For the reactions listed above, forward and backward cross sections satisfied the reciprocity condition to within 20%.

A second conclusion of our study, which we expect to amplify in a forthcoming detailed paper, is that many experiments which initially seem to test TR invariance, actually may not be sensitive to this symmetry. Thus, the lack of TR invariance does not rule out detailed balance in many reactions. This is assured by the Hermitian property of the Hamiltonian, for example, when first-order perturbation theory applies and spins are not measured. A less familiar restriction is imposed by the unitarity property of the S matrix, which implies that $\langle a|S|b\rangle = \exp(i\delta_{ab})\langle b|S|a\rangle$ on the energy shell, when, for example, only two channels are open. An academic illustration is the *s*-wave interaction $\pi^+ + n \rightleftarrows \pi^0 + p$. In most nuclear reactions a model is necessary before the sensitivity of detailed balance with respect to TR invariance can be predicted. The usual models[9,10] predict a lack of sensitivity to TR invariance in $p + p \rightleftarrows \pi^+ + d$, and in the forward angular distributions of direct processes such as (d,p) and (p,d) reactions.

There are effects in elastic scattering which can in principle reveal a breakdown of TR invariance, but those we have examined are only of second order in the force terms that change sign under time reversal. For example, in a double scattering in which the second process takes place at the same energy and angle as the first, $\sigma(\text{left-left}) - \sigma(\text{left-right})$ can be negative only if TR invariance is violated. It is unfortunate that experimental evidence exists[11] only for a system of total spin $\frac{1}{2}$, in which special case the positiveness of the above quantity follows from parity conservation and rotational invariance alone.

We hope that the above discussion will encourage physicists to perform high-precision experiments to test TR invariance in nuclear physics. In detailed balance experiments it is important to have many competing channels open.[12] For correlation experiments of successive radiations, the most sensitive measurement of the interference phase of two competing radiations occurs when these are about equal in strength and are followed or preceded by a pure radiation. In correlation experiments, a null-type test of TR invariance has been suggested by Lee and Yang.[13] The detection of a term of the form $(\mathbf{p}\cdot\mathbf{k}\times\mathbf{k}')\mathbf{k}\cdot\mathbf{k}'$, where $\mathbf{p}$ is the momentum of the electron preceding gamma-ray emission and $\mathbf{k}$ and $\mathbf{k}'$ specify the directions of two successive gammas, would prove that TR invariance cannot hold in strong interactions. A further test of TR invariance in nuclear interactions occurs in beta decay; for example, experiments suggested by Jackson, Treiman, and Wyld[14] determine not only TR invariance in beta decay, but also in strong interactions. If TR invariance is found not to hold in such experiments, it becomes all the more important to determine whether the breakdown occurs because of weak or strong interactions.

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Absence of Interference Effects in the β Decay of Polarized Co^{56} and Co^{58} Nuclei

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In an earlier communication[1] we reported that the asymmetry of the electrons emitted from polarized Co^{58} nuclei was approximately one-third that from Co^{60}.[2] It was concluded that the interference term between the Fermi and Gamow-Teller interactions was quite small, that a reinvestigation of the magnitude of the ratio $|M_{\mathrm{F}}|^2/|M_{\mathrm{GT}}|^2$ would be important for a precise interpretation of the results, and that further information on the coupling constants C_V, C_V', C_A, and C_A' would be necessary in order to correlate the experimentally observed asymmetry with the theoretical predictions.[3]

In order to examine further the effects on this asymmetry of an interference between the Fermi and Gamow-Teller interactions, we have performed additional experiments with polarized Co^{58} and Co^{56} nuclei.

The measurements made on Co^{56} employed essentially the same apparatus and methods used in the measurements on Co^{60} and Co^{58}, the difference being that the warmup times were increased to about 30 minutes. Although the decay scheme of Co^{56} is rather complex,[4,5] the positron group of 1.50-Mev maximum energy decaying to the second excited state in Fe^{56} was used without appreciable interfering effects from other radiations. This state in Fe^{56} decays by cascade emission of 1.24- and 0.845-Mev gamma rays. Although the spin sequence $4^{+}(\beta)4^{+}(\gamma)2^{+}(\gamma)0^{+}$ is well known,[4] the observed gamma-ray anisotropy cannot be used as a reliable criterion for the degree of polarization achieved since both the 1.24- and 0.845-Mev transitions are fed also by transitions from higher levels in Fe^{56} where the spins and level sequence have not been definitely established. Nevertheless, the temperature achieved in the source after adiabatic demagnetization may be taken to be the same as that achieved with sources of Co^{60} and Co^{58} mounted on cerium magnesium nitrate crystals in identical geometries. Knowledge of this temperature combined with the measured value of the magnetic moment[6] of Co^{56} allows the value of $\langle J_z\rangle/J$ to be calculated.[7] The observed asymmetry coefficient $\alpha'=\alpha/[(\langle J_z\rangle/J)(v/c)]$, corrected for scattering effects and Compton-electron background, is 0.221 ± 0.021. In Fig. 1 this value for α' is compared with the predictions of the two-component[8] neutrino theory and the twin-neutrino[9,10] theory as a function of the Fermi to Gamow-Teller mixing ratio for various combinations of the scalar, vector, and tensor beta interactions. The combinations involving the axial vector interaction are not compatible in general with the experimental results.

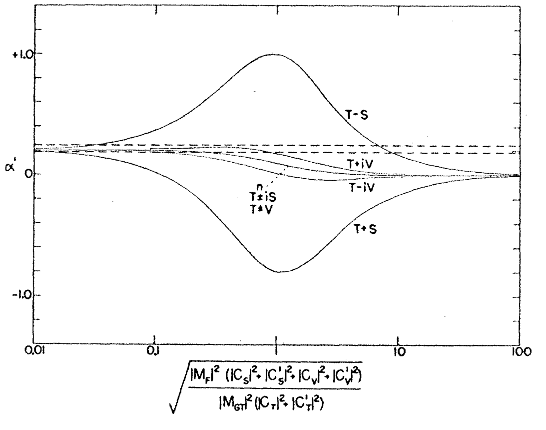

FIG. 1. Theoretical beta asymmetry *vs* Fermi to Gamow-Teller mixing ratio for Co^{56}. The dashed lines represent the range of the experimental value. $T+S$ means that C_T and C_S are real and like in sign. $T+iS$ means that C_S is imaginary but like C_T in sign. The curves representing the two-component theory are labeled with the coupling type, and those representing the twin-component theory are labeled "*n*" for all the coupling types considered. The average momentum of Co^{56} beta particles has been used to calculate terms involving momentum dependence.

In Co^{58}, one of the possible explanations for the apparent lack of an interference term between the Fermi and Gamow-Teller interactions is that the cross products involving the scalar and tensor coupling coefficients are imaginary quantities.[3] This explanation implies, of course, that time-reversal invariance is violated, and it becomes most important to check this aspect. Curtis and Lewis[11] and Morita and Morita[12] have calculated a beta-gamma correlation function for transitions in oriented nuclei which may be used as a means of determining the validity of time-reversal invariance in the beta interaction involving Fermi and Gamow-Teller interference. The pertinent portion of their correlation function is given as

$$\begin{aligned}W(\hat{J},\hat{p},\hat{k})=1+[&(5/7)(\tfrac{3}{2})^{\frac{1}{2}}f_2(\hat{J}\cdot\hat{p}\times\hat{k})(\hat{J}\cdot\hat{k})\\&+(10/3)(\tfrac{2}{3})^{\frac{1}{2}}f_4(\hat{J}\cdot\hat{p}\times\hat{k})P_4'(\hat{J}\cdot\hat{k})]\\&\times\mathrm{Im}\Big[C_SC_T'^*+C_S'C_T^*-C_VC_A'^*\\&-C_V'C_A^*\mp i\frac{Z\alpha}{p}(C_SC_A'^*\\&+C_S'C_A^*-C_VC_T'^*-C_V'C_T^*)\Big]\\&\times|M_F|\,|M_{GT}|\frac{v}{c}2\Big/\left[\xi\left(1+\frac{b}{W}\right)\right],\end{aligned}$$

where

$$f_2=\frac{1}{J^2}[\sum_m m^2a_m-\tfrac{1}{3}J(J+1)],\quad P_4'(u)=\tfrac{5}{2}(7u^3-3u),$$

$$\begin{aligned}f_4=\frac{1}{J^4}[&\sum_m m^4a_m-(1/7)(6J^2+6J-5)\sum_m m^2a_m\\&+(3/35)J(J-1)(J+1)(J+2)],\end{aligned}$$

and where $\hat{J}$, $\hat{p}$, $\hat{k}$ are unit vectors in the direction of the orientation axis, the electron momentum, and the photon momentum, respectively. It should be noted that the correlation function gives a term that is asymmetric under reflection in the plane $\hat{J}$, $\hat{p}$. It should also be noted that the coupling coefficients involved here are the same as those appearing in the interference term of the expression[3] for the beta asymmetry, except that the roles of the imaginary parts and the real parts are interchanged.

An experiment was performed to measure this correlation. Co^{58} nuclei were polarized along the x axis by application of an 800-gauss magnetic field. Coincidences were recorded between betas emitted in a 1.6% solid angle along the z axis with $v/c>0.5$ and each of two gamma-ray channels. Each channel consisted of two detectors connected in parallel and located diametrically opposite one another in the x-y plane, and individually subtending a 2% solid angle at the source. These detector-pairs were positioned symmetrically with respect to, and made an angle of 37° on either side of, the polarization axis. The coincidence resolving time was approximately 0.6 μsec, giving a chance coincidence rate about 0.8 that of the true coincidence rate. The

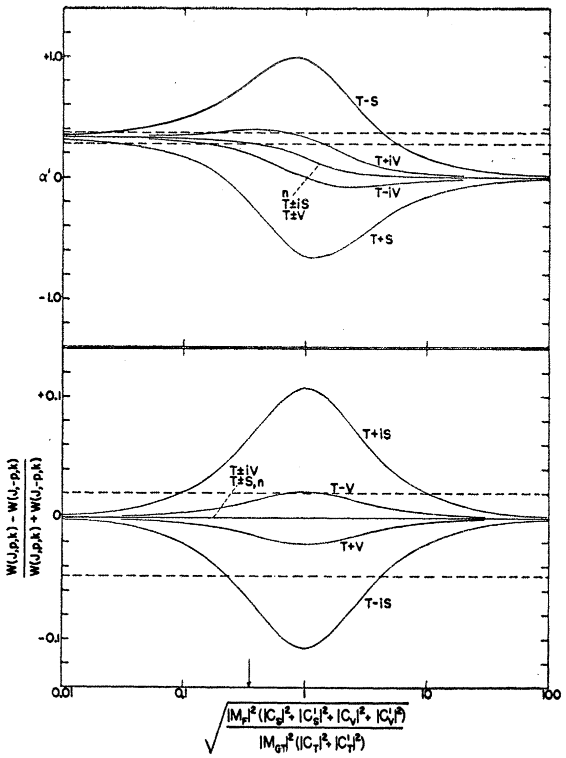

FIG. 2. Theoretical beta-gamma correlation and beta asymmetry *vs* Fermi to Gamow-Teller mixing ratio for Co^{58}. The terminology is the same as in Fig. 1. The arrow indicates the measured value of Griffing and Wheatley for the mixing ratio.

individual counting rates of the beta and gamma channels were observed as well. An additional gamma-ray counter was placed in the plane perpendicular to the axis of the polarization to monitor the gamma-ray anisotropy from which the average nuclear polarization can be determined. About 10^5 coincidences were recorded in each channel with the nuclei polarized, and an equal number recorded with the nuclei randomly oriented.

The observed correlation $[W(\hat{J},\hat{p},\hat{k})-W(\hat{J},-\hat{p},\hat{k})]/[W(\hat{J},\hat{p},\hat{k})+W(\hat{J},-\hat{p},\hat{k})]$ corrected for backscattering effects is -0.014 ± 0.034. In Fig. 2, this value is compared with the predictions of the simple theories referred to above evaluated for the average positron velocity and the values of f_2 and f_4 as determined from the gamma-ray anisotropy. Also in Fig. 2, the beta asymmetry coefficient, $\alpha'=0.325\pm0.047$, obtained from our earlier experiments,[1] is compared with the predictions of these theories.

For the two-component theory, it appears that there is a conflict between the value of the Fermi to Gamow-Teller mixing ratio measured by Griffing and Wheatley[13] and the supposition that the Fermi interaction is scalar, whether the interference terms are either real or imaginary. The measurements of Boehm and Wapstra[14] on the beta-gamma circular-polarization correlation in Co^{58}, involving the real part of the interference terms, are in agreement with our results.

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