

in case screening is important. If there is no screening, then  $Q = (m^2 k / 2E_0 E)$  for bremsstrahlung and  $Q = (m^2 k / 2E_+ E_-)$  for pair production.

Now consider the problem of integrating  $d\sigma_B$  given by Eq. (1) over the angular variables  $u$ ,  $v$ ,  $s$ , and  $t$ . For purely dimensional reasons the result of the integration can be a function only of  $(Q/m)$  multiplied by  $E_0^2$ ,  $k^2$ , or  $E^2$  according as  $M$  is given by Eqs. (3)–(5). But from the Bethe-Heitler formula,<sup>3</sup> the cross section summed over final spin-states is

$$(2E_0^2 + 2E^2 + k^2)(dk/3kE_0^2 R), \quad (14)$$

where  $R$  is a function of  $(Q/m)$  which is given the name of "radiation length." From this it necessarily follows that the angular integrals of Eq. (1) must have the values  $(\frac{2}{3}R^{-1}, \frac{1}{3}R^{-1}, \frac{2}{3}R^{-1})$  for the three separate final spin combinations. We have also checked these values by a direct integration. We therefore conclude that the integrated cross sections for bremsstrahlung with assigned polarizations are given by

$$[d\sigma_{FFF}, d\sigma_{FFB}, d\sigma_{FBF}, d\sigma_{FBB}] \\ = [2E_0^2, k^2, 2E^2, 0](dk/3kE_0^2 R), \quad (15)$$

where the suffixes refer respectively to the incident electron (energy  $E_0$ ), the photon (energy  $k$ ), and the outgoing electron (energy  $E$ ).

A precisely similar argument applied to the pair-production process gives the integrated cross sections

$$[d\sigma_{FFF}, d\sigma_{FFB}, d\sigma_{FBF}, d\sigma_{FBB}] \\ = [k^2, 2E_+^2, 2E_-^2, 0](dE_+/3k^3 R), \quad (16)$$

where the suffixes refer to the polarization of photon, positron, and electron, respectively.

These cross sections are of interest for two reasons. First, they show more clearly than the unpolarized cross sections the symmetry between bremsstrahlung and pair production, and they explain the origin of the unsymmetrical factors  $(2E_0^2 + 2E^2 + k^2)$  and  $(k^2 + 2E_+^2 + 2E_-^2)$  which appear in the unpolarized cross sections. Second, they clearly indicate the possibility of a large-scale persistence of longitudinal polarization in an electromagnetic cascade originated by a single polarized electron of high energy.<sup>4</sup> The latter effect will be the subject of a separate communication.

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<sup>1</sup> T. D. Lee and C. N. Yang, *Phys. Rev.* **104**, 254 (1956); Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, *Phys. Rev.* **106**, 386 (1957); Goldhaber, Grodzins, and Sunyar, *Phys. Rev.* **106**, 826 (1957).

<sup>2</sup> Kirk W. McVoy, *Phys. Rev.* **106**, 828 (1957).

<sup>3</sup> W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, New York, 1954), third edition, p. 248, Eq. (21). In the case of complete screening the cross section is given by Heitler's Eq. (26), and the extra (2/9) in this formula makes a slight change in the coefficients (2, 2, 1) in our Eq. (14). We have neglected the (2/9) term.

<sup>4</sup> This possibility was suggested by M. Goldhaber (private communication).

## Further Experiments on $\beta$ Decay of Polarized Nuclei\*

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IN a previous communication<sup>1</sup> we reported that we observed a large asymmetry in the angular distribution of electrons from polarized  $\text{Co}^{60}$  nuclei. It was concluded that unequivocal proof was thereby established of the nonconservation of parity as well as of noninvariance under charge conjugation in beta decay. It was also pointed out that according to Lee, Oehme, and Yang,<sup>2</sup> invariance under time reversal could also be investigated by studying the momentum dependence of the asymmetry parameter  $\beta$ . Since then we have made further measurements and checks. In particular we have carried out similar experiments<sup>3</sup> with  $\text{Co}^{58}$  and observed an asymmetry in the positron emission with a coefficient opposite in sign and roughly one third of that from  $\text{Co}^{60}$ . Through more detailed measurements on  $\text{Co}^{60}$  we have obtained the general behavior of the momentum dependence of  $\beta$ . The linear dependence of  $\beta$  on  $v/c$  in the range from 0.4 to 0.75 is good.

In order to put upper limits on possible spurious effects in our experimental method, we have performed a similar experiment with  $\text{Bi}^{210}$  incorporated in the crystal. Since the bismuth ion in cerium magnesium nitrate is diamagnetic, there can be no significant nuclear polarization set up and therefore no beta asymmetry should be expected. In fact no effect was observed to an accuracy of better than  $\frac{1}{2}\%$ .

Although no changes were made in the apparatus, a simpler and more effective method was found for preparing samples; a high-specific-activity cobalt nitrate solution was spread on the surface of a crystal so that a small part of it was dissolved. When this was allowed to dry, the solution again crystallized with apparently the same crystallographic orientation as the parent crystal and also formed a very thin source.

The experiment with  $\text{Co}^{58}$  is very similar to that of  $\text{Co}^{60}$ .  $\text{Co}^{58}$  decays by positron emission or electron capture to the first excited state of  $\text{Fe}^{58}$  and then to the ground state with the emission of a  $\gamma$  ray of energy 0.805 Mev. The anisotropy of the 0.805-Mev  $\gamma$  ray was used to determine the degree of nuclear polarization. The sign of the coefficient  $\alpha$  is positive; i.e., more positrons are emitted in the same direction as the spin of the  $\text{Co}^{58}$  nuclei. The reversal of the sign of the coefficient  $\alpha$  in the case of the positron emission as compared with electron emission can best be understood from the two-component theory of the neutrino and pure G-T interaction. The negative coefficient found in our  $\text{Co}^{60}$  experiment can be interpreted by supposing that electron emission is associated with a left-handed

antineutrino.<sup>4</sup> Then in the case of positron decay a right-handed neutrino is emitted, and emission in the direction of the nuclear spin must be preferred. In the case of Co<sup>58</sup>, however, the spin change of 2<sup>+</sup>→2<sup>+</sup> indicates that both allowed Fermi and Gamow-Teller interactions are involved. The magnitude of the asymmetry in a  $J \rightarrow J$  transition is quite different from that in a  $J \rightarrow J-1$  transition. Besides the terms resulting from the interference between the parity-conserving and parity-nonconserving terms in Gamow-Teller interactions, there are also the interference terms between Fermi and Gamow-Teller interactions as shown in Eq. (1).<sup>5</sup>

$$\alpha = \left\{ \pm \frac{\langle J_z \rangle}{J} \lambda_{J'J} \operatorname{Re} \left[ (C_T C_T'^* - C_A C_A'^*) \right. \right. \\ \left. \left. \pm i \frac{Ze^2}{\hbar c p} (C_A C_T'^* + C_A' C_T^*) \right] |M_{GT}|^2 \right. \\ \left. + \delta_{J'J} \frac{\langle J_z \rangle}{J} \left( \frac{J}{J+1} \right)^{\frac{1}{2}} \operatorname{Re} \left[ (C_T' C_S^* + C_T C_S'^* \right. \right. \\ \left. \left. - C_A' C_V^* - C_A C_V'^*) \pm i \frac{Ze^2}{\hbar c p} (C_A' C_S^* + C_A C_S'^* \right. \right. \\ \left. \left. - C_T' C_V^* - C_T C_V'^*) \right] |M_F| \times |M_{GT}| \right\} \\ \times \frac{v}{c} \times \frac{2}{\xi(1+b/W)}; \quad (1)$$

$$\lambda_{J'J} = 1, \quad J \rightarrow J' = J-1 \\ = 1/(J+1), \quad J \rightarrow J' = J \\ = -J/(J+1), \quad J \rightarrow J' = J+1; \\ \xi = |M_F|^2 (|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2) \\ + |M_{GT}|^2 (|C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2), \\ \xi b = 2\gamma \operatorname{Re} [ |M_F|^2 (C_S C_V'^* + C_S' C_V^*) \\ + |M_{GT}|^2 (C_T C_A'^* + C_T' C_A^*) ], \\ \gamma = [1 - (Ze^2/\hbar c)^2]^{\frac{1}{2}}.$$

If the ratio  $|M_F|^2/|M_{GT}|^2$  in Co<sup>58</sup> were negligible, then the asymmetry coefficient would be positive and only one third as large as that of Co<sup>60</sup> on account of the factor  $1/(J+1) = \frac{1}{3}$ . However, a small admixture of Fermi interaction could result in significant changes in the asymmetry observed. The positive or negative sign of the asymmetry coefficient may determine the relative sign between the scalar and tensor interactions. For Co<sup>58</sup> the ratio of  $|M_F|^2/|M_{GT}|^2$  has been determined to be  $\frac{1}{8}$  by the study of the anisotropy of the 0.8-Mev  $\gamma$  ray from aligned Co<sup>58</sup> nuclei.<sup>6</sup> If this ratio

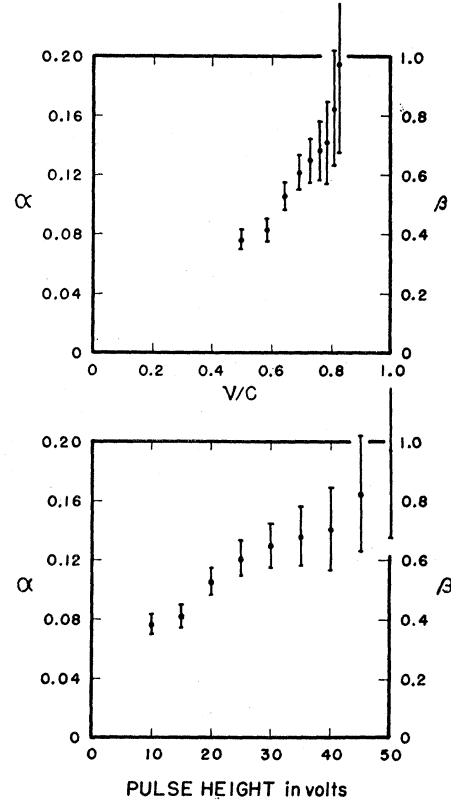


FIG. 1. Experimental asymmetry coefficient  $\alpha$  and the symmetry parameter  $\beta$  for Co<sup>58</sup> as a function of pulse height and  $v/c$ .  $\beta$  has been deduced assuming that the total contribution to the asymmetry comes from the G-T interaction alone.

is used, and the constants  $C_A$ ,  $C_A'$ ,  $C_V$ , and  $C_V'$  are assumed to be small in comparison with  $C_S$ ,  $C_S'$ ,  $C_T$ , and  $C_T'$ , then the calculated asymmetry according to the two-component theory of the neutrino is positive and nearly 81% of that of Co<sup>60</sup> for  $C_S |M_F|/C_T |M_{GT}| < 0$  and nearly 22% of that of Co<sup>60</sup> for  $C_S |M_F|/C_T |M_{GT}| > 0$ . Nevertheless, the observed asymmetry is positive and only one-third of that of Co<sup>60</sup>.<sup>7</sup> Thus it becomes extremely important to reinvestigate the ratio  $|M_F|^2/|M_{GT}|^2$  and also to re-examine the order of magnitude of the constants  $C_V$ ,  $C_V'$ ,  $C_A$ , and  $C_A'$ . It also suggests that a careful study of the asymmetry coefficient of neutron decay where the ratio  $|M_F|^2/|M_{GT}|^2$  can be calculated, will shed much information on questions such as the relative signs of  $S$  and  $T$ .

At the lowest temperature our observed gamma-anisotropy is 17% which corresponds to a polarization of  $\langle J_z \rangle/J = 0.6$ . The asymmetry coefficient  $\alpha$  vs the pulse height and  $v/c$  are shown in Fig. 1. The asymmetry parameter,

$$\beta = \alpha / \left( \frac{\langle J_z \rangle}{J} \times \frac{1}{J+1} \right),$$

calculated considering pure G-T interaction, is labeled

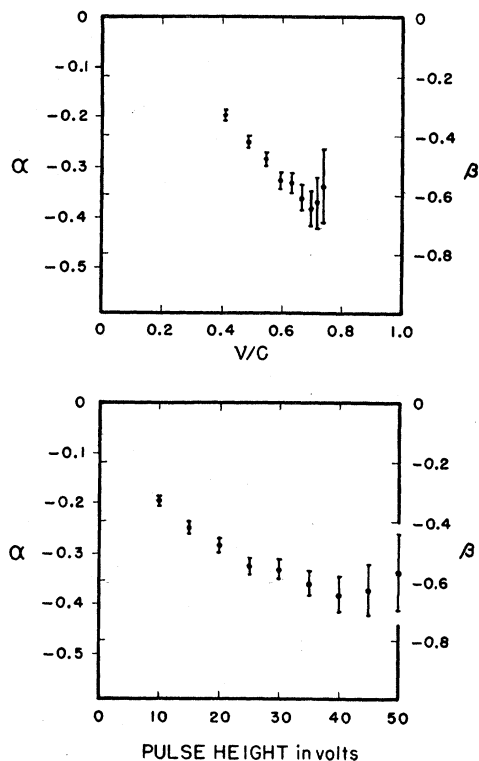


Fig. 2. Experimental asymmetry coefficient  $\alpha$  and the asymmetry parameter  $\beta$  for  $\text{Co}^{60}$  as a function of pulse height and  $v/c$ .

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

From both the oriented nuclei<sup>1</sup> and the  $\pi-\mu-e$  decay experiments,<sup>8</sup> 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  $\beta$ , which is proportional to

$$\frac{v}{c} \text{Re} \left[ C_T C_T'^* - C_A C_A'^* + i \frac{Z e^2}{\hbar c p} (C_A C_T'^* + C_A' C_T^*) \right],$$

where the  $Z$ -dependent term automatically vanishes if  $T$  is conserved. Unfortunately this term for  $\text{Co}^{60}$  is rather small, the upper limit<sup>9</sup> for its contribution to  $\beta$  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<sup>5</sup> that in other possible experiments, where  $\sigma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$  or  $\sigma \cdot (\langle \mathbf{J}_z \rangle \times \mathbf{p}_e)$  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  $\sigma \cdot \mathbf{p}_e$  is measured, the absence of the relevant term would not necessarily provide unequivocal proof of invariance under time reversal.

To evaluate the asymmetry parameter  $\beta$ , 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  $\beta$  for  $\text{Co}^{60}$  given in Fig. 2 is compatible with the predictions of the two-component theory of the neutrino.<sup>4</sup> 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.

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<sup>1</sup> Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).

<sup>2</sup> Lee, Oehme, and Yang, Phys. Rev. **106**, 340 (1957).

<sup>3</sup> These results were reported at the New York Meeting of the American Physical Society of February 2, 1957 (C. S. Wu, post-deadline paper).

<sup>4</sup> Using the convention adopted by T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

<sup>5</sup> 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).

<sup>6</sup> D. F. Griffing and J. C. Wheatley, Phys. Rev. **104**, 389 (1956).

<sup>7</sup> 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  $\text{Co}^{60}$  by measuring the annihilation radiation from the positrons [H. Postma *et al.*, Physica **23**, 259 (1957)].

<sup>8</sup> Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

<sup>9</sup> 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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THERE are now several experimental confirmations<sup>1-5</sup> of the suggestion made by Lee and Yang<sup>6</sup> 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