

Exercise J13

Measurement of neutron flux

Nuclear Physics Laboratory, Faculty of Physics, University of Warsaw

1 Course of the exercise

1.1 Introduction

The purpose of this exercise is to measure the neutron flux as a function of distance from a Pu-Be neutron source. The measurements are performed with scintillation detectors: a europium-activated lithium iodide detector, LiI(Eu), sensitive to thermal neutrons, and a thallium-activated sodium iodide detector, NaI(Tl), used to measure γ radiation.

1.2 Required reading

1. Pu-Be neutron source; how are neutrons produced in it? ([1]-1.V)
2. Neutron moderation. What are thermal neutrons? ([1]-1.V)
3. Interaction of γ rays with matter: photoelectric absorption, Compton scattering, pair production. Which process dominates at which γ -ray energy? ([1]-2.III.A)
4. Interaction of neutrons with matter and their detection. ([1]-14, 15)
5. Detectors used in the exercise: which radiation, and in which energy range, can they measure? Operating principle of a scintillator and a photomultiplier tube. ([1]-8)
6. Electronic signal processing: amplifier, multichannel analyser. ([2]-14.1, 14.2, [1]-16.III, 18.III)
7. Energy resolution, detection efficiency, energy calibration. ([1]-4.V, 4.VI)
8. Decay schemes of radioactive isotopes and how to read them. ([2]-1.1, 1.3)
9. Statistics of radiation measurements; statistical and systematic uncertainties. ([1]-3.II)
10. Biological effects of ionising radiation and dosimetry. ([2]-3)

1.3 Experimental procedure

1. Introduction to the experimental setup: neutron source, calibration sources, detectors, HV power supplies, amplifier, multichannel analyser and computer program (Figure 1).
2. Optimisation of the operating conditions of the LiI detector setup (high voltage, amplifier gain) and determination of the energy resolution.
3. Energy calibration of the LiI detector with standard calibration sources.
4. Measurement with the LiI detector close to the neutron source: unshielded, with lead shielding, and with light-material shielding.
5. Energy calibration of the NaI detector with standard calibration sources.
6. Measurement with the NaI detector close to the neutron source: unshielded, with lead shielding, and with light-material shielding.
7. Measurement of the neutron flux with the LiI detector as a function of distance from the source, for at least 6 positions.

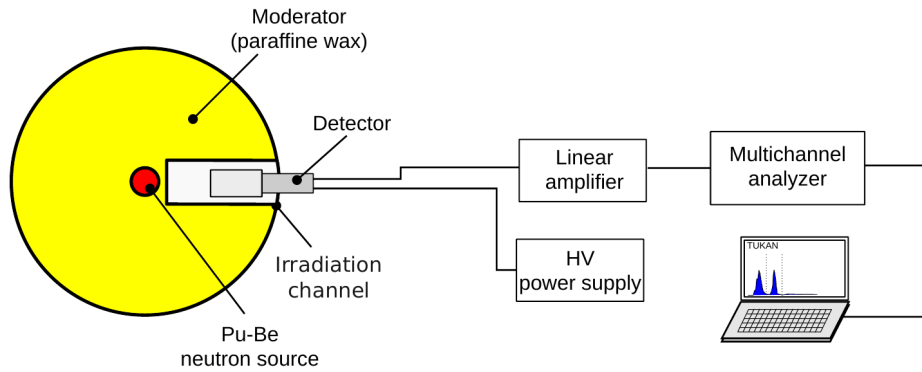


Figure 1: Overview of the experimental setup for the scintillation detectors.

1.4 Data analysis and report

Main analysis steps

1. Energy calibration of the detectors (NaI, LiI) with γ sources.
2. Analysis of the statistical and systematic uncertainties of the calibration.
3. Qualitative analysis of the LiI spectrum: identification of the γ background and other spectral features, based on the measurements with different shielding and on the NaI measurements.
4. Determination of the neutron flux for at least 6 positions of the LiI detector.
5. Comparison of the results with expected values and discussion.

A laboratory report is a kind of essay and should be written with correct spelling, punctuation and grammar. It should follow a logical line of reasoning, so that a person who has never done the exercise can understand its objectives, methods and results.

The report should be structured into sections such as introduction, methods, results and conclusions. The introduction should define the purpose of the experiment and briefly introduce the topic and the method used. The main part should describe the measurement procedure and the data analysis in more detail. Figures and schemes are an essential element here; they should be clearly presented, with labelled axes, legends, units and similar elements.

It is not necessary to describe in detail every element of the setup if this is common (textbook) knowledge; instead, select the key information specific to this experiment or most important for the result, its uncertainty and its verifiability. Do not copy information from the instructions, nor derivations of formulas (except your own). Numerical values should be given with uncertainties. In the conclusions, emphasise the result obtained, discuss whether it agrees with expectations, what the main source of uncertainty or discrepancy is, and what could be improved in the methodology.

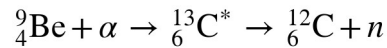
2 Preparatory material

The information in this chapter is an introduction to the topics required for the entry test. It does not contain all the necessary knowledge, which should be found in the references given. Framed text contains questions that should be answered as part of the preparation for the exercise.

2.1 Neutron source

Reading: [1]-1.V

In the neutron source used in the laboratory, neutrons are emitted in the following reaction:



The source is made of a Pu-Be alloy (in a 1:13 ratio), in which the isotope ${}^{239}\text{Pu}$, with a half-life of $T_{1/2} = 2.4 \times 10^4$ years, is the source of alpha particles. The source yield is 8.5×10^4 neutrons per second per gram of plutonium. The energy spectrum of the emitted neutrons is continuous in the range 0–10 MeV, with a mean kinetic energy of about 4 MeV.

The Pu-Be source, in the form of a small pellet (about 3×3 cm), is placed in a cylindrical block of paraffin wax ($\text{C}_n\text{H}_{2n+2}$, $80 \times 80 \times 70$ cm). The paraffin acts as a moderator, slowing the neutrons down to energies of a fraction of an electronvolt. The neutrons lose energy in elastic collisions with hydrogen and carbon nuclei. After a dozen or so collisions, neutrons with an initial energy of the order of MeV reach an energy comparable to the kinetic energy of the thermal motion of the moderator atoms, $E \approx kT = 25$ meV for $T = 300$ K. Such neutrons are called thermal neutrons. The energy dependence of the cross sections for neutron scattering and capture on hydrogen is shown in Figure 2.

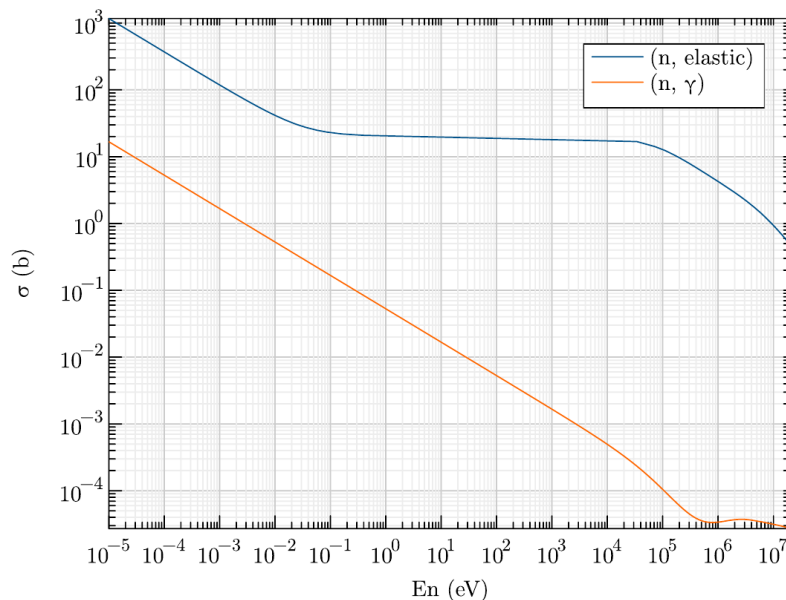


Figure 2: Cross sections for elastic scattering ($n + p \rightarrow n + p$) and neutron capture ($n + p \rightarrow d + \gamma$) on hydrogen (${}^1\text{H}$) as a function of neutron energy.

Why is paraffin wax used as a moderator? What other materials could be used for this purpose?
Why do we want to slow the neutrons down?

2.2 Interaction of γ rays with matter

Reading: [1]-2.III.A

Gamma radiation is one of the types of ionising radiation. As the name suggests, such radiation is capable of ionisation, i.e. of knocking electrons out of the medium it traverses. All radiation detectors make use of this phenomenon in some way. The simplest detectors, such as Geiger–Müller counters, present e.g. in the dosimeters available in the laboratory, can only register an ionisation event, i.e. the mere presence of radiation, and count the number of pulses. In this exercise we need more information – we want to measure the γ -ray spectrum, i.e. the energy distribution of the emitted photons.

A detector can only measure the energy that has been transferred to the material it is made of. Gamma rays have zero mass and zero charge, and interact with matter quite differently from charged particles, which lose energy continuously through electromagnetic interactions with electrons. In the γ -ray energy range measured in the laboratory, the three interaction mechanisms described below are the most important.

Photoelectric absorption. A γ ray can interact with an electron bound in an atom of the medium and be absorbed, transferring all of its energy to the electron. The electron acquires a kinetic energy equal to the difference between the γ -ray energy and the binding energy of the electron in its atomic shell:

$$E_e = E_\gamma - E_B$$

The ejected electron, being a charged particle, moves through the medium and transfers its energy to it through excitation and secondary ionisation of atoms. At the same time, the vacancy in the atom is filled by an electron from a higher shell, accompanied by the emission of an X-ray or an Auger electron. The energy of all these particles is absorbed close to the point of the primary interaction, and all these processes occur very quickly. As a result, from the point of view of detection, the full energy of the primary γ ray is deposited in the medium at once.

Compton scattering. An incident photon can scatter on an electron and change its direction, transferring part of its energy to the electron. If the γ ray is scattered by an angle θ with respect to its original direction, the energy transferred to the electron follows from energy and momentum conservation:

$$E_e = E_\gamma \frac{\alpha(1 - \cos \theta)}{1 + \alpha(1 - \cos \theta)}$$

where $\alpha = E_\gamma/(m_e c^2)$. The subsequent history of the electron is similar to that in the photoelectric effect. As can be seen, its energy depends on the angle θ and can range from zero ($\theta = 0^\circ$) up to a maximum value for photons scattered backwards ($\theta = 180^\circ$).

Calculate the energy transferred to the electron for a 511 keV γ ray and scattering angles of 0° , 90° and 180° .

The scattered γ ray may escape from the detector without further interaction, or undergo another Compton scattering or a different interaction. Unless such a sequence of events ends with photoelectric absorption, the full energy of the γ ray will not be deposited in the detector.

Pair production. According to Einstein's formula $E = mc^2$, a γ ray can be converted into massive particles. To satisfy the other conservation laws, a particle–antiparticle pair must be created, and the process must take place in the field of a third particle, e.g. an atomic nucleus of the medium. The lightest particles that can be created in this process are an electron and an antielectron, i.e. a positron. The minimum photon energy depends on the particle in whose field the process occurs; if it is much heavier than the electron, E_γ must be at least $2m_e c^2 = 1022$ keV. The total kinetic energy of the created pair is:

$$E_{e^+} + E_{e^-} = E_\gamma - 2m_e c^2$$

The created particles lose their kinetic energy in the medium. The history of the electron is similar to the cases above. The positron, after slowing down, forms positronium with an electron of the medium for a time of the order of nanoseconds and then annihilates. Annihilation produces two γ rays of 511 keV each, emitted in approximately opposite directions. Each of them may escape from the detector or undergo scattering, absorption or other processes. This gives rise to additional lines in the observed spectrum, corresponding to the escape of one ($E_\gamma - 511$ keV, single escape) or both ($E_\gamma - 1022$ keV, double escape) annihilation photons.

Cross section. The probability of each of these processes depends on the γ -ray energy and on the atomic number of the medium. Above 10 MeV pair production clearly dominates. Compton scattering depends only weakly on energy ($\sigma_C \propto \ln E_\gamma/E_e$ for $E_\gamma > 511$ keV) and is the main process in the range from about 100 keV to 10 MeV (depending on the material). Below this energy the photoelectric effect starts to dominate; its probability depends strongly on energy, varying approximately as $1/E_\gamma^3$, and shows threshold effects when the energy exceeds the binding energy of electrons in successive shells. An example of the energy dependence of the cross sections is shown in Figure 3. In media with a higher atomic number, such as NaI ($Z = 53$ for iodine), the photoelectric effect dominates up to higher energies.

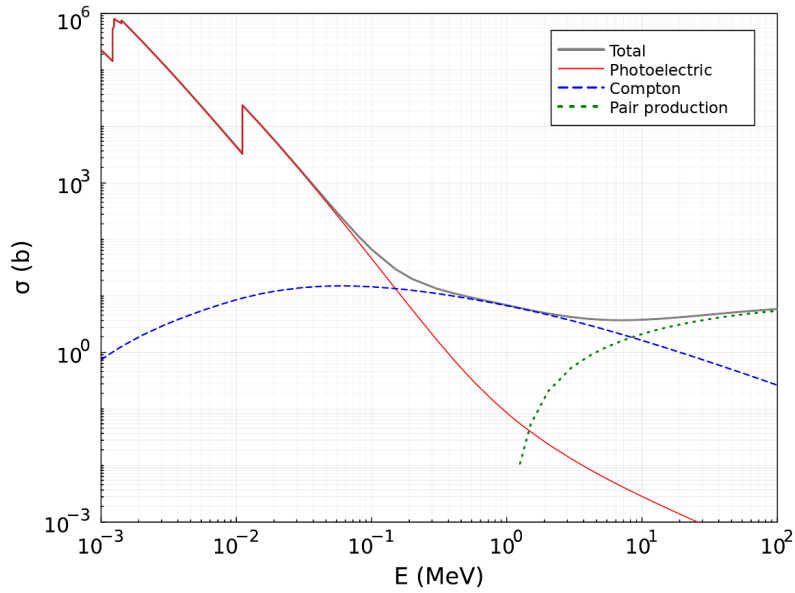


Figure 3: Energy dependence of the cross sections for γ -ray interactions, shown for germanium ($Z = 32$) as an example.

Radiation spectrum. A γ -ray detector registers only the part of the photon energy that has been deposited in the medium. Because of the variety of possible processes, a single γ -ray line corresponds to a whole range of events with different registered energies. Understanding this structure requires an understanding of the processes described above.

Figure 4 shows the pulse-height spectrum from a NaI(Tl) scintillation detector recorded for a ^{137}Cs source emitting 662 keV γ rays. The peak centred around channel 300 corresponds to full absorption of the 662 keV γ rays in the crystal, e.g. by photoelectric absorption. The range of pulse heights from channel 0 up to the so-called Compton edge corresponds to events in which only part of the γ -ray energy was deposited in the crystal. The main contribution to this part of the spectrum comes from Compton scattering, in which the γ ray transfers part of its energy to an electron of the scintillator and the scattered photon escapes from the crystal. The Compton edge corresponds to events in which the γ ray transferred the maximum energy to the electron (scattering angle $\theta = 180^\circ$).

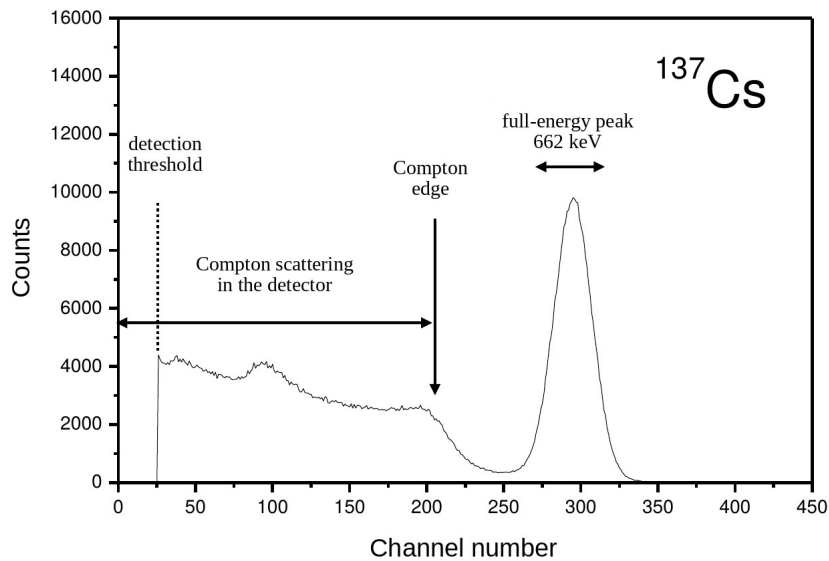


Figure 4: Gamma-ray spectrum of a ^{137}Cs source recorded with a NaI(Tl) scintillation detector.

Study the example spectrum in Figure 4 and the interpretation of the structures visible in it. What additional structures will appear in the spectrum for a γ -ray line with an energy above 1022 keV?

2.3 Scintillation detectors

Reading: [1]-8.II

The energy transferred by a γ ray to the detector medium can be measured as an electric current, i.e. as the flow of the charges created by ionisation. This happens directly in semiconductor detectors, e.g. those made of germanium crystals, which are used in other exercises in the laboratory.

In a scintillation detector, such as the thallium-activated sodium iodide crystal – NaI(Tl) – used in the laboratory, the mechanism is different. This material is an insulator with an empty conduction band, to which electrons are excited by the radiation; about 20 eV is needed to create one electron–hole pair. Electrons in the conduction band undergo a series of non-radiative de-excitations via states of the activator atoms, and then recombine with holes, emitting photons with an energy of about 3 eV, which corresponds to a wavelength of 420 nm. The crystal is transparent to light of this wavelength, which is then detected by a photomultiplier tube. The amount of light produced in the crystal is proportional to the energy deposited in the material.

Depending on the γ -ray energy, the light produced in the scintillation crystal consists of hundreds or thousands of photons, which must be registered. The device that allows very weak light signals to be detected is the photomultiplier tube. It is a vacuum tube with a photocathode made of a material with a low work function, from which the incident light ejects electrons. These electrons are then accelerated in an electric field towards successive electrodes (dynodes), each releasing several secondary electrons. The overall signal gain reaches 10^5 – 10^8 . The result is an electric signal

whose total charge depends on the number of incident photons, which in turn depends on the energy deposited by the γ ray. The structure of a scintillation detector is shown in Figure 5.

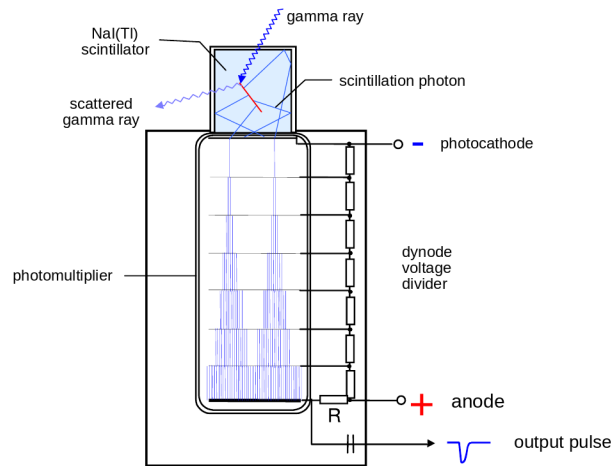


Figure 5: Schematic structure of a scintillation detector.

2.4 Neutron detection

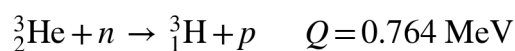
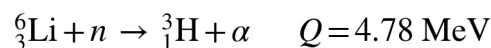
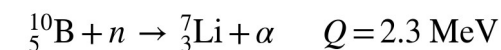
Reading: [1]-14, 15

Neutrons have no electric charge, but have a mass of about $940 \text{ MeV}/c^2$, which means that from the point of view of detection they belong to the category of massive, neutral particles. The lack of charge means that we must rely on indirect reactions. Practically every method of neutron detection involves a target in which reactions produce charged particles, such as protons or alpha particles; these are then detected in the same way as they would be regardless of their origin. The difficulty is that the cross section for neutron interactions depends very strongly on neutron energy and on the material. Therefore, the detector material and the type of reaction must be chosen appropriately for neutrons of a given energy. Most neutron detectors are counters that register the presence of a neutron; measuring the neutron energy spectrum involves even greater difficulties, which will not be discussed here.

Typical reactions used for neutron detection are:

- elastic scattering – recoil nucleus,
- reactions with proton emission (n,p),
- reactions with alpha emission (n, α),
- fission – fission fragments.

The most popular reactions used for neutron detection include:



The cross sections for these reactions as a function of neutron energy are shown in Figure 6.

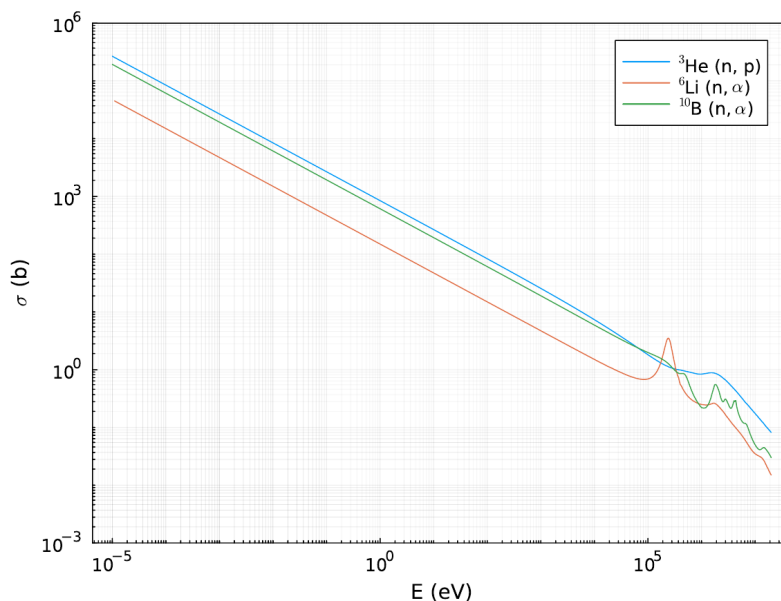
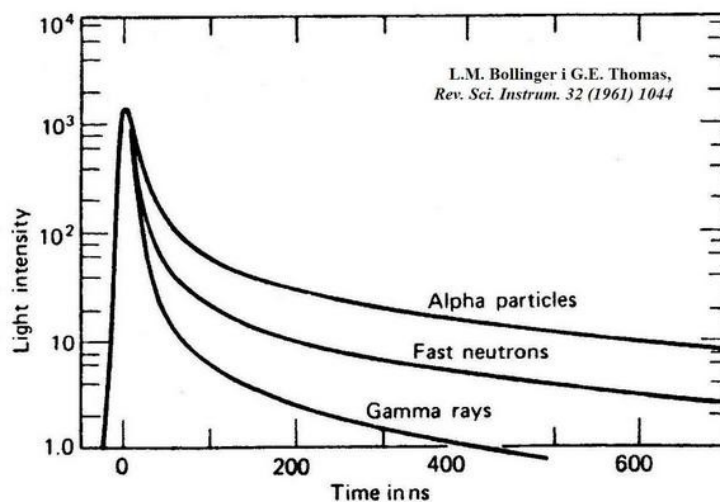


Figure 6: Cross sections for reactions used in neutron detection.

For neutrons of which energy are the reactions above suitable? What other reactions can be used for other energy ranges?

The laboratory uses a scintillation detector with an inorganic, europium-activated lithium iodide crystal – LiI(Eu). Thermal neutrons are detected in it via the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction. This type of scintillator is sensitive both to neutrons and to γ rays. During the calibration of the detector, remember that its response (light yield and pulse shape) differs for γ rays, fast neutrons and alpha particles (Figure 7).

Figure 7: Time dependence of the scintillation light intensity for alpha particles, fast neutrons and γ rays [6].

Note! When performing the energy calibration with γ radiation, remember that the amount of light produced in the scintillator for the same deposited energy depends on the type of particle detected. A calibration obtained with γ rays cannot be applied directly to alpha particles.

2.5 Properties of spectrometers

Reading: [1]-4.V, 4.VI

Spectrometric detectors are characterised by a number of properties which allow them to be compared with each other and the physical characteristics of the radiation source to be determined.

Energy resolution. It determines the minimum separation between two γ -ray lines that can still be resolved. This separation is equal to the full width at half maximum (FWHM) of the line. Since the energy resolution varies with energy, for comparison purposes it has been agreed for γ -ray detectors to quote the ratio of the FWHM to the energy for the 662 keV line (emitted by ^{137}Cs), expressed in percent. For NaI(Tl) spectrometers it is typically 6–8%. Other standards are used for α or β spectrometers.

Detection efficiency. The detection efficiency is the ratio of the number of registered γ rays to the number of all γ rays emitted by the source. It consists of two factors: the geometric efficiency – the probability that the radiation reaches the detector, which depends on the position and size of the detector – and the intrinsic efficiency – the probability that the full energy of a photon incident on the detector is registered. Using a source of known activity, the detection efficiency can be determined for different γ -ray energies. By varying the distance between the calibration source and the detector, its intrinsic efficiency can be determined.

Energy calibration. The electronics connected to the detector measure a certain quantity (electric charge), which is then digitised, i.e. assigned a channel number in the analyser. Energy calibration allows the channel number to be interpreted as the physical quantity of interest, i.e. the γ -ray energy. In the simplest case the relation is linear, and the energy E is given by

$$E = a_0 + a_1 x$$

where x is the channel number. The coefficients a_0 , a_1 are found by measuring the positions of known lines from calibration sources and then fitting the function $E(x)$. To check the quality of the fit, one can plot the deviations of the calibration from the line positions as a function of energy (the so-called residuals):

$$r(E) = E_\gamma - E(x_\gamma)$$

where x_γ is the channel number corresponding to the centre of the line with energy E_γ . In this representation one can, for example, notice systematic deviations indicating higher-order terms in the calibration. A plot of line position versus energy usually does not allow the quality of the fit to be assessed accurately, since the deviations are small and hard to see over the whole energy scale (Figure 8).

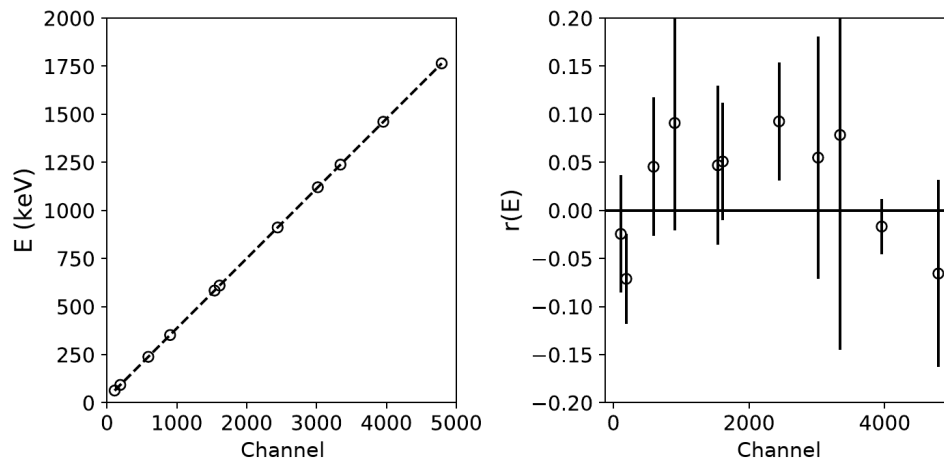


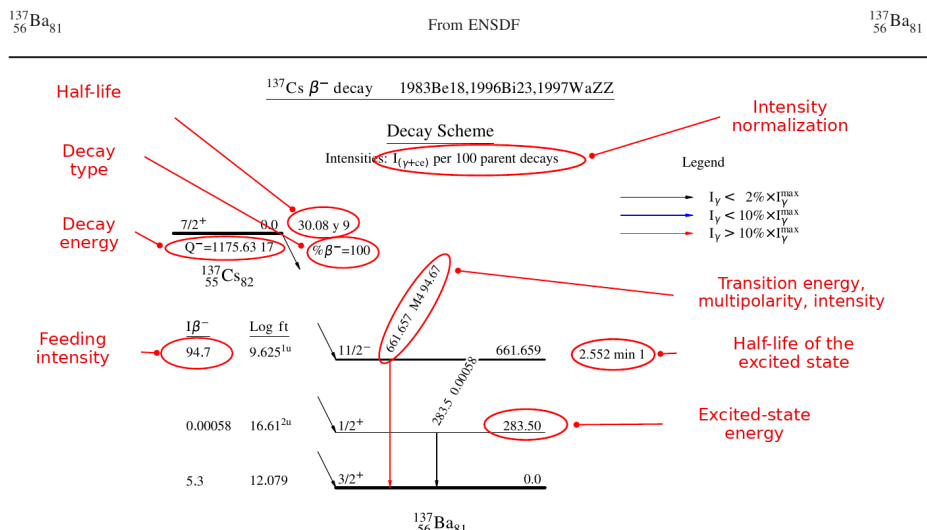
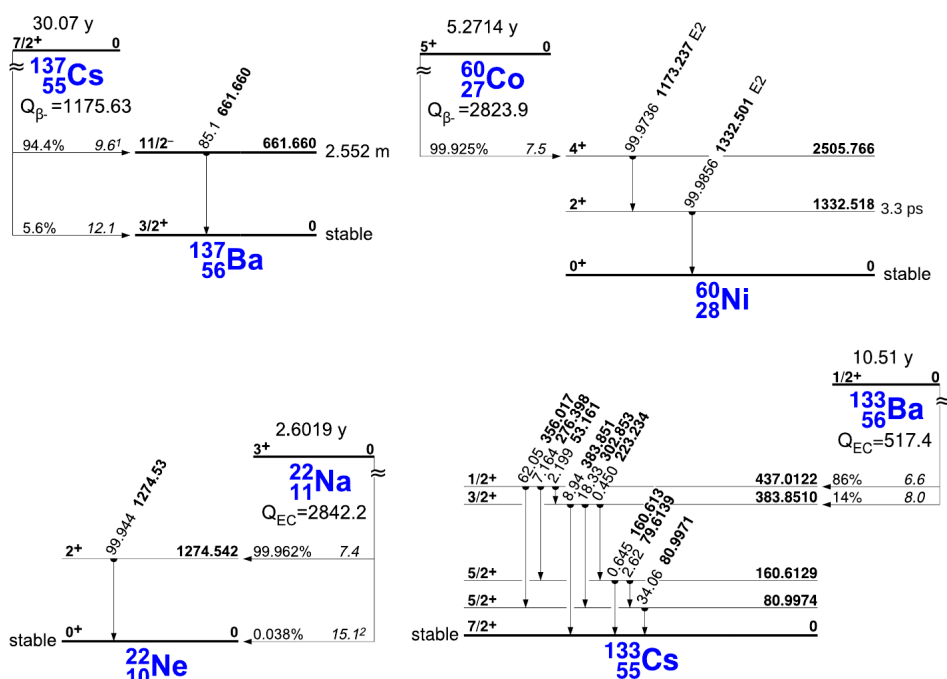
Figure 8: Example of a calibration result: energy as a function of channel number (left) and the difference between the calibration result and the true transition energies (right).

2.6 Decay schemes

Reading: [2]-1.1, 1.3

Decay schemes such as the one shown in Figure 9 can be found in nuclear physics databases, e.g. [5]. A decay scheme provides the information needed to use calibration sources and to identify isotopes and γ transitions. Among other things, a decay scheme contains information on:

- the decay type;
- the half-life – the number given after the unit is the uncertainty of the last significant digit; in the example shown, “30.08 y 9” means 30.08 ± 0.09 years; this notation applies to all quantities in the decay scheme;
- the decay energy (in keV);
- the feeding intensities of the states (in percent);
- the energies, multiplicities and intensities of the transitions (in the units explained in the normalisation);
- the intensity normalisation – in the example, intensities are given per 100 decays (i.e. in percent);
- the half-lives of excited states, if measurable and known;
- the excitation energies of the states (in keV).

Figure 9: Decay scheme of ^{137}Cs [5].Figure 10: Decay schemes of the calibration sources. Level excitation energies and γ -transition energies are given in keV.

Look up the decay schemes of the isotopes used for calibration in this exercise (Figure 10). Analyse them and consider what the spectra recorded by the detector will look like.

2.7 Statistical considerations

Reading: [1]-3.II or [4]

Radioactive decay is statistical in nature. It is impossible to predict, among other things, the moment of a spontaneous decay or the direction of particle emission, which follows from the quantum nature of the phenomenon. This means that the measured quantities have a certain

statistical distribution regardless of the precision of the detectors. The processes used to detect radiation are of a similar nature. For example, the lifetime of a nucleus is described by an exponential distribution with a characteristic decay constant (the probability of decay per unit time). The drift time of electrons to the electrode is described by a similar distribution. All these processes therefore introduce their own statistical distributions into the observed quantities, and the final result depends on the combination of all the random events involved.

Number of events. Suppose we measure radiation from a source whose half-life is much longer than the measurement time (e.g. the half-life of ^{60}Co is 5.27 years, while the measurement takes 5 minutes). The source activity can then be assumed constant during the measurement. This does not mean that we should expect the same number of events registered in the detector every time, since this depends on several random factors. Radiation is emitted in a random direction, so there is only a certain probability that it will be directed towards the detector. A photon reaching the detector may, with a certain probability, undergo the processes described above and be registered or not. These probabilities are small and constant, so the number of registered particles n follows the Poisson distribution:

$$P(n) = \frac{\mu^n e^{-\mu}}{n!}$$

This distribution is characterised by the mean expected number of events μ , and the standard deviation of the observed number of events is $\sigma = \sqrt{\mu}$.

Registered energy. If a γ ray reaches the detector and is fully absorbed, we expect the detector to measure its full energy. The detection process, however, involves several intermediate stages – the photon must transfer its energy to an electron in the photoelectric process, and the ejected electron causes further ionisation and the creation of electron–hole pairs. The number of these excitations is not strictly determined and is subject to statistical fluctuations. Each subsequent process, such as the production of photons in a scintillator, their conversion in the photomultiplier, and the passage of the signal through the electronics, introduces further small random modifications to the final measurement result. By the central limit theorem, the sum of all these small but numerous random factors means that the response of the system to a γ ray of well-defined energy is described by a normal (Gaussian) distribution:

$$P(E) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp \left[-\frac{(E - \mu)^2}{2\sigma^2} \right]$$

where A is the area under the curve (interpreted as the number of registered photons), μ is the mean observed energy and σ is the standard deviation.

Measurement uncertainty. The uncertainty of a result consists of two basic components – statistical and systematic. Imagine measuring the length of a table with a ruler. We repeat the measurement many times to obtain an accurate result. We expect small differences arising from many factors (e.g. the angle of the ruler, the reading angle, hand tremor) to produce a normal distribution of results. The best estimate of the table length is the mean of the individual measurements, and the parameter σ of the distribution is estimated from the standard deviation. This quantity should not, however, be identified with the uncertainty of the length – it is the spread obtained in a single measurement. By performing a series of measurements we can determine the position of the centre of the distribution (our best estimate of the measured quantity) with much

greater accuracy. The relation is analogous to that between the standard deviation of a single measurement from a population:

$$s_x^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

and the standard deviation of the mean for a sample from the same population:

$$s_{\bar{x}}^2 = \frac{1}{n(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2$$

In this way, by repeating measurements, we can reduce the effect of the statistical spread of the results. This will not help, however, if our ruler is slightly bent, badly scaled or too short. This component is the systematic uncertainty of the measurement, which must also be determined or estimated (e.g. by appropriate calibration of the instruments).

References

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