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A magnet system for the suppression of conversion electrons in alpha spectrometry

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HIGHLIGHTS

- A magnet system is constructed for use in alpha-particle spectrometry.
- It accommodates sources with a diameter up to 30 mm.
- It suppresses detection of conversion electrons.
- Summing effects between electrons and alpha particles are drastically reduced.
- Alpha emission probabilities are measured with higher accuracy and precision.

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ABSTRACT

A new magnet system has been designed and constructed to reduce coincidence effects between alpha particles and conversion electrons in high-resolution alpha-particle spectrometry. By means of a magnetic field, the conversion electrons are deflected away from the PIPS® detector. Compared to existing magnet systems, the new system is not restricted to point sources and can accommodate source diameters up to about 30 mm. Two yokes were built, allowing for configurations with 20 mm or 36 mm distance between the magnets. The effectiveness of both configurations is demonstrated by measuring the conversion electron spectrum of a ^{237}Np source. The magnet system effectively rejects 93 (7)% of electrons up to 85 keV (36 mm) and 90 (9)% of electrons up to 320 keV (20 mm). It has been successfully applied in the alpha-particle spectrometry of the long-lived nuclides ^{236}U and ^{238}U, resulting in significant improvement of the accuracy of alpha emission probabilities.

1. Introduction

The high-resolution alpha spectrometers at IRMM (Pommé and Sibbens, 2008) are dedicated to the improvement of our knowledge of nuclear decay data, such as alpha emission energies and probabilities. For these measurements, any other contribution to the spectrum interfering with alpha peaks of interest is unwanted. Of key importance is the use of sources with high enrichment in the nuclide being studied and with low energy absorption of the emitted alpha particles. To further optimise spectral quality, the sources are measured at a convenient distance that conciliates energy resolution and counting statistics. This dilemma is most pertinent for radionuclides with low specific activity, which require relatively big sources being measured close to the detector (Siiskonen and Pöllänen, 2006; Jobbágy et al., 2013; Pommé et al., In this issue).

Such close configurations suffer from the additional problem of true coincidence effects between the alpha particles and conversion electrons, as low-energy gamma transitions of actinides are often highly converted. The detection efficiency for conversion electrons is high for the PIPS® detectors used in these setups (Sibbens et al., 2010) and the simultaneous detection of electrons and alpha particles distorts the energy spectrum. The resulting effects are peak shape deformation, summing-out of the low-energy peaks, summing-in of the high-energy peaks (Hessberger et al., 1989) and as a consequence erroneous peak fitting and emission probability assignments. Ways to mitigate these effects are reducing the effective solid angle (e.g. by increasing the source to detector distance), applying mathematical correction models in the data analysis or applying a magnetic field to bend away the electrons from their path towards the detector.

In the past, the magnetic field between two permanent magnets separated by 10 mm was successfully applied and resulted in a significant reduction of conversion electron peaks below 200 keV in

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a ^{237}Np spectrum (Bortels et al., 1990; Sibbens and Denecke, 2000). However, the use of this suppression system is limited to quasi-point sources.

For the purpose of measuring nuclear decay data of nuclides with extremely long half-lives, like e.g. ^{236}U (Marouli et al., In this issue) and ^{238}U (Pommé et al., 2013), a new magnet system was developed to accommodate sources with a diameter up to 30 mm. A simple physical model was applied to determine the magnetic field strength required to deflect the conversion electrons without too much affecting the detection of the alpha particles.

2. The required magnetic field

2.1. Trajectory of a charged particle

A centripetal magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ acts on a particle with charge q moving with a velocity $\vec{v}$ in a uniform magnetic field $\vec{B}$. The magnetic force will only change the direction of $\vec{v}$ while the magnitude v remains constant (Serway, 1990). This property makes the magnetic force ideally suitable to deflect particles without affecting their kinetic energy. The resulting trajectory is circular, with a gyroradius of

$$r = \frac{mv}{|q|B}, \quad (1)$$

in which m is the mass of the particle. The sign of the charge q determines the direction of the bend, which is different for electrons than for alpha particles. This equation holds also for the relativistic mass $m = \gamma m_0$. The Lorentz factor γ, can be expressed as a function of rest mass m_0 and kinetic energy K or momentum $p = mv$ via

$$\gamma = 1 + \frac{K}{m_0 c^2} \quad = \sqrt{1 + \left(\frac{p}{m_0 v}\right)^2} \quad (2)$$

Inverting Eq. (2) to express p as a function of γ leads to a convenient relativistic formula for the gyroradius (Eq. (1)):

$$r = \frac{m_0 c}{|q|B}\sqrt{(\gamma^2 - 1)} \quad (3)$$

which at a non-relativistic speed reduces to the classical formula:

$$r = \frac{\sqrt{2 m_0 K}}{|q|B} \quad (4)$$

2.2. Electrons

In the particular case of an electron, $q = -e = -1.6022 \times 10^{-19}$C, $m_0 = 9.1094 \times 10^{-31}$ kg, $c = 2.9979 \times 10^8$ m s^{-1} (Mohr et al., 2011), the relativistic gyroradius is

$$r = \frac{1.70 \text{ mmT}}{B}\sqrt{(\gamma^2 - 1)}, \quad (5)$$

in which B is the field strength in tesla (1 T = 1 kg C^{-1} s^{-1}). For an electron with $K = 200$ keV one finds $\gamma = 1.39$ (Eq. (2)) and in a magnetic field of 0.5 T the gyroradius is 3.3 mm. Using the classical formula (Eq. (4)) one would obtain a smaller radius of 3.0 mm.

By means of Eq. (5), one can estimate which magnetic field strength is required to prevent conversion electrons from reaching the detector. Imagine a uniform magnetic field $\vec{B}$ applied between a source and a detector, as shown in Fig. 1. The magnetic field is directed into the page and stretches over a height h and a width that corresponds to at least the diameter of the source. A secure way to assure that an electron ejected at a small angle from the source does not hit the detector is to force it into a circular trajectory with a radius that is smaller than half of the height of the magnetic field, that is $r \le h/2$. This should also be more than sufficient to deflect particles that are emitted in a direction perpendicular to the source surface, as even a radius $r = h$ may suffice in this case. The required field strength can therefore be calculated from

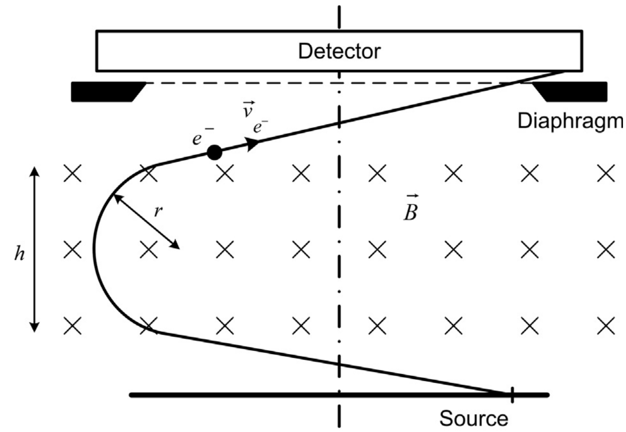

Fig. 1. The direction of the velocity $\vec{v}$ of an electron leaving the source at a small angle is changed when it passes through a magnetic field $\vec{B}$ (directed into the page). When the radius r of circular path is small enough, the electron will not reach the detector.

$$B \ge \frac{3.41 \text{ mmT}}{h}\sqrt{(\gamma^2 - 1)} \quad (6)$$

Assuming, for example, a field height of $h = 10$ mm, one requires a magnetic field strength of 0.33 T to fully deflect electrons of 200 keV, and about half that strength (0.17 T) for 60 keV electrons.

2.3. Alpha particles

The magnetic field should be strong enough to reject the electrons, but on the other hand should preferably not significantly affect the trajectory of the alpha particles. The radius of the trajectory of an alpha particle ($q = 2e$, $m_0 = 6.6447 \times 10^{-27}$ kg) and kinetic energy K (in MeV) in a magnetic field B is (Eq. (4))

$$r = 0.144 \text{ mmT}\frac{\sqrt{K \text{ MeV}^{-1}}}{B} \quad (7)$$

In the assumption that the alpha particle leaves the source at the normal angle and moves through a constant magnetic field stretching over $h = 10$ mm, the particle is deflected over an angle $\delta = \arcsin(h/r)$ when it leaves the field. At that position it is deflected from its normal trajectory by a distance

$$d = r - \sqrt{r^2 - h^2} \approx h^2/2r \quad (8)$$

For a 5 MeV alpha particle in a field of 0.5 T, the gyroradius is 64 cm and the deflection from its original trajectory is $d = 78$ μm. The particle moves further in its new direction and diverts by about 155 μm per extra centimetre distance between the magnet exit plane and the detector plane. Decreasing the alpha energy to 4 MeV makes a change of about 12% in gyroradius (Eq. (7)) and a difference in displacement by $\Delta d = 9$ μm (Eq. (8)) at the exit plane of the field. With every additional centimetre the difference in displacement grows by 19 μm.

Apparently, the energy dependence of the bending radius (Eq. (7)) may introduce a subtle difference of the detection efficiency as a function of alpha energy. This effect has not yet been studied into detail. Therefore, it is recommended to carefully optimise the magnetic field to the intended purpose, based on the energy of the conversion electron of the nuclide of interest and the diameter of the source, rather than using an overly strong