Laboratory #22: Absorption of β and γ Rays

Goal: Detect nuclear radiation with a gas-filled detector; understand statistical uncertainty. Study the absorption of β and γ rays in matter.

Equipment: "The Nucleus" counting station with Geiger-Müller tube, counter and timer. Set of absorbers of varying thickness, $^{90}\text{Sr}$ and $^{60}\text{Co}$ source. Monitor-4 Geiger counter, Vernier interface, computer.

(A) Counting Statistics

Here, we want to convince ourselves that repeating a counting experiment $N$ times leads to results $n_i$ ($i=1,N$) that are distributed like a Gaussian around a mean value $<n>$. In order to demonstrate this well, we need many measurements. Thus we enlist the help of a computer to do this for us.

Place a $^{60}\text{Co}$ source in the source holder in the black wooden bench, turn on the computer and the Monitor-4 (its little red light should now start flashing with each count). Click on SW137 and then double-click on the 'Exp04 Statistics' icon. Click 'experiment', then 'sampling' and set the experiment length to 300s and the count interval to 1s. Click 'collect'. You now should be making 1s measurements, acquiring a histogram as you go. Adjust the distance between the counter and the source until the count per second is between 25 and 30. Click 'stop' and 'collect' again to restart the experiment. Wait till the experiment is finished.

Copy the values $f_n$ (number of times, the result $n$ occurred) of the measured distribution into your logbook. Calculate the average $<n>$ for the $N=300$ measurements from

$$<n> = \frac{\sum n f_n}{\sum f_n},$$

where the sum extends over the bins of the histogram.

Plot the measured distribution $f_n$. On the same graph also plot the theoretically expected distribution. This is a Gaussian with a mean $\mu=<n>$ and a standard deviation $\sigma^2=<n>$:

$$g_n = m_o e^{-\frac{(n-<n>)^2}{2<n>}}.$$

Here, $m_o$ is a normalization constant, which you should choose to be about $f_n$ at the peak of the distribution.
Physics

When passing through matter, \( \beta \) rays (energetic electrons and thus charged particles) loose energy by collisions with atomic electrons or by radiation (bremsstrahlung). Fig. 1 shows the distance traveled before stopping (called 'range') as a function of the initial energy. The ranges of individual electrons have a certain spread because of statistical fluctuations of the loss processes ([SEG77] p.40; [LEO87] p.34-40).

On the other hand, \( \gamma \) rays are quanta of electromagnetic radiation and react less directly with matter. With a certain probability any of a number of processes can remove a quantum from the initial flux \( I_0 \) (see [SEG77], p.54). This leads to an exponential decrease of the intensity \( I \) transmitted through an absorber of thickness \( d \) (usually measured in \( g/cm^2 \)),

\[ I = I_0 e^{-\mu d} \quad , \]

where \( \mu \) is the mass absorption coefficient (units of \( cm^2/g \)). The mass absorption coefficient for lead is shown in fig.2.

Radioactivity usually is associated with the emission of \( \beta \) or \( \gamma \) rays (or both). A schematic of the principal decay modes of the radioactive isotopes \( ^{60}Co \) and \( ^{90}Sr \), which are used in this lab, are shown in figs.3a,b (see also [LED78]). Emission of a \( \gamma \) is indicated by a vertical arrow, emission of a \( \beta \) by an arrow to the right. From these schematics, we see that \( ^{90}Sr \) has a half-life of 28.8 years and decays by \( \beta \) emission into \( ^{90}Y \). Since the latter has a much shorter half-life, we get an \( ^{90}Y \) decay for every \( ^{90}Sr \) decay. The maximum energy of the \( \beta \)'s emitted by \( ^{90}Y \) is much larger than those emitted by \( ^{90}Sr \). \( ^{60}Co \) has several possible \( \beta \) decays, but one is much more probable than the others. This leads to an excited state in \( ^{60}Ni \), which decays to its ground state by a cascade of two \( \gamma \) emissions. The energy of these \( \gamma \)’s is fixed because it is given by the excitation of the \( ^{60}Ni \) nucleus. However, emitted electrons share their energy with a neutrino and thus have a continuous energy distribution extending from 0 to \( E_{max} \) ([LEO87] p.4-6).

By chance, the combination of the statistical range distribution for \( \beta \)'s and their continuous energy spectrum leads to an absorption law for \( \beta \) particles that is also approximated quite well by eq.1. The absorption coefficient in this case gives a rough measure of the maximum energy \( E_{max} \), according to the empirical rule

\[ \mu_{exp} = (14 - 17) \frac{cm^2}{g} \left( \frac{1 MeV}{E_{max}} \right)^{1.14} \]

Fig. 3a

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#### Fig. 3a

- \( ^{60}Co \)
- \( \beta^- (E_{max} = 0.31 \text{ MeV}) \)
- \( ^{60}Ni \)
- \( \gamma (1.17 \text{ MeV}) \)
- \( \gamma (1.33 \text{ MeV}) \)

#### Fig. 3b

- \( ^{80}Sr \)
- \( T_{1/2} = 28 \text{y} \)
- \( \beta^- (E_{max} = 0.34 \text{ MeV}) \)
- \( ^{80}Y \)
- \( T_{1/2} = 6.6 \text{h} \)
- \( \beta^- (E_{max} = 2.26 \text{ MeV}) \)
- \( ^{80}Zr \)
A gas-filled, cylindrical tube with a central electrode and a thin mica entrance window. When a charged particle is slowed down in a gas, most of the deposited energy is used to ionize gas molecules. In the presence of an electrical field, the resulting ions and electrons start drifting in opposite directions. In a cylindrical detector the field is proportional to \(1/r\), where \(r\) is the distance from the central electrode. The potential of the central electrode is chosen positive, so the electrons move towards it. At low voltages (100-400V, "ionization chamber region"), the collected charge is the number of initial ions, \(N_{\text{init}}\), times the elementary charge. At higher voltage the electrons traveling towards the central electrode pick up enough energy, so they themselves are able to ionize gas molecules. Eventually, the secondary ionization completely dominates and the collected charge does not depend on \(N_{\text{init}}\) anymore ("Geiger-Müller region"). More on gas-filled counters can be found in [LEO87], p.119.

The detection of uncharged particles (such as \(\gamma\) rays) is possible only because the secondary processes (mentioned above) yield charged reaction products. Thus, the efficiency with which \(\gamma\)'s are detected is much lower than for \(\beta\)'s.

**Experiment:**

1. **Operating Voltage**
   The counting house features a tray for the source and one for absorbers. The trays are inserted into slots that are numbered top to bottom. Place the \(^{90}\textrm{Sr}\) source in slot 2 and measure the count rate \(n\) as a function of the detector voltage \(U_D\) from 0 to 900V. Determine the region where \(n\) does not depend on \(U_D\). Does this result change if you use the \(^{60}\textrm{Co}\) source? For all subsequent measurements, use an operating voltage in the middle of this region.

2. **Mass Absorption Coefficient for \(^{60}\textrm{Co}\) \(\gamma\) rays**
   Place the \(^{60}\textrm{Co}\) source in slot 3 and the absorber tray in slot 2. Measure the count rate as a function of lead absorber thickness. Cover the range 0 to 14 g/cm\(^2\) (combine absorbers). Plot semi-logarithmically and determine \(\mu\) from eq.1. Note that for thin absorbers, eq.1 may not hold, because absorber may actually convert some \(\gamma\)'s to charged particles and thus increase the efficiency of the detector. Compare with the value in fig.2.

3. **Absorption Coefficient for \(^{90}\textrm{Sr}\) \(\beta\) rays**
   Same measurement as for 3, but with polyethylene absorbers ranging from 0 to 900 mg/cm\(^2\). From the extracted \(\mu\), estimate \(E_{\text{max}}\) using eq.2. Compare with the \(E_{\text{max}}\) value from fig.3b. In this figure, the energy difference between initial and final state (\(E_{\text{max}}\)) is given as \(Q_\beta\). Since there are two \(\beta\) decays in series, there are two \(Q_\beta\) values. With which should you compare your result?
References


[SEG77] E. Segre, Nuclei and Particles, Benjamin, Reading 1977, (QC776.S4). (Classic nuclear physics text, and still one of the best introductions into this field with a broad coverage of subjects)

Fig. 1
Fig. 2

Mass Absorption Coefficients for Lead.
Data taken from Gladys N. White,
N.B.S. Report No. 1003 (1953)