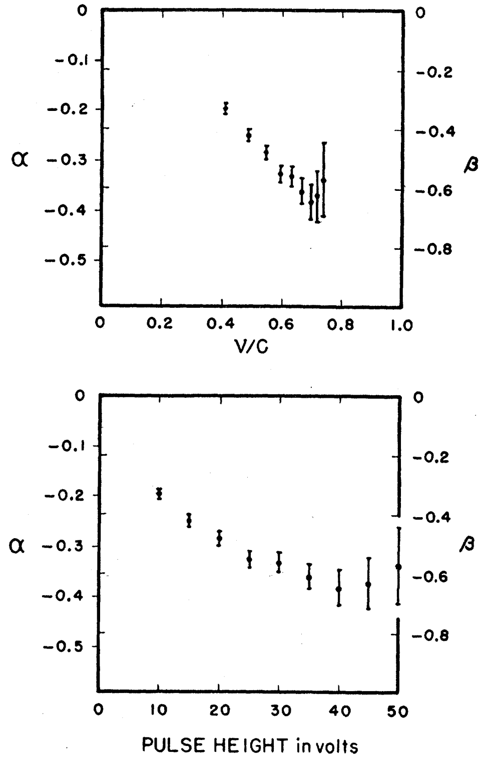

FIG. 2. Experimental asymmetry coefficient α and the asymmetry parameter β for Co^{60} as a function of pulse height and v/c.

on the right side of Fig. 1. The accuracy of the values α is not as good as our results for Co^{60}.

From both the oriented nuclei[1] and the $\pi-\mu-e$ decay experiments,[8] the conservation of parity, P, and invariance under charge conjugation, C, in these interactions are violated. The most important question now is whether the weak interactions violate invariance under the operation of time reversal, T. If T is conserved, then CP is conserved by the Schwinger-Lüders-Pauli-theorem. Theoretically one could determine the question of time reversal by examining the momentum dependence of the asymmetry parameter β, which is proportional to

$$\frac{v}{c}\mathrm{Re}\left[C_TC_T'^*-C_AC_A'^*+i\frac{Ze^2}{\hbar cp}(C_AC_T'^*+C_A'C_T^*)\right],$$

where the Z-dependent term automatically vanishes if T is conserved. Unfortunately this term for Co^{60} is rather small, the upper limit[9] for its contribution to β being only $2\times(28/137)\times(1/\sqrt{3})=0.24$. Furthermore it must be borne in mind that even with high-Z nuclei, the absence of this Z-dependent term cannot be used as the criterion for invariance under time reversal, as it is quite possible that the coupling constants C_A, C_A', C_V, and C_V' are very small. Furthermore it has been shown[5] that in other possible experiments, where $\boldsymbol{\sigma}\cdot(\mathbf{p}_e\times\mathbf{p}_\nu)$ or $\boldsymbol{\sigma}\cdot(\langle\mathbf{J}_z\rangle\times\mathbf{p}_e)$ are involved, the terms which appear if T is not conserved are cross terms containing C_A, C_A', C_V, or C_V'. Thus in these experiments, as well as in the momentum or Z dependence when $\boldsymbol{\sigma}\cdot\mathbf{p}_e$ is measured, the absence of the relevant term would not necessarily provide unequivocal proof of invariance under time reversal.

To evaluate the asymmetry parameter β, the observed asymmetry must be corrected for background and backscattering effects. These corrections *vs* energy were obtained from supplementary experiments, but because of the complexity of the conditions, the accuracy of these correction factors is rather poor. We consider that the v/c dependence of the parameter β for Co^{60} given in Fig. 2 is compatible with the predictions of the two-component theory of the neutrino.[4] However, the presence of the Z-dependent term cannot be determined in view of the uncertainties in the backscattering and multiple scattering corrections. Because of the possibility of C_A and C_A' being small, no conclusion on time reversal can be made from Fig. 2.

We wish to thank Dr. M. Morita of Columbia University for his valuable help in making many theoretical calculations.

* Work partially supported by the U. S. Atomic Energy Commission.

[1] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).
[2] Lee, Oehme, and Yang, Phys. Rev. **106**, 340 (1957).
[3] These results were reported at the New York Meeting of the American Physical Society of February 2, 1957 (C. S. Wu, post-deadline paper).
[4] Using the convention adopted by T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).
[5] We are very grateful to Dr. M. Morita for communicating to us his unpublished results. We also wish to express our deep appreciation for receiving preprints from Jackson, Treiman, and Wyld [Phys. Rev. **106**, 517 (1957)]; Bernard T. Feld [Phys. Rev. (to be published)]; Alder, Stech, and Winther [Phys. Rev. (to be published)]; M. E. Ebel and G. Feldman (to be published).
[6] D. F. Griffing and J. C. Wheatley, Phys. Rev. **104**, 389 (1956).
[7] Since obtaining these results we have learned that H. Postma, W. J. Huiskamp, A. R. Miedma, M. J. Steenland, H. A. Tolhoek, and C. J. Gorter at Leiden have also observed asymmetry in Co^{58} by measuring the annihilation radiation from the positrons [H. Postma *et al.*, Physica **23**, 259 (1957)].
[8] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
[9] B. M. Rustad and S. L. Ruby, Phys. Rev. **89**, 880 (1953); **97**, 991 (1955).

Positron Polarization Demonstrated by Annihilation in Magnetized Iron*

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(Received April 29, 1957)

THERE are now several experimental confirmations[1–5] of the suggestion made by Lee and Yang[6] that the traditional formulation of the conservation of parity may not be valid for weak interactions. The existence of longitudinal polarization of negative beta particles from an unpolarized source has been

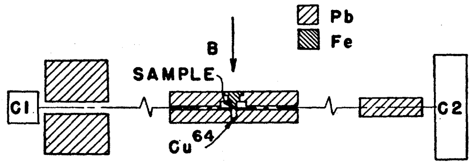

FIG. 1. Experimental arrangement.

demonstrated by the group at Illinois.[5] The purpose of the present investigation was to obtain evidence for the polarization of positive beta particles with quite a different type of experiment.

As shown in Fig. 1, positrons from a Cu^{64} source impinged on the end of a cylindrical sample 4 mm in diameter, and the two-quantum yield was detected with two NaI counters placed 180° apart and operated in coincidence. Appropriate shielding suppressed radiation from positrons annihilating anywhere but in the iron sample. The sample was mounted in a magnetic field which could be made either parallel or antiparallel to the direction of the positrons and hence to the presumed polarization.

One counter, at a distance of 290 cm, had an aperture of 9×10^{-6} steradian. The second counter, at a distance of 165 cm, was uncollimated and subtended an angle of 3×10^{-3} steradian. In order to observe the angular correlation of annihilation radiation, cylindrical lead absorbers of successively increasing diameters were inserted in front of, and coaxial with, the uncollimated counter. A measurement of the angular correlation for annihilation in copper, obtained with this technique, agreed satisfactorily with the result of Lang *et al.*[7]

A lead absorber was selected which effectively eclipsed the central cone (half-angle equals 8.5 milliradians) of the angular distribution for iron, allowing observation of the "wings" of the distribution corresponding to annihilation in the sample by electrons of high momentum. The yield so obtained was normalized to the total intensity with the absorber removed. With fields producing saturation in the iron sample, this normalized yield R was consistently higher by $(5\pm1)\%$ with the field parallel instead of antiparallel to the direction of motion of the positrons. The effect vanished when a copper sample was used. The results from one series of measurements are shown in Fig. 2. Geometrical effects were investigated by reversing the direction of the positrons and the results were not significantly different. A further check on the experimental arrangement was obtained by performing the experiment with first one half and then the other half of the large counter covered with a lead shield. In both cases the same effect was obtained. It is seen in Fig. 2 that the ratio R is higher for copper than for iron, in agreement with reference 7.

A plausible explanation of the above result may be summarized as follows: (1) Positrons emitted from a Cu^{64} source (spin change $1\rightarrow0$) are partially polarized parallel to their direction of motion, i.e., opposite to the direction observed for negative electrons.[5] (2) At the time of their annihilation the positrons still retain a substantial amount of this polarization. (3) Annihilation takes place predominantly in the region midway between nuclei where the d electrons mainly responsible for ferromagnetism have higher momentum than the s electrons. (4) Thus when the field is parallel (electron spin antiparallel) to the positron spin, two-quantum annihilation is enhanced in the high-momentum region of the angular correlation, and when the field is reversed it is diminished.

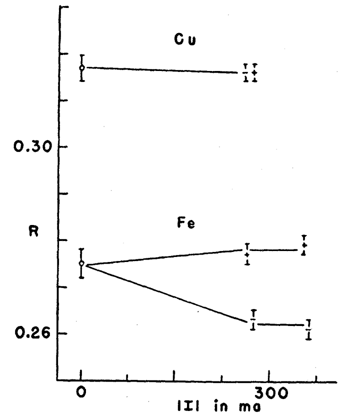

FIG. 2. Normalized coincidence rate R, as defined in the text, plotted against the magnet current. For the (+) points the magnetic field was parallel to the direction of motion of positrons. For the (−) points the field was reversed. The lines are supplied merely to aid in visualizing the data. Fe and Cu signify annihilation in the iron sample and copper sample, respectively.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).
[2] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
[3] J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).
[4] Abashian, Adair, Cool, Erwin, Kopp, Leipuner, Morris, Rahm, Rau, Thorndike, Whittemore, and Willis, Phys. Rev. **105**, 1927 (1957).
[5] Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, Phys. Rev. **106**, 386 (1957).
[6] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[7] Lang, De Benedetti, and Smoluchowski, Phys. Rev. **99**, 596 (1955).

Beta-Gamma Circular Polarization Correlation Measurements*

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(Received April 25, 1957)

OWING to nonconservation of parity in β decay,[1] γ rays following β transitions are circularly polarized. The angular distribution of circularly polarized γ rays emitted under an angle θ with the preceding β particles is $W(\theta,\pm)=1\pm A(v/c)\cos\theta$ (+ for right-hand, − for left-hand circular polarization).[2]

We consider β transitions with spin change 0 or 1 between levels with spin j_i and j, followed by a mixed dipole-quadrupole γ radiation (mixing ratio δ) between