TEST OF TIME-REVERSAL INVARIANCE IN $K_L{}^0 \to \pi^- + \mu^+ + \nu$[†]

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We have measured the polarization of the muon in the decay $K_L{}^0 \to \pi^- + \mu^+ + \nu$ using spark chambers. On the basis of 1458 events, the component of polarization transverse to the decay plane was found to be -0.05 ± 0.18, which is consistent with zero, in agreement with time-reversal invariance.

Prior to 1964, time-reversal invariance, T, was experimentally tested for weak interactions only in neutron decay[1] and lambda decay[2] (nonleptonic). The results of both experiments were consistent with T invariance. Sakurai[3] pointed out a possible text of time reversal invariance for $K_{\mu 3}$ decay (leptonic, strangeness changing). A violation of T would manifest itself as a nonzero component of the polarization of the muon in the direction transverse to the decay plane; namely, along the direction $(\vec{p}_\pi \times \vec{p}_\mu)/|\vec{p}_\pi \times \vec{p}_\mu|$, where $\vec{p}_\pi$ and $\vec{p}_\mu$ are the momenta of the pion and muon, respectively, in the K rest frame. With the discovery[4] of a CP violating decay $K_L{}^0 \to \pi^+ + \pi^-$, possible sizable T violations in $K_L{}^0$ decay[5,6] and $K_{\mu 3}{}^+$ decay[6] were suggested. The result of an experiment[7] on $K_{\mu 3}{}^+$ decay was consistent with time-reversal invariance.

We have performed an experiment in the 30° neutral beam of the Argonne zero-gradient synchrotron (ZGS) to measure the polarization of the muon in the decay $K_L{}^0 \to \pi^- + \mu^+ + \nu$.

$K_L{}^0$ mesons decayed in a vacuum pipe placed in a 9.8-kG magnetic field (see Fig. 1). The pion and muon were observed in a set of foil spark chambers surrounding the vacuum pipe. Immediately downstream from the foil spark chambers was a large absorber (four inches of brass and 20 inches of aluminum) in which pions were removed; the absorber was followed by a set of range chambers (115 plates of $\frac{1}{8}$-in.-thick aluminum) in which the muons were stopped. The polarization of the muons was determined from the angular distribution of the decay positrons. The triggering logic consisted of a four-fold coincidence with anticoincidence; $\overline{\alpha}\beta M_1 M_2 \Omega P \overline{AB}$ (see Fig. 1) during part of the runs and $\overline{\alpha}\beta M_1 M_2 \Omega P$ for the remainder. The logic insured that a neutral particle entered the vacuum pipe, that two charged particles were produced ahead of the M_1 and M_2 counters, and that at least one of them passed through the absorber and reached the range chambers.

To allow a substantial fraction of the stopped muons to decay, the range chambers were fired 2.5 μsec after the coincidence logic pulse. The range chambers were enclosed in a magnetic shield (Mumetal) to reduce the precession of the stopped muons to less than 10°.

The range chambers pictures were scanned for a stopping muon with its decay positron. The following criteria were applied in selecting events: (1) The positron track length was required to be between four gaps (3.8-g/cm^2 aluminum) and 25 gaps. (2) To eliminate con-

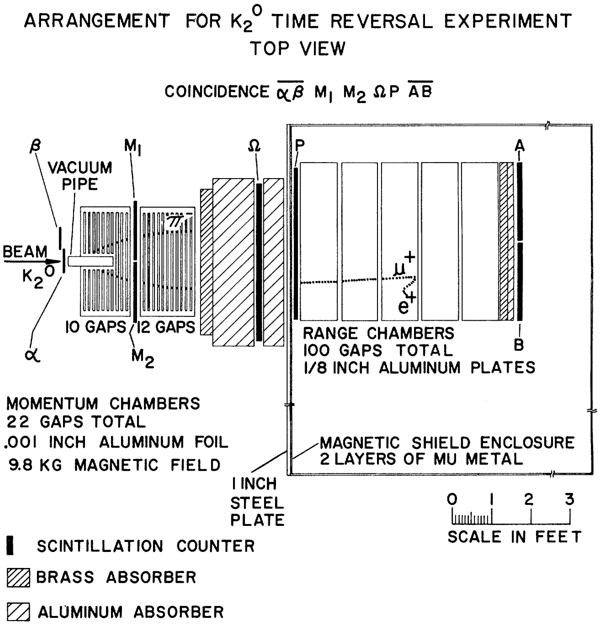

FIG. 1. Experimental arrangement and an idealized event. A $K_L{}^0$ enters the apparatus at the left and decays in the vacuum pipe. The π^- and μ^+ tracks are indicated in the momentum spark chambers. The π^- interacts in the absorber, while the μ^+ goes through the absorber and stops in the range chambers. The μ^+ decays into the e^+ as shown.

tamination from low-energy forward scatters, the positron track was required to have a minimum angle of 30° with respect to the stopping muon; events in the backward 30° cone were removed to preserve symmetry. (3) The reconstructed center-of-mass kinematics were required to be consistent with $K_{\mu 3}$ decay. (4) The spatial location of the track in the range chambers was required to be consistent (within 10 inches) with the positive track extrapolated from the momentum chambers. (5) The momentum and range of the stopping track were required to be consistent with that of a muon to within ±11 %.

We have analyzed 1458 events which satisfied the selection criteria. Because of a twofold ambiguity in the kinematics there were two solutions in the K_L^0 rest frame, corresponding to the two possible values of the energy of the K_L^0 in the laboratory. We have selected a subsample of 777 unambiguous events. The unambiguous data consisted of those events for which both values of $\cos\theta_T = (\vec{p}_\pi \times \vec{p}_\mu)\cdot\vec{p}_e / |(\vec{p}_\pi \times \vec{p}_\mu)\cdot\vec{p}_e|$ fell in the same interval of the angular distribution plus those events for which the higher energy K_L^0 solution was unlikely (E_K greater than 1.96 BeV). We have separately analyzed the total sample of data, using only the lower energy K_L^0 solution.

The observed data on the transverse polarization are shown in Fig. 2(a). The upper points are the total data; the lower points are the unambiguous data. The dashed curves are the efficiencies as determined from Monte Carlo calculations. We have corrected the data for the efficiencies and have made a least-squares fit, using linear functions of the form

$$dN/d\cos\theta_T = 1 + \bar{\alpha}\bar{P}_T\cos\theta_T.$$

$\bar{P}_T$ is the average transverse polarization. The effective analyzing parameter, $\bar{\alpha}$, has been determined from the observed positron range spectrum and from the pion contamination[8] among the muons. The result is $\bar{\alpha} = 0.31 \pm 0.02$.

The best fit to the 777 unambiguous events gave a slope $\bar{\alpha}\bar{P}_T = 0.01 \pm 0.06$, which corresponds to $\bar{P}_T = 0.03 \pm 0.19$.

The best fit to the total data gave a slope $\bar{\alpha}\bar{P}_T = -0.01 \pm 0.04$. About 15 % of the events appear incorrectly in the angular distribution because of the arbitrary use of the low-energy K_L^0 solution. Correlation studies indicate the analyzing parameter $\bar{\alpha}$ is effectively reduced by a factor of 0.8 because of the wrong solutions. Using the reduced value of $\bar{\alpha}$, we obtain

$$\bar{P}_T = -0.05 \pm 0.18.$$

For both samples of data, our results are consistent with time-reversal invariance. A similar result, namely $\bar{P}_T = 0.02 \pm 0.07$, was obtained from the up-down ratio in a counter experiment by Bartlett et al.[9]

We have analyzed the longitudinal polarization, and it constitutes a check on the ability of the apparatus to detect polarized muons. From the total data, 1153 events were found to be unambiguous in the longitudinal distribution [see Fig. 2(b)]. The best fit to the data gave $\bar{\alpha}\bar{P}_L = 0.33 \pm 0.04$, which corresponds to $\bar{P}_L = 1.06 \pm 0.14$, a high polarization. As a further check that the high longitudinal polarization did not arise from an experimental bias, we have analyzed the negative muon events.

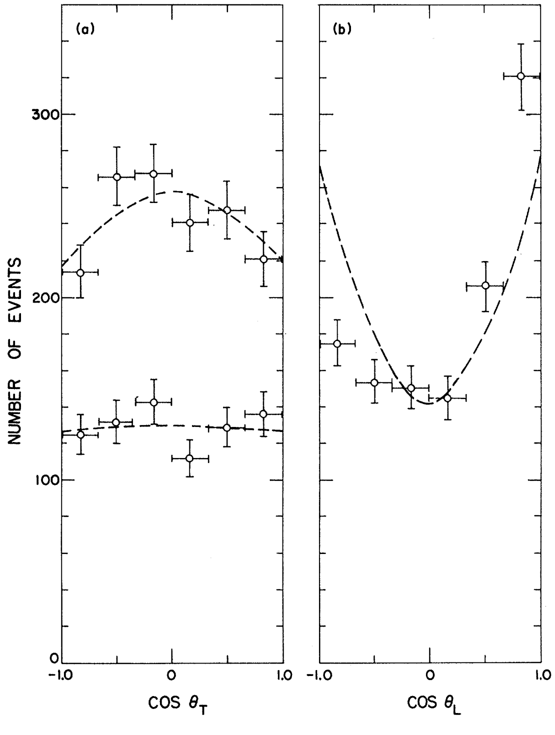

FIG. 2. Experimental data. (a) Transverse angular distribution of positrons in the K_L^0 rest frame. The upper curve is for the total data, the lower curve is for an unambiguous subsample. The dashed curves show the efficiencies. (b) Longitudinal angular distribution of positrons relative to the muon in the K_L^0 rest framed. The dashed curve shows the efficiency.

The polarization of the negative muons was consistent with zero, as expected. A detailed analysis of the longitudinal polarization in terms of the form factors is in progress.

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

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

[3] J. J. Sakurai, Phys. Rev. 109, 980 (1958).

[4] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964); A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, Phys. Rev. Letters 13, 243 (1964).

[5] R. G. Sachs, Phys. Rev. Letters 13, 286 (1964); B. G. Kenny and R. G. Sachs, Phys. Rev. 138, B943 (1965).

[6] N. Cabibbo, Phys. Letters 12, 137 (1964).

[7] U. Camerini *et al.*, Phys. Rev. Letters 13, 318 (1964).

[8] The pion background of about 17% is due to positive pions which either decay in flight or come to rest without interacting. These pions come from the alternate decay modes: $K_L{}^0 \to \pi^+ + \mu^- + \nu$, $K_L{}^0 \to \pi^+ + \pi^- + \pi^0$, $K_L{}^0 \to \pi^+ + e^- + \nu$.

[9] D. Bartlett, C. E. Friedberg, K. Goulianos, and D. Hutchinson, Phys. Rev. Letters 16, 282 (1966).

SMALL-ANGLE ELECTRON-PROTON ELASTIC-SCATTERING CROSS SECTIONS FOR SQUARED MOMENTUM TRANSFERS BETWEEN 10 AND 105 F^{-2}

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We report on the result of an electron-proton scattering experiment in which the elastic-scattering cross section for squared momentum transfers between 10 and 105 F^{-2} was measured with a precision of about 5%. The measurements were performed at the scattering angles $\theta_{\mathrm{lab}} \leq 25°$, where charge scattering contributes noticeably to the cross section. When combined with existing large-angle data,[1-6] separation of the electric and the magnetic form factors is possible over the whole range of squared momentum transfers.

In the experiment, the slowly ejected electron beam of the 6-GeV synchrotron was momentum analyzed and focused onto a liquid-hydrogen target. A Faraday cup,[7] placed in a concrete house 32 m behind the target, acted as an intensity monitor and beam stopper. A secondary emission chamber,[7] located in the beam between target and Faraday cup, served as an additional monitor. Elastically scattered electrons were identified by means of the magnetic spectrometer shown in Fig. 1(a). The spectrometer was composed of six quadrupole magnets and three bending magnets mounted on a turntable, which can be pivoted around the target center. Electrons which approximately satisfied the elastic-scattering kinematics were brought to a horizontal angular focus by quadrupoles Q_1 and Q_2. The horizontal angular acceptance ($\Delta\theta_x = \pm 12.00$ mrad) was defined by a collimator, H, at this focus and was therefore independent of the target size. Under this action of quadrupoles Q_3 and Q_4 and the bending magnets M_1, M_2, and M_3, a dispersed horizontal image of H was produced at counters S_1 and S_2. The electrons were then identified in a 5.5-m-long ethylene-filled threshold Čerenkov counter and registered in counters S_3, S_4, S_5, and S_6. In the vertical plane, the target was imaged onto counters S_1 and S_2, and the angular acceptance ($\Delta\theta_y = \pm 9.11$ mrad) was defined by collimator V behind Q_3. Optics and counter dimensions were chosen such that full transmission through the entire system was assured for all particles having passed colli-