RM3: Neutron activation

Introduction

Radioactivity induced by neutrons plays a critical role in the decommissioning of nuclear power plants and fusion reactors, where understanding neutron interactions is essential. These reactions also hold significance in the field of nuclear astrophysics. A key parameter in characterizing neutron-induced reactions is the cross section, denoted as σ, which is defined as the mean number of interactions per target nucleus divided by the fluence. Fluence represents the average number of particles, particularly neutrons, per unit area, with the area being oriented perpendicularly to the neutron's direction of movement, ensuring equal consideration in all directions.

The cross section σ varies with the energy of the neutrons involved. When neutrons are released from a nucleus, they possess kinetic energy. In the neutron source used here, alpha particles from an alpha emitter collide with beryllium, releasing neutrons with energies up to 11 MeV. These neutrons are subsequently scattered within a moderator, where many are slowed down to become thermal neutrons, characterized by kinetic energies in the tens of meV range. Understanding these energy-dependent interactions is crucial for applications in nuclear decommissioning, reactor management, and the broader scope of nuclear sciences.

Neutron interaction

The -value is a crucial parameter for the classification of neutron interactions. The Q-value represents the difference in rest masses of all reaction partners before and after a reaction. In elastic scattering, reaction partners exchange momentum and energy without changing identities, leading to a Q-value of zero. This interaction is all around and plays a important role in slowing down fast neutrons, particularly in hydrogen-rich materials such as polyethylene and water, a process known as *moderation*.

Threshold reactions occur where the Q-value is negative, meaning energy is required to initiate the reaction. Such reactions can only be induced by fast neutrons with sufficient energy, exemplified by $(\mathrm{n};\mathrm{p})$ reactions. For example,

$$^{32}\mathrm{S} + \mathrm{n} \rightarrow {}^{32}\mathrm{P} + \mathrm{p} \qquad \text{with a short form} \qquad {}^{32}\mathrm{S}(\mathrm{n};\mathrm{p})^{32}\mathrm{P}$$

On the other hand, neutron capture primarily occurs through $(\mathrm{n};\gamma)$ reactions on stable nuclides, characterized by a positive Q-value, releasing energy in the form of photons. For example,

$$^{107}\mathrm{Ag} + \mathrm{n} \rightarrow {}^{108}\mathrm{Ag} + \mathrm{h}\nu \qquad \text{with a short form} \qquad {}^{107}\mathrm{Ag}(\mathrm{n};\gamma)^{108}\mathrm{Ag}$$

In these reactions, slower neutrons have a higher chance of interacting, since the cross-section decreases with increasing neutron velocity.

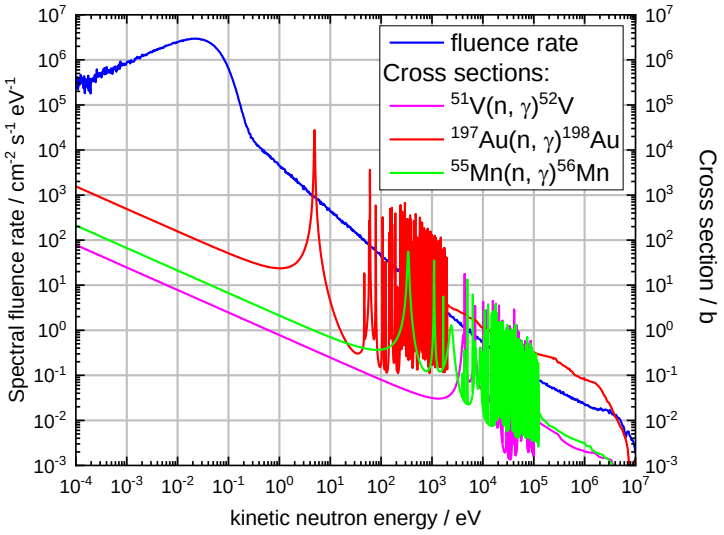


Figure 1 Fluence rate in the source and some selected cross-sections as a function of neutron energy.

In the thermal energy region, the cross sections exhibit a smooth and pure inverse velocity dependence, aligning with the broad maximum in the fluence rate. At higher energies, resonance peaks in the cross sections correspond to specific energy levels within nuclear structures. Gold is notable for its large cross section and with a low energy resonance. To use gold in the determination of the pure thermal neutron fluence raten, a differential measurement is required where one sample is activating with cadmium shielding, as ^{113}Cd efficiently captures all neutrons below 0.5 eV.

Activation

While the sample is in the neutron field, the number of radioactive nuclides adheres to the following differential equation:

$$\mathrm{d}N_{\mathrm{ac}}(t) = N_{\mathrm{st}}\left(\int \sigma(E)\frac{\mathrm{d}\varphi}{\mathrm{d}E}\mathrm{d}E\right)\mathrm{d}t - N_{\mathrm{ac}}(t)\,\lambda\,\mathrm{d}t \qquad (1)$$

where

$N_{\mathrm{ac}}(t)$	Number of activated nuclei at t
N_{st}	Number of stable isotopes
$\sigma(E)$	Activation cross section
$\frac{\mathrm{d}\varphi}{\mathrm{d}E}$	Spectral fluence rate (fluence rate: time derivative of the fluence)
λ	Decay constant of the activated isotope

So the number of activated nuclei changes by two processes: activation by the neutron fluence rate, and decay of the already activated nuclei. Solving this differential equation, we get the number of activated nuclei over time:

$$N_{\mathrm{ac}}(t) = N_{st}\cdot\left(1 - e^{-\lambda t}\right)\int \frac{\mathrm{d}\varphi}{\mathrm{d}E}\sigma(E)\,\mathrm{d}E$$

So the $N_{\mathrm{ac}}(t)$ increases monotonically (see Figure 2) and after sufficiently long time the sample reaches to the saturation activity $A_0 = N_{\mathrm{ac}}(\mathrm{t}\ \rightarrow\ \infty)$:

$$A_0 = N_{\mathrm{st}}\int \sigma(E)\frac{\mathrm{d}\varphi}{\mathrm{d}E}\mathrm{d}E$$

When, the sample is removed from the neutron source, only the decay term remains in Eq. (1), which describes an exponential decay of the number of activated nuclei, see Figure 2.

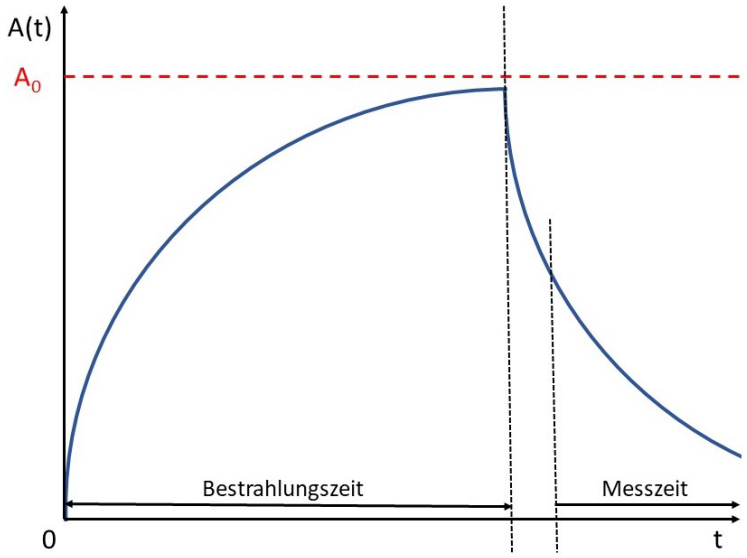
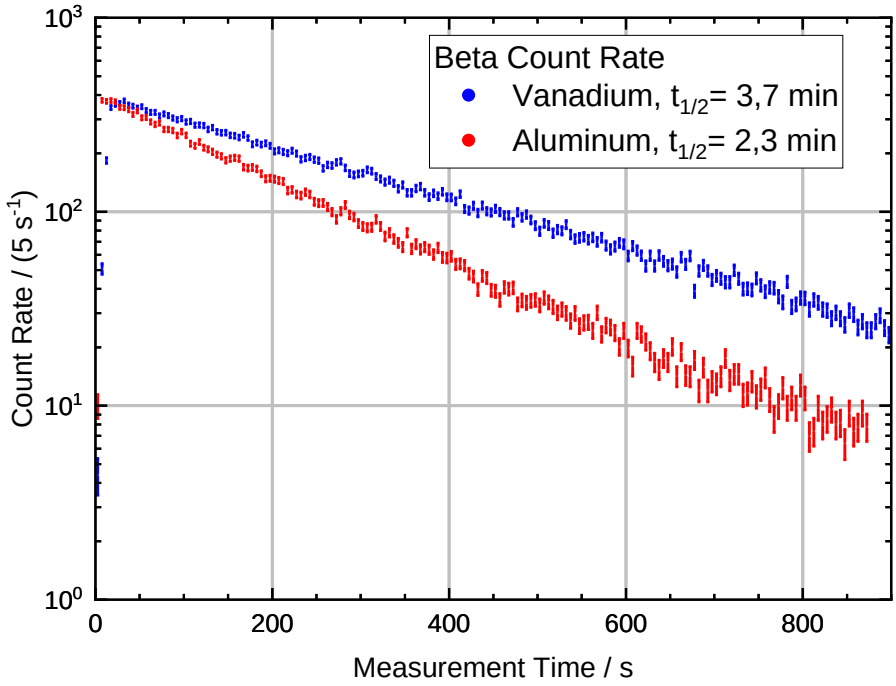


Figure 2 Time dependence of the number of activated nuclei over time. In the monotonic increasing part the sample is exposed to the neutron radiation. In the exponentially decreasing part, the sample is removed for the measurement.

Measurement

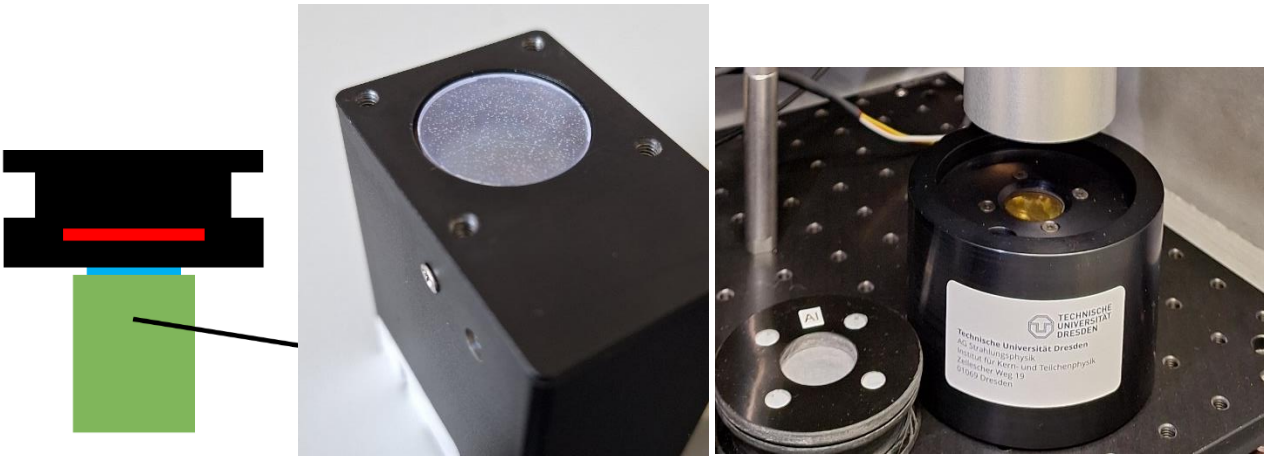
When neutrons are captured by a target nucleus, the resulting reaction products have one more neutron than the stable target nucleus, typically leading them to become β^- emitters. A well-known example is cobalt-60 (^{60}Co), which accumulates in steel used in nuclear reactors and contributes significantly to the radioactive activity observed during nuclear decommissioning.

Measurement of the beta activity starts at the moment the sample is removed from the radiation chamber. Measurement of beta activity begins after transporting the sample from the radiation chamber to the detection equipment, which may cause some delay. An example of the count rate of different reaction products is presented below:



Beta radiation is detected as follows: electrons emitted during the decay process pass through a thin foil and into a scintillation detector. In the scintillation material, weak light pulses are generated with intensities proportional to the energy deposited by the electrons. These light pulses are then captured by a photomultiplier that converts the optical signal into a voltage signal. Because the light emission is proportional to the energy deposited, this method allows for beta radiation spectroscopy. The efficiency of detecting beta radiation is strongly dependent on the geometry of the sample and the likelihood of an electron escaping the sample to interact with the scintillator.

The detector can only count events with a minimum signal amplitude which has to extend the electronic noise of the system. Smaller signals cannot be detected and are lost. To optimize the detectors settings in the respect of detection efficiency, the high voltage of the photomultiplier and the threshold settings of the data acquisition system have to reviewed on each day. This is the first task in the lab.



Sample and sample holder with the beta detector

Task definition

The task involves three major components: First, the calibration of the detector using a ^{137}Cs beta source is essential to determine the detector threshold and the appropriate high voltage settings. Second, the measurement of thermal neutron flux density is carried out through differential measurement, which involves recording the decay curves of both cadmium-coated and uncoated gold samples. This allows for the calculation of the fraction of activity attributable specifically to thermal neutrons, alongside the determination of the detector efficiency. Lastly, the investigation extends to the time dependence and detector efficiencies of various samples. This includes calculating the irradiation time needed to reach 95% of saturation activity, estimating expected sample activity based on the thermal neutron flux, and determining the appropriate radiation measurement time. The process involves recording the decay curve and verifying consistency with expected reaction products.

Notes on the experiment

Accessories:

1. Beta-scintillation detector
2. Measuring electronics for voltage supply and pulse analysis and counting
3. PC, connected via network to the measuring electronics of the scintillation detector;
4. Cesium beta source for detector calibration.
5. Various samples for irradiation and radiation
    - cadmium-shielded and unshielded pure gold
    - Aluminum, silver, vanadium, manganese, sodium chloride
6. shielded neutron irradiation facility
7. Sample holder for introduction to the neutron irradiation system

Experiment Procedure and Evaluation

(Details in the course instructions)

1. The detector is connected to the PC following the instructions.
2. ^{137}Cs beta source is inserted into the detector. Detector configurations (threshold and high-voltage) is determined using the instructions in the manual. Ask the supervisor for additional guidance if necessary.
3. Each activated gold samples are inserted into the detector and recorded for a duration of 10 minutes.
4. Two different test materials are selected. The corresponding reaction products are determined.
5. Irradiation time is determined, which is required to reach 95% of maximum activity. The sample radiation measurement time is determined.
6. Samples are placed into a neutron source for a duration calculated in point 5 above.
7. Samples are quickly moved into the detector when they reach the target activity.
8. The count rate of beta radiation is measured.
9. The measurements from the experiment are analyzed using the spreadsheet program EXCEL.
10. Specification and discussion of the analysis result.
11. Uncertainty considerations (for basics see instructions RM1 and F2).