254469	0,020%
	779	0.00000012	0.003769911	0,007%
	1086	0.00000006	0.001884956	0,004%
	1408	0.00000003	0.000942478	0,003%
LaBr3	122	0.00147	0.799539682	94.248%
Diam 3.8 cm	244	0.001157	0.629297559	81.134%
x3.8 cm	344	0.000841	0.457423723	66.888%
	779	0.000316	0.171873836	56.087%
	1086	0.000212	0.115307764	53.281%
	1408	0.000145	0.078866159	49.514%

Table 15: Nuclides concentrations (in g) in a LWR irradiated fuel versus Time Power= 30000MW, Burnup=33000 MWD, Flux=2.986E+13N/cm2/s

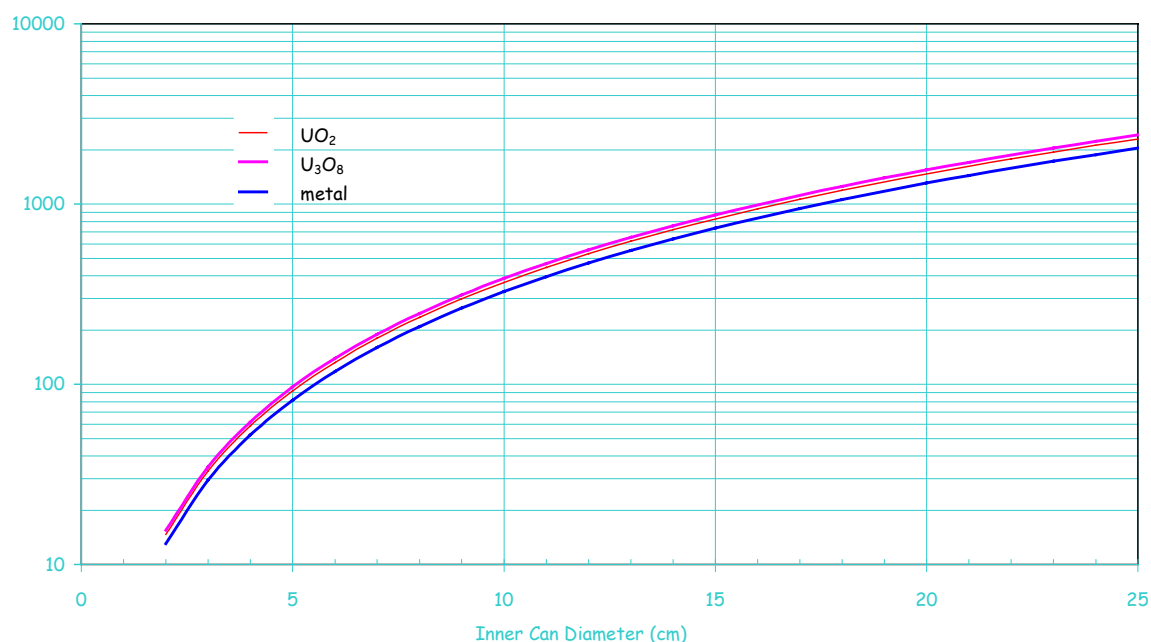| radionuclides	charge	discharge	6 months	3 years	6 years	10 years
He 4	0	2.415E-01	4.260E-01	5.644E-01	6.706E-01	9.354E-01
Tl207	0	5.025E-15	8.880E-15	1.637E-14	2.363E-14	4.082E-14
Tl208	0	1.865E-12	2.845E-12	9.393E-12	1.334E-11	1.996E-11
Tl209	0	1.130E-17	1.891E-18	2.506E-18	3.016E-18	4.425E-18
Pb206	0	1.105E-13	1.916E-13	1.710E-12	5.205E-12	3.719E-11
Pb207	0	3.181E-10	5.026E-10	2.720E-09	5.743E-09	1.800E-08
Pb208	0	4.652E-07	8.014E-07	5.887E-06	1.353E-05	4.199E-05
Pb209	0	4.622E-14	7.734E-15	1.025E-14	1.234E-14	1.310E-14
Pb210	0	7.238E-12	1.022E-11	4.279E-11	9.358E-11	3.692E-10
Pb211	0	3.872E-14	4.827E-14	1.261E-13	1.821E-13	3.145E-13
Pb212	0	1.083E-09	1.653E-09	5.456E-09	8.037E-09	1.159E-08
Pb214	0	4.813E-16	5.886E-16	1.535E-15	2.664E-15	7.032E-15
Bi209	0	6.034E-11	7.348E-11	1.156E-10	1.570E-10	2.959E-10
Bi210	0	4.729E-15	6.591E-15	2.796E-14	6.114E-14	2.412E-13
Bi211	0	2.306E-15	2.875E-15	7.510E-15	1.084E-14	1.873E-14
Bi212	0	1.032E-10	1.575E-10	5.198E-10	7.658E-10	1.105E-09
Bi213	0	1.118E-14	1.871E-15	2.480E-15	2.985E-15	4.379E-15
Bi214	0	3.538E-16	4.327E-16	1.129E-15	1.959E-15	5.169E-15
Po210	0	8.319E-14	1.243E-13	6.064E-13	1.393E-12	6.644E-12
Po211	0	2.788E-20	3.477E-20	9.082E-20	1.311E-19	2.260E-19
Po212	0	5.449E-21	3.315E-21	2.745E-20	4.044E-20	5.834E-20
Po213	0	1.629E-23	2.725E-24	3.612E-24	4.348E-24	6.378E-24
Po214	0	5.449E-21	7.320E-23	1.910E-22	3.314E-22	8.746E-22
Po215	0	3.278E-20	4.087E-20	1.068E-19	1.542E-19	2.663E-19
Po216	0	4.337E-15	6.618E-15	2.185E-14	3.219E-14	4.644E-14
Po218	0	5.579E-17	6.824E-17	1.780E-16	3.089E-16	8.152E-16
At217	0	1.293E-19	2.163E-20	2.867E-20	3.451E-20	5.062E-20
Rn219	0	7.421E-17	9.252E-17	2.417E-16	3.490E-16	6.028E-16
Rn220	0	1.649E-12	2.516E-12	8.308E-12	1.224E-11	1.766E-11
Rn222	0	1.025E-13	1.253E-13	3.269E-13	5.673E-13	1.497E-12
Fr221	0	1.185E-15	1.983E-16	2.628E-16	3.163E-16	4.640E-16
Fr223	0	3.487E-16	4.662E-16	1.136E-15	1.640E-15	2.833E-15
Ra223	0	1.861E-11	2.320E-11	6.060E-11	8.751E-11	1.511E-10
Ra224	0	9.431E-09	1.439E-08	4.751E-08	6.998E-08	1.010E-07
Ra225	0	5.356E-12	8.954E-13	1.188E-12	1.430E-12	2.097E-12
Ra226	0	1.596E-03	1.950E-08	5.091E-08	8.835E-08	2.332E-07
Ra228	0	1.133E-14	1.677E-14	6.335E-14	1.175E-13	3.022E-13
Ac225	0	3.619E-12	6.055E-13	8.025E-13	9.661E-13	1.417E-12
Ac227	0	1.309E-08	1.750E-08	4.264E-08	6.156E-08	1.064E-07
Ac228	0	1.235E-18	1.750E-18	6.612E-18	1.226E-17	3.154E-17
Th227	0	2.982E-11	3.817E-11	9.711E-11	1.402E-10	2.412E-10
Th228	0	1.936E-06	2.793E-06	9.257E-06	1.363E-05	1.968E-05
Th229	0	1.563E-07	1.649E-07	2.179E-07	2.622E-07	3.846E-07
Th230	0	8.806E-04	1.023E-03	1.867E-03	2.543E-03	4.296E-03
Th231	0	1.421E-0.6	3.065E-08	3.065E-08	3.065E-08	3.065E-08
Th232	0	2.353E-04	2.919E-04	6.227E-04	8.810E-04	1.527E-03
Th233	0	4.965E-10	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Th234	0	1.371E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05
Pa231	0	5.007E-04	5.054E-04	5.241E-04	5.386E-04	5.386E-04

Table 15(cont): Nuclides concentrations (in g) in a LWR irradiated fuel versus time
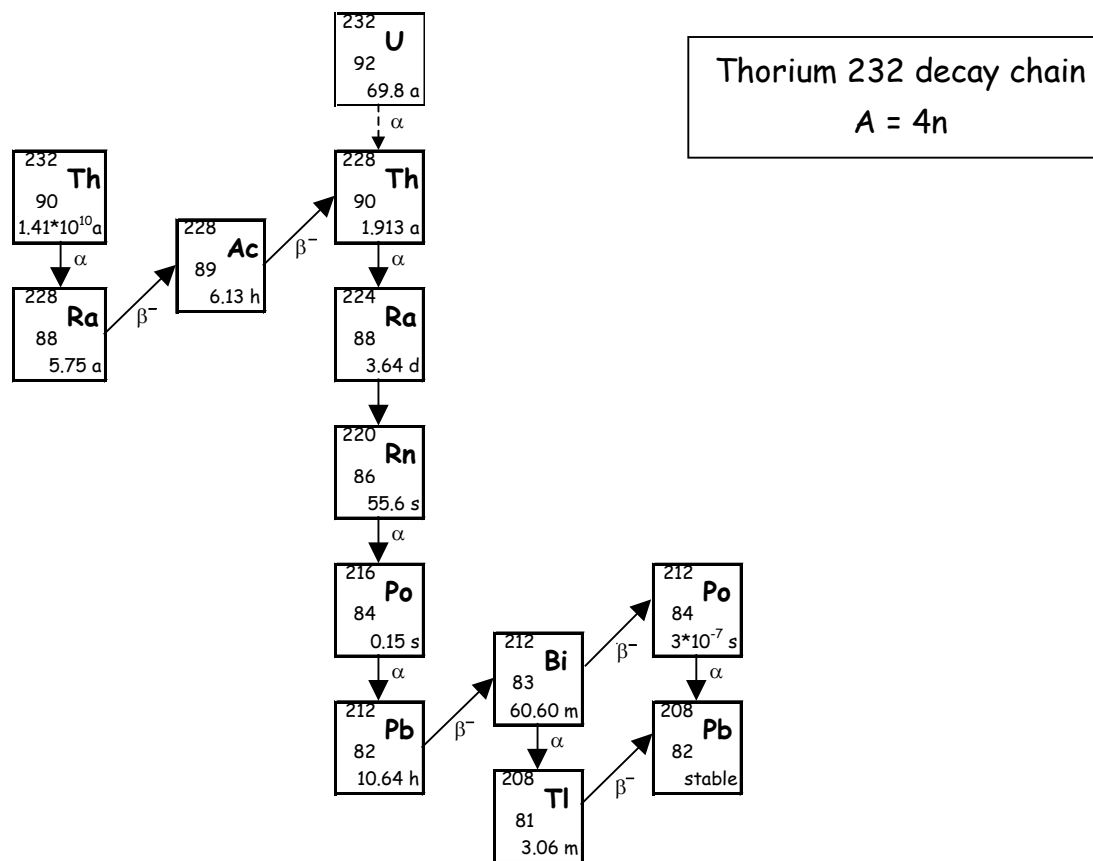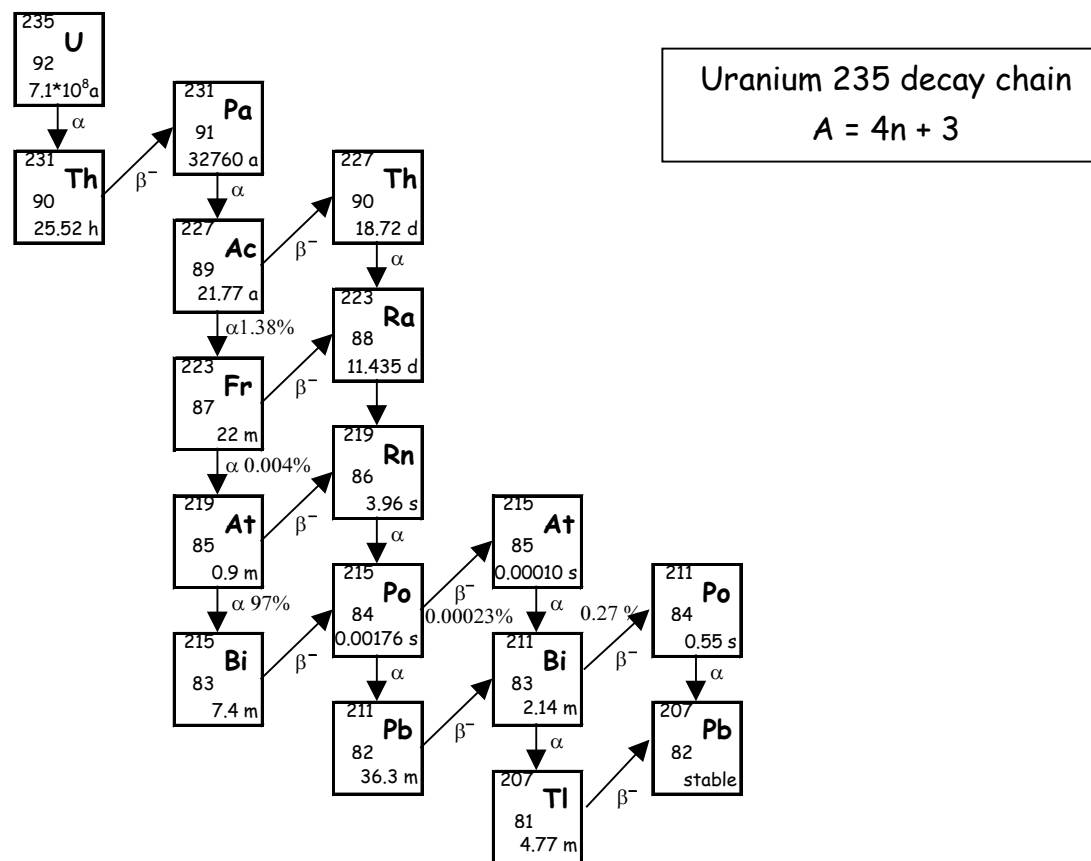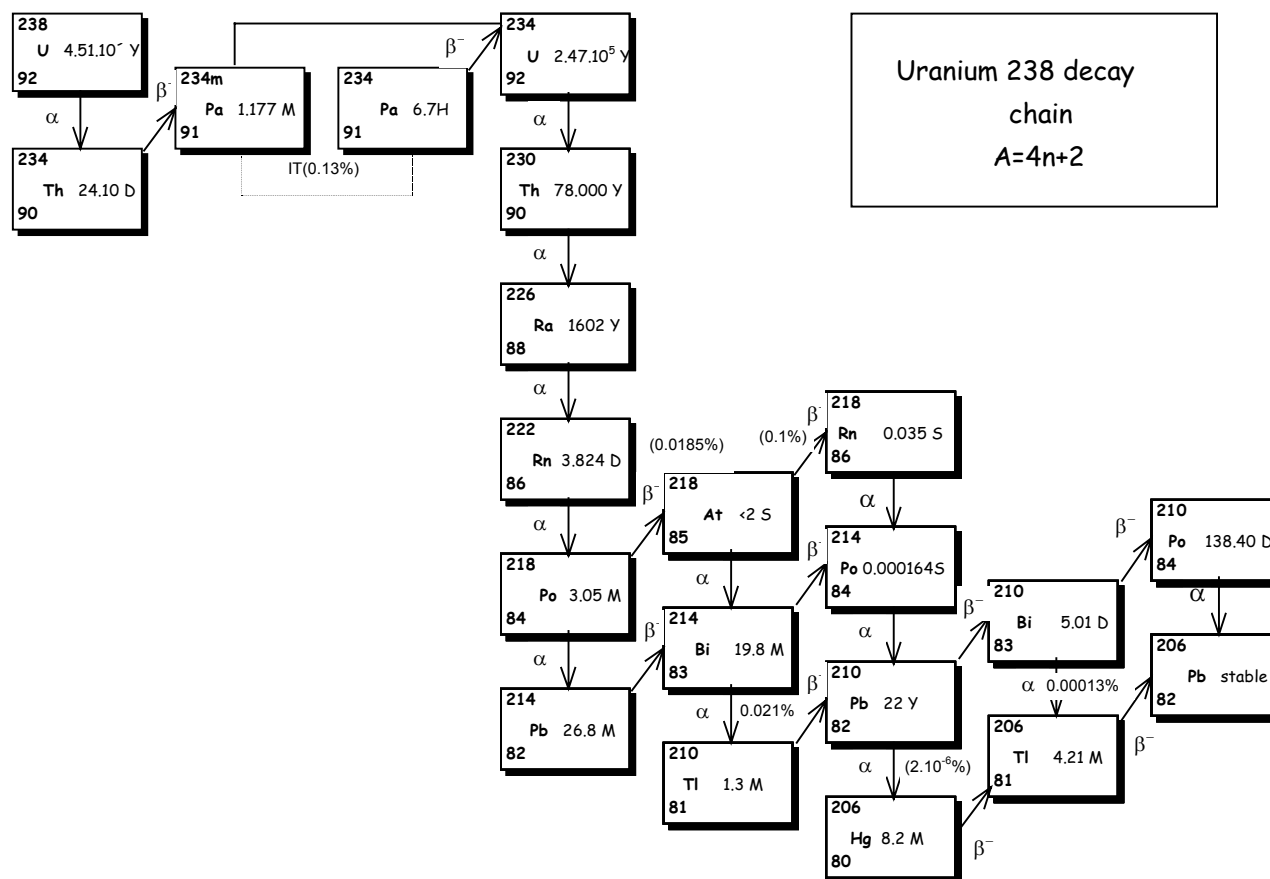Power= 30000MW, Burnup=33000 MWD,
Flux=2.986E+13N/cm2/s

radionuclides	charge	discharge	6 months	3 years	6 years	10 years
Pa232	0	8.054E-07	2.613E-43	0.000E+00	0.000E+00	0.000E+00
Pa233	0	1.679E+05	1.655E-05	1.656E-05	1.659E-05	1.668E-05
Pa234m	0	4.721E-10	4.616E-10	4.616E-10	4.616E-10	4.616E-10
Pa234	0	3.433E-09	1.598E-10	1.598E-10	1.598E-10	1.598E-10
U232	2.57E+02	2.851E-04	3.512E-04	6.138E-04	7.233E-04	8.231E-04
U233	3.20E+04	4.643E-03	4.710E-03	5.118E-03	5.440E-03	6.208E-03
U234	9.677E+05	1.163E+02	1.169E+02	1.203E+02	1.230E+02	1.294E+02
U235	0	7.516E+03	7.516E+03	7.516E+03	7.517E+03	7.517E+03
U236	0	4.437E+03	4.437E+03	4.438E+03	4.438E+03	4.439E+03
U237	0	1.021E+01	3.103E-05	2.689E-05	2.450E-05	1.942E-05
U238	0	9.434E+05	9.434E+05	9.434E+05	9.434E+05	9.430E+05
U239	0	5.469E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00
U240	0	2.203E-21	5.616E-21	2.556E-20	4.114E-20	8.008E-20
Np236	0	4.728E-06	1.354E-58	0.000E+00	0.000E+00	0.000E+00
Np237	0	4.700E+02	4.802E+02	4.806E+02	4.813E+02	4.839E+02
Np238	0	1.497E+00	1.744E-23	0.000E+00	0.000E+00	0.000E+00
Np239	0	7.861E+01	8.328E-05	8.326E-05	8.325E-05	8.321E-05
Np240m	0	1.901E-23	4.846E-23	2.206E-22	3.550E-22	6.911E-22
Np240	0	2.576E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Pu236	0	6.683E-04	6.032E-04	3.236E-04	1.990E-04	5.904E-05
Pu238	0	1.639E+02	1.698E+02	1.714E+02	1.688E+02	1.523E+02
Pu239	0	5.201E+03	5.280E+03	5.280+03	5.280E+03	5.279E+03
Pu240	0	2.137E+03	2.188E+03	2.190E+03	2.192E+03	2.195E+03
Pu241	0	1.055E+03	1.033E+03	9.173E+02	8.359E+02	6.625E+02
Pu242	0	3.693E+02	3.693E+02	3.693E+02	3.693E+02	3.693E+02
Pu243	0	1.427E-01	1.132E-13	1.132E-13	1.132E-13	1.132E-13
Pu244	0	1.154E-10	2.943E-10	1.340E-09	2.156E-09	4.197E-09
Pu245	0	2.192E-16	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Am241	0	2.526E+01	4.651E+01	1.621E+02	2.429E+02	4.136E+02
Am242m	0	9.487E-01	9.468E-01	9.358E-01	9.273E-01	9.064E-01
Am242	0	7.774E-02	1.137E-05	1.124E-05	1.114E-05	1.088E-05
Am243	0	1.005+02	1.007E+02	1.007E+02	1.006E+02	1.006E+02
Am244	0	4.368E-03	2.284E-25	1.040E-21	1.673E-24	3.257E-24
Am245	0	1.055E-14	7.389E-15	9.380E-16	1.872E-16	3.332E-18
Cm242	0	1.023E+01	5.216E+00	1.001E-01	6.624E-03	2.185E-03
Cm243	0	8.353E-02	8.274E-02	7.828E-02	7.496E-02	6.727E-02
Cm244	0	3.296E+01	3.242E+01	2.939E+01	2.722E+01	2.248E+01
Cm245	0	2.143E+00	2.143E+00	2.143E+00	2.142E+00	2.141E+00
Cm246	0	2.521E-01	2.521E-01	2.520E-01	2.519E-01	2.517E-01
Cm247	0	3.321E-03	3.321E-03	3.321E-03	3.321E-03	3.321E-03
Cm248	0	2.299E-04	2.299E-04	2.299E-04	2.299E-04	2.300E-04
Cm249	0	2.557E-09	3.471E-18	5.454E-34	2.500E-46	0.000E+00
Cm250	0	1.367E-12	1.367E-12	1.367E-12	1.367E-12	1.367E-12
Bk249	0	2.591E-06	1.822E-06	2.313E-07	4.617E-08	8.215E-10
Bk250	0	1.964E-09	2.888E-20	2.888E-20	2.887E-20	2.887E-20
Cf249	0	3.394E-07	1.111E-06	2.691E-06	2.865E-06	2.882E-06
Cf250	0	4.201E-07	4.124E-07	3.660E-07	3.239E-07	2.485E-07
Cf251	0	2.137E-07	2.136E-07	2.132E-07	2.129E-07	2.121E-07
Cf252	0	1.189E-07	1.060E-07	5.420E-08	3.211E-08	8.672E-09
Cf253	0	2.302E-10	4.548E-13	7.145E-29	3.275E-41	0.000E+00
Cf254	0	1.978E-13	3.163E-14	7.043E-19	1.642E-22	1.364E-31
Es253	0	2.623E-10	5.774E-12	2.423E-25	6.160E-36	0.000E+00

G1: Minimum Mass (g) of UF4 and UF6 in cylindrical Containers to fulfill the Infinite Thickness Condition
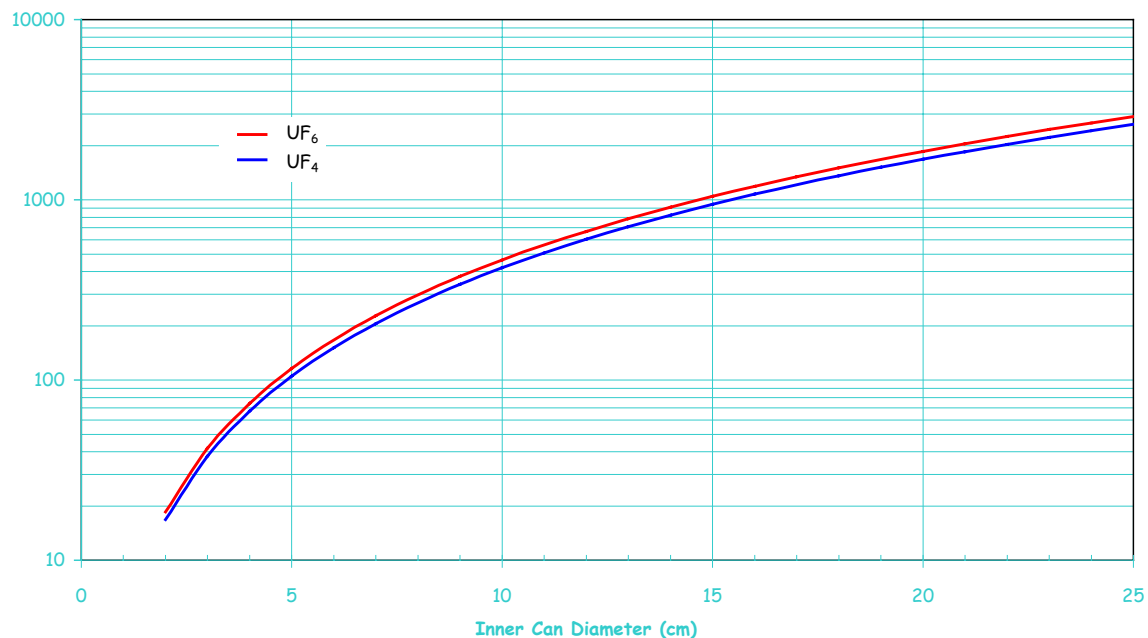
G1(cont.): Minimum Mass (g) of UO2 and U3O8 and U metal in cylindrical Containers to fulfill the Infinite Thickness Condition

Thorium 232 decay chain
A = 4n

Uranium 235 decay chain

$A = 4n + 3$

Uranium 238 decay chain
$A = 4n+2$

G5: Build-up of Pu, Am and Cm from ^{235}U and ^{238}U

^{242}Cm $\xrightarrow{(n,\gamma)}$ ^{243}Cm $\xrightarrow{(n,\gamma)}$ ^{244}Cm

β^- β^-

^{241}Am $\xrightarrow{(n,\gamma)}$ ^{242}Am ^{243}Am $\xrightarrow{(n,\gamma)}$ ^{244}Am

β^- β^-

^{236}Pu ^{238}Pu $\xrightarrow{(n,\gamma)}$ ^{239}Pu $\xrightarrow{(n,\gamma)}$ ^{240}Pu $\xrightarrow{(n,\gamma)}$ ^{241}Pu $\xrightarrow{(n,\gamma)}$ ^{242}Pu $\xrightarrow{(n,\gamma)}$ ^{243}Pu

β^- β^- β^-

^{236}Np $\xleftarrow{(n, 2n)}$ ^{237}Np $\xrightarrow{(n,\gamma)}$ ^{238}Np $\xrightarrow{(n,\gamma)}$ ^{239}Np

β^- β^-

^{234}U ^{235}U $\xrightarrow{(n,\gamma)}$ ^{236}U $\xrightarrow{(n,\gamma)}$ ^{237}U $\xleftarrow{(n, 2n)}$ ^{238}U $\xrightarrow{(n,\gamma)}$ ^{239}U
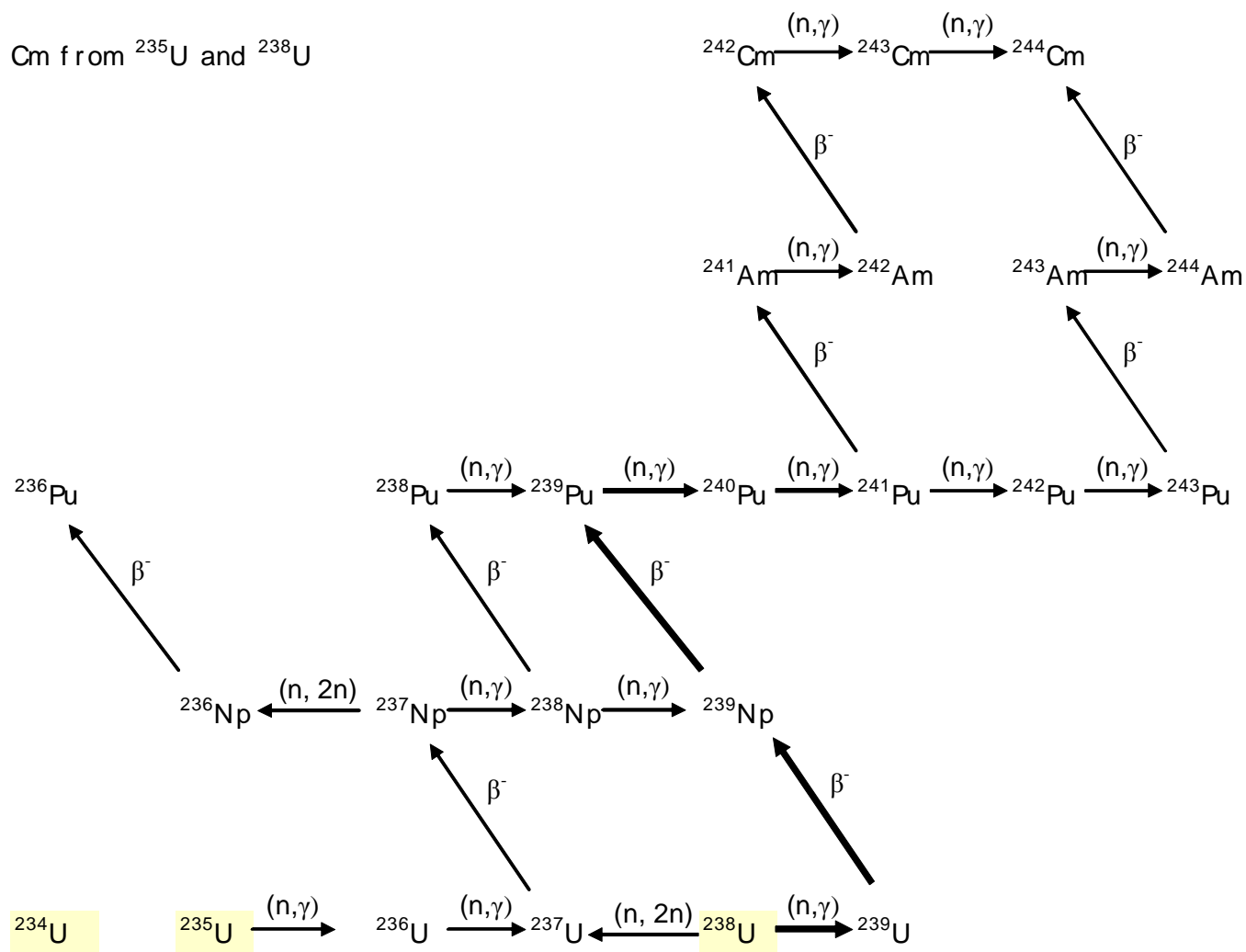
G6: Build-up of ^{233}U from ^{232}Th and U
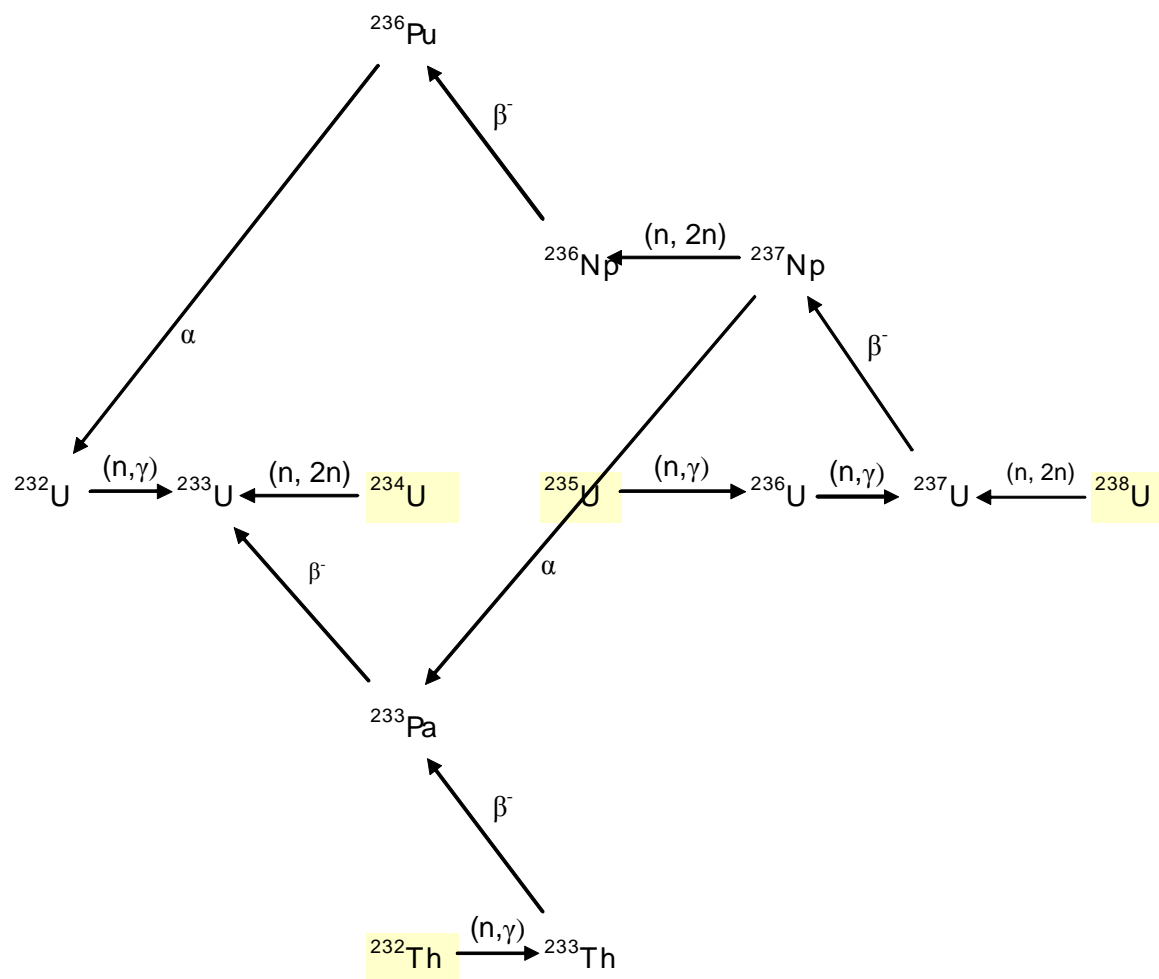
G7: Build-up of ^{232}U from U
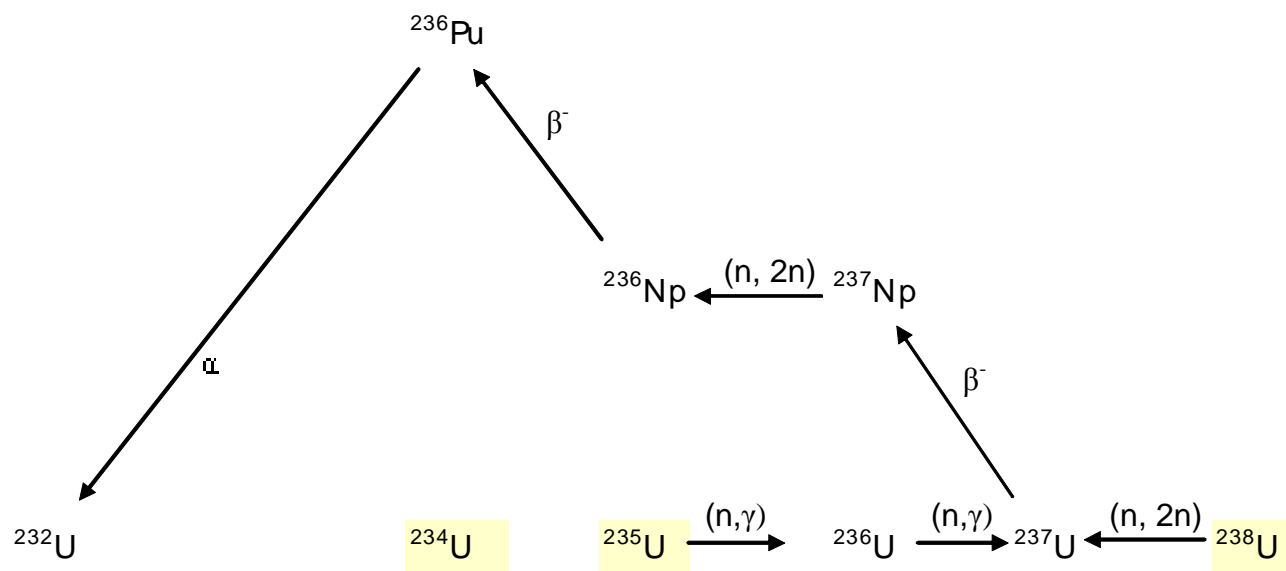
G8: Build-up ^{234}U from ^{238}U in nature

Equilibrium between ^{234}Th and ^{234}Pa with ^{238}U
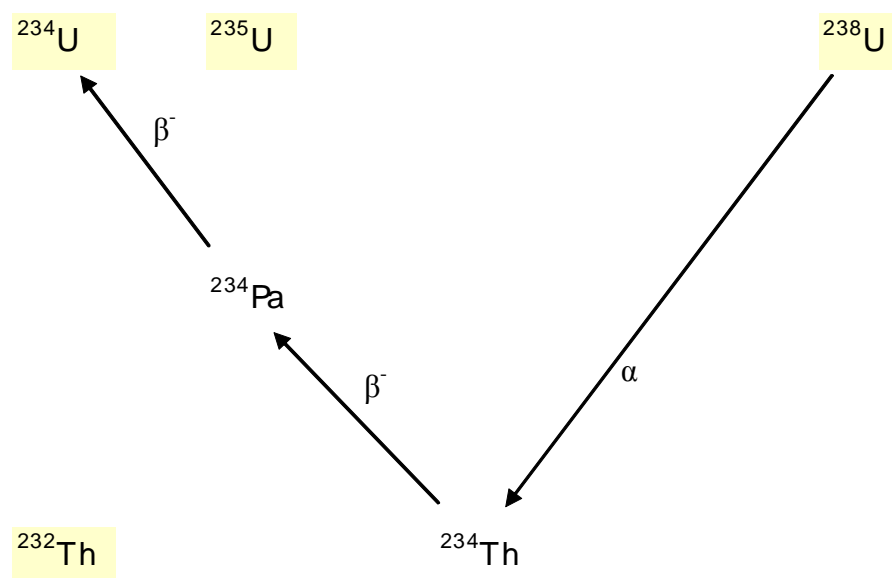
PUREX Process
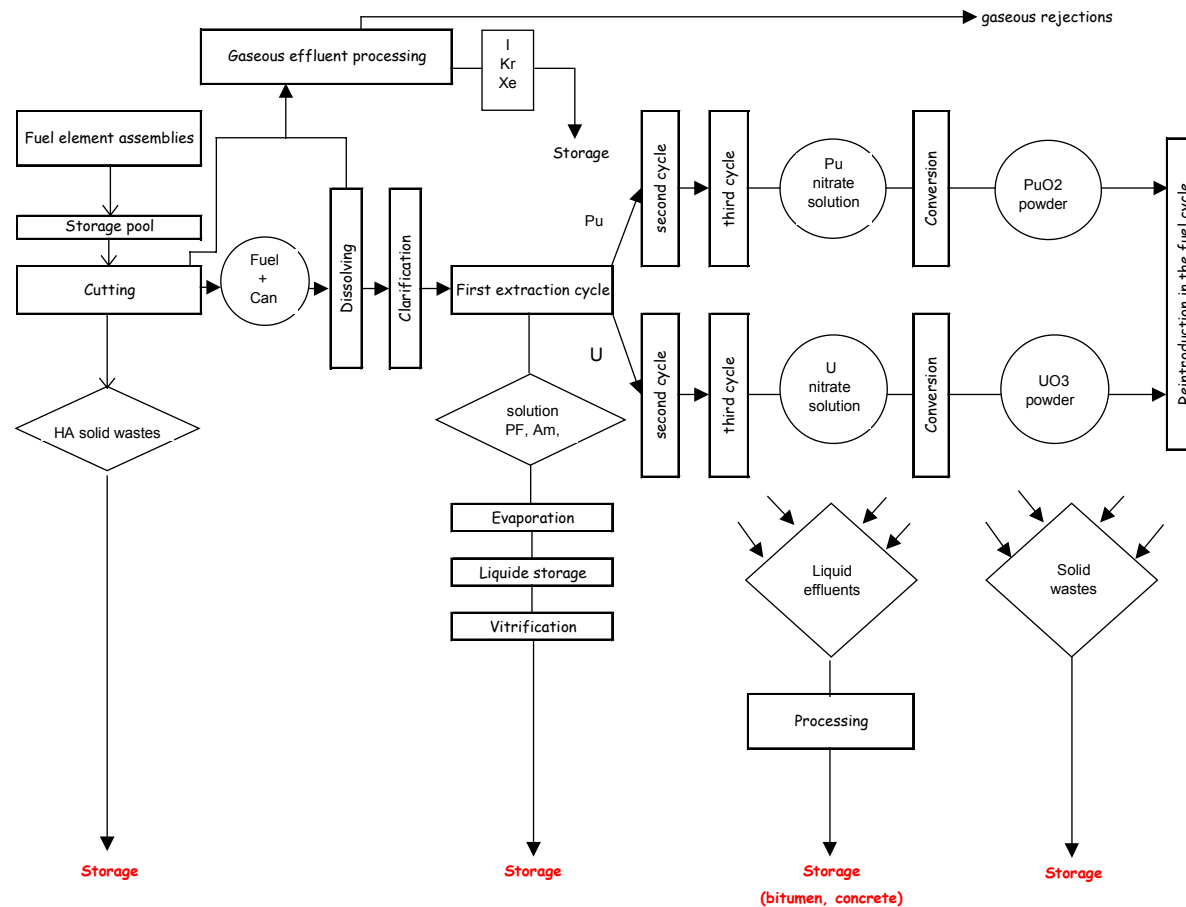
Mean Uranium Dwell Times at various stages of the PWR Fuel Cycle

t = 81.5 months

t = 0

Pu extraction -2 months

Natural uranium

Conversion- 4 months

Reprocessing- 9 months

Enrichment- 6 months

IRRADIATED FUEL REPROCESSING
(24 months)

Fuel element production- 7 months

Deactivation-Transportation
(13 months)

FUEL ELEMENT FABRICATION
(21.5 months)

Storage- 4.5 months

t= 21.5 months

REACTOR CHARGE

REACTOR DISCHARGE

t = 57.5 months

STAY IN THE REACTOR
(36 months)
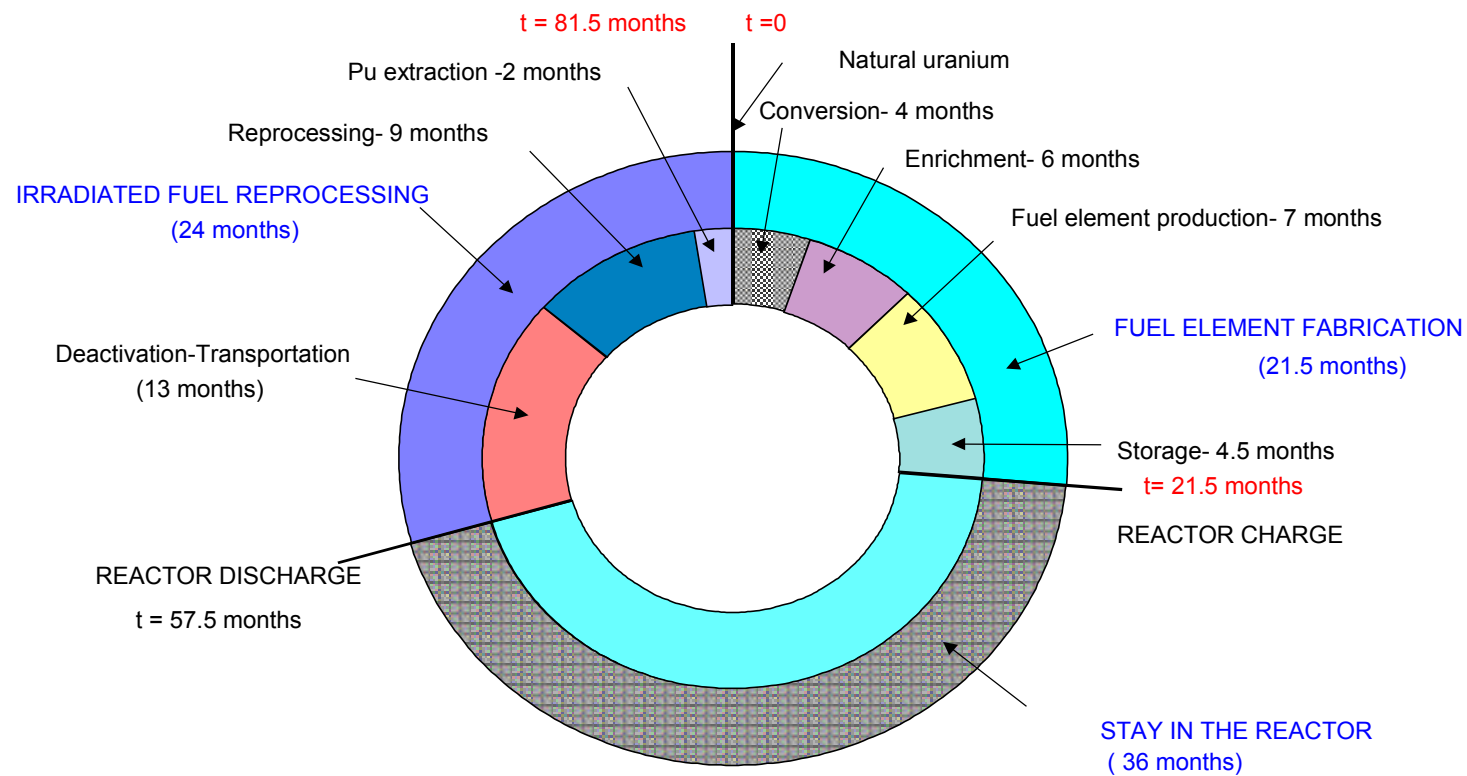
G11: Absolute Full-Energy Peak Efficiency of Different Detector
　　　Types for Axial Irradiation from 25 cm Distance *(see also*
　　　Annex A1e, Annex A2 Tab.14)
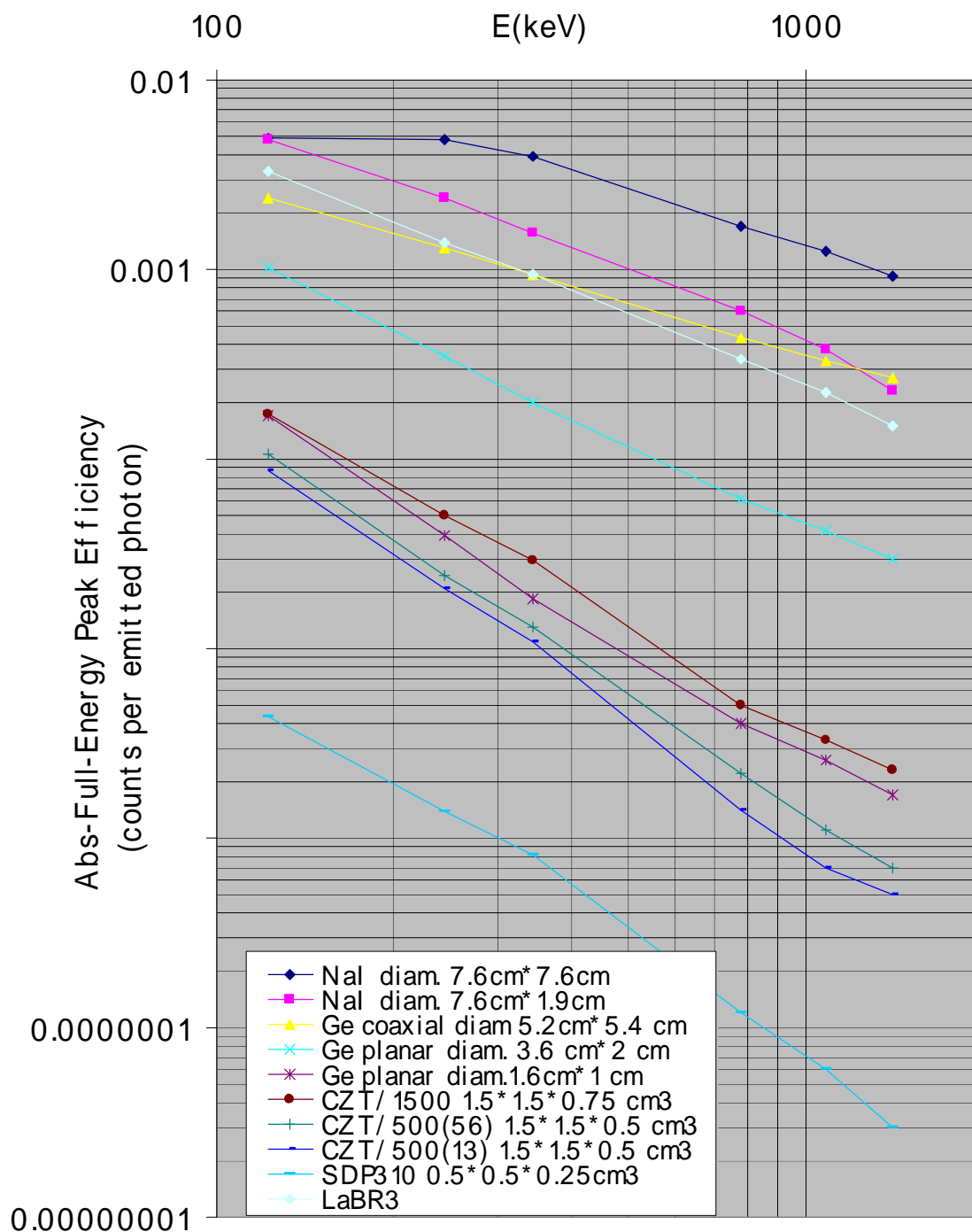
ANNEX A3

TROUBLE SHOOTING

1. HP-200

The HP-200 cannot be switched on or
the message "main batteries low" is given or
HP-200 beeps and turns off immediately after turning on:
> Change or charge the main batteries,
> see glossary, *batteries for HP-200.*

The HP-200 contrast is low (or the screen is too dark):
> Press the "**ON**" and "**+**" keys simultaneously
> (or the "**ON**" and "**-**" keys, respectively).

The menu with the list of MCA programs is not displayed:
> Press "CRTL", "ALT", "DEL" simultaneously.

2. MCA-166

Message "MCA not connected":
> Check if the MCA-166 is switched on.
> Check the connection between MCA-166 and HP-200.

The green ON LED of the MCA-166 does not flash after switching on the MCA-166:
> The battery is flat.
> See glossary, *batteries for MCA-166.*

Message "MCA power fail" or
HP-200 beeps:
> The MCA-166 battery is very low.
> Connect MCA-166 charger, see glossary, *batteries for MCA-166.*

MCA-166 does not charge:
> Charger connected in the wrong order. Connect **first** the LEMO
> connector to the MCA-166 and **then** the mains power plug to the
> grid.

3. During setup or measurements

HV cannot be switched on <u>and</u> there is some condensation on the Ge detector:
    Loss of cryostat vacuum.
      The detector is defect – contact E4.

No counts arrive on the graphic screen or strange spectrum shape:
    Wrong polarity of the amplifier input signal. Go to the amplifier setup menu and change the polarity.

      Count rate too high. Reduce it.

      Wrong ADC input mode. Go to the amplifier setup menu and change the ADC input mode to "**MCA**".

      High voltage not applied. Switch it on.

      If the problem persists, check the Preamplifier output signal with an oscilloscope.

Counting stops during a measurement:
    Cable defect or MCA-166 battery low.

The message "HV inhibit! Check detector!" appears:
    The detector is not cold. Fill liquid nitrogen and wait about 6 hours.
      The cables input signal and HV inhibit are inverted. Check cable connections.
      The inhibit cable is defective.
      The wrong producer name was selected. Check the HV setup.

The peaks are shifted to other positions.
    Go to the amplifier setup menu and readjust the gain. If necessary use the stabilisation.

A low energy background or peak appears with very high count rate:
    A high frequency signal or noise disturbs the MCA-166. Check the preamplifier output signal with an oscilloscope. Check cables and connectors, look for ground loops.

A large low-energy part of the spectrum is missing or the spectrum as a whole or peaks are completely deformed:

   A strong high frequency signal is disturbing. Identify the origin (electrical engines, power supplies, electrical control systems, disturbances on the electrical grid or on the ground, …).

With a Ge detector, all peaks have low-energy or high-energy tails.

   Pole zero correction wrong. Go to the Amplifier menu setup and readjust the gain.

The connection between computer and MCA-166 is lost, but the HV is still on:

   Software problem. **Do not switch off** the MCA-166, the break-down of the HV might damage the detector!

   Restart the computer by pressing "Ctrl.", Alt.", and "Del" simultaneously. Restart the same program as before, do not choose "Reset to default …".
   If the problem persists, try to start the program MCA.EXE, save the spectrum and switch off.

   As a last way out, leave the MCA-166 switched on and disconnect the MCA-166 battery charger. The battery will run out within about 10 hours and an automatic mode of operation will safely switch off first the HV and then the MCA-166. This is completed when the green light is off.
   Then, switch off the MCA-166 with its toggle switch. Connect the charger, charge for a quarter of an hour and switch on the MCA. Start your program and save the last spectrum.

4. Typical mistakes with U enrichment measurements

With U235, UF6, and NaIGEM the *infinite thickness condition* must be fulfilled, i.e. the samples must be large enough.

The measured enrichment is <u>underestimated</u>:

   The condition of <u>infinite thickness</u> is not fulfilled. You cannot apply the enrichment meter principle, i.e. these codes.
   See Glossary, Infinite thickness condition checking.

The <u>matrix</u> of the unknown sample is different from that of the sample used for the calibration.
If you use UF6 or NaIGEM, check this parameter and change the input.
If you use U235 the input cannot be changed.

The <u>Cd filter</u> is thicker than that used for the calibration or the container wall of the sample is thicker. If you use UF6 or NaIGEM, check these parameters and change the input.

The <u>collimator height or/and diameter</u> are smaller than that used for the calibration. You must redo the measurement with the collimator used for the calibration.

The enrichment is <u>overestimated</u>:
The <u>matrix</u> of the unknown sample is different from that of the calibration sample.
If you use UF6 or NaIGEM, check this parameter and change the input.
If you use U235 the input cannot be changed.

The <u>Cd filter</u> is thinner than that used for the calibration or the container wall of the sample is thinner. If you use the UF6 or NaIGEM software, check this parameter and change the input. If you use the U235 the input cannot be changed.

-The <u>collimator height or/and diameter</u> are larger than that used for the calibration. You must redo the measurement with the collimator used for the calibration.

ANNEX A4
RADIATION PROTECTION

*Don't be afraid of radiation,
but be informed!*

1. MEASURE the radiation fields.

Radiation fields **must to be measured** with instruments. Human beings cannot detect ionizing radiation.

If you measure a radiation field yourself**, use only instruments you know well** and operate them carefully.

There may be gamma **and** neutron radiation. **Both** fields must be measured separately.

There may be **contamination** of surfaces by alpha or beta activity. If there is any suspicion ask for smear tests.

2. REDUCE radiation exposure.

Work with **LOW ACTIVITIES** if possible (remove samples as soon as possible).

Keep at a **DISTANCE** from highly active material. Use appropriate tools to handle radiation sources. Do not touch contaminated areas.

Reduce the **WORKING TIME** in radiation fields.

Use **RADIATION SHIELDING** (e.g. lead bricks) if necessary.

3. LIMIT for radiation exposure

The radiation exposure is characterised by the effective equivalent dose, given in mSv (milli Sievert).

As a mean, everybody receives from the environment an effective equivalent dose of about 3 mSv per year (cosmic radiation, natural radioactivity in earth and stones, …).

For radiation workers, the maximum permitted effective equivalent dose **is 50 mSv per year, but only 100 mSv in 5 consecutive years** (ICRP recommendation, applied in the EU). The first limit corresponds to a mean value of 0.03 mSv/h (milli Sievert per hour) for people continuously exposed for 1600 working hours per year.

For the general public, the annual dose caused by dealing with radiation and radioactive substances must be below
1 mSv/a (emissions from nuclear facilities or mining, transportation of nuclear material, application of X-rays, …). This is an ICRP recommendation, there is no uniform international regulation.

4. EXAMPLES from the PERLA Laboratory, JRC, Ispra

Attention!
Never extrapolate from an example
to another radiation exposure situation!
For safe work you have to measure!

4.1. Dose Rates for URANIUM Sample 128

Material: UO_2
^{235}U mass: 1667 g
Enrichment: 93%,
Can: cylindrical Al can, 4 mm wall thickness

Effective equivalent dose rates:

Distance	Gamma Radiation	Neutron Radiation	Sum
…. (m)	(mSv/h)	(mSv/h)	(mSv/h)
0	0.018	0.00001	0.018
0.2	0.005	0	0.005
1	0.002	0	0.002
3	0.0013	0	0.0013

4.2. Dose Rates for PLUTONIUM Sample Pu120

Material: PuO_2 (plus ^{241}Am from ^{241}Pu decay)
Pu mass: 2348 g
Pu isotopic composition (03.03.1999):
    ^{238}Pu: 1.64%, ^{239}Pu: 60.69%,
    ^{240}Pu: 25.85%, ^{241}Pu: 5.92%,
    ^{242}Pu: 5.90%
^{241}Am content (03.03.1999): 5750 μg per g Pu,
Can: Double cylindrical steel cans,
           together 5 mm wall.

Effective equivalent dose rates:

Distance	Gamma Radiation	Neutron Radiation	**Sum**
(m)	(mSv/h)	(mSv/h)	**(mSv/h)**
0	2.300	2.100	**4.400**
0.2	0.400	0.330	**0.730**
1	0.038	0.020	**0.058**
3	0.005	0.002	**0.007**

4.3. Dose Rates for Gamma Radiation Sources

4.3.1. ^{137}Cs source No. 8463GK

Isotope: ^{137}Cs
Radiation: 1 gamma line, Eγ = 662 keV, Iγ = 87%
Activity: 370 MBq on the 12th May 1999
Time of half-life: 30.1 a

Effective equivalent dose rates (^{137}Cs, 17.2.99):

Distance	Gamma Radiation	Neutron Radiation	**Sum**
(m)	(mSv/h)	(mSv/h)	**(mSv/h)**
0	2.130	0	**2.130**
0.2	0.690	0	**0.690**
1	0.030	0	**0.030**
3	0.005	0	**0.005**

4.3.2. ^{137}Cs gamma source No. DC868
Calibration source

Isotope: ^{137}Cs
Radiation: 1 gamma line, Eγ = 662 keV, Iγ = 87%
Activity: 410 kBq on the 01th November 1992
Time of half-life: 30.1 a

Effective equivalent dose rates (^{137}Cs, 17.2.99):

Distance	Gamma Radiation		Neutron Radiation	Sum
(m)	(mSv/h)		(mSv/h)	**(mSv/h)**
0	0.014	0		**0.014**
0.2	0.001	0		**0.001**
1	0	0		**0**
3	0	0		**0**

4.4. Dose Rates for Neutron Sources

4.4.2. ^{252}Cf neutron source No. 5947NC

Isotope: ^{252}Cf
Radiation: fast neutrons, fission spectrum
Source strength: 420 000 n/s on the 17.2.99
Time of half-life: 2.64 a

Effective equivalent dose rates (^{252}Cf 5947NC, 17.2.99):

Distance	Gamma Radiation	Neutron Radiation	Sum
(m)	(mSv/h)	(mSv/h)	**(mSv/h)**
0	0.080	0.460	**0.540**
0.2	0.007	0.060	**0.066**
1	0.002	0.004	**0.006**
3	0.0013	0.0004	**0.0017**

4.4.3. AmLi neutron source No. 86 for AWCC

Isotope: ^{241}Am, gamma source, shielded
Radiation: fast neutrons
Source strength: 120 000 n/s on the 17.2.99
Time of half-life: 432 a

Effective equivalence dose rates (AmLi No. 86, 1999):

Distance	Gamma Radiation	Neutron Radiation	Sum
(m)	(mSv/h)	(mSv/h)	**(mSv/h)**
0	2.800	0.090	**2.900**
0.2	0.220	0.023	**0.240**
3	0.002	0.001	**0.003**

Legend:
- β+ decay
- α decay
- β⁻ decay
- spontaneous fission
- isomeric transition

			Cm 238 2.4h ε α 6.52	**Cm 239** 3h ε γ 188… g	**Cm 240** 27d sf α 6.291; 6.248… Sf	**Cm 241** 32.8 d sf α 5.939… γ 472;431;132… e- g	**Cm 242** 162.94 d sf α 6.113; 6.069… sf; g γ (44…); e- σ 20 σf 5	**Cm 243** 29.1 a sf α 5.785; 5.742… ε; sf; g γ 278; 228; 210…; e-	**Cm 244** 18.11 a sf α 5.805; 5.763… sf; g γ (43…) e- σ 15; σf 1.1
	Am 234 2.32 m ε α 6.46 βsf	**Am 235** 15 m ε	**Am 236** 4.4 m ε α 6.41	**Am 237** 73.0 m sf α 6.042 γ 280;438;474; 909… g	**Am 238** 1.63 h sf α 5.94 γ 963;919;561; 605… g	**Am 239** 11.9 h sf α 5.774 γ 278; 228… e- g	**Am 240** 50.8 h sf α 5.378… γ 988;889… g	**Am 241** 432.6a sf α 5.486; 5.443 sf; γ 60; 26…; e-; g σ 50+750 σf 3.1	**Am 242** 141 a γ (49) e-;sf α5.206 (γ(49…) σ1700; σ₁ 7000 / 16 h β– 0.6; 0.7 γ(42…) e-; g σf 2100	**Am 243** 7370 a sf α 5.275; 5.233 sf, γ 75; 44… σ 75+5 σf 0.074
Pu 232 34.1 m ε α 6.60; 6.54 γ	**Pu 233** 20.9 m ε α 6.31 γ 235; 535…	**Pu 234** 8.8 h ε α 6.202; 6.151 γ; e-	**Pu 235** 25.3 m sf α 5.85 γ 49; (758;34…) e-	**Pu 236** 2.858 a sf α 5.768; 5.721 sf; Mg 28 γ(49,109…); e- σf 160	**Pu 237** 45.2 d ε α 5.334… γ 60; e- σf 2300	**Pu 238** 87.74 a sf α 5.499; 5.456… Sf; γ (52;…) γ (43; 100…), e- σ 510; σf 17	**Pu 239** 24110 a sf α 5.157; 5.144… Sf; γ (52…) e-; m σ 270; σf 752	**Pu 240** 6563 a sf α 5.168; 5.124… sf; γ (45…) e-; g σ 290; σf 0.044	**Pu 241** 14.35 a sf β⁻ 0.02; g α 4.896 γ (149…); e- σ 370; σf 1010	**Pu 242** 376 300 a α 4.901; 4.856… Sf; γ (45…) e-; g σ 19; σf<0.2
Np231 48.8 m ε α 6.28 γ 371; 348; 264… e-	**Np232** 14.7 m ε γ 327;820; 867;864;282… e-	**Np233** 36.2 m ε α 5.54 γ (312; 299; 547…)	**Np234** 4.4 d ε; β+ γ 1559; 1528; 1602… sf~900	**Np235** 396.2 d ε, α 5.022; 5.007… γ 642; 688…; e-; g; sf 2700	**Np236** 22.5 h ε; β⁻0.5… γ 642; 688…; e-; g; σf 2600 / 1.54*10⁵a ε; β⁻; α γ 160; 104…; e⁻; g; σf 2600	**Np 237** 2.144*10⁶a sf α 4.790; 4.774 γ 29; 87… e- σ 180; σf 0.020	**Np 238** 2.117 d β- 1.2… γ 984; 1029; 1026; 924…; e-; g σf2100	**Np 239** 2.355 d β-0.4; 0.7… γ 106; 278; 228… e-; g σ 32+19; σf<1	**Np240** 7.22 m β- 2.2… γ 555; 597… e-; γ…; g / 65 m β-0.9 γ 566; 974; 601; 448…;g	**Np 241** 13.9 m β⁻1.3… γ 175; (133…) g
U 230 20.8 d α 5.888; 5.818… γ (72;154; 230…);e- σf 25	**U 231** 4.2 d ε;α 5.456; 5,471; 5.404 γ 26; 84; 102… e-; σf 250	**U 232** 68.9 a α 5.320; 5.263… Ne 24; γ (58; 129…); e- σ 73; σf 74	**U 233** 1.592*10⁵a α 4.824; 4.783… Ne 25; γ (42; 97…); e- σ 47; σf 530	**U 234** 0.0055 2.446*10⁵ a α 4.775; 4.723…; sf Mg 28; Ne; γ(53;121… e-; σ 96; σf <0.005	**U 235** 0.720 26 m Iγ (0.07) / 7.038*10⁸a α 4.398; sf; Ne; γ 186… e-; σ 95; σf 586	**U 236** 120 ns Iγ 1783 642… / 2.342*10⁷a α 4.494; 4.445…; sf γ(49; 113…) e-; σ 5.1	**U 237** 6.75 d β⁻0.2… γ 60; 208… e- σ 100; σf<0.35	**U 238** 99.2745 270 ns Iγ 2514; 1879… sf / 4.468*10⁹a α 4.198…; sf 2β⁻; γ(50…) e-; σ 2.7	**U 239** 23.5 m β⁻1.2; 1.3… γ 75; 44… σ 22; σf 15	**U 240** 14.1 h β⁻ 0.4… γ 44; (190…) e- m
Pa229 1.5d ε;α 5.580; 5.670; 5.615… γ (119; 40; 146…) e-	**Pa 230** 17.4 d ε; β⁻ 0.5… α 5.345; 5.326… γ 952; 919; 455; 899; 444; σf 1500	**Pa 231** 3.276*10⁴ a α 5.014; 4.952; 5.028 Ne24; F23?; γ 27; 303; 300…; e-; σ 200; σf < 0.020	**Pa 232** 1.31d β⁻ 0.3; 1.3…; ε γ 969; 894; 150…; e- σ 460; σf 700	**Pa 233** 27.0d β⁻ 0.3; 0.6… γ 312; 300; 341… e- σ 20+19; σf < 0.1	**Pa 234** 1.17 m β⁻2.3… γ(1001; 767…) e- σ(74…);e⁻ σf<500 / 6.7h β⁻ 0.5; 1.2… γ131; 881 883…; e- σf <5000	**Pa 235** 24.2 m β⁻ 1.4… γ 128 - 659.. m	**Pa 236** 9.1 m β⁻ 2.0; 3.1… γ 642; 687; 1763…; g βsf ?	**Pa 237** 8.7 m β⁻ 1.4; 2.3… γ 854; 865; 529; 541…	**Pa 238** 2.3 m β⁻ 1.7; 2.9… γ 1015; 635; 448; 680…; g	
Th 228 1.913 a α 5.423; 5.340… γ 84; (216…); e- O 20 σ 123; σf <0.3	**Th 229** 7880 a α 4.845; 4.901; 4.815… γ 194; 211; 86; 31… e-; Ne 24; σ ~60; σf 30	**Th 230** 75400 a α 4.687; 4.621… γ (68; 144…); e-; σ 23.4 σf < 0.0005	**Th 231** 25.5 h β⁻ 0.3; 0.4… γ 26; 84… e-	**Th 232** 100 1.405*10¹⁰ a sf α 4.013; 3.950…; sf γ (64…); e- γ 7.37; σf 0.000 003	**Th 233** 22.3 m β⁻ 1.2… γ 87; 29; 459…; e- σ 1500; σf 15	**Th 234** 24.10 d β⁻ 0.2… γ 63; 92; 93… e-; m σ 1.8; σf < 0.01	**Th 235** 7.1 m β⁻ 1.4… γ 417; 727; 696…	**Th 236** 37.5 m β⁻ 1.0… γ 111; (647; 196…)	**Th 237** 5.0 m β⁻

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" CdZnTe Nuclear radiation detector- Model CZT/500"- User manual
http://www.ritec.mt.lv

Instrument Canberra catalogue (Edition nine)

$LaBr_3$:Ce Scintillators for gamma ray spectroscopy
IEEE, LBNL-51793
K.S. Shah, J.Glodo, M.Klugerman,W,W. Moses, S.E. Derenzo, and M.J. Weber

Legal notice

Abstract

This document forms the third edition of the report untitled "Handbook of Gamma Spectrometry methods for Non-Destrucutive Assay of nuclear materials" (EUR 19822 EN). It has been updated from the June 2004 release.

The organization by chapters has remained unchanged, but the content has been revised. Were added to the contents:
-about a dozen of key words in the glossary,
-spectrum pictures (for example spectra taken with a LaBr3 detector),
-new data (for instance, built up of heavy nuclides),
-new measurement results making references to results from our laboratory,
-new links providing an easy navigation through the glossary and annexes.
-new references.

Clearly, some minor mistakes of the second version were corrected, but avoided adding too much new information, since the booklet should stay restricted to inspector needs.

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