# Polarization of Electrons in $\beta$-Decay

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Experiments have been made to test the law of conservation of parity by observing the longitudinal polarization of electrons in $\beta$-decay. It is found that the $\beta$-electrons have their spin directed opposite to their direction of motion. The degree of longitudinal polarization is equal to $(v/c)$.

AFTER THE LAW of conservation of parity in weak interactions had been called in question[1,2] Landau[3] proposed the hypothesis of a two-component neutrino possessing only longitudinal polarization. He showed that in this case the electrons from $\beta$-decay would be emitted with a polarization of magnitude $(v/c)$ along their direction of motion.

We have set up an experiment to observe the phenomenon predicted by Landau. To determine the polarization of $\beta$-decay electrons, we use the azimuthal asymmetry of the large-angle single scattering of a transversely polarized electron by a thin foil composed of a heavy element. Longitudinally polarized $\beta$-electrons are passed through crossed magnetic and electric fields. In the magnetic field the electron spins turn through an angle $\varphi = 300\, Hl/pc$. Here $l$ is the path length in the magnetic field, measured in centimeters, $p$ the electron momentum in $ev/c$, and $H$ is the magnetic field in oersteds. The electric field is arranged so as to compensate the effect of the magnetic field on the particle orbits. Particles with velocity $\beta_0 = E/H$ travel in straight lines. Thus the crossed fields produce a transverse polarization of the electrons.

This method, well-known as the Wien velocity selector, was chosen for a variety of reasons.

1. The apparatus has a simple geometry with axial symmetry. Thus the chance of a spurious experimental asymmetry is reduced.

2. The spin of the electron can be rotated through any desired angle, and so the measurements can be made over a wide range of velocities.

3. When the directions of both magnetic and electric fields are reversed, the optics of the apparatus are unchanged while the sign of the azimuthal asymmetry is reversed. This allows a separation of true from spurious assymmetry.

4. When $E$ and $H$ are changed, the ratio $E/H = \beta_0$ being fixed, the energy-resolution of the apparatus changes very little. Since the polarization is proportional to $\beta = v/c$ and varies little with energy, any loss of energy-resolution has a small effect on the results and may give a large increase in the counting-rate.

The path of the electrons in the crossed fields measures 25 cm. The gap between the condenser-plates is 12 mm. When they emerge from the fields, the electrons are scattered by a gold foil making an angle of 45° with the beam direction. Electrons scattered through 90 ± 4° are detected by two Geiger counters in coincidence. Without breaking vacuum, the scatterer and the counters can be rotated through any angle about an axis coinciding with center of the beam. Between the counters there is an absorber which suppresses low-energy electrons.

We used a strontium-yttrium source of thickness 4 mg/cm² and intensity $4 \times 10^8$ disintegrations per second. The decay scheme is

$$ {}_{38}Sr^{90}\,(0^+) \xrightarrow[540\text{ Kev}]{\beta^-\,28y.} {}_{39}Y^{90}\,(2^-) \xrightarrow[2260\text{ Kev}]{\beta^-\,64h.} {}_{40}Zr^{90}\,(0^+). $$

Measurements were made with the energy in the neighborhood of 300 kev. The electric field was 18.3 kev/cm, and the magnetic field was $H = 79$ Oe, thus $\beta_0 = E/H = 0.775$. The angle through which the spins were turned was $\varphi \approx 50°$. The expected azimuthal asymmetries may be calculated from the data shown in Table 1. In a plane perpendicular to the spin direction, the expected azimuthal effect is

$$ \delta_{\text{theor}} = \sum f(N)\,\Delta\beta \sin\varphi \Big/ \sum f(N) = 27.7\%. $$

The experimental results are shown in Table 2. One sees that (1) there is no asymmetry in the plane 0°–180° in which the spin is rotated, (2) asymmetry is observed in the plane 90°–270°, and changes

TABLE I. $\mathcal{E}$ is the electron kinetic energy in kev; $\beta = v/c$; $f(N)$ is the number of electrons of given energy which reach the counters in arbitrary units; $f(N)$ is the product of the energy-resolution curve of the apparatus, the probability that an electron of given energy will penetrate the absorber between the counters, the cross section for scattering the electron through 90°, and the energy-spectrum of the source; $\varphi$ is the angle through which the electron spin turns in the magnetic field; $\Delta$ is the azimuthal asymmetry for a 100% transversely polarized electron. The values are taken from Ref. 8.

| $\mathcal{E}$ | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|---|---|---|---|---|---|---|---|
| $\beta = v/c$ | 0.70 | 0.74 | 0.78 | 0.81 | 0.83 | 0.84 | 0.86 |
| $f(N)$ | 15 | 70 | 61 | 41 | 28 | 15 | 10 |
| $\sin\varphi$ | 0.88 | 0.81 | 0.75 | 0.70 | 0.66 | 0.62 | 0.59 |
| $\Delta$ | 51.5 | 50 | 48.5 | 46.5 | 45 | 43.5 | 42 |
| $\Delta\cdot\sin\varphi\cdot\beta$ | 31.7 | 30.0 | 28.4 | 26.4 | 24.6 | 22.7 | 21.3 |

TABLE II.

| 0 | 180 | 90 | 270 | |
|---|---|---|---|---|
| 129.7±5.7 | 132.7±5.8 | 150.1±3.9 | 125.2±4.0 | Number of counts per minute. Field negative. |
| 31.2±2.5 | 31.0±2.5 | 31.3±1.2 | 24.2±1.0 | Background with no scatterer. |
| 98.5±6.2 | 101.7±6.3 | **118.8±4.0** | *101.0±4.1* | Effect |
| 128.6±4.0 | 142.7±3.8 | 136.5±1.8 | 145.9±2.4 | Number of counts per minute. Field positive. |
| 29.8±2.2 | 34.2±2.4 | 37.4±1.1 | 27.5±1.1 | Background with no scatterer. |
| 98.6±4.8 | 108.5±4.2 | *99.1±2.0* | **118.4±2.4** | Effect |
| 200.3±7.8<br>207.0±7.3 | | 199.0±3.6<br>237.2±4.2 | | Sum of effects with positive and negative field. |

sign when the fields are reserved, and (3) the sign of the asymmetry indicates that electrons in $\beta$-decay are emitted with spins oriented in the direction opposite to their velocity, in agreement with the experimental result of Wu *et al.*[4]

The magnitude of the measured asymmetry is

$$\delta_{obs} = (17.4 \pm 2.6)\,\%.$$

Hence the degree of polarization of $\beta$-decay electrons appears to be

$$\beta(17.4 \pm 2.6)/27.7 = (0.63 \pm 0.09)\,\beta.$$

The gold scatterer which we used had a thickness of 0.537 mg/cm². To determine the ratio of multiple to single scattering in the foil, we used the criterion of Alikhanian, Alikhanov and Vaisenberg.[5] The intensity of single scattering should vary linearly with the foil thickness, and thus the excess intensity observed with thicker foils indicates the amount of multiple scattering. From the relative intensity of the scattering from foils of thickness 0.537 and 0.17 mg/cm², we deduce that the fraction of multiple scattering in the thicker foil is ~ 30%. Since the azimuthal asymmetry $\Delta$ varies strongly with the scattering angle and decreases sharply for angles less than 90°, the asymmetry will be small for multiply scattered electrons. Hence the measured value of the asymmetry should be increased by $\sim$ 30%. In addition, the multiple scattering in a thick source produces a significant depolarization of electrons at a given energy. These corrections are so large that it is not possible to incorporate them in our final results, although the sign and the approximate magnitude of the corrections are known.

To reduce the depolarization in the source, and also to reduce the background and thus allow the use of a thin scattering foil, we made measurements of the polarization of electrons of energy $\sim$ 1000 kev. In this energy range the electrons come from the $_{39}Y^{90}$ decay. The electric field was 20 kev/cm, and the magnetic field 71 Oe. Between the two coincidence counters there was an absorber (0.08 g/cm² Al + 0.08 g/cm² Cu) which stopped electrons of energy below 600 kev. The scatterer was a gold foil of thickness 1.9 mg/cm². The expected azimuthal asymmetry (see Table 3) was

$$\delta_{\text{theor.}} = \sum \Delta \sin\varphi \cdot \beta \cos\vartheta \cdot f(N) \Big/ \sum f(N) = 10{,}3\%.$$

TABLE III. Cos $\theta$ is the depolarization in the source; $\theta = \sqrt{\overline{\theta^2}}$ is the root-mean-square angle of multiple scattering.

| $\mathcal{E}$ | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $f(N)$ | 2 | 15 | 21 | 22 | 20 | 16 | 14 | 10 | 7 | 4 | 2 |
| $\sin\varphi$ | 0.54 | 0.47 | 0.43 | 0.39 | 0.37 | 0.34 | 0.32 | 0.30 | 0.28 | 0.27 | 0.25 |
| $\beta$ | 0.89 | 0.91 | 0.92 | 0.93 | 0.94 | 0.95 | 0.95 | 0.96 | 0.96 | 0.97 | 0.97 |
| $\Delta$ | 39 | 37 | 34 | 32 | 30 | 28 | 27 | 26 | 25 | 24 | 24 |
| $\cos\theta$ | 0.91 | 0.94 | 0.94 | 0.96 | 0.96 | 0.97 | 0.97 | 0.97 | 0.98 | 0.98 | 0.98 |
| $\Delta\beta \sin\varphi\cos\theta$ | 16 | 14.9 | 12.7 | 11.2 | 9.9 | 8.8 | 7.9 | 7.2 | 6.6 | 6.1 | 5.7 |

The experimental results are shown in Table 4. The azimuthal asymmetry, in the plane perpendicular to the plane of the spin rotation, is in this experiment

$$\delta_{\text{obs}} = (7.8 \pm 1.7)\,\%.$$

Observations with a thinner scatterer showed that multiple scattering is here only 6% of single. We thus find for the degree of polarization of 1000 kev electrons

$$(0.8 \pm 0.17)\,\beta.$$

In the energy-range around 1000 kev, the energy-resolution of the apparatus is poor. The number of scattered particles reaching the counters is practically independent of the applied fields, and is determined by the energy-spectrum of the source, the stopping-power of the absorber between the counters, and the scattering cross-section. This allowed us to make a control experiment with electrons of the same energy in zero electric and magnetic field. In this case the electrons remain longitudinally polarized, and no azimuthal asymmetry in scattering should be observed. The data in Table 4 show that in zero field there is indeed no azimuthal asymmetry (1.5 ± 3.5%).

The experiment was then repeated at an energy of $\sim$ 300 kev with the same scatterer and a thinner source ($\sim$ 1.5 mg/cm²) in order to reduce the depolarization in the source. The observed degree of polarization was

$$(0.77 \pm 0.16)\,\beta,$$

definitely larger than the earlier result obtained with a thicker source. A comparison of the results at 300 kev and at 1000 kev shows that the polarization is proportional to $(v/c)$, and the observed degree of polarization comes closer and closer to $(v/c)$ as the experimental conditions are improved.

Our experiments on the polarization of electrons in $\beta$-decay, together with the experiments of Wu *et al.*[4] Lederman *et al.*[5] and of Vaisenberg and Smirnitskii,[6] demonstrate that parity is not conserved in weak interactions, and give strong evidence that the two-component neutrino theory proposed by Landau is in agreement with experiment.

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TABLE IV.

| 0 | 180 | 90 | 270 | |
|---|---|---|---|---|
| 31.7±0.7 | 32.8±0.7 | 33.2±0.4 | 30.7±0.4 | Number of counts per minute. Field negative. |
| 2.2±0.3 | 3.0±0.4 | 1.88±0.2 | 1.98±0.2 | Background with no scatterer. |
| 29.5±0.7 | 29.8±0.8 | *31.3±0.4* | **28.7±0.5** | Effect. |
| 31.6±0.9 | 31.1±0.9 | 30.6±0.4 | 31.9±0.4 | Number of counts per minute. Field positive. |
| 2.2±0.4 | 2.2±0,4 | 2,96±0,26 | 2.37±0,23 | Background with no scatterer. |
| 29.4±1.0 | 28.9±1.0 | **27.6±0.5** | *29.6±0.5* | Effect. |
| 58.4±1.3<br>59.2±1.3 | | 60.9±0.6<br>56.3±0.6 | | Sum of effects with positive and negative field. |
| 31.6±0.9 | 32.6±0.8 | 32.6±0.7 | 32.0±0.7 | Number of counts per minute. Zero field. |
| 2.7±0.4 | 2.7±0.3 | 2.9±0.4 | 2.8±0.3 | Background with no scatterer. |
| 28.9±1.0 | 29.9±0.9 | 29.7±0.8 | 29.2±0.8 | Effect. |

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## APPENDIX

New measurements have been made at 300 kev with a thin source and a thin scatterer (0.17 mg/cm²). The electrons were scattered at an angle (105 ± 4)°. The expected azimuthal asymmetry, including a 5% correction for depolarization in the source, was 36.2%. In this experiment the spurious asymmetry (~ 7%) in the spin rotation plane was measured by scattering the electrons with an aluminum foil, for which the theoretical asymmetry is less than 3%, and the results with the gold foil were corrected accordingly. The measured degree of polarization of the electrons was

$$(0.98 \pm 0.14)\beta.$$

Recently the group of S. Ia. Nikitin obtained similar results in our laboratory, confirming the longitudinal polarization of electrons in $\beta$-decay. Their method differed from ours in using a condenser bent through 108° to rotate the spins. They used $Cu^{64}$ (forbidden decay) for their source.

After this work was finished, we learned from L. D. Landau that H. Frauenfelder had earlier obtained similar results. Frauenfelder's measurements were, as he himself said, qualitative in character. The method was similar to that used by Nikitin's group.

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# On the Structure of the Electron Spectrum in Lattices of the Tellurium Type

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The general properties of the energy spectrum of an excess electron in a crystal with a lattice of the tellurium type are studied by group-theoretical methods, without resort to the approximation of weak or strong coupling. The possibility of contact between the zones in definite directions in the **k**-space is demonstrated. The effect of the spin-orbit interaction is investigated. It is shown that in semiconductors of this type there can be present two kinds of carriers of the same sign. Dispersion laws in the approximation quadratic in **k** are found on various assumptions about the location of the extrema of $E(\mathbf{k})$.

THE PROBLEM OF the energy spectrum of electrons in semiconductors is of extreme importance in the study of all the properties of semiconductors and, in particular, for the understanding of the kinetics of processes occurring in these materials. The complex structure of the electron spectrum in germanium was predicted theoretically and has been convincingly confirmed in relatively recent experiments on the cyclotron resonance.[1] There is every reason to suppose that, within the framework of the one-electron approximation, the effective mass by no means always has the properties of a tensor quality (for example, for holes in germanium[2]). Therefore it is of interest to see what information on this point can be obtained by considering the symmetry properties of the lattice.

The experiments of Shalyt obviously provide evidence that two kinds of holes are present in tellurium.[3] This is not possible in the simplified theory of the zone spectrum of tellurium recently proposed by Callen[4,5]. Moreover, the group-theoretical formula he used do not correspond to the actual structure of tellurium. Although some of the conclusions of Callen's work are also confirmed in our exact theory, the reasons for the occurrence of the effects in question are entirely different. But the considerations given by Callen on the origin of the zones do not encounter any contradictions, and we make use of them in the choice of the theoretical possibilities, which, as it will turn out, can occur.

## 1. METHOD OF TREATMENT

The method* we have used is based on general premises of group theory. The idea of the method is as follows: as is well known, the wave function of an electron in an ideal crystal can be written in the form $\Psi_{n\mathbf{k}} = e^{i\mathbf{k}\mathbf{r}}u_{n\mathbf{k}}$. The Schrödinger equation for the modulating factor takes the form:

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_l^2} - i\frac{\hbar^2}{m}k_l\frac{\partial}{\partial x_l} + \frac{\hbar^2k^2}{2m} + U(\mathbf{r})\right]u_{n\mathbf{k}}(\mathbf{r}) = E_n(\mathbf{k})\,u_{n\mathbf{k}}(\mathbf{r}). \quad (1)$$

Here summation is understood over the twice repeated indices $l$, and $U(\mathbf{r})$ is the self-consistent periodic potential. The function $U(\mathbf{r})$ possesses definite symmetry properties. We introduce the symme-

* A more rigorous exposition of this method can be found in a paper by Seitz.[6]