Test of $T$ Invariance in Electromagnetic $\Sigma$ 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 $A^0$ in the decay $\Sigma^+ \rightarrow A^0 + e^+ + \nu_e$. The result of this experiment, combined with a previous measurement (also using stopping $K^-$ mesons in hydrogen bubble chambers as a source of $\Sigma^+$ hyperons), is a polarization of $(3 \pm 0.6)\%$.

INTRODUCTION

In 1956, Lee and Yang suggested that the $\tau-\theta$ 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. However, tests of $T$ in free-neutron and $\Lambda$ decays, in $K_{\beta \delta}$ decays, and in $\beta$ decay of polarized nuclei have not yet shown any $T$ violation (see Table I). The observation in 1964 of the CP-nonconserving decay $K_{\pi \rho} \rightarrow \pi^\pm \pi^\mp$ led Bernstein, Feinberg, and Lee to review the experimental evidence for $C$, $P$, and $T$ invariance of the strong and electromagnetic interactions.

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

The method suggested by Bernstein, Feinberg, and Lee for the detection of a time-reversal violation in the decay $\Sigma^+ \rightarrow A^0 + e^+$ was applied by a Maryland-Columbia-Heidelberg collaboration to a sample of 907 events; the results were ambiguous (about a two-standard-deviation effect). \(^{18}\)


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

<table>
<thead>
<tr>
<th>Quality studied</th>
<th>T invariance predicted value</th>
<th>Observed value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse polarization to the decay plane in ( K^+ \rightarrow e^+\mu^+\nu )</td>
<td>0.0</td>
<td>0.04 ± 0.35</td>
<td>U. Camerini et al., Phys. Rev. Letters 14, 989 (1965)</td>
</tr>
<tr>
<td>Transverse polarization to the decay plane in ( K^0 \rightarrow \pi^+\pi^-\nu )</td>
<td>≤0.01</td>
<td>0.02 ± 0.07</td>
<td>D. Barta et al., Phys. Rev. Letters 16, 282 (1966)</td>
</tr>
<tr>
<td>Phase angle between ( S )- and ( P )-wave amplitudes in ( \Delta^o \rightarrow \pi^+\pi^- )</td>
<td>(6.5±1.5)°</td>
<td>(9.0 ± 5.5)°</td>
<td>O. E. Overstreet and R. Roth, Phys. Rev. Letters 19, 391 (1967)</td>
</tr>
<tr>
<td>Neutron-electron-antineutrino correlation coefficient in the decay of free polarized neutrons ( n \rightarrow p\pi^-\nu )</td>
<td>0.0</td>
<td>0.04 ± 0.05</td>
<td>M. T. Burgi et al., Phys. Rev. 120, 1829 (1966)</td>
</tr>
<tr>
<td>Neutron-electron-antineutrino correlation coefficient in the decay ( Ne^{19} \rightarrow F^{19}+e^+\pi^-\nu )</td>
<td>0.02±0.014</td>
<td>0.01±0.01</td>
<td>B. G. Frosolinsky et al., Phys. Letters 27B, 557 (1968)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Quantity studied</th>
<th>T invariance predicted value</th>
<th>Observed value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosine of the angle between proton and normal to the ( \Sigma^0 ) decay plane in ( \Sigma^0 \rightarrow A^0e^+\nu ), with ( A^0 \rightarrow p\nu )</td>
<td>0.0</td>
<td>0.020±0.020</td>
<td>R. G. Glasser et al., Phys. Rev. Letters 17, 603 (1966)</td>
</tr>
<tr>
<td>Neutron electric dipole moment</td>
<td>0.0</td>
<td>&lt;5×10^{-3} cm</td>
<td>J. K. Baird et al., Phys. Rev. 179, 1285 (1966)</td>
</tr>
<tr>
<td>Phase angle between the ( E2 ) and ( M1 ) amplitudes in the 90-keV ( \gamma ) transition of ( Ru^{106} )</td>
<td>0.0 or π</td>
<td>(1.0±1.7)×10^{-3}</td>
<td>G. G.行动1, Phys. Rev. Letters 19, 872 (1967)</td>
</tr>
<tr>
<td>Phase angle between the ( E2 ) and ( M1 ) amplitudes in the 73-keV ( \gamma ) transition of ( Ir^{191} )</td>
<td>0.0 or π</td>
<td>(0.6±2.1)×10^{-3}</td>
<td>M. Atac et al., Phys. Rev. Letters 20, 691 (1968)</td>
</tr>
<tr>
<td>Polarization of recoil deuterons in the elastic scattering reaction ( e^+d \rightarrow e^+d )</td>
<td>0.0</td>
<td>0.075±0.088</td>
<td>R. Prepost et al., Phys. Rev. Letters 21, 1271 (1968)</td>
</tr>
<tr>
<td>Changes in the intensity of scattered electrons upon reversal of proton target polarization</td>
<td>no changes</td>
<td>no changes</td>
<td>J. R. Chen et al., Phys. Rev. Letters 21, 1279 (1968)</td>
</tr>
</tbody>
</table>

EXPERIMENTAL METHOD

In this experiment\(^4\) we have applied the same analysis as used by the Maryland-Columbia-Heidelberg collaboration\(^5\) on an independent sample of 1062 events of the type \( \Sigma^0 \rightarrow A^0e^+\nu \) followed by the charged decay of the \( A^0 \). The time-reversal test consists of looking at the average polarization \( a_\Delta \cdot \mathbf{N} \) along a direction \( \mathbf{N} \), where \( a_\Delta \) is the \( \Delta \) spin vector and \( \mathbf{N} \) is the normal to the \( \Sigma^0 \) decay plane defined as

\[
\mathbf{N} = \hat{p}_\Delta \times (\hat{k}_+ + \hat{k}_-).
\]

Here \( \hat{p}_\Delta \), \( \hat{k}_+ \), and \( \hat{k}_- \) are unit vectors along the directions of the \( \Delta \), positron, and electron in the \( \Sigma^0 \) 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 \( \Sigma^0 \) rest frame). Since the decay plane is not defined in such a situation, the polarization must vanish.

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

In the \( \Lambda \) rest frame, the proton angular distribution is given by

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

where \( P_\Lambda \) is the \( \Lambda \) polarization along \( \mathbf{N} \) (normal to the production plane of the \( \Lambda \)) and \( \theta \) is the angle between the proton momentum vector and \( \mathbf{N} \). Experimentally,\(^6\)

\[
\alpha = 0.65 \pm 0.02.
\]

Thus a \( \Lambda \) 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 \( \Lambda \) 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

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

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

Letting $R_0 = \Delta \left( \frac{dG}{dk} \right) F_0^{-1}$ and $\phi$ be the relative phase of $F$ and $G$, the $\Lambda$ polarization along $N$ is approximately (for unpolarized $\Sigma$)

$$P_\Lambda = \frac{2R_0}{\Delta} \left( \frac{y}{k_+ - k_-} \right) \sin \phi \frac{|k_+ - k_-| k_+ \sin \theta}{k_+^2 + k_-^2 - k_+ k_- (1 - \cos \theta)} N,$$

where $k_\pm = |k_\pm|$ and $\beta$ is the pair opening angle $(\sin \theta = |k_+ X k_-|)$ and $\Delta$ is the available energy, $\Delta = M_{\Sigma^0} ^2 - M_{\Lambda^0}^2$. It is useful to write this as a function of two dimensionless variables:

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

$$y = (k_+ - k_-)/|P_\Lambda|.$$

Then

$$P_\Lambda = \frac{2R_0 \sin \phi}{1 + y^2} \frac{|y| [x(1 - y^2)]^{1/2}}{N}.$$

A more exact form of this formula is

$$P_\Lambda = \frac{2R_0 \sin \phi}{1 + y^2} \frac{|y| [x(1 - y^2)]^{1/2}}{N}.$$

If $T$ invariance holds, $\phi$ must be 0 or $\pi$, 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 $K^-\pi^0$s per frame. Approximately 227 000 of the 565 000 frames obtained have been analyzed to date.

We investigated the Dalitz decays of $\Sigma^0$ produced in the reactions

$$K^- p \rightarrow \Sigma^0 + \pi^0$$

and

$$\Sigma^- p \rightarrow \Sigma^0 + n,$$

The $\Sigma^0$ travels less than $5 \times 10^{-5}$ 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 $\Sigma^- p$ interactions (5) have no significant sources of background. There are, however, two other channels which have the same topology as (4). These are

$$K^- p \rightarrow \Sigma^0 + e^0,$$

and

$$\Sigma^- p \rightarrow \Delta^0 + e^0.$$

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

To ensure that the events could be analyzed correctly, several cuts were applied to the data. These were (a) $\Lambda$ projected length less than 1 mm, (b) $p$ projected length less than 1 mm, (c) $\Lambda$ vertex undefined ($\sim 180^\circ$ 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 $\Sigma^0$ 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 $\Sigma^0$ Dalitz decay from at rest $K^-$. Events were removed if (a) either the $\Lambda$, electron, or

\[ \begin{align*}
\text{(a)} & \quad K^- p \rightarrow \Sigma^0 + \pi^0, \\
\text{(b)} & \quad K^- p \rightarrow \Sigma^0 + e^0
\end{align*} \]


TABLE III. Results for time-reversal-noninvariant observables.

\( N = p \times (k_+ + k_-) \) is normal to decay plane of \( \Sigma^0 \), in \( \Sigma^0 \) rest frame. \( \dot{N} \cdot \dot{p}_P/N \) equals cosine of angle between \( N \) and proton momentum vector in \( \Lambda^0 \) rest frame.

|                        | Unweighted cosine \( \sum \dot{N} \cdot \dot{p}_P/N \) | Cosine weighted by \( N \) \( \sum \dot{N} \cdot \dot{p}_P/\sum |N| \) |
|------------------------|--------------------------------------------------|--------------------------------|
| Present experiment, 1062 events | \(-0.028 \pm 0.018\)                          | \(-0.015 \pm 0.028\)          |
| Previous experiment, 907 events | \(+0.020 \pm 0.020\)                          | \(+0.006 \pm 0.030\)         |
| Combined experiments, 1969 events | \(-0.006 \pm 0.013\)                          | \(+0.020 \pm 0.020\)         |
| 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) | \(0.052\)                                    | \(0.080\)                     |

A recent calculation indicates that the \( T \)-violating correlation of this type expected from interference of one- and two-photon exchange processes would lead to \( \sum \dot{N} \cdot \dot{p}_P/N \) being negligible. The average polarization of the \( \Lambda \) determined from the average unweighted cosine of the decay angle for the combined sample of 1969 events is \((3 \pm 6)\%\).

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