The Activation technique

n_TOF Nuclear Physics Winter School 2024
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Why to talk about the activation technique at n_TOF winter school?

“TOF technique is definitely the best choice when stable isotopes are considered or when enough sample material is available (e.g. long-lived radioactive isotopes) “

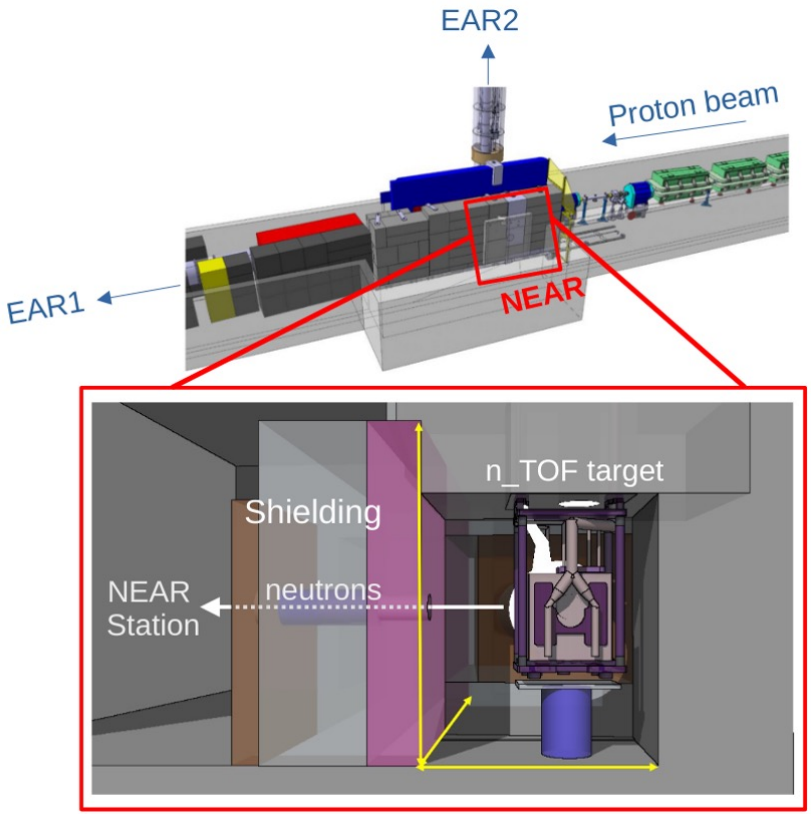
BUT

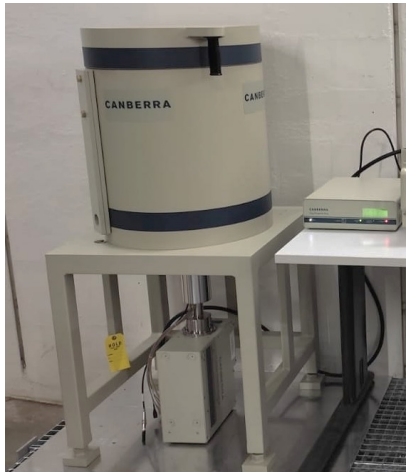
This is not always the case…

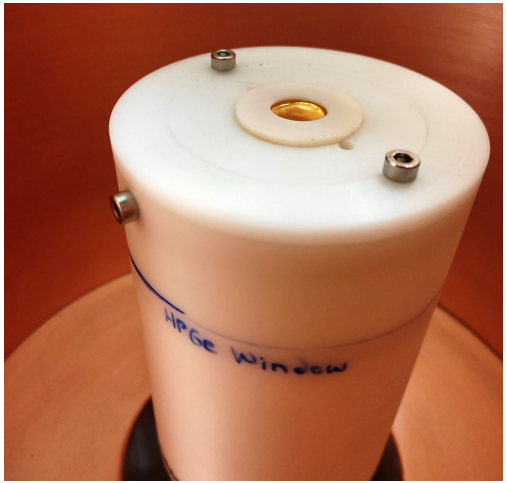
e.g. when very small sample masses and/or very small cross sections are considered

→**NEAR measurements**

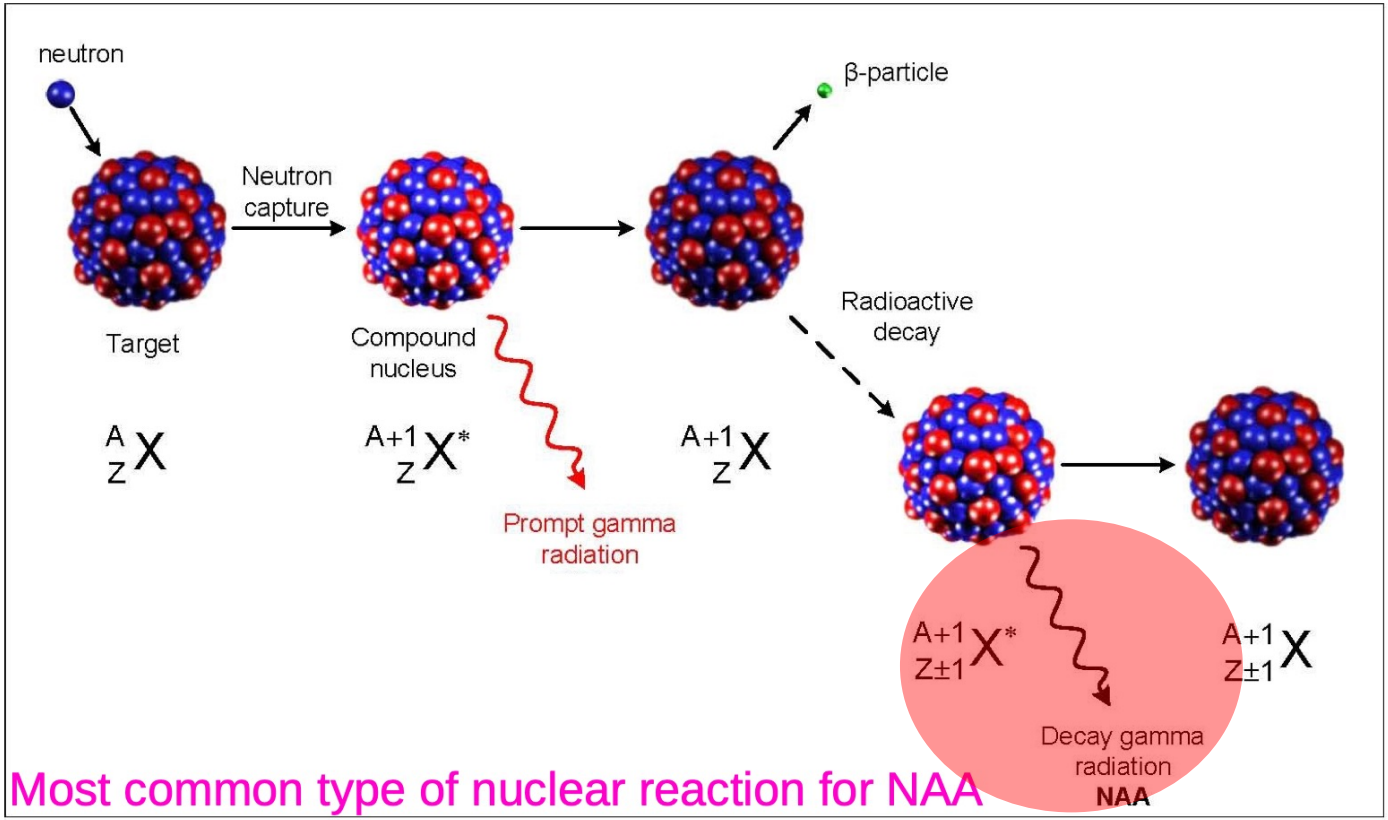
The NEAR station





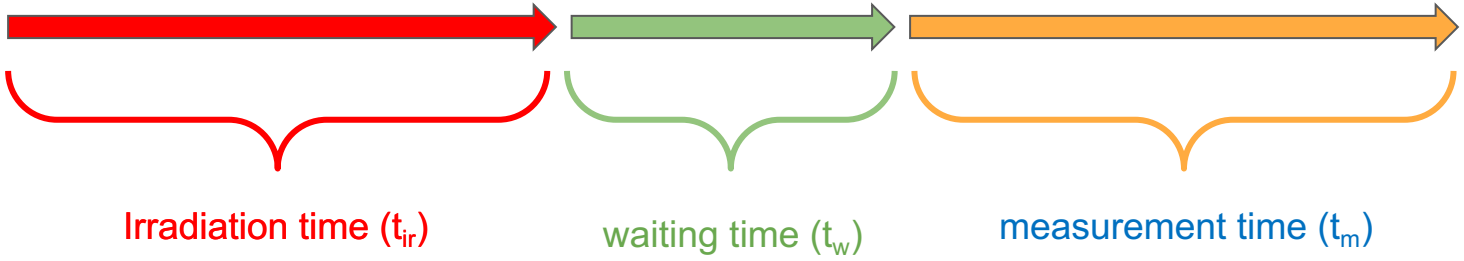


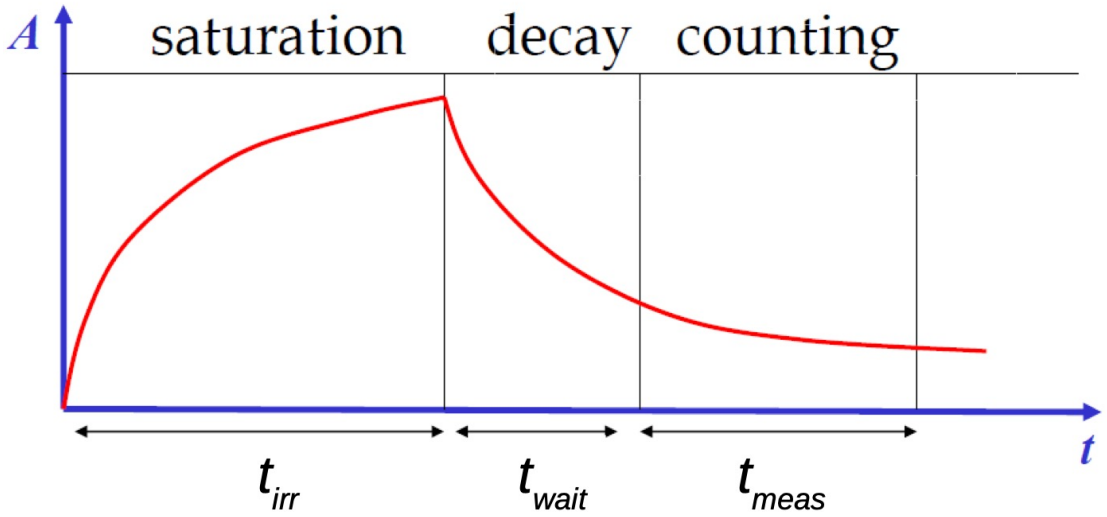
The Activation technique



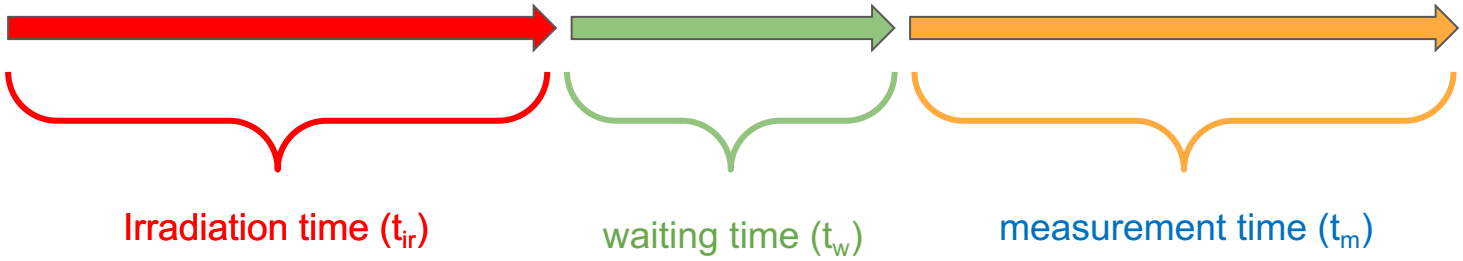
Most common type of nuclear reaction for NAA

The Activation technique





The Activation technique



The activation technique is a two-step process:

1) Irradiation of the sample
2) Measurement of the induced activity

The activation technique can only be applied when the product nucleus is unstable with "reasonable decay characteristics"

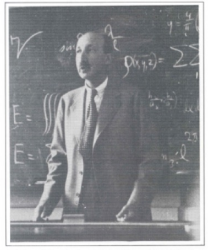
- ~sec<$T_{1/2}$<~10 y
- Detectable decay radiation (preferentially γ-rays, due to the excellent energy resolution provided by HPGe detectors)

The Activation technique

Today, the activation technique is applied in many fields, such as at:

- fundamental research
- engineering
- medicine
- qualitative and quantitative analysis of samples
- forensic science
- …

The Activation technique



First applied by Hevesy and Levi at 1936
→ determination the amount of dysprosium in an yttrium sample.
G. Hevesy and H. Levi, Nature 137, 185 (1936)

The activation technique offers:

- **Sensitivity** (e.g. MACS with a few ngr of samples can be obtained)
- **Selectivity** (e.g. no need for monoisotopic samples, cross sections can be obtained for isotopic abundances lower than 0.1% in natural composition elemental samples)
- **Doesn't suffer from counting rate issues** (dead-time/pile-up, …)
- **Can be applied in harsh environments**

The activation technique can be used:

- to obtain high accuracy reaction cross section data
  or
- to determine traces of isotopes in samples
  or
- to characterize the radiation field (usually neutron beams/fields)

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Letters to the Editor

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NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 192.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Action of Slow Neutrons on Rare Earth Elements

In view of the discrepancy between the values obtained by different workers for the periods and the intensity of radiation emitted by the radio rare earth elements[1-4] after neutron bombardment, we carried out a detailed investigation on this subject and also on the absorption of slow neutrons in rare earth elements. The latter measurements were carried out chiefly to ascertain the possible presence of strongly capturing isotopes but leading to the formation of a stable instead of an active isotope, as was actually found to be the case for europium. Our investigations lead to the result that the periods of decay of the radio rare earth elements secured by different workers and also absorption data obtained by us. A detailed account of our work will be published in the *Proceedings of the Royal Society*.

G. HEVESY.
Institute of Theoretical Physics, HILDE LEVI.
Copenhagen.

[1] E. Amaldi, E. Fermi and others, *Proc. Roy. Soc.*, A, **146**, 522 (1935).
[2] I. Curie and P. Savitch, *J. Phys. Rad.*, **6**, 376 (1935).
[3] I. Curie and P. Savitch, NATURE, **136**, 916 (1935).
[4] G. Hevesy and H. Levi, NATURE, **136**, 101 (1935).
[5] Amaldi, Fermi Ll., according to Segrè Lc. not active; with McLennan finds a period of 6·4 hours (CANADA, **134**, 857 (1935)).

Artificial Radioactivity of Rare Earth Elements

Element Bombarded	Half-life Value	Relative Intensity
Yttrium	10 h.	0·5
Lanthanum	1·9 d.?	—
Cerium		—
Praseodymium	19 h.? 1 m.?	4·5
Neodymium	1 h.	0·04
Samarium	40 m.? 5 m.?	0·4
Europium	9 h.?	0·5
Gadolinium	3 d.	very low
Terbium	2·5 h.?	0·4
Dysprosium	2·5 h.?*	100
Holmium	1·2 h.?*	10
Erbium	13 h.? 7 m.?	0·12
Ytterbium	2·5 h.?*	0·05
Lutecium	0·6 ?, 4 h.?	1·4 : 1

Absorption of Slow Neutrons in Rare Earth Elements
(thickness necessary to reduce the activity of the indicator by ten per cent)

Element	Indicator	mgm./cm.²
Europium	Europium	13
Dysprosium	Dysprosium	40
Holmium	Holmium	120
Europium	Rhodium	16
Dysprosium	"	45
Holmium	"	160
Gadolinium	Rhodium	2
Samarium	"	12
Yttrium	"	300
Scandium	"	300
Caesium	Rhodium	10

discrepancies can in most cases be explained through the presence of small amounts of impurities showing a very strong activity, like dysprosium in the samples investigated, while some of the very high absorption data found by different workers are due to the presence of highly absorbing substances like gadolinium, samarium or dysprosium in the samples used.

In the accompanying tables we give a list of the

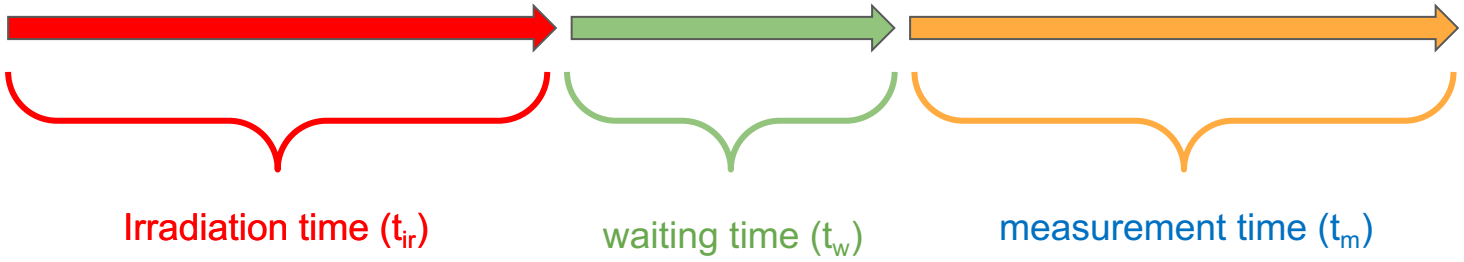
Effect of Scattering Neutrons on Induced Radioactivity

M. DANYSZ, J. Rotblat, L. Wertenstein and M. Zyw[illegible] have found that iodine and silver exposed to neutrons acquire a stronger radioactivity if the neutrons are allowed to pass through lead or gold. We have investigated further this effect using different substances as scatterers, in the form of cylinders of 55 mm. height and 24·5 mm. diameter, with a coaxial cylindrical hole of 7 mm. diameter for the source of neutrons consisting of 35 millicuries of radon mixed with beryllium. Silver tubes of 25 mm. inside diameter were placed around the cylinders for activation. In this arrangement, practically all primary and scattered neutrons pass through the receiver. For comparison, sources and receiver were placed in exactly the same positions but without any scatterer. With all substances we have found that the activity is increased, the effects ranging from a few per cent to about 18 per cent.

We have worked out our results in order to establish separately the increase produced in the amount of the two radioactive isotopes of silver by neutrons scattered in different elements. In the table below this increase is presented for each element as a percentage of the value obtained when no scatterer was used; in the second line of the table are products of the radial path of the neutrons in a given scatterer by its density.

The two isotopes behave in a different way. The product of 140 sec. half-period is enhanced in the case of all scatterers investigated with the exception of carbon and aluminium. If this effect is due to inelastic collisions of neutrons, as was assumed in the paper quoted above and also by Ehrenberg[1], then it should not occur when neutrons before passing through the scatterer are slowed down in the usual way by collisions with protons. The experiment must be restricted to elements which do not absorb slow neutrons. We have found, in fact, that the slow

The Activation technique: Irradiation of the sample



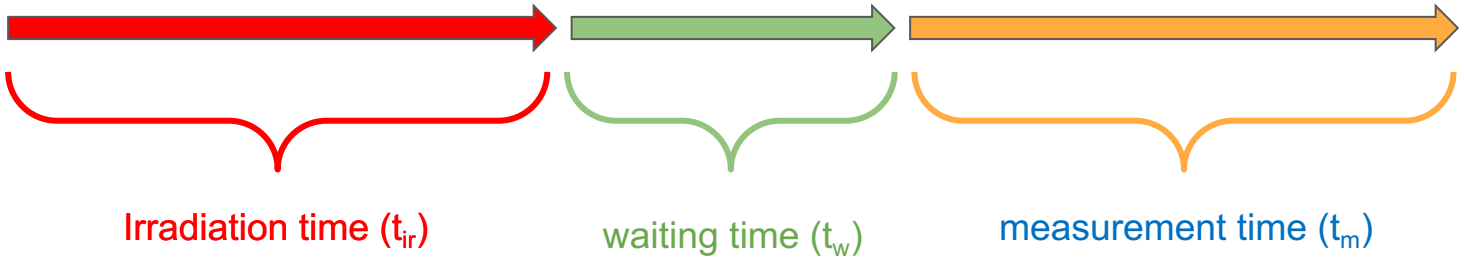
Unstable nuclei produced just after irradiation (t_{irr})

$$N_0 = \sigma * \Phi * N_T * f_B$$

Correction for the decay of the product-nuclei during irradiation

$$f_B = \frac{\int_0^{t_{irr}} f(t) * e^{\lambda t} dt}{\int_0^{t_{irr}} f(t) dt} * e^{-\lambda t_{irr}}$$

The Activation technique: Irradiation of the sample



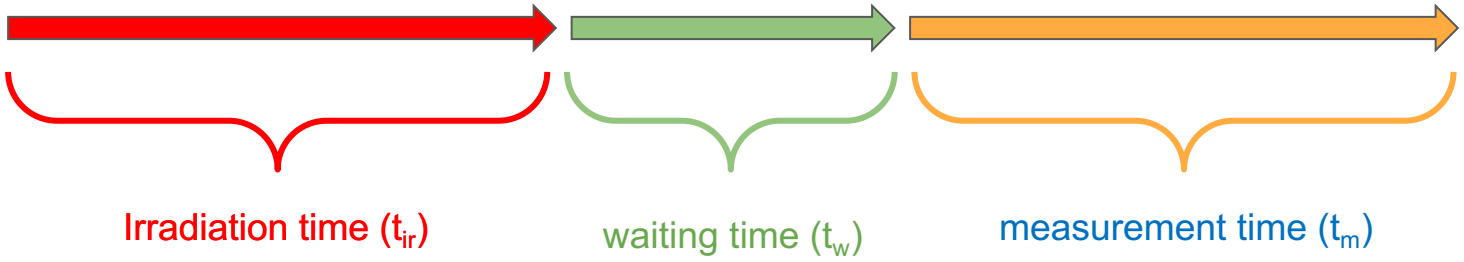
Unstable nuclei produced just after irradiation (t_{irr})

$$N_0 = \sigma * \Phi * N_T * f_B$$

Correction for the decay of the product-nuclei during irradiation (*in case of constant neutron flux*)

$$f_B = \frac{(1 - e^{-\lambda t_{irr}})}{\lambda * t_{irr}}$$

The Activation technique: Measurement of the induced activity



Expected Counts (A = peak AREA) after:

- Waiting time t_w (the time interval between the end of measurement and start of the activity measurement)
- Measurement time t_m (the duration of the induced activity measurement)

$$A = N_0 * \varepsilon * I * e^{-\lambda t_w} * (1 - e^{-\lambda t_m})$$

More details on the equations can be found in the appendixes of the thesis of Efstathia GEORGALI

Let's start from a simple physics case (maybe the simplest one…)

$$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha, \text{ for } E_n = 8 \text{ MeV}$$

Main steps to organize this activation study:

- Check on the possible products (depends on the sample/holder, projectile & projectile energy); One convenient tool is the Q-calc
- Define Irradiation time (depends on the $T_{1/2}$ of the product nucleus)
- Adjust detection setup according to decay characteristics
- Waiting time (according to RP constraints,…)
- Measurement time (according to $T_{1/2}$ of the product nucleus)
- Analysis (background, possible peak contamination, correction factors…)

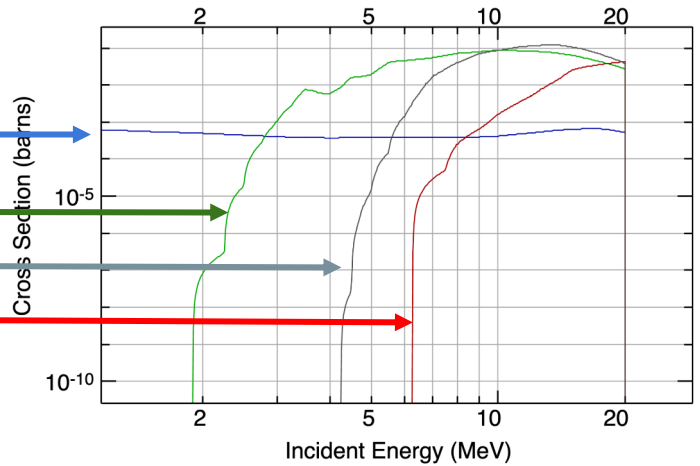
$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV

Expected reactions for 100% pure ^{27}Al sample at $E_n = 8$ MeV

$^{27}Al + NN$
($E_{lab} = 8000$ keV)

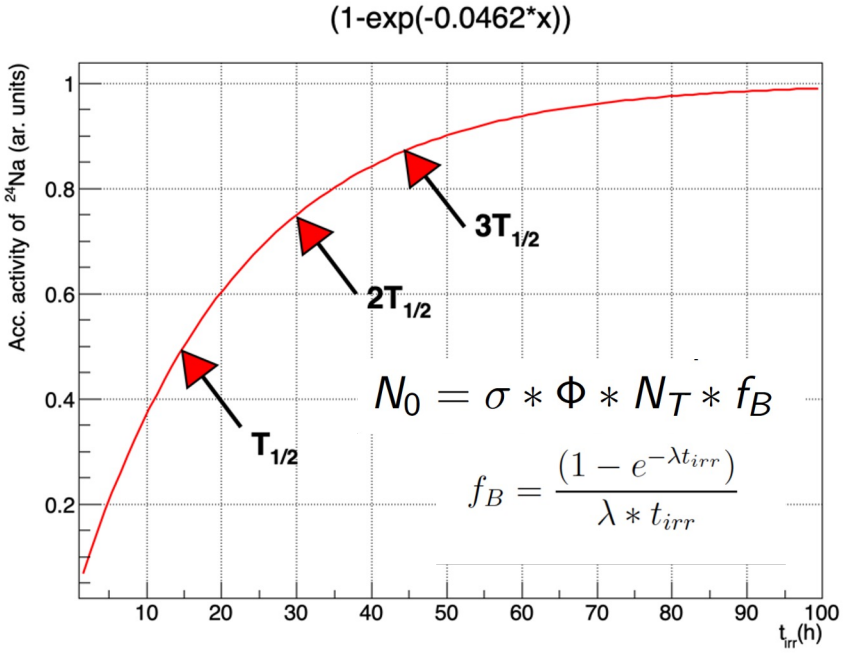
- ^{28}Al; $T_{1/2} = 2.2$ min (low cross section; decays fast)
- Inelastic scattering is not producing long term activity
- ^{27}Mg; $T_{1/2} = 9.5$ min (decays fast)
- ^{26}Mg; stable
- ^{24}Na is the one we are interested in, $T_{1/2} = 15$ h

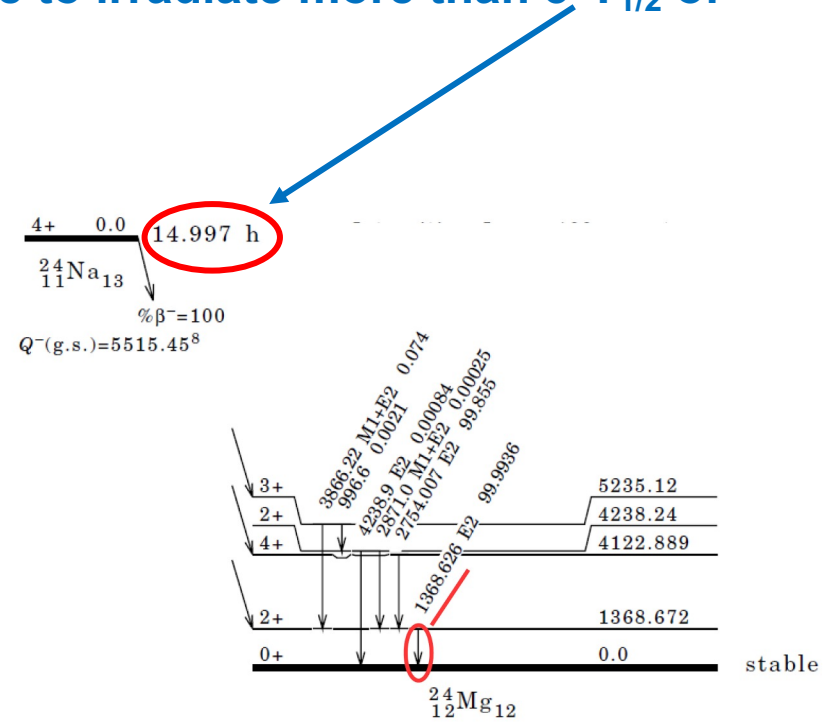
Reaction Products	Q-Value (keV)		Threshold (keV)	
$^{28}Al + \gamma$	7725.17	*7*	0	
$^{27}Al + NN$	0		0	
$^{27}Mg + p$	-1827.92	*7*	1896.31	*7*
$^{24}Na + \alpha$	-3132.56	*5*	3249.75	*5*
$^{26}Mg + d$	-6046.73	*6*	6272.93	*6*



n + ^{27}Al → ^{24}Na + α, for E_n = 8 MeV; Irradiation

Irradiation time: It doesn't make sense to irradiate more than 3*$T_{1/2}$ of the product isotope

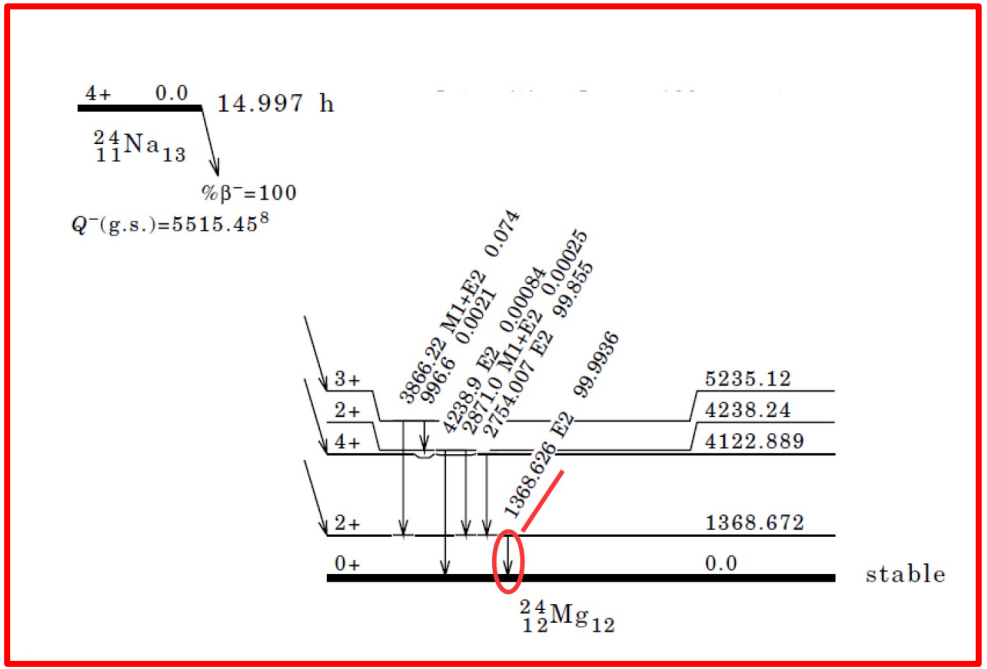


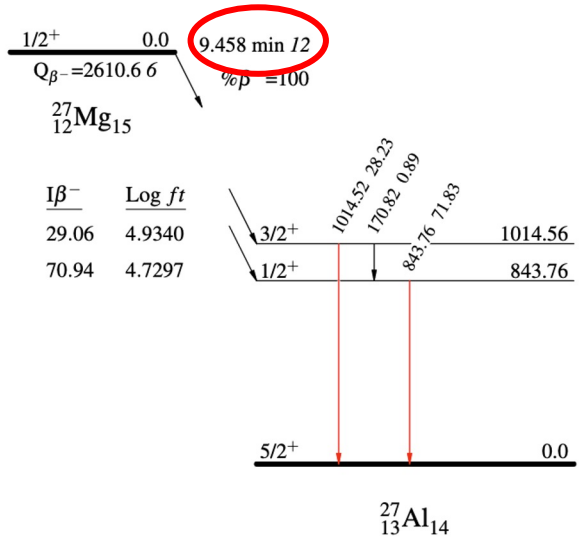


n + ^{27}Al → ^{24}Na + α, for E_n = 8 MeV; Irradiation

We can adjust the "waiting time" as to get rid of the unwanted short lived isotopes or even better…

We can reject the first collected spectra accordingly

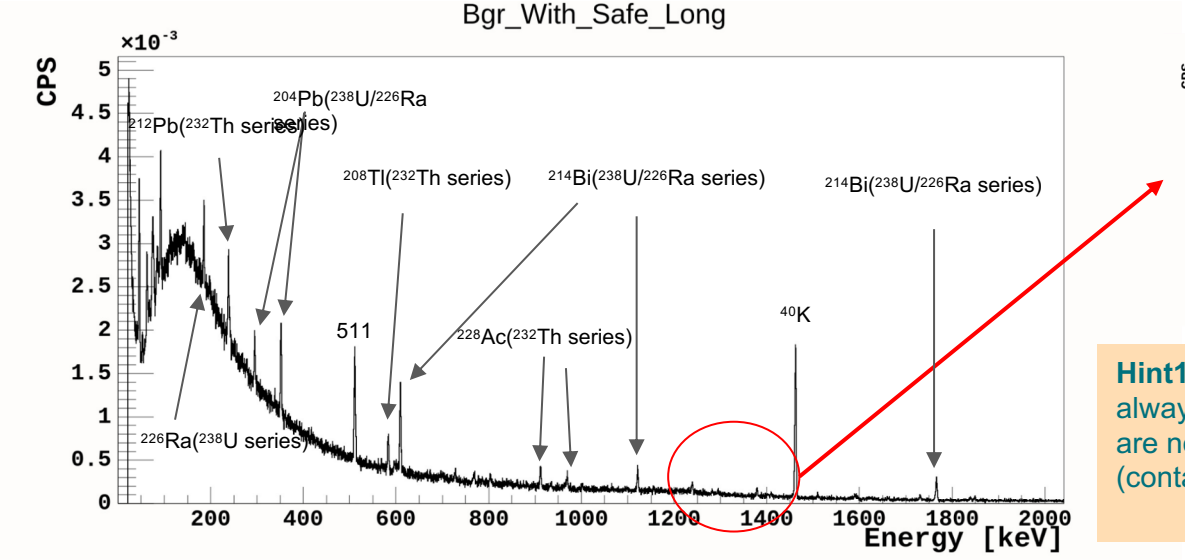


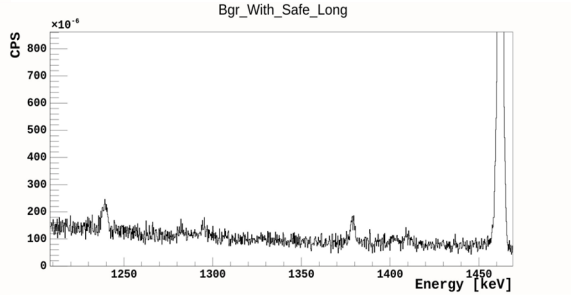


$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Activity measurements

Before deciding the γ-ray(s) to be used in the analysis we have:

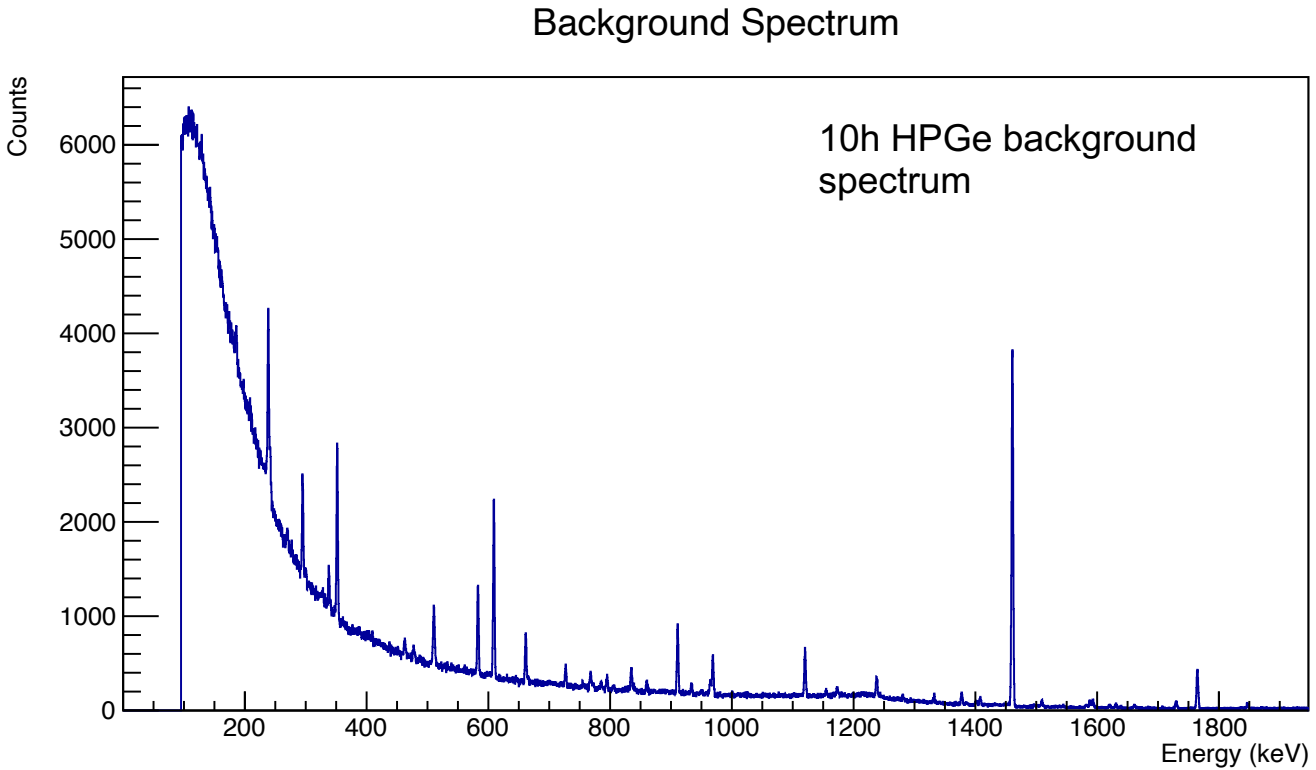
- **To perform a long background measurement**
- **To determine the counting rate in the region of interest as to answer two questions:**
  - **Is the ROI free of background peaks?**
  - **Are we above detection limits or not?**





Hint1: The background of an irradiated sample will be always bigger than the ”room” background even if there are no photopeaks around from competitive (contaminating) channels. Especially in low energies.

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Activity measurements

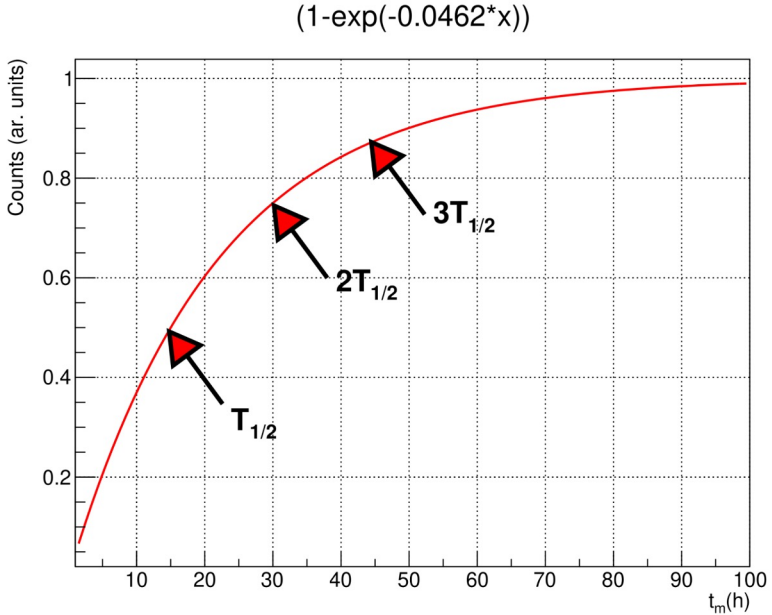


Eγ(keV)	Eγ(keV)
72.8/75	911.1
238.6	969.1
295.2	1120.3
338.3	**1460.8**
351.9	1764.5
583.1	2614.7
609.3	…

*For the full list of the room background photopeaks have a look in the extra slides

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for E_n = 8 MeV; Activity measurements

- Similarly to the irradiation time, the measurement time should not last longer than ~3*$T_{1/2}$ as we do not expect more counts in the net area while the background is increasing constantly.
- The γ-ray measurement should be saved in regular time intervals as to confirm that the growth of the peak follows the half-life time of the product nucleus



$$A = N_0 * \varepsilon * I * e^{-\lambda t_w} * (1 - e^{-\lambda t_m})$$

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Activity measurements

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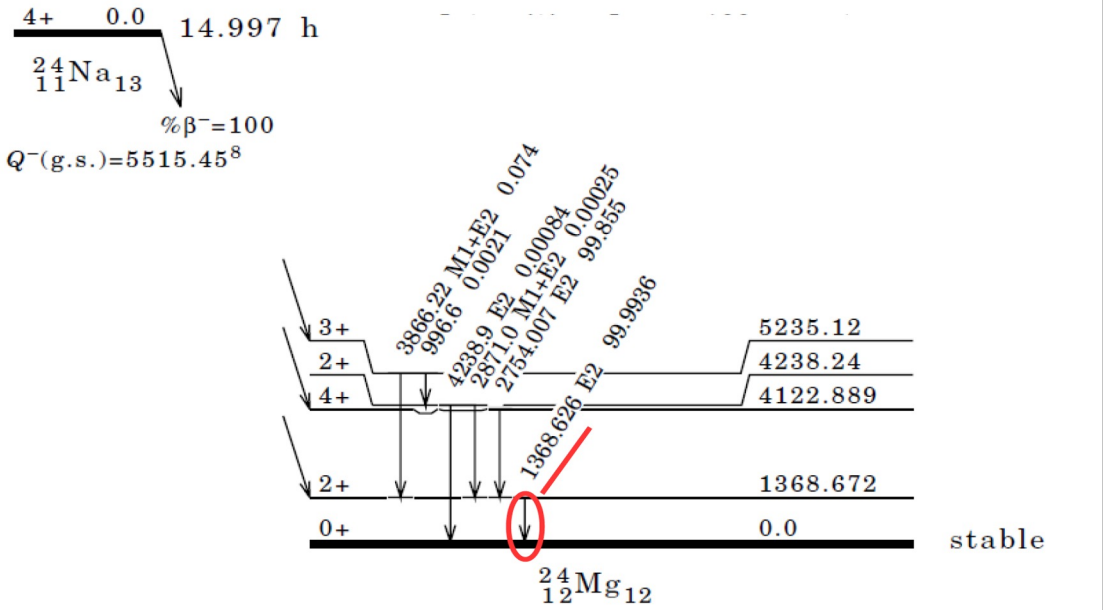

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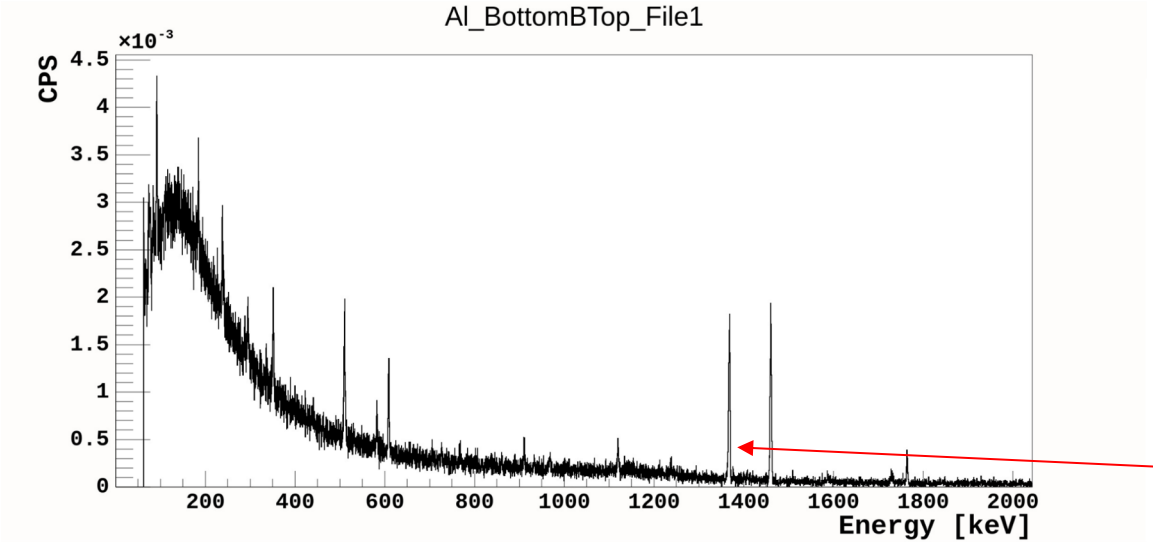
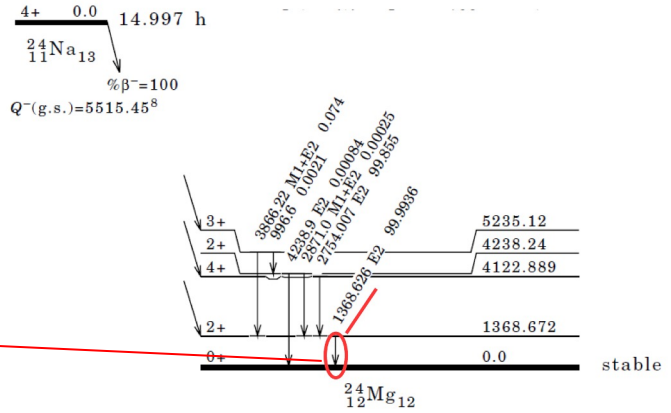
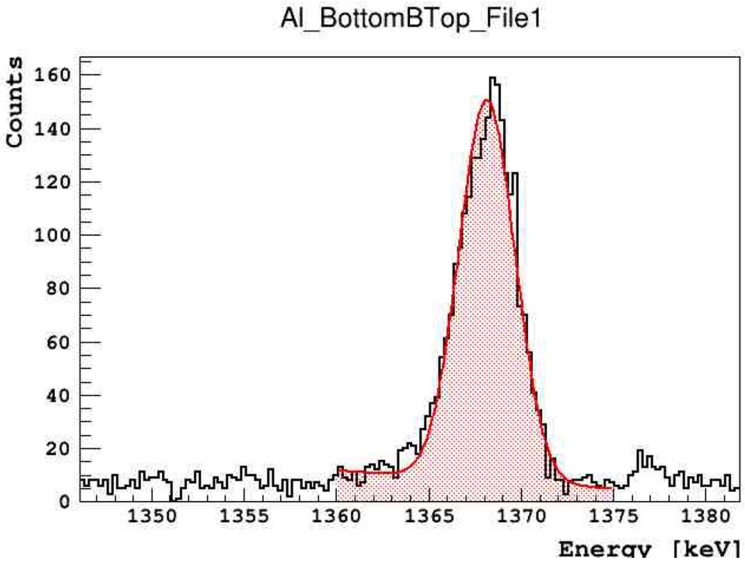




$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Analysis

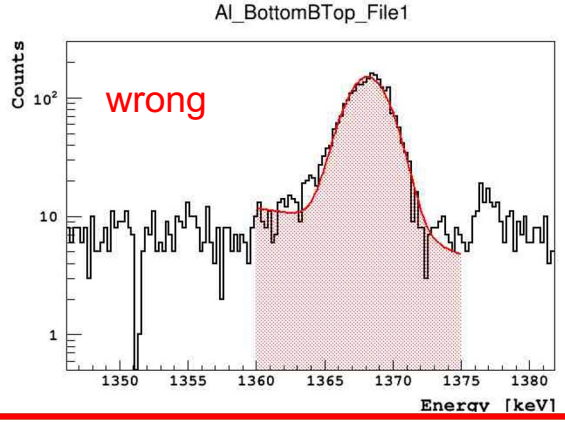
$$\sigma = \frac{counts}{\Phi * N_T * \varepsilon * I * e^{-\lambda t_w} * \left(1 - e^{-\lambda t_m}\right) * f_B}$$



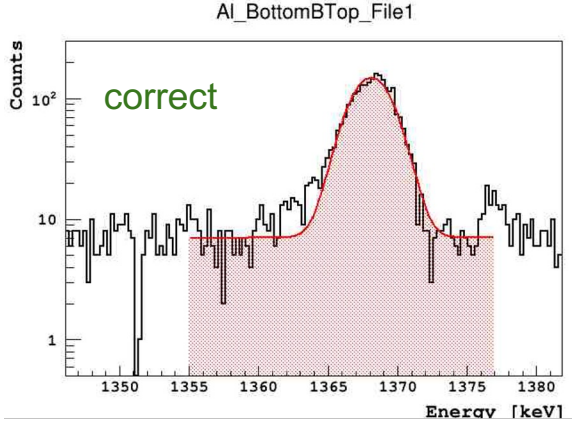
Counts = A (Net Area Peak) = Total - Background

Hint: Log y axis is always better since it gives you the right feeling if you considered correctly the background or not. This is especially the case when large peaks have to be analyzed.

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for E_n = 8 MeV; Analysis




```
root [8] FitSinglePeak(h_energy_counts,1360,1375)
 FCN=81.1288 FROM MIGRAD    STATUS=CONVERGED     212 CALLS         213 TOTAL
                     EDM=1.15181e-07    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                          STEP         FIRST
  NO.   NAME      VALUE            ERROR                 SIZE      DERIVATIVE
   1  BgConstant   6.37788e+02   1.28830e+02   2.19090e-03  -2.44945e-04
   2  BgSlope     -4.60376e-01   9.41526e-02   1.60094e-06  -3.31609e-01
   3  Sigma        1.51850e+00   3.39169e-02   1.25716e-04  -7.69412e-03
   4  Content      2.17680e+03   5.43258e+01   2.17730e-01  -1.48625e-06
   5  Mean         1.36813e+03   4.03891e-02   6.52377e-04  -5.46827e-03
      Chi Square: 81.128801
            FWHM: 3.575787 +- 0.079868
```




```
root [9] FitSinglePeak(h_energy_counts,1355,1377)
 FCN=152.083 FROM MIGRAD    STATUS=CONVERGED     218 CALLS         219 TOTAL
                     EDM=2.61272e-11    STRATEGY= 1  ERROR MATRIX UNCERTAINTY   0.0 per cent
  EXT PARAMETER                                          STEP         FIRST
  NO.   NAME      VALUE            ERROR                 SIZE      DERIVATIVE
   1  BgConstant   1.29826e+00   6.53278e+01  -2.23833e+00   5.91618e-06
   2  BgSlope      4.20581e-03   4.78847e-02   1.64069e-03   8.22462e-03
   3  Sigma        1.53689e+00   3.26116e-02  -1.88056e-04  -1.74922e-04
   4  Content      2.20306e+03   5.22130e+01  -2.60488e-01   6.79556e-08
   5  Mean         1.36809e+03   4.00498e-02  -1.27101e-04  -5.04961e-06
      Chi Square: 152.083482
            FWHM: 3.619095 +- 0.076795
```

n + ^{27}Al → ^{24}Na + α, for E_n = 8 MeV; Analysis

$$\sigma = \frac{counts}{\Phi * N_T * \varepsilon * I * e^{-\lambda t_w} * (1 - e^{-\lambda t_m}) * f_B}$$

For the flux determination the safest way is to “sandwich” the sample with ”monitor” foils with well known reaction cross section and (if possible) with similar excitation function.

Commonly used reference reactions:

- ^{197}Au(n,γ)
- ^{197}Au(n,2n)
- ^{27}Al(n,a)
- …

In practice we substitute the term “Φ” with the corresponding equation as to deduce the unknown reaction cross section with respect to the reference reaction cross section.

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Analysis

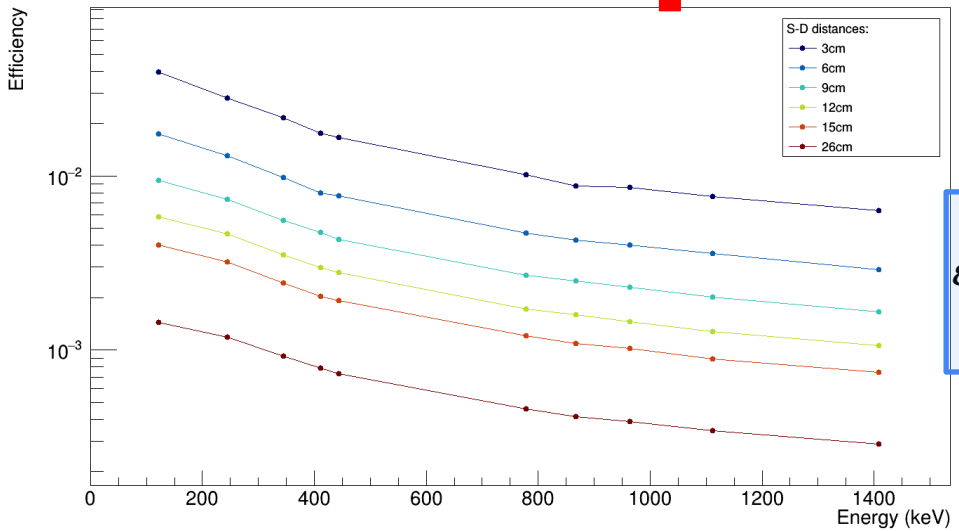
$$\sigma = \frac{counts}{\Phi * N_T * \varepsilon * I * e^{-\lambda t_w} * \left(1 - e^{-\lambda t_m}\right) * f_B}$$

- It is always **safer** to determine the detection efficiency **using multiple point-like calibrated gamma ray sources**. The usage of **mono-energetic gamma** ray sources (^{137}Cs, ^{54}Mn, …) **is preferable** (avoiding summing effects is important when small source to detector distances are adopted..
- The ^{152}Eu gamma ray source is a commonly used calibration source that provides calibration points for an extended energy range (100 keV – 1400 KeV).
- The **accuracy** of the **efficiency calibration is better when large source to detector distances are adopted** (smaller sensitivity to the actual geometry). But this is not possible when low counting rates are expected.

$$\varepsilon = \frac{N_{g_{counted}}}{N_{g_{emitted}}} = \frac{N_{g_{counted}}}{A\ I_g\ t_m} = \frac{N_{g_{counted}}}{A_0\ e^{-\lambda\ \tau_{passed}}\ I_g\ t_m}$$

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for $E_n = 8$ MeV; Analysis

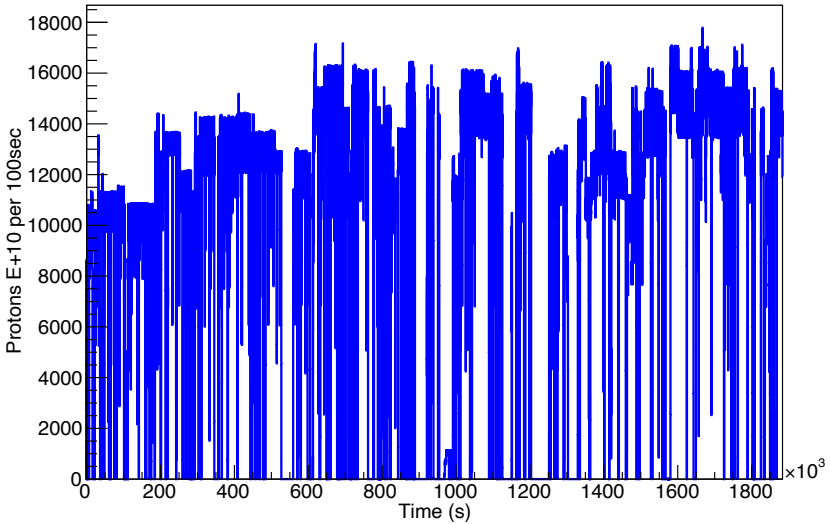
$$\sigma = \frac{counts}{\Phi * N_T * \varepsilon * I * e^{-\lambda t_w} * (1 - e^{-\lambda t_m}) * f_B}$$



$$\varepsilon = \frac{N_{g_{counted}}}{N_{g_{emitted}}} = \frac{N_{g_{counted}}}{A\, I_g\, t_m} = \frac{N_{g_{counted}}}{A_0\, e^{-\lambda\, \tau_{passed}}\, I_g\, t_m}$$

n + ^{27}Al → ^{24}Na + α, for E_n = 8 MeV; Analysis

$$\sigma = \frac{counts}{\Phi * N_T * \varepsilon * I * e^{-\lambda t_w} * (1 - e^{-\lambda t_m}) * f_B}$$



$$f_B = \frac{\int_0^{t_{irr}} f(t) * e^{\lambda t} dt}{\int_0^{t_{irr}} f(t) dt} * e^{-\lambda t_{irr}} \Rightarrow$$

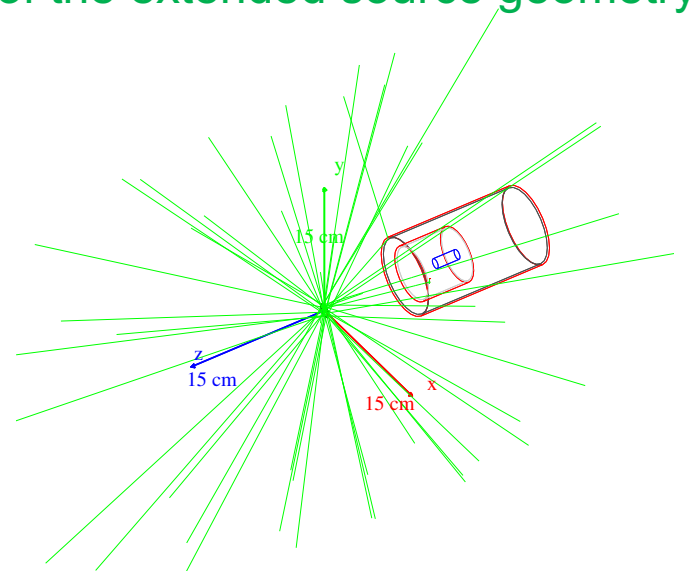
$$f_B = \frac{\sum_{lower}^{upper} f(t) * e^{\lambda t} \Delta t}{\sum_{lower}^{upper} f(t) \Delta t} * e^{-\lambda t_{irr}}$$

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$, for E_n = 8 MeV; Analysis

Correction factors:

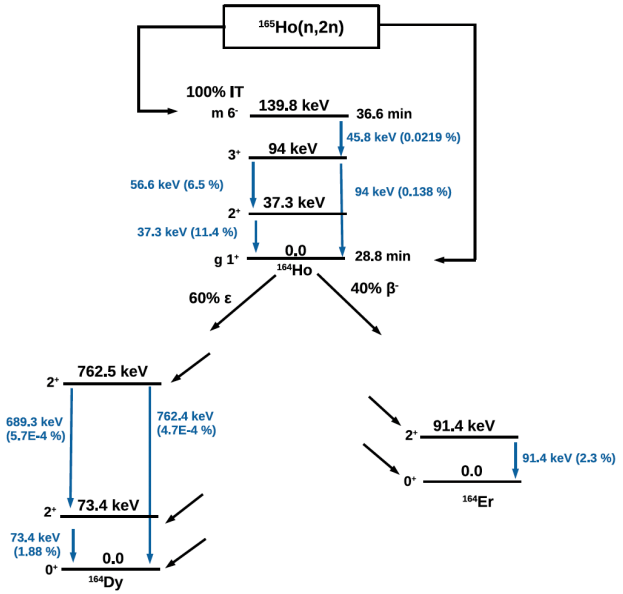
- Dead time (if applicable)
- Backround or “contamination peaks” subtruction (if needed)
- Self attenuation of gamma rays
- Effect of the extended source geometry in detection efficiency

MC Simulations:
Geant4 ("Shielding”)
or
FLUKA



The activation technique: Analysis

Hint: The mathematical formulation can become complicated when the same nuclear state can be populated through two (or more) different reaction "paths" with comparable decay time characteristics



$$f_C = \frac{1 - e^{-\lambda_g t_{irr}}}{\lambda_g * t_{irr}} - \frac{e^{-\lambda_m t_{irr}} - e^{-\lambda_g t_{irr}}}{(\lambda_g - \lambda_m) * t_{irr}}$$

$$f_C = \frac{\sum_{lower}^{upper} f(t) * e^{\lambda_g t} dt}{\sum_{lower}^{upper} f(t) dt} * e^{-\lambda_g t_{irr}} - \frac{\sum_{lower}^{upper} f(t) * (e^{\lambda_g - \lambda_m t}) dt}{\sum_{lower}^{upper} f(t) dt} * e^{-\lambda_g t_{ir}}$$

$$\sigma_g = \frac{counts_g C_g}{\Phi N_T \varepsilon_g I_g e^{-\lambda_g t_w} (1 - e^{-\lambda_g t_m}) f'_B} -$$

$$\sigma_m \left(\frac{f_B}{f'_B} \frac{\frac{1}{\lambda_g - \lambda_m} (\lambda_g e^{-\lambda_m t_w} (1 - e^{-\lambda_m t_m}) - \lambda_m e^{-\lambda_g t_w} (1 - e^{-\lambda_g t_m}))}{e^{-\lambda_g t_w} (1 - e^{-\lambda_g t_m})} + \frac{f_C}{f'_B} \right)$$

More details on the equations can be found in the appendixes of the thesis of Efstathia GEORGALI

The activation technique: Analysis

Literature:

a) Measurement and Detection of Radiation, Nicholas Tsoulfanidis, Sheldon Landsberger, https://doi.org/10.1201/9781003009849

b) Radiation Detection and Measurement, Glenn F. Knoll, ISBN-13 : 978-0470131480

c) PhD thesis of Efstathia GEORGALI: https://www.didaktorika.gr/eadd/handle/10442/49286?locale=en http://nuclear.physics.uoi.gr/publications/EfiPhD.pdf

d) A nice presentation of the activation technique can be found here

e) …

More details on the equations can be found in the appendixes of the thesis of Efstathia GEORGALI

Your first activation measurement

Let me remind you the activation experiment steps:

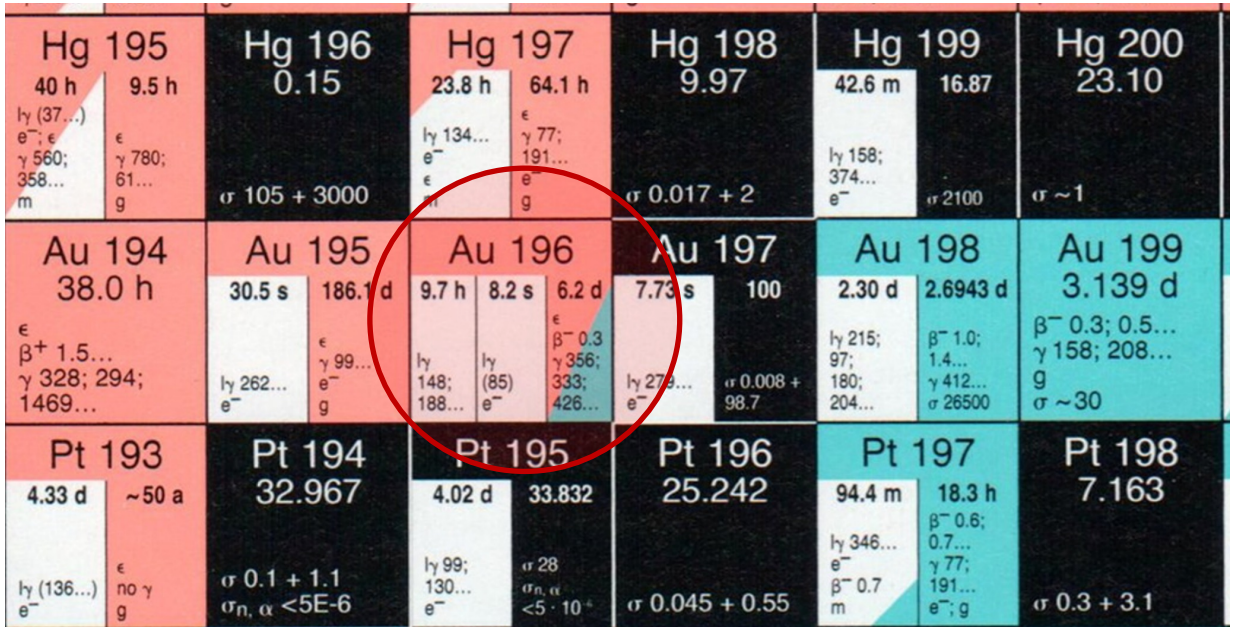
a) Irradiation
b) Measurement of activity
c) Analysis

Let's assume we want to measure the ^{197}Au(n,2n) cross section at the energy of 11 MeV.

Exercise: Run the experiment from beginning to end! …ENJOY!

Your first activation measurement

"Prepare" the experiment -> decay relevant info



First of all, we need to find all the relevant information as to check **if** we can apply the activation technique.

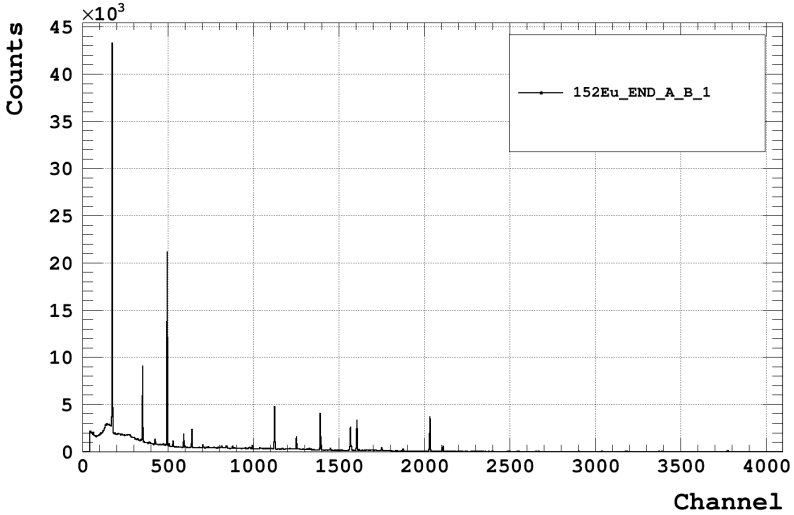
We go to NNDC and check out what we need:

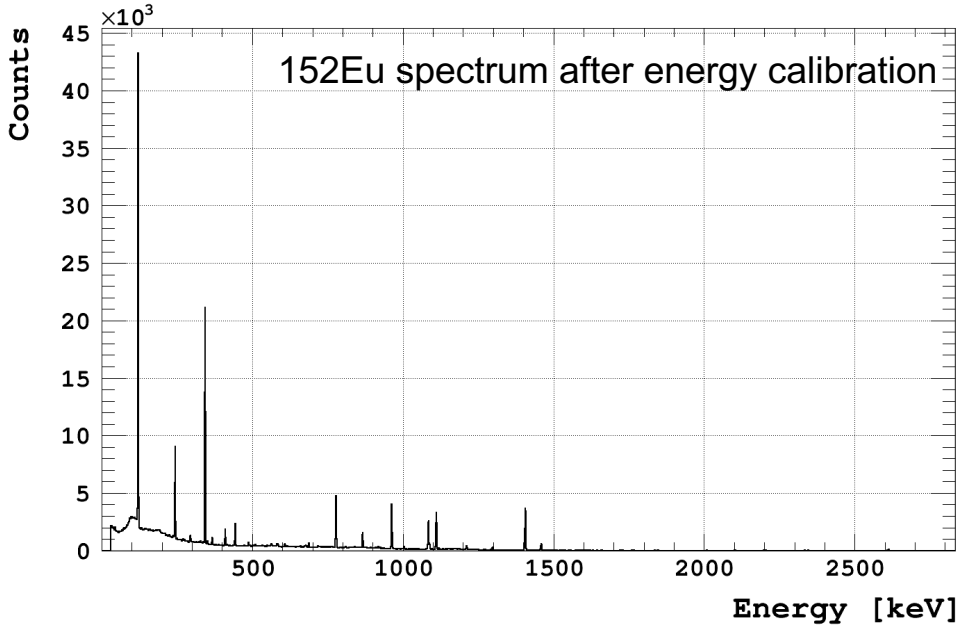
- Half life = 6.16 days ✓
- No long-lived isomer (the equations are away more complicated) ✓
- Energy: 333 keV or 356 keV? ✓
- Intensity: 0.22 or 0.87 ✓

Your first activation measurement

HPGe efficiency calibration (exercise #1):

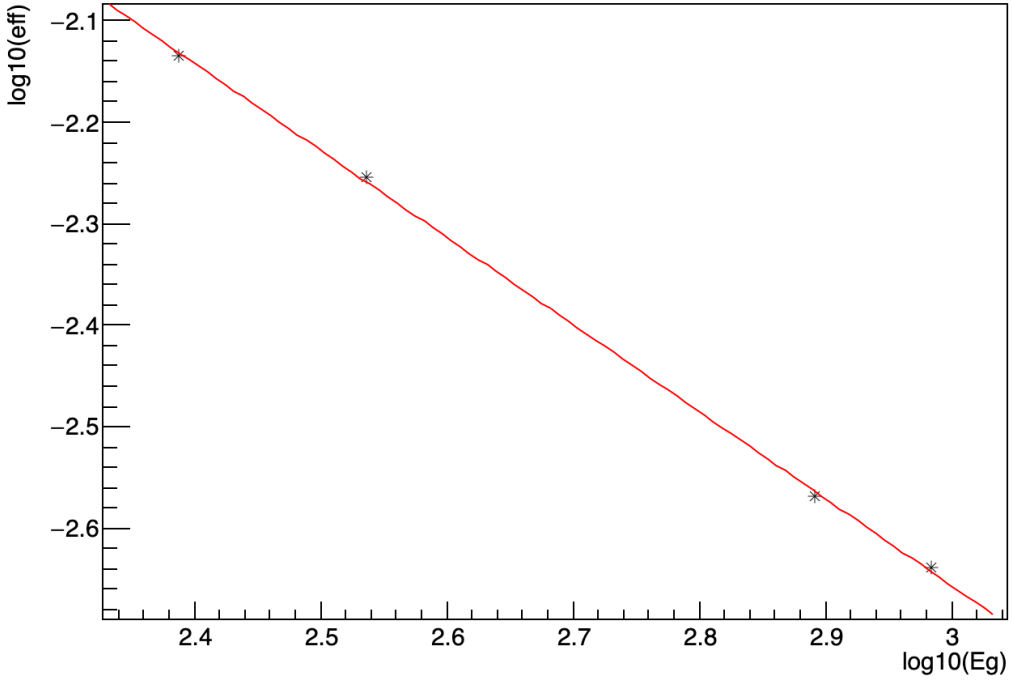
- Source 152Eu at 9cm
- LIVE_TIME - 4491.567 sec
- REAL_TIME - 4501.311 sec
- File: https://cernbox.cern.ch/s/n0nVIi1GAZom6TV
- Activity of 14.47 kBq measured on 09.05.2017.
- Measurement at 19.10.2021
- Uncertainty = 5%.





Your first activation measurement

HPGe efficiency calibration (exercise #1): Getting the efficiency at 333 keV -> 0.0057 (5%)




```
root [0]
Processing eff_plot.c...
Info in <TCanvas::MakeDefCanvas>:  created default TCanvas with name c1

****************************************
Minimizer is Minuit / Migrad
Chi2                      =  8.54939e-05
NDf                       =              2
Edm                       =  1.39541e-22
NCalls                    =             35
p0                        =   -0.0835237   +/-   0.0360587
p1                        =    -0.857734   +/-   0.0133013

 The efficiency at 333 keV is: 0.00566096
root [1]
```

Hint1: Try to avoid complicated efficiency functions. The simplest one is the logeff = f(logE). This can be used for energies Eg>150 keV for Al window or for Eg>50 keV for carbon-fiber window

Hint2: The uncertainty of the efficiency can be extracted from the confidence level band and NOT from the uncertainty in the parameters

Hint3: The MC codes are reliable. If a common modelling of the detector is possible for a variety of gamma ray energies and for different source to detector distances then the required efficiency can be directly extracted from MC simulations with all the correction factors included

Extra Slides

Your first activation measurement

The measurement (exercise #2):

Sample: 197Au with mass = **1.2 g**
Atomic Weight = **196.96 g/mole**
Avogadro Number = **6.022E23**
Irradiation at **11 MeV**
Irradiation time = **35580 s**
Time interval between end of irradiation and start of γ-ray activity measurement = **136450 s**
Duration of the activity measurement = **3599 s**
Neutron flux = **7.8E10 neutrons/cm2**

Analysis:

Photopeak net area counts: **1659**

Your first activation measurement

The measurement (exercise #2):

Result: The 197Au(n,2n)196Au reaction cross section at 11 MeV is: 1.2 b

If you have something similar then:

Your first activation measurement

The measurement (exercise #2):

Result: The 197Au(n,2n)196Au reaction cross section at 11 MeV is: 1.2 b

If not:

Extra Slides

Counting rates in background peaks for a HPGe re. eff. 25%

Count rates in the peaks of a background spectrum obtained with a high-purity germanium detector ($\epsilon_r = 25\%$): (a) without shielding; (b) with the whole detector assembly (including dewar) shielded by lead 5-cm thick.

E (keV)	Origin of photons	Count rate (10^{-3} s^{-1}) a	b
32.2	Ba x	650	
36.4	Ba x	160	
46.5	^{210}Pb (Ra)		20
63.3	^{234}Th		13
72.8/75.0	Pb x	888	26
85/87	Pb x	345	13
92.5	^{234}Th	190	19
129.1	^{228}Ac (Th)	65	
185.7	^{235}U		8
186.2	^{226}Ra	160	
209.3	^{228}Ac (Th)	105	
238.6	^{212}Pb (Th)	1122	10
241.0	^{224}Ra (Th)	100	
241.9	^{214}Pb (Ra)	155	3
270.2	^{228}Ac (Th)	110	
277.4	^{208}Tl (Th)	48	
295.2	^{214}Pb (Ra)	392	5
300.1	^{212}Pb (Th)	85	
327.6	^{228}Ac (Th)	71	
332.4	^{228}Ac (Th)	10	
338.3	^{228}Ac (Th)	250	
351.9	^{214}Pb (Ra)	702	10
409.5	^{228}Ac (Th)	44	
438.8	^{40}K Escape	17	
452.8	^{212}Bi (Th)	15	
463.0	^{228}Ac (Th)	90	
510.8	^{208}Tl (Th)	151	
511.0	Annihilation	111	56
562.3	^{228}Ac (Th)	17	
583.1	^{208}Tl (Th)	530	4
609.3	^{214}Bi (Ra)	678	10
661.7	^{137}Cs	14	
665.5	^{214}Bi (Ra)	20	
727.2	^{212}Bi (Th)	116	
755.2	^{228}Ac (Th)	13	
763.1	^{208}Tl (Th)	8	
768.4	^{214}Bi (Ra)	63	
772.2	^{228}Ac (Th)	19	
785.9	^{214}Pb (Ra)	32	
794.7	^{228}Ac (Th)	71	
806.2	^{214}Bi (Ra)	14	

Table 2.9 (continued)

E (keV)	Origin of photons	Count rate (10^{-3} s^{-1}) a	b
835.5	^{228}Ac (Th)	23	
840.0	^{228}Ac (Th)	19	
860.4	^{208}Tl (Th)	67	
904.5	^{228}Ac (Th)	10	
911.1	^{228}Ac (Th)	389	6
934.1	^{214}Bi (Ra)	40	
949.8	^{40}K Escape	25	
964.6	^{228}Ac (Th)	67	
969.1	^{228}Ac (Th)	223	3
1001.0	^{234}Pa (U)	10	1
1120.3	^{214}Bi (Ra)	179	5
1155.2	^{214}Bi (Ra)	18	
1173.2	^{60}Co		4
1238.1	^{214}Bi (Ra)	66	3
1281.0	^{214}Bi (Ra)	15	
1332.5	^{60}Co		3
1377.7	^{214}Bi (Ra)	45	2
1385.3	^{214}Bi (Ra)	11	
1401.5	^{214}Bi (Ra)	14	
1408.0	^{214}Bi (Ra)	27	
1460.8	^{40}K	2183	91
1495.8	^{228}Ac (Th)	10	
1509.3	^{214}Bi (Ra)	22	
1583.2	^{214}Bi (Ra)	13	
1588.0	^{228}Ac (Th)	30	1
1592.7	^{208}Tl Escape	46	4
1620.6	^{212}Bi (Th)	19	
1630.4	^{228}Ac (Th)	20	1
1661.3	^{214}Bi (Ra)	11	
1729.6	^{214}Bi (Ra)	30	2
1764.5	^{214}Bi (Ra)	156	10
1847.4	^{214}Bi (Ra)	21	1
2103.7	^{208}Tl Escape	54	5
2118.6	^{214}Bi (Ra)	12	1
2204.2	^{214}Bi (Ra)	45	3
2293.4	^{214}Bi (Ra)	4	
2447.9	^{214}Bi (Ra)	13	1
2614.7	^{208}Tl (Th)	352	30

Energy Diagrams for the 162Er+n

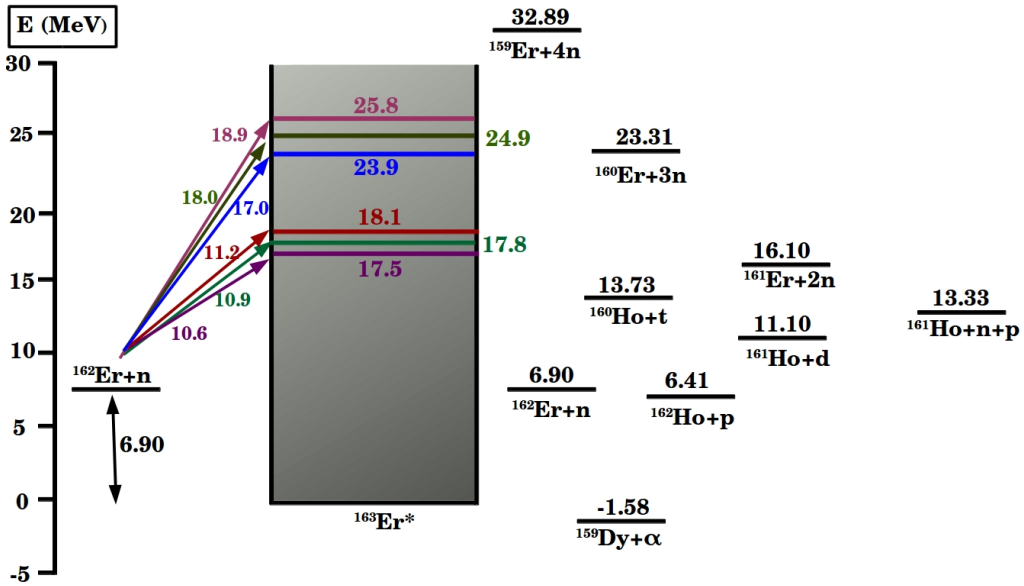
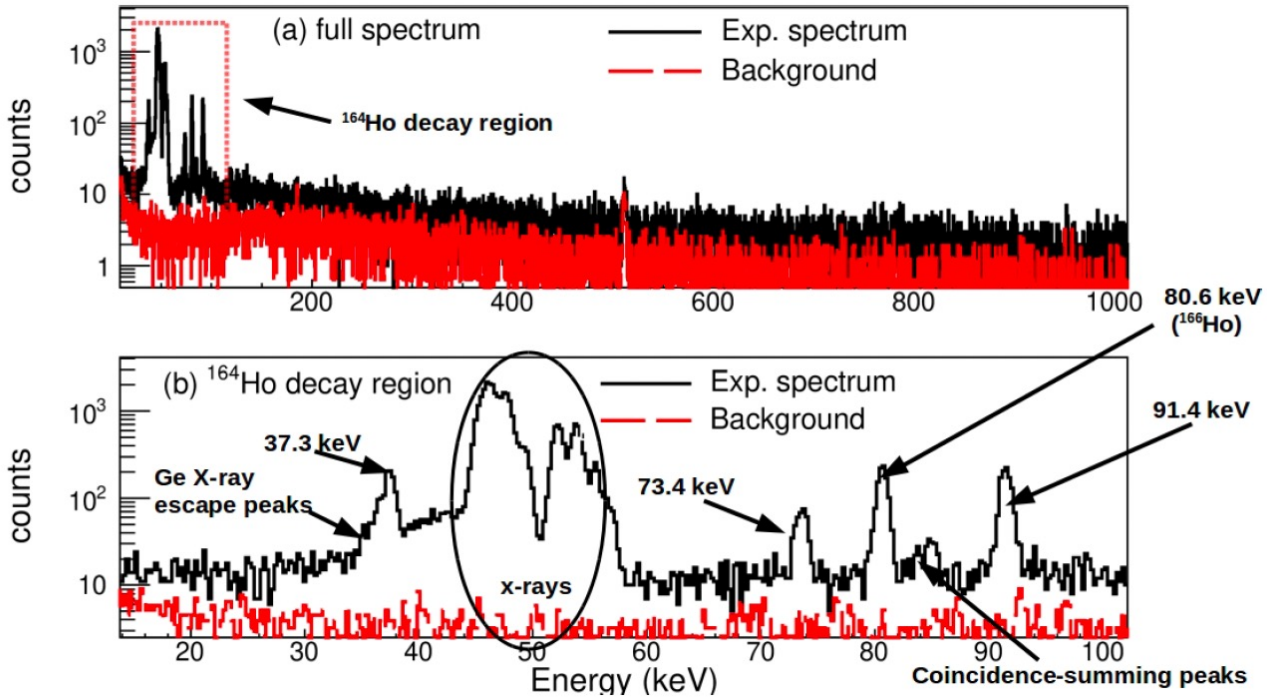
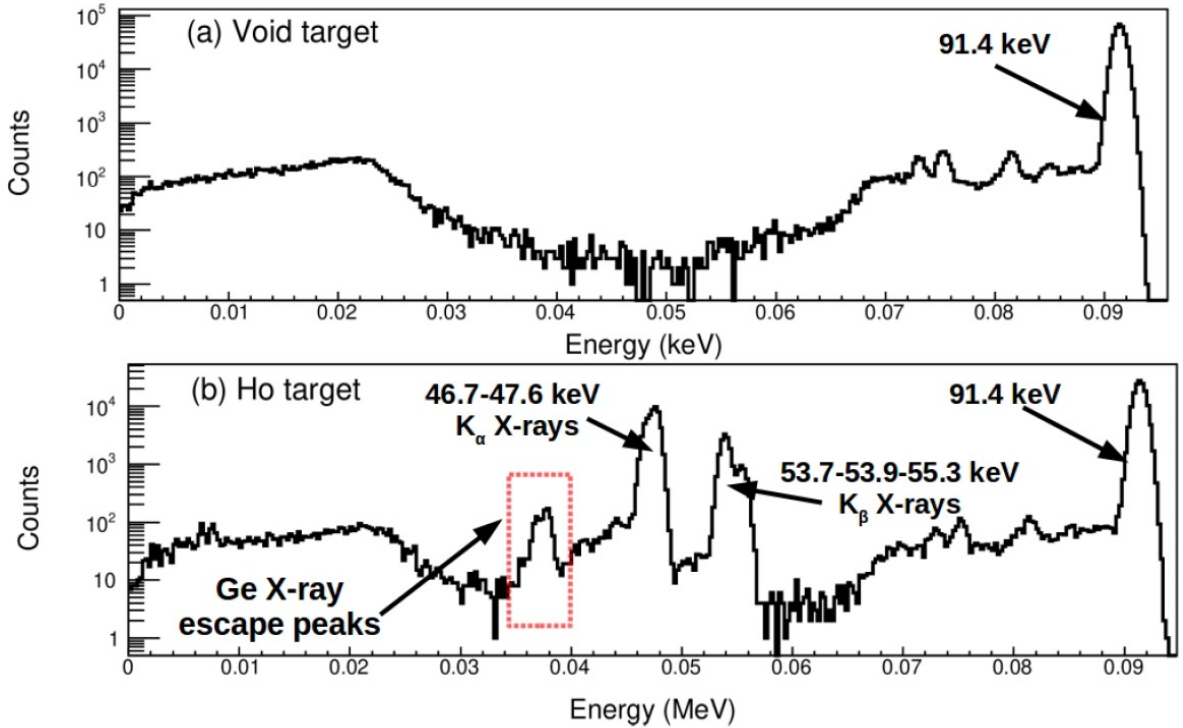


Figure 2.2: The energy diagram of the ^{162}Er+n interaction.

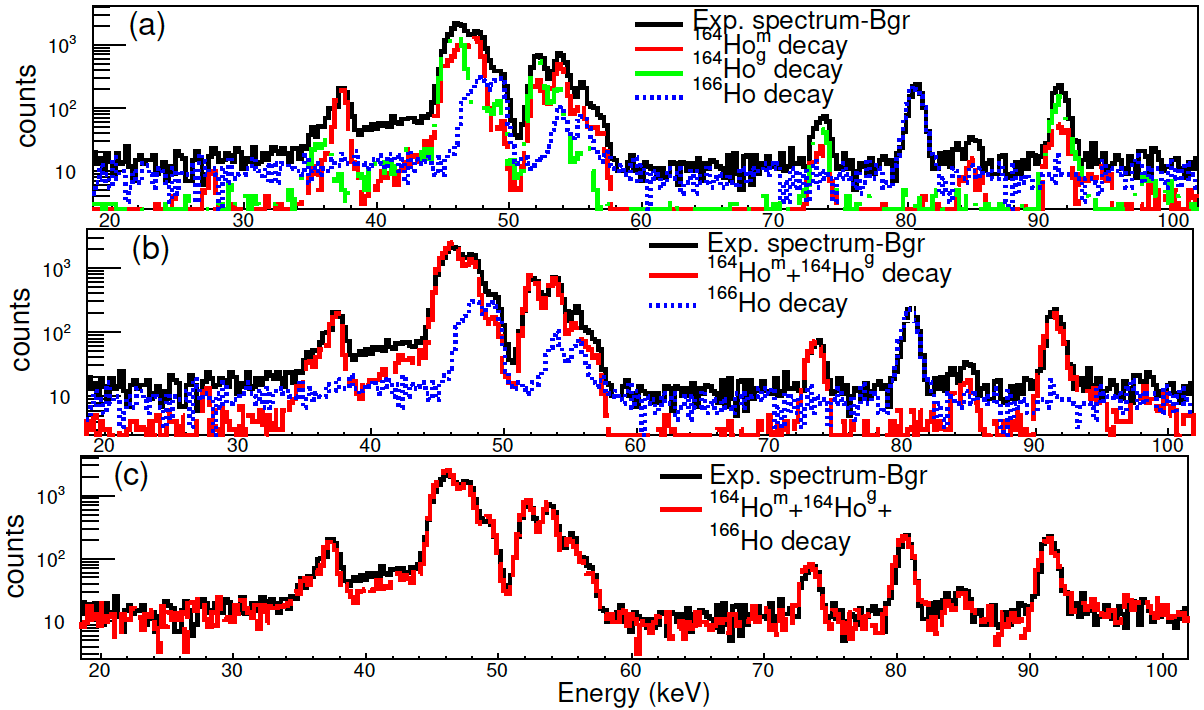
A complicated peak analysis



A complicated peak analysis



A complicated peak analysis



A complicated peak analysis

Isotope	Reaction channel	Decay mode	$T_{1/2}$	X-rays	Energy (keV)	Intensity (%)	Escape peaks energy (keV)
$^{164}Ho^{m}$	$^{165}Ho(n,2n)$	100% IT	36.6 min	$K_{\alpha 2}$	46.7	21.2 ± 1.6	36.9, 35.7
				$K_{\alpha 1}$	47.6	37 ± 3	37.8, 36.6
				$K_{\beta 1}$	53.9	7.6 ± 0.6	44.1, 42.9
				$K_{\beta 2}$	55.3	2.55 ± 0.20	45.5, 44.3
				$K_{\beta 3}$	53.7	3.9 ± 0.3	43.9, 42.7
$^{164}Ho^{g}$	$^{165}Ho(n,2n)$	60% ε	28.8 min	$K_{\alpha 2}$	45.21	14.4 ± 1.4	35.34, 34.23
				$K_{\alpha 1}$	46.0	25 ± 3	36.2, 35.0
				$K_{\beta 1}$	52.1	5.1 ± 0.5	42.3, 41.1
				$K_{\beta 2}$	53.5	1.72 ± 0.17	43.7, 42.5
				$K_{\beta 3}$	51.9	2.7 ± 0.3	42.1, 40.9
$^{164}Ho^{g}$	$^{165}Ho(n,2n)$	40% β^-	28.8 min	$K_{\alpha 2}$	48.22	0.823 ± 0.018	38.35, 37.24
				$K_{\alpha 1}$	49.1	1.45 ± 0.03	39.3, 38.1
				$K_{\alpha 1}$	46.0	25 ± 3	36.2, 35.0
				$K_{\beta 1}$	55.7	0.298 ± 0.006	45.9, 44.7
				$K_{\beta 2}$	57.1	0.1000 ± 0.0021	47.3, 46.1
				$K_{\beta 3}$	55.5	0.154 ± 0.003	45.7, 44.5
$^{166}Ho^{g}$	$^{165}Ho(n,\gamma)$	100% β^-	26.824 h	$K_{\alpha 2}$	48.22	2.96 ± 0.10	38.35, 37.24
				$K_{\alpha 1}$	49.13	5.21 ± 0.17	39.26, 38.15
				$K_{\alpha 1}$	45.99	25 ± 3	36.12, 35.01
				$K_{\beta 1}$	55.7	1.07 ± 0.03	45.9, 44.7
				$K_{\beta 2}$	57.1	0.360 ± 0.012	47.3, 46.1
				$K_{\beta 3}$	55.5	0.555 ± 0.017	45.7, 44.5

Calibration data

Energy	Intensity	Counts	Time	Efficiency
121	28.87	139610	4491	0.009363
244	7.55	28632	4491	0.007343
344	26.59	76485	4491	0.005570
778	12.93	18005	4491	0.002696
964	14.51	17197	4491	0.002295
Isotope	**RP #**	**Ref Date**	**Ref A [kBq]**	**On 19.10.2021**
152Eu	3693	9.5.2017	14.47	11.5