Experiment 601
Characteristics of β radiation scintillation detector. Absorption of β radiation in matter.

Before starting the experiment students should know the following theory topics:
a) atom and atomic nucleus structure
b) nuclear reactions
c) natural and artificial radioactivity
d) emission and energy spectrum of β particles
e) detection methods for radioactive radiation; operation principle of scintillation counter

The aim of the experiment

To explore absorption of β radiation in solid bodies by determination of:

- ✓ absorption curve,
- ✓ effective range, maximum energy and velocity of β particles of maximum range,
- ✓ thickness of half-value layer for a beam of β particles,
- ✓ unknown thickness of absorber

1. Theoretical background

The β radiation is directly ionizing radiation, consisting of beta particles, i.e. of electrons with positive and negative charge, emitted during nucelar tranformations or decay of unstable particles. The β radiation is characterized by continuous spectrum with clearly visible maximum energy, above which the particles are absent. The maximum energy of the beta particles falls within range from 15 keV to 15 MeV, and their velocity may be close to the velocity of light.

There are two kinds of β radiation:
– β^+ – emission of positon and neutrino, which accompany nuclear fission, where at constant mass number the charge number of the nucleus decreases by one; in this decay an additional particle of almost zero rest mass and zero charge is created, which carries out part of the energy – it's electron neutrino: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e$.
– β^- – emission of electron and antineutrino; in this case the mass number remains constant, and the charge number of the resulting nucleus increases by one: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \overline{\nu_e}$.

In beta decay the energy distribution of the emitted particles (their energy spectrum) is continuous, in effect we deal with particles of energies ranging from zero to the maximum energy value, defined by masses of the nuclei taking part in the decay.

The result of ionization caused by the beta particles is the process of absorption of the β radiation. The beta particles, passing through a medium, are being slowed down until they stop. The range of the beta radiation depends on the type of particles and kind of the absorber.

2. Measurement method

The measurement of absorption consists in counting the number of particles passing through the absorber, in a defined period of time. The intensity I of the beta particles beam decreases with thickness x of the absorber according to exponential dependence:

$$I = I_0 e^{-\mu x} \qquad (1)$$

Where I_0 is initial intensity of the beam, I is the radiation intensity after passing the absorber layer of thickness x, μ, (with dimension m^{-1}), is the linear absorption coefficient. In absorption measurements, it's more convenient to express the thickness of absorber in terms of the, so called, surface density (expressed in kg/m^2 or similar, like mg/m^2). It's calculated with formula:

$$x = \frac{m}{S} \qquad (2)$$

where m is the mass of the absorber (being a piece of foil or a plate), and S denotes its surface. Such approach gives practical profit, as determination of mass and surface of a piece of thin foil is more precise than the measurement of its thickness. Sometimes a mass absorption coefficient μ_m is used, it's defined as a quotient of the linear absorption coefficient μ and density ρ of the absorbing material

$$\mu_m = \frac{\mu}{\varrho} \qquad (3)$$

It's dimension is $m^2 \cdot kg^{-1}$. Such definition of the coefficient is convenient because its value is approximately equal for most absorbing materials.

It should be noted that for very thick samples of absorber the count number measured by detector, does not fall to zero, but to the level of background radiation.

The thickness of the absorber sample, for which the radiation intensity falls to half its initial value is called the half-value thickness $d_{1/2}$. The notion of the half-value thickness may be related to the absorption coefficient. If the thickness of the absorber layer equals to the half-value:

$$x = d_{½} \qquad (4)$$

then

$$I = \frac{1}{2} I_0 \qquad (5)$$

Substituting the above formulas into the formula (1) we obtain

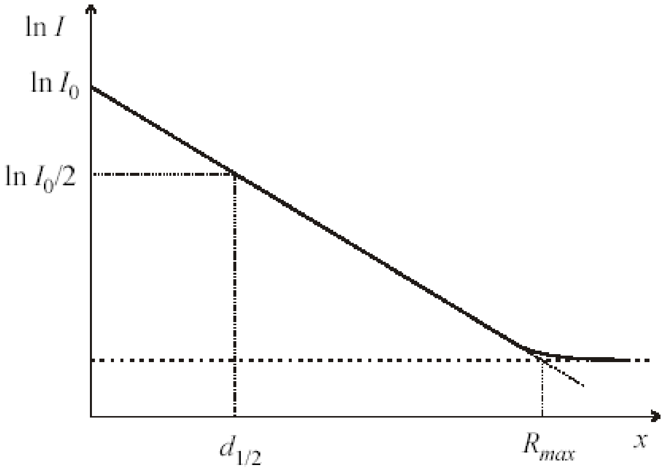
$$\frac{1}{2} I_0 = I_0 e^{-\mu d_{½}} \qquad (6)$$

from which the relation between the absorption coefficient and the half-value thickness follows:

$$\mu = \ln \frac{2}{d_{½}} \qquad (7)$$

The absorption of beta radiation mostly depends on the density of electrons in the absorbing material, and its values are similar in different absorbers.

The exponential law of nuclear radiation absorption is well satisfied for absorber thicknesses not greater than two half-value thicknesses. Were the exponential law of absorption exactly satisfied, the maximum range of β particles should not exist. Constant value of half-value thickness should rather be expected, i.e. for a given surface mass the number of particles should always decrease by half. In reality, for big thicknesses of absorber, the fall of intensity is faster} than exponential, and after several half-value thicknesses the intensity falls below the background level. The figure below presents typical absorption curve of the β radiation.



Rys. 1. Wykres zależności ln$I$=f(x) i sposób wyznaczenia grubości połówkowej i zasięgu maksymalnego.

Abscissa of the point where the absorption curve tends to the background level defines the maximum range $R_{\max}$. It's the maximum thickness of the absorber that the investigated particles may pass through. As the value of $R_{\max}$ is only extrapolated, it is possible to observe small number of β particles in a very thin layer at slightly bigger distances. The maximum ranges of β particles, expressed in meters, are different for different media. However, if we express them in terms of surface densities, the maximum range is almost independent of the kind of the absorber, depending only on maximum kinetic energy E_k of the β particles. In the case of beta particles with energies smaller than a few MeV, the $R_{\max}$ dependence on E_k is almost linear.
Approximate range of β particles of maximum kinetic energy smaller than 1 MeV, may be calculated using the Feather formula:

$$R_{max} = 0.571\,E_k - 0.161 \qquad (8)$$

Where the energy is expressed in MeV and the range is expressed in g/cm^2.

For measurement of beta radiation intensity most often the scintillation counters and Geiger-Müller counters are used. The operation of scintillation counters is based on scintillation phenomenon: some substances can transform the kinetic energy of the incident particle into visible light. Charged particles, or photons, colliding with atoms of scintillator cause excitation; excited atom, after time of 10^{-6}–10^{-9} s, returns to its ground state emitting a photon. The operation principle of the Geiger-Müller counter is based on registering electrical impulses caused by discharges in ionized gas.

3. Measurements

Before the measurement begins students should read the instruction of the measurement stand. The apparatus should be switched on only when the students obtained the permission from the tutor. The apparatus is ready for measurement 15 minutes after turning it on.

1. When the apparatus is ready the optimum parameters of the scintillating counter should be set. The voltage should be set between 1200-1400 V, preferred value is 1350 V. **Attention: Voltages above 1500 V will damage the equipment!**

2. Perform 10 measurements of background radiation and calculate their average value and their standard deviation.
3. Using tweezers insert the β radiation source and perform measurements as in point 1.
4. Perform the measurements (counts) for different surface masses of absorber (i.e. for different numbers of plates of known thickness placed between the source and the counter). For every number of plates three measurements should be performed. The kind of absorber should be defined by the tutor.
5. Perform measurements for the plate of unknown thickness.
6. Repeat measurements for another absorber (according to the tutor's decision).

5. Report

1. Create a semilog plot of counts number N vs. the surface density of the absorber x (i.e. $\ln N = f(x)$).
2. Using the plot determine the effective range of β particles and the half-value thickness of the layer $d_{½}$.
3. Using the plot data determine the surface density of the unknown absorber.
4. Calculate the maximum energy E_k and its error (using the approximate formula of Feather, where R_{max} is expressed in g/cm^2).
5. Using the calculated E_k and isotopes tables determine what radionuclide was used.
6. Calculate the maximum velocity v_{max} and its error Δv_{max} using the formula below:

$$E_k = m_0 c^2 \left(\sqrt{\frac{1}{1 - \left(\frac{v_{max}}{c}\right)^2}} - 1 \right)$$

where $m_0 = 9.1 \cdot 10^{-31}$ kg is the rest mass of a β particle and $c = 3.0 \cdot 10^8$ m/s.

6. Requirements

1. Types of ionizing radiation.
2. Mechanisms of beta decay.
3. Principle of Geiger- Müller counter operation.
4. Principle of scintillation counter operation.
5. What causes energy losses of beta particles passing through matter.