IIA5

Modul Atomic/Nuclear Physics

Deflection in Magnetic Field

This experiment aims to investigate various aspects of radioactivity using a cesium source, such as the distance law and the deflectability of beta radiation. The theoretical part introduces concepts like α-, β-, and γ-rays, decay laws, lifetime, and half-life. The most important and widely used detector for radioactivity is the Geiger-Müller counter, which is also used in this experiment, and its operation is explained in the experimental section.

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1.1 Preliminary Questions

- What is meant by the term *radioactivity*? Explain in your own words.
- It makes no physical sense to speak of *radioactive radiation* when α-, β-, or γ-radiation is meant. The correct term for this is *ionizing radiation*. Why is that?
- How can various types of ionizing radiation be shielded?
- How does a Geiger-Müller counter work?
- What is meant by the *activity* of a radioactive source?
- In the knowledge of the phenomenon of *bremsstrahlung*, is it sensible to store a β source like ^{137}Cs in a lead container?
- What important rules must be strictly followed for radiation protection when working with radioactive sources?
- What happens predictably to an electron beam in a magnetic field? How can this be explained?

1.2 Theory

1.2.1 Discovery of Radioactivity

In 1896, H. Becquerel discovered that uranium minerals emit extremely penetrating radiation, which darkens a photographic plate even through quite thick layers. Subsequently, in 1898, the husband and wife Marie and Pierre Curie managed to separate small amounts of two new elements, *radium* and *polonium*, from a very large amount of uranium ore (Joachimstal pitchblende), in which this effect was concentrated to the utmost. An admirable achievement! Because in pitchblende, only one radium atom decays for every 3×10^6 uranium atoms. Today, more than 40 naturally occurring atomic species are known to possess this property of *natural radioactivity*. The investigation of the deflection of the radiation emitted by these substances in a magnetic field shows that they can be of three types.

- **α-rays** are a *particle radiation* and consist of very fast helium nuclei ^4_2He, carrying two positive elementary charges. Their mass is $6.643 \times 10^{-27}\ kg$. Their velocity lies - depending on the type of radioactive nucleus - between about $5 - 7.5\%$ of the speed of light. This corresponds to a kinetic energy of about $4.6 - 10.4\ MeV$. The gradual formation of helium from an α-radiating substance can be spectroscopically detected, as well as from the always present helium content of all minerals containing such substances.
- **β-rays** are also a *particle radiation* and consist of very fast electrons. Their speeds range from very small velocities to more than 99% of the speed of light. Their kinetic energy reaches values up to $12\ MeV$.
- **γ-rays** are very short-wavelength *electromagnetic wave radiation* or very energetic *photons*. The smallest observed wavelength is $4.66 \times 10^{-13}\ m$. This corresponds to an energy $h\nu = 2.66\ MeV$ (h is Planck's constant, ν is the frequency of radiation). In general, however, the wavelengths are much larger, and thus the energies are correspondingly smaller.

1.2.2 The Decay Law

A radioactive nucleus that will decay in the next second is indistinguishable from one that will live for $10,000$ years. In general, there is no characteristic that allows the prediction of atomic single events such as a nuclear decay. The radioactive decay is therefore a nuclear property that depends solely on the internal state of the nucleus.

On the other hand, the *probability* that a given nucleus decays in the next second is very precisely given. It is numerically equal to the *decay constant* λ and is approximated in a large number of nuclei by the actually observed relative frequency of decay events arbitrarily well. Of N nuclei, $\lambda \cdot N \cdot dt$ decay on average in the next time interval dt:

$$dN = -\lambda N dt \tag{1.1}$$

from which the *decay law* follows by integration:

$$N(t) = N_0 e^{-\lambda t} \tag{1.2}$$

Here, N_0 is the number of atoms at time $t = 0$, $N(t)$ is the number of atoms still present at time t. After the time $\tau = 1/\lambda$ has elapsed, the number of atoms has decreased to the e-th part (see Figure 1.1); τ is its *mean lifetime*. The *half-life* $T_{1/2}$, after which the number of initially present atoms has decreased to half by decay, is given by:

$$N\left(T_{1/2}\right) = \frac{1}{2} N_0 = N_0 e^{-\lambda T_{1/2}} \tag{1.3}$$

or

$$\lambda T_{1/2} = \ln(2) = 0.693 \tag{1.4}$$

The exponential dependence of radioactivity on time is so strictly fulfilled that the radioactive decay is used for the age determination of minerals and the like.

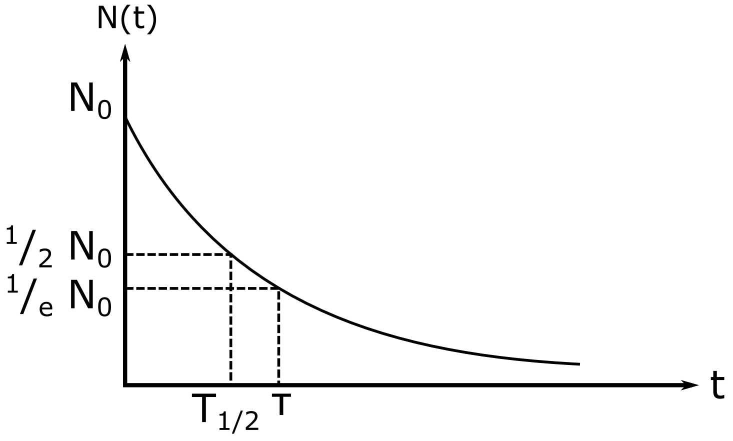

Figure 1.1: Half-life $T_{1/2}$ and mean lifetime τ.

1.3 Experiment

1.3.1 Experimental Accessories

Component	Quantity
Control unit for the counter	1
Counter tube	1
Plugboard	1
Cesium source	1
Magnet	2
β-shielding	1
Rod for mounting the magnets	2
Plug holder for the counter tube	1
Plug holder for the cesium source	1
Stopwatch	1

1.3.2 The Geiger-Müller Counter

This ingeniously simple, today on the whole world widespread device (H. Geiger, 1921) consists mostly of a metal tube of some *cm* diameter that is filled with air or argon (from some *mbar* up to the atmosphere pressure) and about 10 *mbar* alcohol vapor (see Figure 1.2). In the axis is a as possible thin tungsten or steel wire stretched that is over a high resistance R (more than 1 $M\Omega$) to the earth led away. Between tube wall and wire is a high voltage applied. The voltage does not yet suffice for an enduring independent glow discharge.

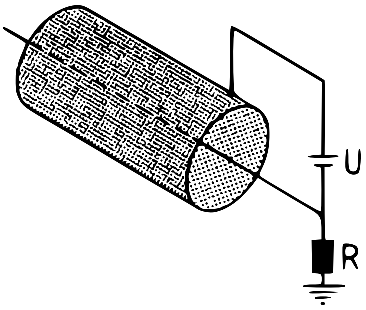

Figure 1.2: Geiger-Müller-Counter.

When a particle of ionizing radiation, such as α, β, or γ rays, enters the interior of the pipe, it guides the ions it generates, leading to the creation of a discharge pulse. This pulse essentially flares up again through the action of alcohol molecules. After each discharge pulse, the counter tube becomes insensitive against newly entering radiation particles until the positive ions formed at the wire in the immediate vicinity have migrated to the cathode. Only after the passage of this dead time and subsequent recovery time, which together extend to about 10^{-4} s, it is ready to detect a following particle.

The negative ions and electrons flowing to the wire and from there to the earth generate, at the very large resistance R, a voltage drop that activates a counting device via an electronic amplifier. Such a Geiger-Müller counter responds to a single fast electron; the size of the triggered pulse is independent of the number of electrons or ions generated by the registered elementary particle.

Note, during the operation of the counter tube, absolutely follow the safety instructions:

- Make sure to protect the sensitive mica window from mechanical damage, as any harm to it can render the counter tube unusable.
- Remember to remove the protective cap only during the measurement and put it back on afterward.
- Carefully remove and set aside the cap, ensuring not to turn it.
- Avoid touching the mica window.
- Store the counter tube only with the protective cap securely in place.

1.3.3 Experiment Setup and Adjustment

The gray mounting plate can be used to mount the source, the counter tube, and the magnets (Figure 1.3). The source will be provided by the assistant.
Warning: Do not touch the source at the borehole, as radioactive material could be released. Also make sure that you are not in the beam path of the source.

- Screw the counter tube cable into the connector socket on the electronics.
- Set the switch under the display to the middle position (Figure 1.4).
- Stop both the display and the counter.
- Set the display to 0 using the button to the right of it.
- Start the display and the counter and also start the stopwatch.
- If you want to take an intermediate result, stop the display, read it off, and start it again. In the meantime, the counter has continued to count and the display shows the current status again.
- Use the toggle switch at the top right to activate the speaker.

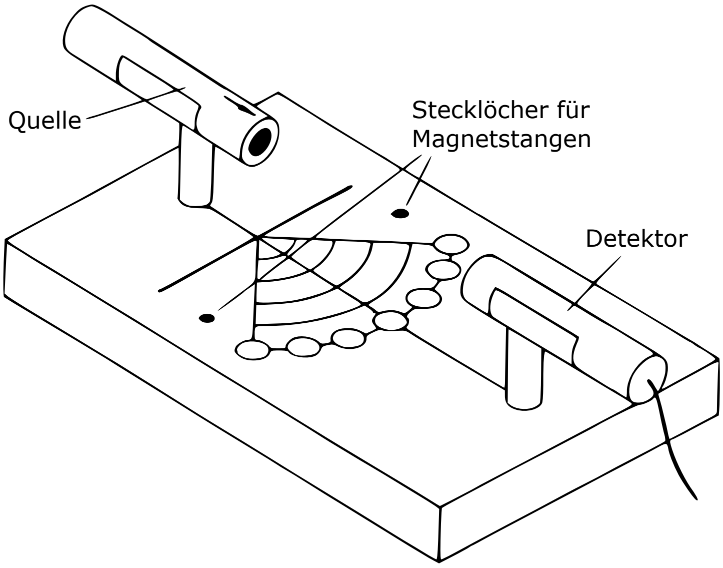

Figure 1.3: Experimental setup.

For task 6, the two magnets must be mounted between the source and the counter tube. To do this, insert the two magnets in their holders onto the two small rods. Slide the magnets onto the rods so that they snap into place. Once the two magnets are snapped into place, they have the required distance for the experiment.
Also note that the magnets have a red dot. In order for the polarity of the two magnets to be correct, the points must either both point up or both point down.

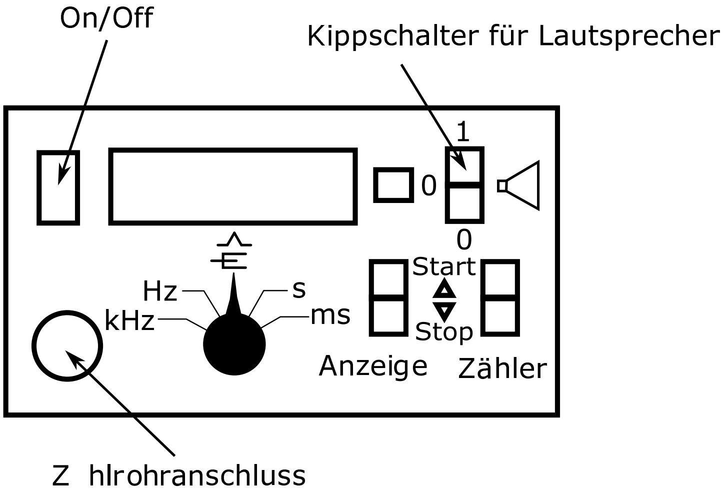

Figure 1.4: Readout electronics.

1.3.4 Term scheme and range diagram

The term scheme (Figure 1.5) shows the decay scheme of ^{137}Cs. The energies of the individual levels in MeV are given on the right. The blue arrows symbolize β decays and the red arrow a γ transition. The half-life of each element is given below it.

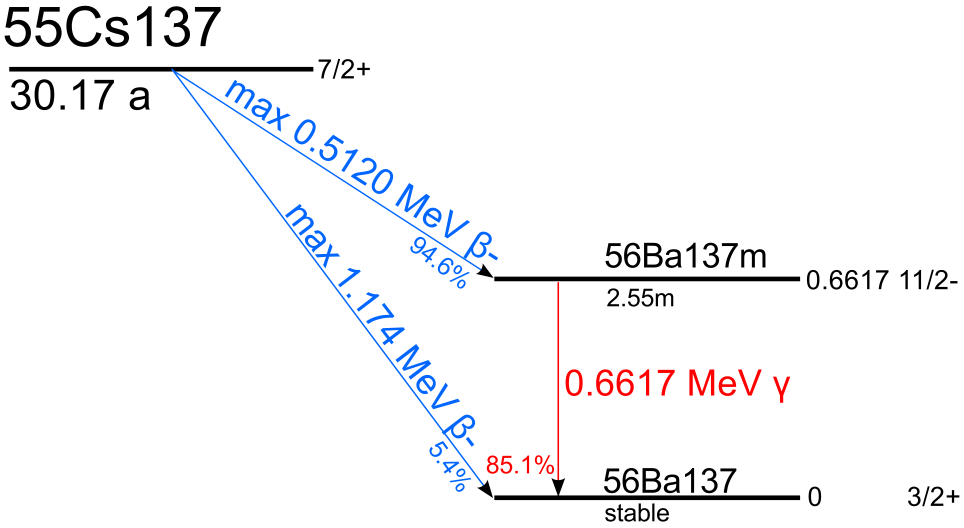

Figure 1.5: Term scheme of ^{137}Cs. Cesium can either decay directly into the stable ground state of ^{137}Ba, or into an excited state of ^{137}Ba which then further decays to the ground state by γ emission.

The dependence of the ranges (Figure 1.6) of different particle types on the energy can be only approximately expressed by the mass density alone; therefore, the curves for light and heavy braking substances are somewhat different.

Together with the corresponding density of the substance in which the range is to be determined, the range in *cm* can be easily specified from the diagram. To do this, form the ratio between the diagram value and the corresponding density in g/cm^3 and you already have the range in *cm*.

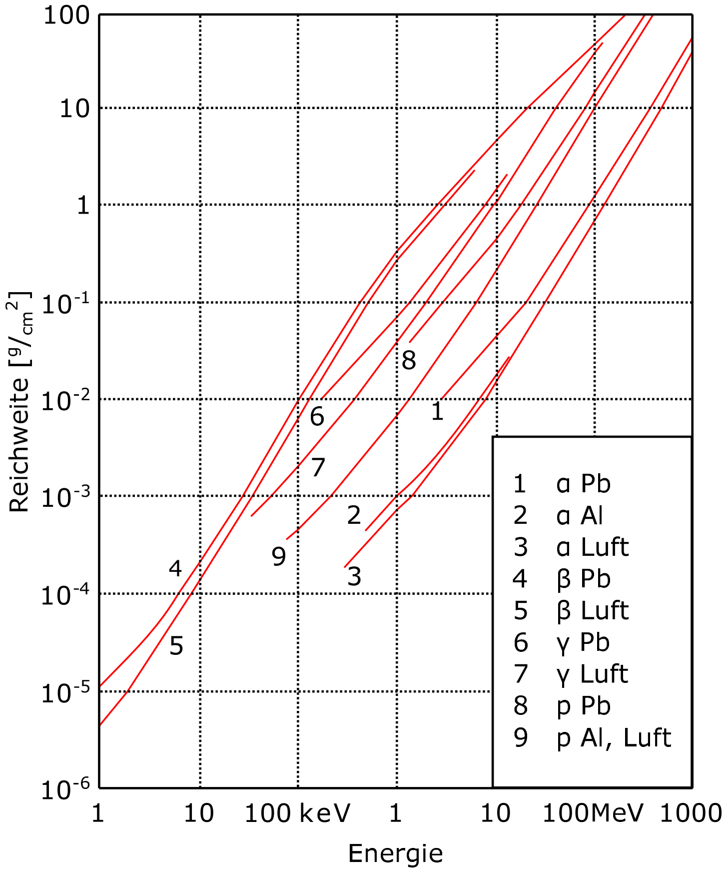

Figure 1.6: Range diagram

1.3.5 Exercises for Evaluation

1. The statistical error of a measurement with N events is given by $\Delta N = \sqrt{N}$. Consider how large the number N must be to achieve an accuracy of $\frac{\Delta N}{N} = 3\%$. Choose the measurement times accordingly for the following tasks.

2. The Geiger-Müller counter responds to all three types of radiation (α, β, γ). Determine, based on the energy level diagram (Figure 1.5), the type of radiation emitted by the cesium source (^{137}Cs).

3. Measure the count rate as a function of distance. For this measurement, place the detector at 5 different distances (2, 4, 6, 8, and 10 *cm*). Plot the count rate versus $1/r^2$. Why should one expect a $1/r^2$ law, and why does the count rate decrease with distance?

4. You will likely observe that the count rate decreases more than expected based on a pure $1/r^2$ law. Something is lost somewhere. What and where? Consider how your curve would look if the source emitted many more electrons than photons. What would happen to the $1/r^2$ law?

5. What is the benefit of increasing the distance in the context of radiation protection?

6. Measure the count rate as a function of the angle θ, with and without a mounted magnet at a distance of 5cm (to provide space for the magnets), and plot the results. What do you observe and why?

7. Estimate, using the energy of the decay electrons that you can read from the energy level diagram, and the range diagram (Figure 1.6), the range of electrons emitted by this cesium source in air. To determine the range, you also need the density of air, which you can find in a table.

8. On April 26, 1986, during the Chernobyl reactor disaster, cesium-137 was also released. From the decay diagram (Figure 1.5), you can determine the half-life of ^{137}Cs. Calculate what percentage of this cesium has already decayed.

9. Estimate the source strength. The activity of the source is the sum of all decays emitted in any direction into space. With the Geiger-Müller counter, you count only a fraction of these decays. To calculate the activity of the source, you need to extrapolate your count rate, which only applies to the detector surface a, to the entire spherical surface A. Estimate the detector surface for this purpose. Activity is measured in the SI system in *becquerel* (Bq), where 1 Bq corresponds to one decay per second. The unit *curie* (Ci) is also commonly used, and the conversion is $1\ Ci = 3.7 \times 10^{10}\ Bq$.

10. Estimate the pure γ activity of the source. Introduce β shielding in front of the source. Then proceed as in the last task.

1.4 Literature

- Povh, Rith, Scholz & Zetsche, *Particles and Nuclei*, Springer
- Wolfgang Demtröder, *Experimental Physics 3: Nuclear, Particle, and Astrophysics*, Springer