INVESTIGATION OF POLARIZATION OF INTERNAL CONVERSION ELECTRONS IN TRANSITIONS FOLLOWING DECAY OF HEAVY ELEMENTS

M. E. VISHNEVSKIĬ, V. A. LYUBIMOV, E. F. TRETYAKOV, and G. I. GRISHUK

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Polarization of conversion electrons has been measured for transitions following β^- decay in Tm^{170}, Re^{186}, Hg^{203} and Pa^{233}. The conversion electrons were found to be polarized in the direction of emission of the β^- particles for Tm^{170} and Re^{186}, and in the opposite direction for Hg^{203} and Pa^{233}. The most probable value of the ground state spin of β^--decaying nuclei has been determined for Hg^{203} and Pa^{233}. Experimental data for Tm^{170} and Re^{186}, for which all transition constants are known, are compared with the theoretical polarization values.

PARITY nonconservation in weak interactions has now been firmly established. In some cases one can use the laws of weak interaction to investigate the characteristics of nuclear transitions.

Thus, old methods of nuclear spectroscopy can be supplemented with new "non-classical" methods (experiments with polarized particles, participating in weak interactions).

One of these methods, particularly suitable for the study of heavy nuclei, is the measurement of the polarization of the electrons in internal conversion following β^- decay. The effect of polarization of the conversion electrons following the decay was predicted by A. I. Alikhanov and V. A. Lyubimov (see reference 1), and was experimentally observed by Lyubimov and Vishnevskiĭ.[2] The theory of this phenomenon was developed by V. B. Berestetskiĭ and A. P. Rudik[3] and by B. V. Geshkenbeĭn.[4]

The results of the present paper were reported at the International Conference on High-Energy Physics in Kiev, July 1959.[2]

DESCRIPTION OF THE APPARATUS

The internal-conversion electrons were polarized in the direction of the nuclear polarization due to the preceding β decay. If the conversion electrons emitted at 90 deg to the momentum of the particles are separated, the polarization is found to be transverse, and this greatly facilitates its measurement. Transverse polarization of conversion electrons was determined from the azimuthal asymmetry of the Mott scattering by gold nuclei.

A diagram of the instrument is shown in Fig. 1.

The β electrons from a given source b were registered in counters 1 and 2. The conversion electrons emitted after the β decay were separated by a toroidal spectrometer after being scattered from gold scatterer d through an average of 135 deg, and registered by counters 3 and 4, connected pairwise for coincidence with β counters 1 and 2. Counters 3 and 4 were oriented in a plane perpendicular to the axis of counters 1 and 2

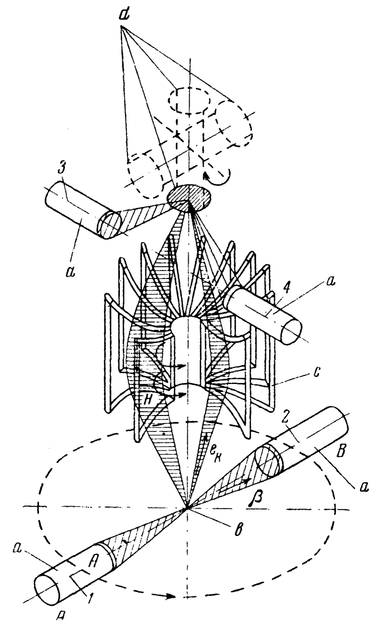

FIG. 1. Diagram of the instrumentation. a – scintillation counters, b – beta source, c – toroidal coil, d – scatterers.

Since the conversion electrons were monochromatic and the transverse component of their polarization exhibited little dependence on the angle θ between the directions of the β and conversion electrons for θ close to 90 deg, it became possible to separate the conversion electrons from the β particles by a wide-angle high-aperture magnetic spectrometer[5] with good energy resolution for the electrons.

Counters 1 and 2 separate the oppositely-directed β particles from the source. Thus, depending on which of the β counters, 1 or 2, coincides with the pulses from the conversion-electron pulses in counters 3 or 4, one measures the azimuthal asymmetry in the scattering of electrons with opposite spin directions. This is equivalent to replacement of the "right-hand" counter by the "left-hand" one, customarily used to measure scattering asymmetry. In addition, as a check on the measurements, counters 1 and 2 were rotated 180 deg, from position AA to position AB (Fig. 1). In this case asymmetry due to the instrumentation can be excluded without additional measurements. Actually, after subtracting the background, the coincidences between the conversion electrons and the β electrons are given by

$$(N_{13})_{AA} = a(\eta_1\eta_3)_{AA}\eta_{13}(1 - S\langle\sigma\rangle),$$
$$(N_{14})_{AA} = a(\eta_1\eta_4)_{AA}\eta_{14}(1 + S\langle\sigma\rangle),$$
$$(N_{23})_{AA} = a(\eta_2\eta_3)_{AA}\eta_{23}(1 + S\langle\sigma\rangle),$$
$$(N_{24})_{AA} = a(\eta_2\eta_4)_{AA}\eta_{24}(1 - S\langle\sigma\rangle),$$
$$(N_{13})_{AB} = a(\eta_1\eta_3)_{AB}\eta_{13}(1 + S\langle\sigma\rangle),$$
$$(N_{14})_{AB} = a(\eta_1\eta_4)_{AB}\eta_{14}(1 - S\langle\sigma\rangle),$$
$$(N_{23})_{AB} = a(\eta_2\eta_3)_{AB}\eta_{23}(1 - S\langle\sigma\rangle),$$
$$(N_{24})_{AB} = a(\eta_2\eta_4)_{AB}\eta_{24}(1 + S\langle\sigma\rangle),$$

where a is a proportionality coefficient, η_i is the probability of registering an electron by an individual counter (determined by the solid angles, the efficiency of the counter, etc.) and may not be the same in positions AA and AB; η_{ik} are the corresponding probabilities, which depend on the counter combination (for example, the efficiency of coincidences in channel ik). The values of η_{ik} are independent, with sufficiently good approximation, of the positions of counters AA or AB; S is the asymmetry of single scattering of fully polarized electrons by gold, with allowance for the geometric parameters of the instrument, and $\langle\sigma\rangle$ is the degree of transverse polarization of the electrons.

It is easily seen that one can make up of the measured eight quantities $(N_{ik})_{AB}$ and $(N_{ik})_{AA}$ an expression that depends only on the degree of polarization of the electrons. Actually, the asymmetry coefficient

$$R = \left[\left(\frac{N_{13}N_{24}}{N_{14}N_{23}}\right)_{AA}\left(\frac{N_{14}N_{23}}{N_{13}N_{24}}\right)_{AB}\right]^{1/4} = \frac{1 - S\langle\sigma\rangle}{1 + S\langle\sigma\rangle},\; S\langle\sigma\rangle = \frac{1-R}{1+R}$$

does not include the instrumentation asymmetry.

As a rule, to exclude the instrumentation asymmetry, additional measurements are made with a scatterer made of light material. In this case the azimuthal asymmetry due to the polarization of the electrons should be practically zero. In our case there is no direct need for such measurements. Measurements with an aluminum scatterer were made by us only for control purposes and disclosed a high degree of exclusion of the instrumentation asymmetry for all the substances investigated, namely:

β source	Tm^{170}	Pa^{233} ($E_\gamma = 312.6$ kev)
R	1.00 ± 0.02	0.98 ± 0.02
β source	Pa^{233} ($E_\gamma = 74.8$ kev)	Hg^{203}
R	1.01 ± 0.03	0.97 ± 0.03

The measurements were made in the following sequence: first with a gold scatterer, then with an aluminum scatterer, and finally with an empty frame (to exclude the cases of scattering from the walls of the instrument and from the frame of the scatterer). The background of random coincidences was measured directly for each case. All the measurements and the interchange of the scatterers were automatic, the result being recorded on corresponding groups of mechanical counters. The measurements were carried out both in position AA and in position AB, at approximately equal times for each measurement. It can be seen from the definition of the asymmetry coefficient R (see also Fig. 1) that if the measured R is greater (less) than unity the internal-conversion electrons following the β decay should be polarized against (with) the direction of emission of the β particle.

MEASUREMENT RESULTS

Thulium, Tm^{170}. The β decay of Tm^{170} is accompanied by strong γ-ray conversion, and the constants of the transitions of Tm^{170} are well known.[6] This source is therefore very convenient for experimental verification of the theory of conversion-electron polarization. In approximately 24% of the cases, the β decay is to the excited level Yb^{170} with E = 84.23 kev, which is then de-excited by the internal-conversion electron with multipolarity E2 in accordance with the scheme

$$1^- \xrightarrow[\beta, 864 \text{ kev}]{} 2^+ \xrightarrow[e,\,\gamma,\,84.2 \text{ kev}]{} 0^+.$$

We measured the polarization of the conversion electrons emitted from the L shell (E_{eL} = 75 kev). The measured asymmetry of scattering by a gold scatterer (0.07 mg/cm^2) was

$$R_{Au} = \left[\left(\frac{N_{13}N_{24}}{N_{14}N_{23}}\right)_{AA}\left(\frac{N_{14}N_{23}}{N_{13}N_{24}}\right)_{AB}\right]^{1/4} = 0.83 \pm 0.03.$$

It follows therefore that

$$2S\langle\sigma\rangle = 2(1-R)/(1+R) = 0.19 \pm 0.03.$$

The value obtained for the asymmetry S corresponds to conversion electrons polarized in the direction of the emitted β electron.

It is necessary to correct the measured asymmetry for the finite thickness of the scatterer. The value of this correction for electrons of different energies, at an identical scatterer placement, was carefully measured by Alikhanov, Eliseev and Lyubimov.[7] Corrected for finite scatterer thickness, the result was

$$(2S\langle\sigma\rangle)_0 = +0{,}22 \pm 0{,}03.$$

Using the data tabulated by Sherman[8] and the corrections for these data from reference 7, we can obtain, allowing for the geometrical parameters of the instrument, the polarization of the conversion electrons

$$\langle\sigma\rangle_{\exp} = (0{,}49 \pm 0{,}06)\, v/c.$$

In this case the average value of v/c for the registered part of the β spectrum is 0.78.

According to the theory of Geshkenbeĭn[4] the polarization of conversion electrons from the L level in electrical transitions is

$$\langle\sigma\rangle = \alpha \frac{\mathscr{L}(\mathscr{L}+1) + J_2(J_2+1) - J_3(J_3+1)}{2\mathscr{L}(\mathscr{L}+1)J_1(1+|\eta_{L_i}|^2)}$$

$$\times \{(\mathbf{vn})\mathbf{n} + \sqrt{\mathscr{L}(\mathscr{L}+1)}\operatorname{Re}\eta_{L_i}[\mathbf{v} - (\mathbf{vn})\mathbf{n}]\},$$

where α depends on the same combination of constants and matrix elements as the angular distribution of the electrons in β decay of polarized nuclei,

$$\alpha = \frac{\lambda_{J_1J_2}|C_A|^2|M_{GT}|^2 2\delta_{J_1J_2}\sqrt{J_2(J_2+1)}\operatorname{Re}C_V C_A^* M_F M_{GT}}{|C_A|^2|M_{GT}|^2 + |C_V|^2|M_F|^2},$$

$$\lambda_{J_1J_2} = [J_2(J_2+1) - J_1(J_1+1) + 2]/2(J_2+1);$$

M_F and M_{GT} are the nuclear matrix elements, $\mathscr{L}$ is the multipolarity of the γ quantum, J_1 is the spin of the nucleus prior to β decay, J_2 is the spin of the nucleus prior to conversion, J_3 is the spin of the nucleus after conversion, $\mathbf{v}$ is the electron velocity, $\mathbf{n}$ is the unit vector in the direction of emission of the conversion electron, η_{L_i} is a function of the radial integrals, while C_A and C_V are the interaction constants.

The main contribution to the polarization is made by the electrons from the L_{II} and L_{III} shells.

According to the Geshkenbeĭn calculations, $\eta_{L_{II}} = 0.51 \pm 0.25$ and $\eta_{L_{III}} = 0.534$.

This gives for the polarization

$$\langle\sigma\rangle_{\text{theor}} = +0.488\, v/c,$$

which is in good agreement with the experimental value.

Protactinium, Pa^{233}. The decay scheme of protactinium and the characteristics of the transition are given in the book by Dzhelepov and Peker.[6] Principal attention was paid here to a measurement of the polarization of the conversion electrons produced by de-excitation of the 312.6-kev excited level of U^{233}, in accordance with the scheme

$$(1/2,\ 3/2,\ 5/2) \xrightarrow[E_\beta=257\text{ kev}]{} (3/2)^+ \xrightarrow[E_\gamma=312.6\text{ kev}]{} (5/2)^+.$$

We measured directly the polarization of the conversion electrons from the K shell, arising as a result of a type-M1 transition at $E_\gamma = 312.6$ kev. The experimental value of the scattering asymmetry is $R = 1.10 \pm 0.02$, i.e., the electrons are polarized against the direction of the β-particle momentum.

After introducing corrections for the finite thickness of the scatterer (0.45 mg/cm²) and for the contamination by cascade transitions, we obtained the experimental value of the polarization $\langle\sigma\rangle = (-0.48 \pm 0.14)\, v/c$ (the average value of v/c is 0.56).

For the proposed values of the spin of the ground state of Pa^{233} ($1/2$, $3/2$, or $5/2$), the calculated values of the polarization are respectively

$$\langle\sigma\rangle_{1/2} = -0.334\, v/c,\quad \langle\sigma\rangle_{3/2} = (-0.334 \div +0.200)\, v/c,$$

$$\langle\sigma\rangle_{5/2} = 0.200\, v/c.$$

If the ground state of Pa^{233} has a spin $3/2$, the transition is between the levels $3/2$ and $3/2$. In this case the calculated value of the polarization depends on the combination of the matrix elements of the β transition. Figure 2 shows the calculated

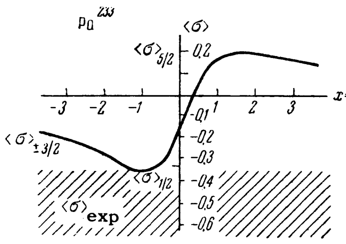

FIG. 2. Polarization $\langle\sigma\rangle$ calculated as a function of the ratios x of the matrix elements of the β^- transition $Pa^{233} \to U^{233}$. The shaded area shows the region of possible experimental values of $\langle\sigma\rangle$.

value of the polarization as a function of the ratio of the matrix element $x = M_F/M_{GT}$ ($C_A = -1.2\, C_V$), and shows also the experimental value of $\langle\sigma\rangle$. Bearing in mind the possible inaccuracies in the intensity of the transitions between the levels of the "daughter" nucleus Pa^{233}, as well as experimental errors, our data agree with the theory if a value of $1/2$ or $3/2$ is assumed for the spin of the ground state of Pa^{233}. In the latter case there is an interference between the Fermi and the Gamow-Teller interactions, and the matrix elements have opposite signs.

For purposes of control, we measured the polarizations of the conversion electron from the 74.5-kev γ quanta produced in the transition between two excited levels of U^{233} in accordance with the scheme

$$(1/2,\ 3/2,\ 5/2) \xrightarrow[E_{\beta^-}=145\ \text{kev}]{} (3/2)^+ \xrightarrow[e,\ E_\gamma=74.5\ \text{kev}]{} (5/2)^+$$

(excited state). This transition is almost analogous with the previous one and differs in the energies of the β particles and of the conversion electrons. The asymmetry obtained is $R = 1.06 \pm 0.04$ and corresponds to the same direction of conversion-electron polarization as in the case of a 312.6-kev γ transition.

Mercury, Hg^{203}. A study of the polarization of the conversion electrons accompanying the β decay of Hg^{203} is of interest, because we can establish here a connection between the spin ($1/2$, $3/2$, or $5/2$) of the ground state of Hg^{203}, which is not accurately known (see reference 6). The decay of Hg^{203} is characterized by the fact that the conversion electrons have an energy exceeding the end-point energy of the β spectrum. Because of this, the measurements were carried out with a spectrometer of lower resolution (see reference 2). The measurements have shown that the electrons are polarized against the direction of emission of the β particles, and the polarization has a value $\langle\sigma\rangle = (-0.32 \pm 0.09)\mathbf{v/c}$ at an average $V/C = 0.55$. The calculated values of the polarization are

$$\langle\sigma\rangle_{\pm 1/2} = 0.495\ v/c;\quad \langle\sigma\rangle_{\pm 3/2} = (0.495\ \text{to} - 0.297)\ v/c;$$
$$\langle\sigma\rangle_{\pm 5/2} = -0.297\ v/c,$$

for spins $\pm 1/2$, $\pm 3/2$, and $\pm 5/2$, respectively.

Figure 3 shows the calculated values and the experimental data of polarization.

The results of the measurements agree with the values of the spin of the ground state of Hg^{203}, $\pm 5/2$ and $\pm 3/2$, and disagree with the value $\pm 1/2$.*

In the case of a $3/2 \to 3/2$ type of transition, there is an interference between the Fermi and the Gamow-Teller interactions. The matrix elements have like signs.

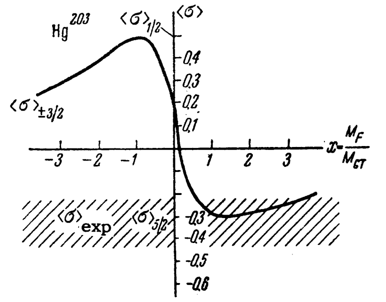

FIG. 3. Polarization $\langle\sigma\rangle$ calculated as a function of the ratios x of the matrix elements of the β^- transition $Hg^{203} \to Tl^{203}$. The shaded area shows the region of possible experimental values of $\langle\sigma\rangle$.

Rhenium, Re^{186}. The setup of reference 2 was used to measure the sign of the electrons of the conversion that follows the beta decay of Re^{186}. The decay of Re^{186} is similar to the decay of Tm^{170}. As in the decay of Tm^{170}, the electrons of the conversion following the beta decay of Re^{186} are polarized in the direction of the beta-particle momentum.

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*The results of the experiments were interpreted differently earlier.[2] The experimental data were compared with the Geshkenbeĭn formulas,[4] in which the sign of polarization was in error. The error in the formula was discovered by Geshkenbeĭn after we measured the polarization of the conversion electrons in Tm^{170}, where all the characteristics of the transitions were known, and the result had a sign opposite that of the theoretical value computed with the old formula.

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