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Test of T Invariance in Electromagnetic Σ Decay

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As a test of time-reversal invariance in electromagnetic interactions, a measurement was made of a T-invariance-forbidden polarization of the Λ^0 in the decay $\Sigma^0 \to \Lambda^0 + e^+ + e^-$. The result of this experiment, combined with a previous measurement (also using stopping K^- mesons in hydrogen bubble chambers as a source of Σ^0 hyperons), is a polarization of $(3 \pm 6)\%$.

INTRODUCTION

IN 1956, Lee and Yang[1] suggested that the τ-θ puzzle might be explainable by a violation of parity in the weak interactions. Experiments soon found that both P and C were violated in the weak interactions.[2,3] However, tests of T in free-neutron[4] and Λ decays,[5] in $K_{\mu 3}$ decays,[6] and in β decay of polarized nuclei[7] have not yet shown any T violation (see Table I). The observation[8] in 1964 of the CP-nonconserving decay $K_2^0 \to \pi^+\pi^-$ led Bernstein, Feinberg, and Lee[3] and Barshay[9] to review the experimental evidence for C, P, and T invariance of the strong and electromagnetic interactions.

The results of experiments looking for the C-nonconserving decay[10] $\eta \to \pi^0 e^+ e^-$ and for an energy asymmetry between the charged particles in the decay[11] $\eta \to \pi^+\pi^-\gamma$ are all consistent with charge-conjugation invariance. However, in experiments looking for an energy asymmetry between the π^+ and π^- produced in the decay $\eta \to \pi^+\pi^-\pi^0$, Baltay *et al.* and Gormley *et al.* found evidence of an asymmetry, while three other experiments obtained results consistent with no asymmetry.[12] Tables I and II summarize the existing data on T invariance in weak and electromagnetic decays.

The method suggested by Bernstein, Feinberg, and Lee[3] for the detection of a time-reversal violation in the decay $\Sigma^0 \to \Lambda^0 e^+ e^-$ was applied by a Maryland-Columbia-Heidelberg collaboration to a sample of 907 events; the results were ambiguous (about a two-standard-deviation effect).[13]

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TABLE I. Tests of time-reversal invariance in the weak interactions.

Quality studied	T invariance predicted value	Observed value	Reference
Transverse polarization to the decay plane in $K^+ \to \pi^0\mu^+\nu$	0.0	0.04 ± 0.35	U. Camerini *et al.*, Phys. Rev. Letters **14**, 989 (1965)
		0.003 ± 0.014	K. K. Young *et al.*, Phys. Rev. Letters **18**, 806 (1967)
Transverse polarization to the decay plane in $K_L^0 \to \pi^-\pi^+\nu$	≤ 0.01	0.02 ± 0.07	D. Bartlett *et al.*, Phys. Rev. Letters **16**, 282 (1966)
		-0.05 ± 0.18	R. J. Abrams *et al.*, Phys. Rev. Letters **17**, 606 (1966)
Phase angle between S- and P-wave amplitudes in $\Lambda^0 \to \pi^- p$	$(6.5 \pm 1.5)°$	$(9.0 \pm 5.5)°$	O. E. Overseth and R. Roth, Phys. Rev. Letters **19**, 391 (1967)
		$(15 \pm 20)°$	J. W. Cronin and O. E. Overseth, Phys. Rev. **129**, 1795 (1963)
Neutron-electron-antineutrino correlation coefficient in the decay of free polarized neutrons $n \to pe^-\nu$	0.0	0.04 ± 0.05	M. T. Burgy *et al.*, Phys. Rev. **120**, 1829 (1960)
		0.01 ± 0.01	B. G. Erozolimsky *et al.*, Phys. Letters **27B**, 557 (1968)
Neutron-electron-antineutrino correlation coefficient in the decay $Ne^{19} \to F^{19} + e^+ + \nu$	0.0	0.002 ± 0.014	F. P. Calaprice *et al.*, Phys. Rev. Letters **18**, 918 (1967)

TABLE II. Tests of time-reversal invariance in the electromagnetic interactions.

Quantity studied	T invariance predicted value	Observed value	Reference
Cosine of the angle between proton and normal to the Σ^0 decay plane in $\Sigma^0 \to \Lambda^0 e^+ e^-$, with $\Lambda^0 \to p\pi^-$	0.0	0.020 ± 0.020	R. G. Glasser *et al.*, Phys. Rev. Letters **17**, 603 (1966)
Neutron electric dipole moment	0.0	$<5\times10^{-23}\ e$ cm	J. K. Baird *et al.*, Phys. Rev. **179**, 1285 (1969).
Phase angle between the $E2$ and $M1$ amplitudes in the 90-keV γ transition of Ru^{99}	0.0 or π	$(1.0 \pm 1.7)\times10^{-3}$	O. C. Kistner, Phys. Rev. Letters **19**, 872 (1967)
Phase angle between the $E2$ and $M1$ amplitudes in the 73-keV γ transition of Ir^{193}	0.0 or π	$(0.6 \pm 2.1)\times10^{-3}$	M. Atac *et al.*, Phys. Rev. Letters **20**, 691 (1968)
Polarization of recoil deuterons in the elastic scattering reaction $e^- + d \to e^- + d$	0.0	0.075 ± 0.088	R. Prepost *et al.*, Phys. Rev. Letters **21**, 1271 (1968)
Changes in the intensity of scattered electrons upon reversal of proton target polarization	no changes	no changes	J. R. Chen *et al.*, Phys. Rev. Letters **21**, 1279 (1968)

EXPERIMENTAL METHOD

In this experiment[14] we have applied the same analysis as used by the Maryland-Columbia-Heidelberg collaboration[13] on an independent sample of 1062 events of the type $\Sigma^0 \to \Lambda^0 e^+ e^-$ followed by the charged decay of the Λ^0. The time-reversal test consists of looking at the average polarization $\boldsymbol{\sigma}_\Lambda \cdot \mathbf{N}$ along a direction $\mathbf{N}$, where $\boldsymbol{\sigma}_\Lambda$ is the Λ spin vector and $\mathbf{N}$ is the normal to the Σ^0 decay plane defined as

$$\mathbf{N} = \hat{p}_\Lambda \times (\hat{k}_+ + \hat{k}_-). \quad (1)$$

Here $\hat{p}_\Lambda$, $\hat{k}_+$, and $\hat{k}_-$ are unit vectors along the directions of the Λ, positron, and electron in the Σ^0 rest frame. $|\mathbf{N}|$ will be zero when any two of the particles have a zero opening angle, because then all three particles are collinear (in the Σ^0 rest frame). Since the decay plane is not defined in such a situation, the polarization must vanish.

[14] M. J. Baggett (Ph.D. thesis), University of Maryland Technical Report No. 974, 1969 (unpublished). This reference provides a detailed discussion of this experiment.

The quantity $\boldsymbol{\sigma}_\Lambda \cdot \mathbf{N}$ is invariant under the parity operation, and under interchange of the leptons, but changes sign under time reversal. Thus a nonzero average for this Λ polarization can be obtained to first order in perturbation theory only if time-reversal invariance is violated.

In the Λ rest frame, the proton angular distribution is given by

$$w(\theta) = (1/4\pi)(1 + \alpha P_\Lambda \cos\theta),$$

where P_Λ is the Λ polarization along $\mathbf{N}$ (normal to the production plane of the Λ) and θ is the angle between the proton momentum vector and $\mathbf{N}$. Experimentally,[5]

$$\alpha = 0.65 \pm 0.02.$$

Thus a Λ polarization along $\mathbf{N}$ will give rise to a nonzero value for the average of the cosine of the angle between the decay proton and $\mathbf{N}$.

Bernstein *et al.*[3] have derived the theoretical spin-momentum distribution for the Λ in terms of form factors F and G. To lowest nonvanishing order in the square of the pair energy k, they show that one can

represent F and G by

$$F=F_0+O(k^2),$$

$$G=\left(\frac{dG}{dk^2}\right)_0 k^2+O(k^4).$$

Letting $R_0=\Delta|(dG/dk^2)_0F_0^{-1}|$ and ϕ be the relative phase of F and G, the Λ polarization along $\mathbf{N}$ is approximately (for unpolarized Σ^0)

$$\mathbf{P}_\Lambda=\frac{2R_0}{\Delta}\sin\phi\frac{|k_+-k_-|k_+k_-\sin\beta}{k_+^2+k_-^2-k_+k_-(1-\cos\beta)}\hat{N}, \quad (2)$$

where $k_\pm=|\mathbf{k}_\pm|$ and β is the pair opening angle ($\sin\beta=|\hat{k}_+\times\hat{k}_-|$) and Δ is the available energy, $\Delta=M_{\Sigma^0}-M_{\Lambda^0}$. It is useful to write this as a function of two dimensionless variables:

$$x=2k_+k_-(1-\cos\beta)/\Delta^2,$$

$$y=(k_+-k_-)/|\mathbf{P}_\Lambda|.$$

Then

$$\mathbf{P}_\Lambda=2R_0\sin\phi\frac{|y|[x(1-y^2)]^{1/2}}{1+y^2}\hat{N}. \quad (3a)$$

A more exact form of this formula is[13]

$$\mathbf{P}_\Lambda=\frac{2R_0\sin\phi\,|y|[x(1-y^2)]^{1/2}}{(1+y^2)+R_0^2x(1-y^2)}\hat{N}. \quad (3b)$$

If T invariance holds, ϕ must be 0 or π, i.e., the form factors are relatively real and the polarization vanishes.

DESCRIPTION OF EXPERIMENT

A separated beam of low-energy K^- mesons at the Brookhaven National Laboratory entered the 30-in. hydrogen bubble chamber. There were about eight stopping K^-'s per frame. Approximately 227 000 of the 565 000 frames obtained have been analyzed to date.

We investigated the Dalitz decays of Σ^0 produced in the reactions

$$K^-p\rightarrow\Sigma^0+\pi^0$$
$$\searrow \quad (4)$$
$$\Lambda^0e^+e^-$$

and

$$\Sigma^-p\rightarrow\Sigma^0+n$$
$$\searrow \quad (5)$$
$$\Lambda^0e^+e^-.$$

The Σ^0 travels less than 5×10^{-5} cm in one mean life at the momentum ($\sim$180 MeV/c) typical of this experiment. Thus events of type (4) have the topology shown in Fig. 1(a), while those of type (5) have the topology shown in Fig. 1(b).

Events coming from Σ^-p interactions (5) have no significant sources of background. There are, however, two other channels which have the same topology as (4). These are

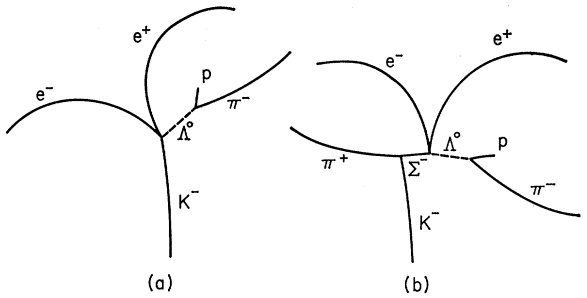

FIG. 1. Topologies of events involved in this experiment: (a) topology associated with $K^-p\rightarrow\Sigma^0\pi^0$, and (b) topology associated with $K^-p\rightarrow\Sigma^-\pi^+$ followed by $\Sigma^-p\rightarrow\Sigma^0n$.

$$K^-p\rightarrow\Sigma^0+\pi^0$$
$$\searrow\ \searrow \quad (6)$$
$$\Lambda^0\gamma\ \gamma e^+e^-$$

and

$$K^-p\rightarrow\Lambda^0+\pi^0$$
$$\searrow \quad (7)$$
$$\gamma e^+e^-.$$

The relative abundances expected for the Σ^0 Dalitz reaction and these two background channels from at-rest K^-p interactions are 2:4.3:1, respectively.[15]

5775 events of the topologies described were found in the 227 000 scanned frames.

Events were measured on standard film-plane and image-plane measuring machines and processed through the regular Maryland analysis system.[16]

To ensure that the events could be analyzed correctly, several cuts were applied to the data. These were (a) Λ projected length less than 1 mm, (b) p projected length less than 1 mm, (c) Λ vertex undefinable ($\sim$180° opening angle), (d) electron momentum less than 3 MeV/c (tight spirals), (e) picture quality poor, and (f) out of fiducial volume.

Events which were kinematically incompatible with Σ^0 Dalitz decay were removed by the analysis system.

Some events of the topology shown in Fig. 1(a) were removed from the sample by looking at the event on the scanning table with partial computer output. The aim was to remove events that could not be the Σ^0 Dalitz decay from at rest K^-.

Events were removed if (a) either the Λ, electron, or

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[16] R. G. Glasser, University of Maryland Technical Report No. 648, 1966 (unpublished); T. B. Day, University of Maryland Technical Report No. 649, 1966 (unpublished); R. G. Glasser, University of Maryland Technical Report No. 663, 1967 (unpublished); F. T. Solmitz, A. D. Johnson, and T. B. Day, LRL Alvarez Group Programming Note No. P-117, 1966 (unpublished); O. I. Dahl, T. B. Day, F. T. Solmitz, and N. L. Gould, LRL Group A Programming Note No. P-126, 1968 (unpublished).

TABLE III. Results for time-reversal-noninvariant observables. $\mathbf{N}=\hat{p}_\Lambda\times(\hat{k}_+ + \hat{k}_-)$ = normal to decay plane of Σ^0, in Σ^0 rest frame. $\hat{N}\cdot\hat{p}_P$ equals cosine of angle between $\mathbf{N}$ and proton momentum vector in Λ^0 rest frame.

	Unweighted cosine $\sum \hat{N}\cdot\hat{p}_P/n$	Cosine weighted by N $\sum \mathbf{N}\cdot\hat{p}_P/\sum\|\mathbf{N}\|$
Present experiment, 1062 events	-0.028 ± 0.018	-0.015 ± 0.028
Previous experiment, 907 events	$+0.020\pm0.020$	$+0.060\pm0.030$
Combined experiments, 1969 events	-0.006 ± 0.013	$+0.020\pm0.020$
Theory, $\sin\phi=1.0$, $R_0=1.0$ (see text)	0.017	0.030
Theory, $\sin\phi=1.0$, $R_0=5.0$ (see text)	0.052	0.080

positron had too large a momentum[17]; (b) the sum of the energies of the Λ, electron, and positron was greater than the energy available from an at rest K^-p production of a Σ^0, 1205.92 MeV; (c) the invariant mass or the momentum of the $\Lambda^0e^+e^-$ system differed significantly (4 standard deviations) from the required values for a Σ^0.

After all cuts, there were 1062 Σ^0 Dalitz decays available for analysis.

Both a simple average of the cosine, $\sum \hat{N}\cdot\hat{p}_P/n$, and an average weighted by the magnitude of $\mathbf{N}$, $\sum \mathbf{N}\cdot\hat{p}_P/\sum|\mathbf{N}|$, where $\hat{p}_P$ is a unit vector along the proton direction in the Σ^0 rest frame, were calculated for these events. The results are shown in Table III. Also included in that table are the results obtained by combining these 1062 events with 907 events from the previous Maryland-Heidelberg-Columbia collaboration.

Also shown in Table III are the expected values of these quantities for $\sin\phi=1.0$ and $R_0=1.0$ and 5.0. The expected values assume that R_0 is independent of x and use equation (3b) for the Λ polarization. $R_0=1.0$ is the largest value of the form-factor ratio consistent with the observed average pair mass.[14] $R_0=5.0$ is the value of the form-factor ratio which results in the largest predicted value of the weighted and unweighted polarizations.

Fifteen events which fit the Σ^0 Dalitz decay and also the reaction

$$K^-p\rightarrow\Lambda^0\pi^0,\quad \pi^0\rightarrow\gamma e^+e^-$$

were not included in this table. Including them has a negligible effect.

The computations were also performed separately for events selected on the basis of Λ-decay proton dip angle and on the basis of the polar angle of the plane determined by the electron pair. No significant dependence on these selection criteria was found.

To search for possible biases which could either conceal a true polarization or produce a false apparent polarization, the polarization was computed relative to the electron plane with the direction given by $\mathbf{N}'=\hat{k}_+\times\hat{k}_-$ instead of $\mathbf{N}$. The value obtained was

$$\sum \hat{N}'\cdot\hat{p}_P/n=-0.009\pm0.017,$$
$$\sum \mathbf{N}'\cdot\hat{p}_P/\sum|\mathbf{N}'|=-0.002\pm0.023.$$

A recent calculation[18] indicates that the T-violating correlation of this type expected from interference of one- and two-photon exchange processes would lead to $|\sum \hat{N}'\cdot\hat{p}_P/n|\approx0.7\times10^{-4}$, well below our detection ability.

CONCLUSION

The values reported in Table III are consistent with the absence of any T-noninvariant polarization of the Λ in the $\Sigma\rightarrow\Lambda+e^++e^-$ decay. Thus there is no evidence for a T-noninvariant term contributing to this process as expected if the hypothesis of minimal electromagnetic interaction is valid[3,9] or if SU_3 symmetry is not badly broken.[19] The average polarization of the Λ determined from the average unweighted cosine of the decay angle for the combined sample of 1969 events is $(3\pm6)\%$.

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[17] The maximum Λ lab momentum possible for this reaction is 245.1 MeV/c and the maximum lab momentum possible for an electron or positron is 85.7 MeV/c.

[18] L. A. Kondratyuk and V. B. Kopeliovich, Institute for Theoretical and Experimental Physics, Government Commission on the Use of Atomic Energy of the U.S.S.R., Report No. 727, 1970 (unpublished).

[19] T. D. Lee, Phys. Rev. **140**, B967 (1965).