TIME REVERSAL INVARIANCE IN Λ^0 DECAY*

O. E. Overseth
University of Michigan, Ann Arbor, Michigan

and

R. F. Roth†
Princeton University, Princeton, New Jersey
(Received 19 June 1967)

The decay parameters of $\Lambda^0 \to p+\pi^-$ have been determined to be $\alpha = +0.65 \pm 0.02$, $\beta = -0.10 \pm 0.07$, $\gamma = +0.75 \pm 0.02$. Under time-reversal invariance, $\beta/\alpha = -\tan(\delta_s - \delta_p)$, where δ_s and δ_p are appropriate pion-nucleon scattering phase shifts; from this experiment $\beta/\alpha = -0.16 \pm 0.10 = -\tan(9° \pm 5.5°)$ in good agreement with the known value of $(\delta_s - \delta_p) = 6.5° \pm 1.5°$.

The observation of PC nonconservation in K^0 decay[1] combined with the assumption of the validity of the PCT theorem implies the violation of time-reversal invariance in physical processes somewhere. We report here a spark-chamber experiment to study time-reversal invariance in the decay $\Lambda^0 \to p+\pi^-$.

For the process $\Lambda^0 \to p+\pi^-$ the polarization $\vec{P}_p$ of the decay proton is given by

$$\vec{P}_p = \frac{(\alpha + \vec{P}_\Lambda \cdot \hat{q}_p)\hat{q}_p + \beta(\vec{P}_\Lambda \times \hat{q}_p) + \gamma q_p \times (\vec{P}_\Lambda \times \hat{q}_p)}{1 + \alpha \vec{P}_\Lambda \cdot \hat{q}_p},$$

where $\vec{P}_\Lambda$ is the polarization of the Λ^0, $\hat{q}_p$ is a unit vector along the direction of the proton momentum in the center of mass of the Λ^0, and α, β, and γ are the decay parameters given by Lee and Yang.[2] In the convention used here α is the helicity of the decay protons from unpolarized Λ^0 hyperons.

Thus $\beta = 2\,\mathrm{Im}\,s^*p/(|s|^2 + |p|^2)$ is proportional to the quantity $\vec{P}_p \cdot (\vec{P}_\Lambda \times \hat{q}_p)$, which is odd under the time-reversal operation. Hence, neglecting final-state interactions, if time-reversal invariance is valid in this decay, $\beta = 0$, and s and p must be relatively real. Including the final-state interaction between the outgoing proton and pion, s and p are given by $s = s' \exp(i\delta_s)$ and $p = p' \exp(i\delta_p)$, where s', p' are real, and δ_s and δ_p are the s and p π^--p scattering phase shifts at the appropriate center-of-mass energy. Thus, if time-reversal invariance is valid, $\beta/\alpha = -\tan(\delta_s - \delta_p)$. The test of time-reversal invariance in hyperon decay then is a comparison of Δ determined by $\Delta = -\arctan(\beta/\alpha)$ with $\delta_s - \delta_p$ given for π^--p scattering experiments. Since the time-reversal parameter β depends on the interference of the s- and p-wave amplitudes, the test is only sensitive if both s and p are appreciably different from zero. In the decay $\Lambda^0 \to p+\pi^-$ it is known[3] that s and p are roughly comparable, and since good data exist on the final-state interaction, this decay mode provides a good test for time reversal invariance.[4]

The decay parameters for $\Lambda^0 \to p+\pi^-$ were measured several years ago by Cronin and Overseth[3] (CO). The experiment reported here is essentially a repeat of the CO experiment modfied to increase sensitivity in the determination of β and increased in statistics by a factor of 10. The details of the experiment and of the analysis will be published elsewhere. Polarized Λ^0 hyperons were produced by associated production by 1070-MeV/c π^- mesons on the protons of a polyethylene target. The Λ^0 decay is observed in a thin-plate spark chamber and the polarization of the decay proton is determined from the scattering of the proton in a carbon-plate spark chamber. The experiment was run at the Princeton-Pennsylvania Accelerator where a total of 1 250 000 spark-chamber pictures were taken at an average rate of one per second. One in four of these pictures showed a Λ^0 decay, and one in 30 of the Λ^0 decays had a proton with a scatter useful for polarization analysis, yielding a sample of 10 000 good events.

The analyzing power graphs compiled by Peterson[5] were used in the analysis. Peterson gives polarization analyzing powers for protons on carbon for four cases of ΔE, the maximum inelasticity in the scatter that goes unresolved. Graphs are given for $\Delta E = 0$, 10, 30, and 50 MeV. We believe the graphs for $\Delta E = 30$ MeV to be appropriate in this experiment, although results will be given for all four cases.

The first sample studied extensively consisted of 5309 selected events where the proton range calculated from kinematics agreed with the observed range to an uncertainty of two sparks, i.e., to within ±20 MeV. The Λ^0 polarization was determined in 3° intervals of the laboratory production angle for use in the subsequent analysis. Analysis of the proton scattering to the left or right with respect to the direction $\vec{p}_{lab}\times(\hat{n}\times\hat{q}_p)$ determines α and γ, and with respect to $(\hat{n}\times\vec{p}_{lab})$ gives β/α, where $\hat{n}$ is perpendicular to the production plane. In the whole analysis the results are determined by maximizing the appropriate likelihood functions, and errors are taken to be the $e^{-1/2}$ points on the curves. No geometrical approximations are made in the analysis and the relativistic spin transformation in going from center of mass to the laboratory has been included in all cases.

The results for this selected sample of 5309 events are $\alpha=+0.650\pm0.024$, $\beta/\alpha=-0.16\pm0.13$, and $\gamma>0$. In the analysis, the value of γ is determined from $\gamma=\pm(1-\alpha^2-\beta^2)^{1/2}$ but the sign is determined directly. The average polarization of the sample was 58%. Geometrical bias in the sample can be examined by determining a parameter α' in a manner analogous to the determination of α. Whereas α is determined by studying the left-right scattering asymmetry of the proton with respect to the appropriate direction, α' is similarly determined by studying the up-down asymmetry with respect to the same direction. In the absence of bias, $\alpha'=0$. Experimentally it was found that $\alpha'=-0.002\pm0.024$. The results given above are for the $\Delta E=30$ MeV graph of analyzing powers. In Table I the results are presented for the other choices of analyzing-power data. It is clear that the results are insensitive to analyzing-power assignment. We find that a 10% increase in analyzing power increases α by less than 3%.

Since the results were found to be insensitive to analyzing-power assignment, the sample was increased by relaxing the proton-range agreement requirement. In Λ^0 decay the proton opening angle is small (typically less than 8° in this experiment), and the calculated proton momentum depends sensitively on this angle. However, in the analysis for the decay parameters this uncertainty only affects the assignment of analyzing power to the event which depends on the energy of the proton at the time of scatter. In addition to the 5309 events with good range fits, the enlarged sample included 3680 events in which the scattered proton stopped in the carbon-plate chamber and 1141 events in which the scattered proton left the chamber. For those additional events which stopped in the chamber the analyzing power was based on the residual range observed. For the 1141 events where the proton left the chamber a constant analyzing power of 0.52 was assigned to each event. The value of analyzing power equal to 0.52 was the average of the 5309 selected events, and that value gave $\alpha=0.65$ for the 1141 events. The results of likelihood calculations for the large sample using the $\Delta E=30$-MeV tables are presented in Table II, where they are compared with results of CO. The results of the larger sample are essentially the same as the subsample but, of course, the errors are smaller.

The results for the decay parameters for $\Lambda^0\to p+\pi^-$ determined from this experiment are summarized in Table III. The errors quoted are larger than statistical to include a ~5%

Table I. Results for 5309 selected events for analyzing-power determinations given by Peterson[a] for several choices of scattering inelasticities ΔE.

ΔE	α	β/α
0 (elastic)	0.674 ± 0.024	-0.13 ± 0.13
10 MeV	0.670	−0.15
30 MeV	0.650	−0.16
50 MeV	0.637	−0.17

[a]Ref. 5.

Table II. Results from this experiment compared with results from previous experiment (CO).

	Present experiment	CO
α	$+0.645\pm0.017$	$+0.62\pm0.07$
β/α	-0.16 ± 0.10	$+0.28\pm0.40$
$\Delta=-\arctan(\beta/\alpha)$	$9.0°\pm5.5°$	$-15°\pm20°$
number of events	10 130	1156

Table III. Summary of the results of this experiment.

$\alpha=+0.65\pm0.02$
$\beta=-0.10\pm0.07$
$\gamma=+0.75\pm0.02$
$\beta/\alpha=-0.16\pm0.10$
$\Delta=-\arctan(\beta/\alpha)=9.0°\pm5.5°$
$|p|/|s|=0.38\pm0.01$

uncertainty in analyzing-power assignments. The quantities measured directly in this experiment are α, β/α, and the sign of γ. Since $\alpha > 0$, the helicity of the decay proton is positive, and $\gamma > 0$ means that s wave predominates over p wave in this decay. Since the errors for the decay parameters are interrelated, it is desirable to express our results in terms of the more orthogonal quantities α, φ defined by

$$\beta = (1-\alpha^2)^{1/2} \sin\varphi,$$

$$\gamma = (1-\alpha^2)^{1/2} \cos\varphi.$$

In this parametrization the results for the experiment can be stated as $\alpha = +0.65 \pm 0.02$ and $\varphi = -8° \pm 6°$.

The test for time-reversal invariance comes from comparing $\Delta = -\arctan(\beta/\alpha)$ with the appropriate π^--p scattering phase shifts. Assuming the $\Delta I = \frac{1}{2}$ rule[6] applies in this decay, the phase shifts appropriate to the problem are the $I = \frac{1}{2}$ π^--p phase shifts at 37 MeV. Barnes et al.[7] have measured these phase shifts and their data give $\delta_S - \delta_P = 6.5° \pm 1.5°$,[8] to be compared with $9.0° \pm 5.5°$ determined for Δ in this experiment. The results of this experiment are consistent with time-reversal invariance in this decay.

Three other direct tests of time-reversal invariance in weak interactions have been published. Results from free-neutron decay,[9] $K_{\mu 3}$ decay,[10] and β decay of polarized nuclei[11] are all consistent with time-reversal invariance.

If the PC nonconservation occurs in the weak interactions, the expected degree of time-reversal-invariance violation in this experiment is model dependent. If the violation occurs in the $\Delta I \geq \frac{3}{2}$ component, as is suggested from the results of $K^0 \to 2\pi^0$ experiments,[12] large violation would not be expected in this decay since Λ^0 decay does not appear to violate the $\Delta I = \frac{1}{2}$ rule to any large degree. If the PC nonconservation were due to the electromagnetic interaction,[13] the effect here would presumably be less than 1% and would go undetected in this experiment.

It is a pleasure to acknowledge the excellent cooperation and support of the enitre staff of the Pricneton-Pennsylvania Accelerator. We are indebted to Robert Ball and Al Smith who assisted in the running of the experiment. We appreciate many conversations about this experiment we have had with J. W. Cronin.

*Work supported by U. S. Office of Naval Research under Contract Nos. Nonr-1224 (23) (University of Michigan) and Nonr-1858 (06) (Princeton University) (unpublished).

†Present address: Commission on College Physics, Ann Arbor, Michigan.

[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2]T. D. Lee and C. N. Yang, Phys. Rev. 108, 1645 (1957).

[3]J. W. Cronin and O. E. Overseth, Phys. Rev. 129, 1795 (1963).

[4]Of the other nonleptonic hyperon decays, only $\Lambda^0 \to n + \pi^0$ and $\Sigma^+ \to p + \pi^0$ satisfy these criteria and can provide a good test of time-reversal invariance.

[5]Vincent Z. Peterson, University of California Radiation Laboratory Report No. UCRL-10622, 1963 (unpublished).

[6]For a summary of the experimental situation regarding the $\Delta I = \frac{1}{2}$ rule for Λ^0 decay, see N. P. Samios, Argonne National Laboratory Report No. ANL 7130, 1965 (unpublished), p. 189.

[7]S. W. Barnes, H. Winick, K. Miyake, and K. Kinsey, Phys. Rev. 117, 238 (1960).

[8]Using Roper's best fit parametrization of π-N phase shifts between 0 and 350 MeV, $\delta_s - \delta_p = 6.65°$. L. D. Roper, R. M. Wright, and B. T. Feld, Phys. Rev. 138, B190 (1965).

[9]M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. 120, 1829 (1960).

[10]K. K. Young, M. J. Longo, and J. A. Helland, Phys. Rev. Letters 18, 806 (1967).

[11]F. P. Calaprice, E. D. Commins, H. M. Gibbs, G. L. Wick, and D. A. Dobson, Phys. Rev. Letters 18, 918 (1967).

[12]J.-M. Gaillard, F. Krienen, W. Galbraith, A. Hussri, M. R. Jane, N. H. Lipman, G. Manning, T. Ratcliffe, P. Day, A. G. Parham, B. T. Payne, A. C. Sherwood, H. Faissner, and H. Reithler, Phys. Rev. Letters 18, 20 (1967); J. W. Cronin, P. F. Kunz, W. S. Risk, and P. C. Wheeler, Phys. Rev. Letters 18, 25 (1967); T. N. Truong, Phys. Rev. Letters 13, 358a (1964); T. T. Wu and C. N. Yang, Phys. Rev. Letters 13, 380 (1964).

[13]J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139, B1650 (1965); S. Barshay, Phys. Letters 17, 78 (1965).