Atomic and Nuclear Physic

Radioactivity

Particle beams

LD
Physics
Leaflets

P6.5.7.1

Beta radiation in a magnetic field

Objectives of the Experiment

- Setting up an electron beam passing through a magnet
- Record the different count rates at different combinations of angle and field.

Principles

When nuclei decay, they emit different kinds of radioactive radiation, historically called α,β, and γ radiation. Each kind of radiation consists of different particles, with γ particles (photons) being a bit different to α and β–particles, through carrying neither charge nor having a finite rest mass. α-particles are helium nuclei without electrons, thus carrying a charge of +2: $_4\text{He}^{2+}$. β-particles are electrons, which carry exactly one elementary charge, e = 1.602×10^{-19} C. Both have a finite mass.

In this experiment, we will investigate the motion of β particles in a magnetic field. The source of our electrons is a Strontium 90 radioactive source. Strontium 90 decays to Yttrium-90 and finally to Zirconium-90. Both decays are β decays, the first has a total energy of 546 keV, the latter 2274 keV. Since the preparation is encapsulated in metal foil, only electrons from the second decay can pass the foil, the foil absorbs those from the first decay.

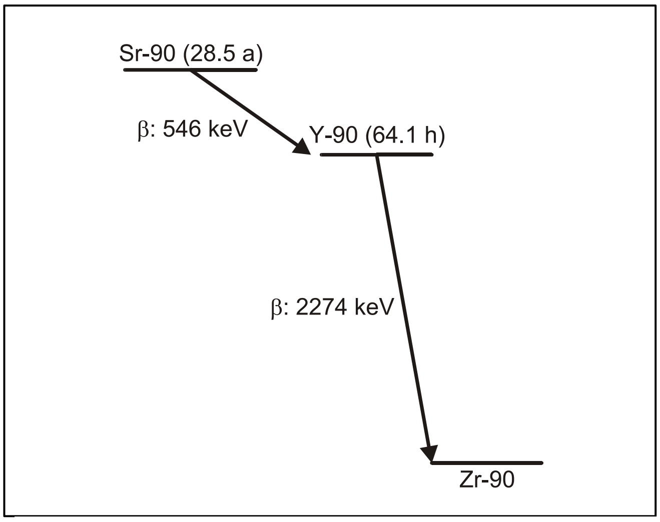

Fig. 1: Decay path of Strontium 90.

Since the beta decay is a three-particle decay involving an antineutrino (to ensure lepton number conservation), the energy spectrum of the electron doesn't consist of one characteristic line but of continuous spectrum from 0 keV up to the maximum energy, and the remaining energy carried away by the antineutrino.

When a beam of charged particles passes through a magnetic field, Lorentz force influences the motion of the beam. In a homogeneous field this results in a circular motion of the particles aroud the field lines.

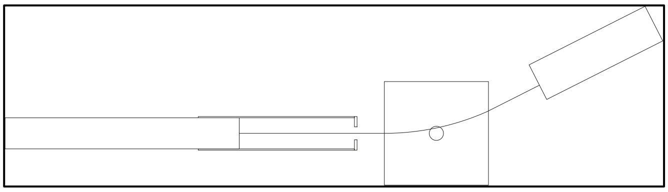

Fig. 2: Motion of charged particles in a magnetic field, with source and detector.

Describing Fig. 1: Particles emitted from a radioactive source (left) follow linear trajectories until they reach the magnetic field (middle) where they start to follow circular paths. After leaving the magnetic field, they move again linear until reaching the detector (right).

Safety Note

When handling radioactive preparations, in addition to following the Radiation Protection Ordinance, country-specific stipulations and the requirements of the school authorities must be met. The preparations used in this experiment are type-approved in accordance with German StrlSchV (2001).

Since the preparations used emit ionizing radiation, the following safety rules must be followed when handling them:

- Prevent **unauthorised persons** from gaining access to the preparations.
- Check that preparations are in **good condition** before use.
- Keep preparations in protective containers for **shielding** purposes.
- In order to **minimise exposure and keep activity as minimal as possible,** only remove the required preparations from the protective container in order to carry out the experiment.
- In order to ensure that the **greatest distance** to the preparations is maintained, only grab it at the top end of the metal rod.

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Apparatus

1	End-window counter with cable	559 01
1	Radioactive preparations, set of 3	559 835
1	Counter S	575 471
1	Multimeter LDanalog 20	531 120
1	U-core with yoke	562 11
2	Coil, 250 turns	562 13
1	Bored pole pieces, pair	560 31
1	Swiveling clamp	559 23
1	Holder with absorber foils	559 18
1	Variable extra-low voltage transformer S	521 35
1	Saddle base	300 11
1	Stand rod 25 cm, 12 mm Ø	300 41
1	Leybold multiclamp	301 01
2	Connecting lead 32 A, 50 cm, red	501 25
2	Connecting lead 32 A, 50 cm, blue	501 26
1	*Mobile-CASSY	524 005
1	*Combi B sensor S	524 0381
1	*Extension cable, 15-pole	501 11

Articles marked with * are not essential, we do however recommend them to carry out the experiment.

Since the energy of the electrons (up to 2274 keV) is much larger than the rest mass (511 keV) of the electrons, relativistic calculation is needed.

Theory

Inside the magnetic field, the electrons follow a path where the sum of centrifugal force vector and Lorentz force vector is zero:

$$\Rightarrow \frac{m\cdot v^2}{r} = evB. \qquad \text{(I)}$$

Therefore, the circular path has radius of $r = \frac{mv}{eB}$. The angular deflection of a beam passing through a magnetic field of length l (short compared to the radius r) is:

$$\alpha \approx \frac{l}{r} = \frac{leB}{mv}, \qquad \text{(II)}$$

with α in radians.

These equations are also valid for the relativistic case, though the calculation of mass and velocity is different.

$p = m \cdot v$ is called the momentum of a particle. Following Albert Einstein's Theory of Relativity, momentum, mass and energy of a relativistic particle are related trough the equation:

$$E = \sqrt{(m_0c^2)^2 + p^2c^2}, \qquad \text{(III)}$$

with the rest mass m_0. Thus, the momentum of a particle is given by:

$$p = \sqrt{\frac{E^2}{c^2} - m_0^2c^2}, \qquad \text{(IV)}$$

and the total Energy by:

$$E = E_{kin} + m_0c^2. \qquad \text{(V)}$$

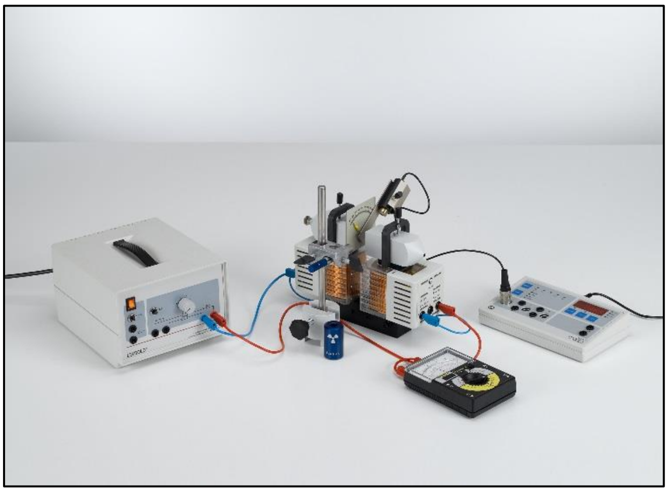

Fig. 3: Setup of the experiment.

Setup

The experiment's setup is shown in Fig. 4, while the setup of the coils is shown in Fig. 3 in more detail.

- Mount the two coils on the U-core, and the two bored pole pieces on top of the coils, one carrying the swiveling clamp.
- This can be seen in Fig. 5: the bored pole piece (3) carries the scale (2) and the clamp (1).
- Stick the round rod through the pole piece and fix it on the other side with a ring (4), a spring washer (5) and finally a fastening screw (6).
- Tighten the screw (6), so the swiveling clamp can be moved, but does not turn on its own weight.
- Place the end window counter in the swilling clamp and fixed with the screw (1.1) (see Fig. 5).
- Connect the two "E"-sockets of the coils with one another.
- Connect the variable extra-low voltage transformer S and the Multimeter LDanalog with the coils as shown in Fig. 4.
- Connect the variable extra-low voltage transformer S to the multimeter.
- Finalize the setup as shown in Fig. 4. The radioactive preparation is held by the multiclamp, attach the collimator 559 18 to it, with a 5 mm diameter plate at the end.

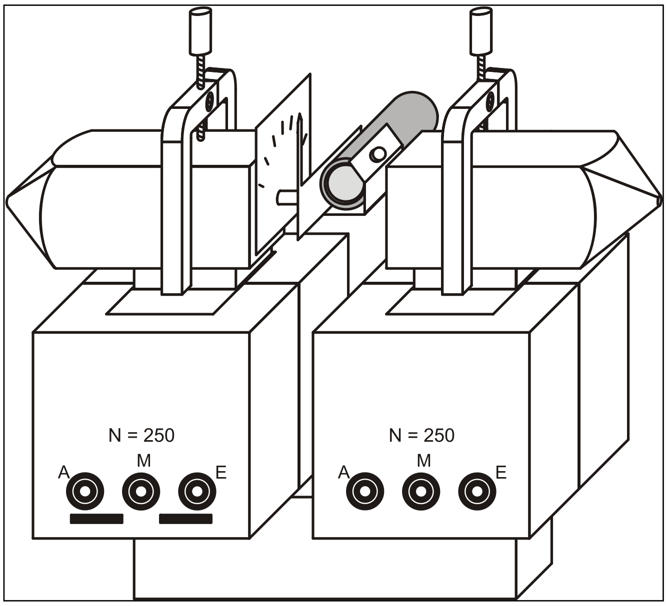

Fig. 4: Setup of the pole pieces.

- Only insert the radioactive preparation halfway into the collimators tube, as indicated in Fig. 6, to further collimate the beam.

Carrying out the Experiment

Magnetic field calibration

- If Mobile-CASSY, Combi B sensor S and the extension cable were acquired additionally, the following calibration of the magnetic field can be executed. If not, the magnetic field calibration in Fig. 7 can be used.
- First, calibrate the magnetic field. To do this, attach the combi B sensor to the included stand rod and fix it into the multiclamp, replacing the preparation.
- Note that the hall plate in the tip of the combi B sensor is only sensitive to magnetic fields perpendicular to its surface, so an additional stative rod and multiclamp have to be used to bring the combi B sensor into the correct position.
- Hold the tip of the magnetic field sensor in the center of the magnetic field between the pole pieces.
- Connect Combi B sensor S and Mobile-Cassy with the extension cable.
- Switch on the Mobile-CASSY.
- Vary the current through the coils from 0 A to 2 A, measuring the current using the multimeter, and measure the magnetic field using the Mobile-CASSY.
- The magnetic field depends linearly on the current, in the measurement example approximately 20 mT per Ampere. The exact value depends on the separation of the pole pieces.
- Remove Combi B sensor and Mobile-CASSY from the setup and attach the radioactive preparation with collimator back in place.

Angular deflection measurement

- Turn the swivel arm to zero and set the current to zero.
- On the Counter S, use the button “GATE” to select a gate time of 100 seconds, and press the button “START”.
- After 100 seconds, the counter finishes the measurement, note the value and press “START” to execute the next measurement.
- Scan the swivel arm into different positions, for example in 5°-steps from 40° to –10°.
- After scanning for zero current setting, vary the current and the magnetic field to 1 A, resulting in a magnetic field of approximately 20 mT, scan the whole angular range again, then set the current to 1.5 A (30 mT) respectively 0.75 A (15 mT).
- If there is no significant maximum visible, change the direction of current through the coils by swapping the connecting leads in the “A” sockets of the coils.

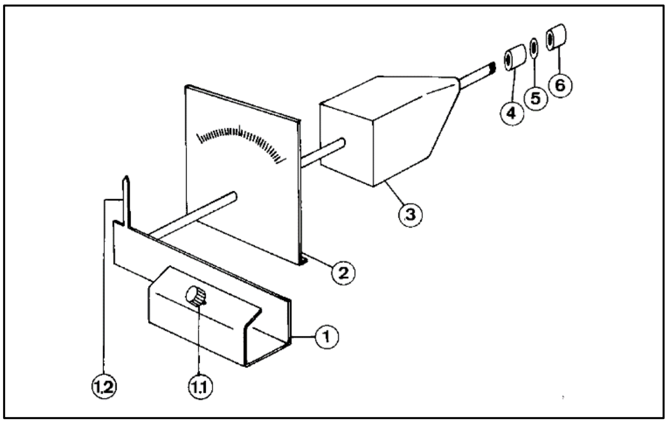

Fig. 5: Mounting the swivel clamp to one pole piece.

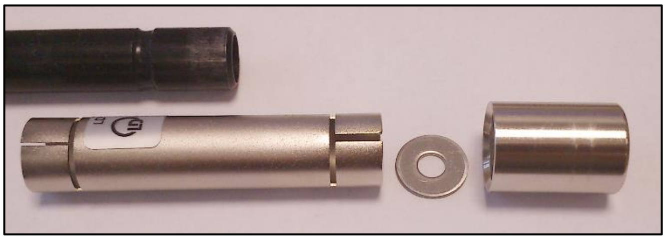

Fig. 6: Silver: Parts from 559 18 required to assemble the collimator, black: The radioactive preparation.

Measurement Example

The result of the magnetic field calibration can be seen in Fig. 7 and can be used if the optional field probe etc are not available.

The measurement of count rate versus angle and magnetic field is depicted in Fig. 8. The graphs were calculated by CASSYLab, using a Gaussian fit.

For zero magnetic field, the angular distribution is symmetric to the undeflected beam. As can be seen, a magnetic field will shift the maximum of the count rate distribution to higher angles. With increasing current, the beam of electrons is deflected. Additionally, the width of the Gaussian distribution increases.

Due to the statistical noise, a measurement time of 100 seconds per point is just enough to see the shift of the maximum, but the curves do not fit perfectly to the Gaussian. To achieve a better statistic, the gate time can be increased using the “manual” setting of the Counter S and a stop clock.

Evaluation

The angular maximum of the count rate varies with different magnetic field strengths.

The total decay energy is 2274 keV. Due to the beta decay being a three-particle decay, the spectrum of the kinetic energy of the electrons is continuous from 0 keV up to the maximum, 2274 keV.

For a rough calculation, the energy with the highest electron rate is about one third of the maximum energy, 758 keV. Additionally, the total energy of the electrons includes the rest mass of 9.11×10⁻³¹ kg. Therefore, according to (V), the total energy of the electrons with the highest rate is:

$$E_{tot} = 758\,keV + m_0c^2 = 1269\,keV$$

Using 1 keV = 1.602×10^{-16} J, the energy of those electrons is E = 2.033×10^{-13} J

Knowing this, the relativistic momentum of the electrons can be calculated via equation (IV), with the result:

$$p = 6.2 \times 10^{-22}\,\frac{kg \cdot m}{s}$$

Using equation (II) with l = 0.04 m, e = 1.602×10^{-19} C and B = 0.02 T, the calculated expected deflection is 12 degree.

In the measurement, the value is in the 20 degree range.

Result

As can be seen, the particles are deflected more than theoretically expected. On one hand, the electrons loose energy while passing through the metal foil on top of the source. Therefore, energy and momentum of the electrons are smaller than expected and they are deflected more. On the other hand, the magnetic field extends much wider than just the size of the iron pole pieces affecting the beam over a longer path length, different from Fig. 1.

Finally, the approximation that l is much smaller than r, used to acquire equation (II), is not very correct, which increases the errors of the calculation.

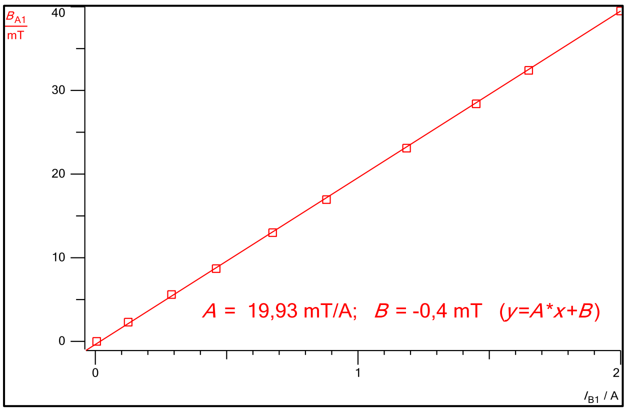

Fig. 7: Magnetic field calibration.

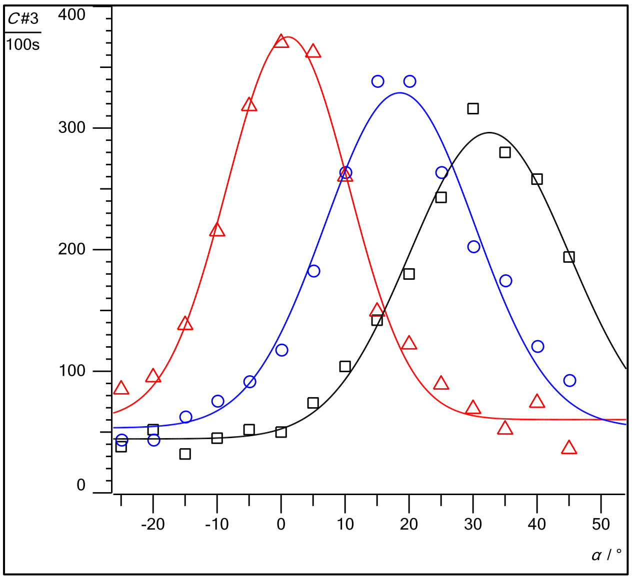

Fig. 8: Measured count rates depending on the angle at different currents;, Δ: no magnetic field, ○: magnetic field of 20 mT (1A), □: magnetic field of 40 mT (2A).