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Abstract

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A LONGITUDINAL β -SPECTROMETER WITH COMPENSATED SPHERICAL ABERRATION

(Presented by Academician L. A. Artsimovich, December 14, 1956)

In the present work a β -spectrometer with a longitudinal uniform magnetic field is described, whose spherical aberration is compensated by a transverse magnetic field with intensity varying according to the law $H = H_1/r$. The additional field was produced by a winding, the shape of whose turns was chosen so that electrons emerging from the source within a large solid angle formed a linear annular focus*.

The calculation of electron trajectories in the region of a uniform field presents no difficulty. In the region where a field of intensity $H = H_1/r$ is superposed on the uniform magnetic field, the differential equations of electron motion reduce to quadratures ⁽¹⁾, which can be represented in the form:

$$\begin{aligned} \frac{z - z_0}{r_0} &= \int_1^\rho \frac{(\cos \psi_0 + K \ln \rho) d\rho}{\sqrt{1 - (\sin \psi_0 \sin \varphi_0 \rho)^2 - (\cos \psi_0 + K \ln \rho)^2}}, \\ \varphi - \varphi_0 &= \int_1^\rho \frac{\sin \varphi_0 \sin \psi_0 d\rho}{\sqrt{1 - (\sin \psi_0 \sin \varphi_0 \rho)^2 - (\cos \psi_0 + K \ln \rho)^2}}. \end{aligned} \quad (1)$$

Here a cylindrical coordinate system r, φ, z has been used, whose z -axis coincides with the axis of the instrument, and whose origin is placed at the source. The direction of the axes $z = 0, \varphi = 0$ coincides with the direction of the projection of the velocity of the electron emerging from the source onto the plane $z = 0$; $\rho = r/r_0$; r_0, φ_0, z_0 are the coordinates of the point of entry of the electron into the inhomogeneous field; ψ_0 is the angle between the direction of the electron velocity at the moment of its emission from the source and the z -axis; $K = -H_1/H\rho$, where $H\rho$ is a quantity characterizing the momentum of the electron.

Since the compensating field was located near the vertex of the trajectories, it could be assumed that ρ in equation (1) varies relatively little, and one may set

Fig. 1. β -spectrometer with compensated spherical aberration

Figure 1: Fig. 1. β -spectrometer with compensated spherical aberration

$\rho = 1 + x$, where $x \ll 1$, and $\ln \rho = x - x^2/2$. Under this assumption, equations (1) can be integrated:

$$\frac{z - z_0}{r_0} = \frac{1}{\sqrt{-c}} \left[\cos \psi_0 - \frac{bK}{2c} - \frac{K}{2} \left(\frac{3b^2}{8c^2} - \frac{a}{2c} \right) \right] \left(\arcsin \frac{b}{\sqrt{-\Delta}} - \arcsin \frac{2cx + b}{\sqrt{-\Delta}} \right) + \frac{K}{c} \left[1 - \frac{1}{4} \left(x - \frac{3b}{2c} \right) \right] \sqrt{a + bx + cx^2} - \frac{K}{c} \left(1 + \frac{3b}{8c} \right) \sqrt{a},$$

* Compensation of aberrations can also be carried out in other types of longitudinal fields. Thus, upon becoming acquainted in 1955 with our instrument, which at that time was in the process of assembly, B. S. Dzheleпов informed us that in his laboratory a β -spectrometer with a short magnetic lens was being tested, in which compensation of the spherical aberration of the lens is produced by a transverse field formed by turns arranged near the source. Subsequently this work was reported at the conference on β -spectroscopy in February 1956.

$$\varphi - \varphi_0 = \sin \psi_0 \sin \varphi_0 \frac{1}{\sqrt{-c}} \left(\arcsin \frac{b}{\sqrt{-\Delta}} - \arcsin \frac{2cx + b}{\sqrt{-\Delta}} \right),$$

where

$$a = 1 - \sin^2 \psi_0 \sin^2 \varphi_0 - \cos^2 \psi_0; \quad b = -2 \sin^2 \psi_0 \sin^2 \varphi_0 - 2K \cos \psi_0;$$

$$c = -\sin^2 \psi_0 \sin^2 \varphi_0 - K^2 + \cos \psi_0 K; \quad \Delta = 4ac - b^2.$$

Using these formulas, the shape of the boundary of the inhomogeneous field was found that ensures the production of an aberration-free annular focus (when a point source is used), coinciding with the linear annular focus formed by an infinitely narrow beam of electrons emitted with initial angles close to 30° . Electron trajectories were calculated for which the emission angle ψ_0 varies from 20 to 40° in steps of 2° , under the condition that $K = -0.07$ and the intensity of the uniform magnetic field H_0 is characterized by the relation

Fig. 1. β -spectrometer with compensated spherical aberration

$$K_0 = -\frac{H_0}{2(H\rho)} = -0.07.$$

Fig. 2. Shape of the boundary of the compensating magnetic field (without allowance for the stray field). The dashed line indicates the calculated shape of the boundary

Figure 2: Fig. 2. Shape of the boundary of the compensating magnetic field (without allowance for the stray field). The dashed line indicates the calculated shape of the boundary

Fig. 3

Figure 3: Fig. 3

In this case, the electron trajectories with emission angle $\psi_0 = 30^\circ$ pass at all times through a uniform field.

The longitudinal field was produced by coil 1 (Fig. 1), with an internal diameter of 33 cm and a length of 110 cm, wound on a copper tube that at the same time served as the chamber of the spectrometer. To improve the field uniformity, correction coils 2 were used. This system provided uniformity of the longitudinal magnetic field in the working region (50 cm long) with an accuracy up to 0.4%. Coil 3, producing the transverse compensating field, consisted of 30 turns of wire 1 mm in diameter, arranged symmetrically with respect to the axis. It was connected in series with coils 1 and 2. The shape of the turns coincided with the calculated shape of the field boundary everywhere, except for those portions of the additional field where the trajectories of electrons emitted at angles of 20 and 40° pass (Fig. 2).

Fig. 2. Shape of the boundary of the compensating magnetic field (without allowance for the stray field). The dashed line indicates the calculated shape of the boundary.

The radioactive source was glued to holder 4 (Fig. 1), which, through a Wilson seal and a vacuum stopcock, was introduced into the chamber without breaking the vacuum. As the detector, an end-window G-M counter 5 with a window diameter of 90 mm was used. The window was covered with a cellophane film 17 μ thick, which at 80 keV transmits about

50% of the electrons. The entrance diaphragm 6 made it possible to select electrons in the solid angle $\Omega = 8.7\%$ (ψ_0 from 20 to 40°) or in the solid angle $\Omega = 7\%$ (ψ_0 from 25 to 40°) of the full solid angle 4π .

Fig. 3. Microphotograms of the ring image. **1**—in a uniform field; **2**—in a field with compensated spherical aberration. Along the abscissa axis is plotted the distance from the outer edge of the ring image; along the ordinate axis, the intensity in arbitrary units.

The transmission of the instrument decreased because the inner correcting coil blocked part of the beam, approximately 15%. At the position of the annular focus an annular diaphragm 7 was placed.

Fig. 4

Figure 4: Fig. 4

At first, the properties of the instrument were studied with the aid of an electron gun and a movable fluorescent screen placed perpendicular to the axis of the instrument. This showed that the use of a compensating field reduces the width of the ring image by approximately a factor of 2.5 in comparison with the image width in a uniform field.

Further investigations were carried out with a radioactive source (active deposit of ThB) of size $1 \times 1 \text{ mm}^2$. To determine the position of the annular focus and its dimensions, an x-ray film was placed in the path of the β -particle beam; on it an image of the annular focus was obtained, formed by the conversion electrons of the F -line of ThB (energy 148 keV). The position of the film was determined for which the image width was the smallest, both in the case of a uniform field (with the internal coil switched off) and in the field with corrected spherical aberration. Fig. 3 shows microphotograms characterizing the distribution of electron-beam density in the ring image. The blurring of the ring image on the inner side may be explained by scattered electrons; therefore, as a characteristic of the line width, the extrapolated width at the base was chosen. For a uniform field the extrapolated line width is 12 mm, whereas the extrapolated line width in the field with compensated spherical aberration is only 5 mm. But the main intensity of the electrons is concentrated in a narrower ring; therefore the width of the annular diaphragm can be made smaller than the extrapolated line width without appreciable loss of intensity.

On the basis of the microphotograms obtained, for the field with compensated spherical aberration an annular diaphragm was chosen with an outer diameter of 108 mm and a slit width of 3 mm, which transmitted about 88% of all electrons. With this diaphragm, tests of the β -spectrometer were carried out during operation with a counter. With a source size of $1 \times 1 \text{ mm}^2$ and a solid angle of 8.7% of 4π (transmission 6.5%), the half-width of the line proved to be 1.9%. Using a circular source 5 mm in diameter and under otherwise unchanged conditions, it was possible to obtain a line half-width of 3%. For a solid angle of 7% of 4π (transmission 5.2%) with a $1 \times 1 \text{ mm}^2$ source, the half-width—

Fig. 4. Line shape at a transmission of 5.2% ($\Omega = 7\%$). Along the abscissa axis is plotted the current strength in the spectrometer coils.

For a solid angle of 7% and a $1 \times 1 \text{ mm}^2$ source, the half-width ...

the line was 1.4% (Fig. 4). For comparison, the F -line was also recorded in a homogeneous magnetic field; moreover, according to the data obtained from microphotograms, the width of the slit of the annular diaphragm was made equal to 9 mm. This diaphragm also transmitted about 88% of the radiation. With source dimensions $1 \times 1 \text{ mm}^2$ and a solid angle of 8.7% (transmission 7.7%), the half-width of the line was found to be 5.7%. Thus, at a solid angle of

8.7%, the use of a compensating field increases the resolving power by a factor of 3. However, the presence of the compensating coil inside the instrument, as already noted, reduces the transmission. In a homogeneous field without an internal coil, the same transmission can be obtained at a smaller solid angle. At a transmission of 6.5% (equal, in the ideal case, to the solid angle), the theoretical half-width of the line in a homogeneous field is 3.6% (²), which is approximately 2 times worse than in a field with compensated spherical aberration at the same value of the transmission.

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