for a $\gamma$ ray of energy ($990\pm30$) Mev. The error is statistical. We estimate systematic errors to be about 30% primarily arising from uncertainty about the bremsstrahlung spectrum close to the upper end. The beam integration was carried out using a total absorption ion chamber.[2]

Measurements of the photoproduction of $K$ mesons by 1-Bev $\gamma$ rays have been reported previously by Donoho and Walker at the California Institute of Technology.[3] Their measurements together with ours are plotted in Fig. 2. The curves drawn are from calculations by Fujii and Marshak.[4] The curve labeled $S'$ is calculated for a scalar $K$ meson and the one labeled $PS'$ is for a pseudoscalar $K$ meson. An anomalous magnetic moment of 1.793 nm is taken for the proton and 1.212 nm for the $\Lambda^0$ in both cases. The form of the curve for scalar $K$ mesons is typical of photoelectric production (retarded $\sin^2\theta$) and seems to be rather insensitive to the detailed assumptions of the theory. The $PS'$ curve depends critically on the assumption of the theory, particularly the sign and magnitude of the anomalous moment of the $\Lambda^0$. The absolute values of the cross sections determine the coupling constant $G_{NK\Lambda}{}^2/4\pi$ which is otherwise arbitrary in the theory. The results are consistent with a scalar $K$ meson with a coupling constant $G_{NK\Lambda}{}^2/4\pi=3\pm1$. This is a rather large coupling constant. It should be emphasized that the above statement is meant to indicate a trend and should not be taken as strong evidence against pseudoscalar $K$ mesons.[5] Because of the sensitivity of the calculations to the precise choice of anomalous moment, the present experimental data are insufficient to allow a reliable choice between the scalar and pseudoscalar theories to be made. This decision must await more complete information about the angular distribution, particularly at forward angles.

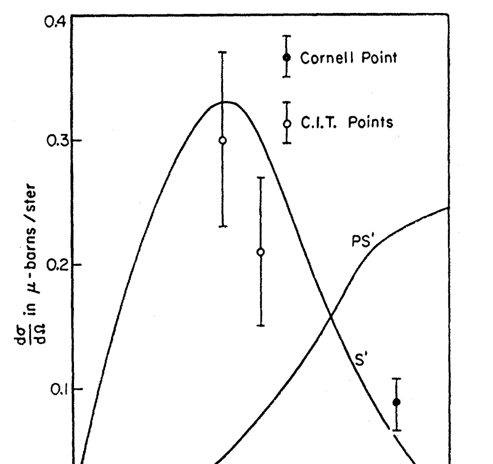


FIG. 2. Plot of the measured differential cross sections from this experiment and that of Donoho and Walker. The curves labeled $PS'$ and $S'$ are taken from the calculations of Fujii and Marshak. The assumptions under which the calculations were made are discussed in the text.

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
[1] Hoang, Kaplon, and Yekutieli, Phys. Rev. **105**, 282 (1957). This paper contains many other references.
[2] R. R. Wilson, Nuclear Instr. **1**, 101 (1957).
[3] P. L. Donoho and R. L. Walker, Phys. Rev. **107**, 1198 (1957).
[4] A. Fujii and R. Marshak (private communication). See also A. Fujii and R. Marshak, Phys. Rev. **107**, 570 (1957), and M. Kawaguchi and M. J. Moravcsik, Phys. Rev. **107**, 563 (1957).
[5] In fact, the $K$ meson could be a parity doublet and have both scalar and pseudoscalar components.

## Time Reversal in Nuclear Interactions*

E. M. HENLEY, *Department of Physics, University of Washington, Seattle, Washington; and Brookhaven National Laboratory, Upton, New York*

AND

B. A. JACOBSOHN, *Department of Physics, University of Washington, Seattle, Washington*

(Received August 19, 1957)

THE recent demonstration[1] that parity conservation, charge-conjugation invariance, and perhaps time-reversal (TR) invariance do not hold in weak interactions should cause physicists to re-examine the foundations of their beliefs that strong interactions are invariant with respect to these symmetries. Lee and Yang[2] summarize some of the older evidence for believing in the parity conservation of strong interactions; their conclusions have been considerably strengthened by recent experiments,[3] which indicate that states with opposite parity are not mixed by nuclear forces with amplitudes as large as $10^{-3}$ to $10^{-4}$.

We have accepted the evidence for parity conservation in strong interactions as amply convincing, and have examined in some detail TR invariance in nuclear interactions. One conclusion of this study is that the present data do not exclude the possibility that nuclear forces which are odd with respect to TR may be present with a strength of as much as 10–20% of the total force. This figure is obtained from angular correlation studies[4] of successive radiations in $Hg^{198}$, as well as from the reactions[5–7] $p+H^3\rightleftarrows n+He^3$, $p+He^3\rightleftarrows \gamma+He^4$, and $p+Li^7\rightleftarrows d+Li^6$. In angular correlations, if one of the radiations in a cascade consists of a superposition of two angular momenta, then TR invariance predicts[8] an interference term with a phase of 0° or 180°. The most sensitive determination of the phase that we have found is in the angular correlation of the[4] $2(E2+M1)2(E2)0$ cascade in $Hg^{198}$ in which the phase is found to be larger than 159°. In nuclear reactions, the lack of TR invariance would be manifested by the nonreality of certain matrix elements and by the consequent lack of the reciprocity property of the $S$ matrix, 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, $\sigma$(left-left)$-\sigma$(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.

* Supported in part by the U. S. Atomic Energy Commission.
1 Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957); Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957); J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).
2 T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
3 D. H. Wilkinson (private communication); N. Tanner, Phys. Rev. **107**, 1203 (1957).
4 C. D. Schrader, Phys. Rev. **92**, 928 (1953).
5 J. H. Coon, Phys. Rev. **80**, 488 (1950); Willard, Bair, and Kingston, Phys. Rev. **90**, 865 (1953); W. Selove, Phys. Rev. **103**, 136 (1956).
6 J. E. Perry, Jr., and S. J. Bame, Jr., Phys. Rev. **99**, 1368 (1955); E. G. Fuller, Phys. Rev. **96**, 1306 (1954).
7 J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956); Levine, Bender, and McGruer, Phys. Rev. **97**, 1249 (1955).
8 S. P. Lloyd, Phys. Rev. **81**, 161 (1951).
9 M. Gell-Mann and K. M. Watson, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1954), Vol. IV, p. 219; A. H. Rosenfeld, Phys. Rev. **96**, 139 (1954).
10 S. T. Butler, Phys. Rev. **106**, 272 (1957) and Proc. Roy. Soc. (London) **A208**, 559 (1951); Austern, Butler, and McManus, Phys. Rev. **92**, 139 (1954).
11 Chamberlain, Segrè, Tripp, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).
12 Comparison of $(\alpha,d)$ and $(d,\alpha)$ reactions on light nuclei are under way at the University of Washington cyclotron.
13 T. D. Lee and C. N. Yang (private communication).
14 Jackson, Treiman, and Wyld, Phys. Rev. **106**, 517 (1957).

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

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson

*National Bureau of Standards, Washington, D. C.*
(Received August 19, 1957)

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 $|M_F|^2/|M_{GT}|^2$ 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]