the starquake theory of pulsar speed-ups, which can plausibly account for the behavior of the Crab pulsar, can also explain the observed features of the Vela pulsar only if it is assumed that the Vela possesses a solid core. Pines, Shaham, and Ruderman[1] have argued that the solid core has sufficient elastic energy to power the starquakes of the magnitude and frequency in the Vela pulsar.

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Muon Polarization in the Decay $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$, an Experimental Test of Time-Reversal Invariance*

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We report the results of a high-statistics scintillation-counter electronics experiment measuring the muon polarization in the decay $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ by the method of spin precession. We present results for the real and the imaginary parts of the form-factor ratio.

CP noninvariance is well established in the neutral-kaon system. Time-reversal noninvariance is implied, but has never been directly observed.[1] In the $K_L{}^0$ c.m. system a component of muon polarization normal to the decay plane $(\vec{\sigma}_\mu \cdot \vec{P}_\pi \times \vec{P}_\mu)$ in $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ is odd under time reversal T and forbidden by T invariance.[2] In this Letter we report the results of an attempt to observe T noninvariance directly by measurement of muon polarization in the decay $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$.

Briefly, our experimental technique is to record in plastic scintillation counters a prompt coincidence signifying π^- and μ^+ from in-flight $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ decay, degrade the muon to rest, and record a delayed coincidence signifying the e^+ preferentially emitted along the polarization vector of μ^+ in the decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$. To measure the muon polarization we have used the method of spin precession, recording the time distribution of the e^+ from μ^+ precessing in a 60-G magnetic field (1.8 turns per μ^+ lifetime) superimposed on the μ^+ stopping volume. The phase and magnitude of the observed sinusoidal modulation of the μ^+ decay intensity are directly related to the direction and magnitude of the muon polarization projected into the plane perpendicular to the precession field. Similar experiments have been performed previously.[3] The experiment reported here[4] is the first to use the method of spin precession and thus determine the analyzing power of the polarization measurement experimentally.

The experiment was performed in a 10° neutral beam at the Argonne zero-gradient synchrotron. Figure 1 is a cut-away perspective view of the apparatus which consists of (1) a front section of scintillation-counter hodoscopes to detect the π^- and μ^+, (2) a downstream polarimeter in which the μ^+ are degraded to rest and the e^+ detected. The counters were constructed in a way which allowed an unambiguous determination of the muon stopping sector and rejection of events in which the muon stopped in the scintillator panels. A "decay" count required a double coincidence between two counters (separated by $\frac{1}{8}$ in. of aluminum). Unambiguous definition of decay counters was required. A toroidal Fe magnet between the "π hodoscope" and "μ hodoscope" absorbs pions and deflects μ^+'s (μ^-'s) toward (away) from the $K_L{}^0$ beam axis. μ^+'s stop in the aluminum cylinders in the interior of the polarimeter and precess in either a vertical or axial precession field. The axial field precesses the two spin components transverse to the $K_L{}^0$ beam axis. Since for the events selected by our apparatus a T-noninvariant component is mostly transverse, if it exists at all, this is the one used to record the bulk of the data. In this Letter, we report only data taken with the axial field. Figure 1 is not drawn to scale for reasons of clarity, but approximate dimensions of the apparatus are, for the diameter of toroidal magnet, ~1.5 m; length of uranium beam stop, ~3 m; diameter of polarimeter stopping rods, ~17 cm; and their length, ~114 cm. Following the detection of a $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ candidate, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decays were detected in the intervals 0.100 → 4.500 μsec by the triangular prisms of counters that surround each aluminum cylinder.

The physical dimensions of the counters, their efficiency and relative locations, and the symmetry and regulation of the axial precession field were controlled with a precision corresponding to a systematic error of 0.002 in the components of transverse polarization, approximately 5 times less than the statistical error of the experimental data.

Taking account of the sixfold azimuthal symmetry of the apparatus, there are five inequivalent $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ event types shown in Fig. 2(a).

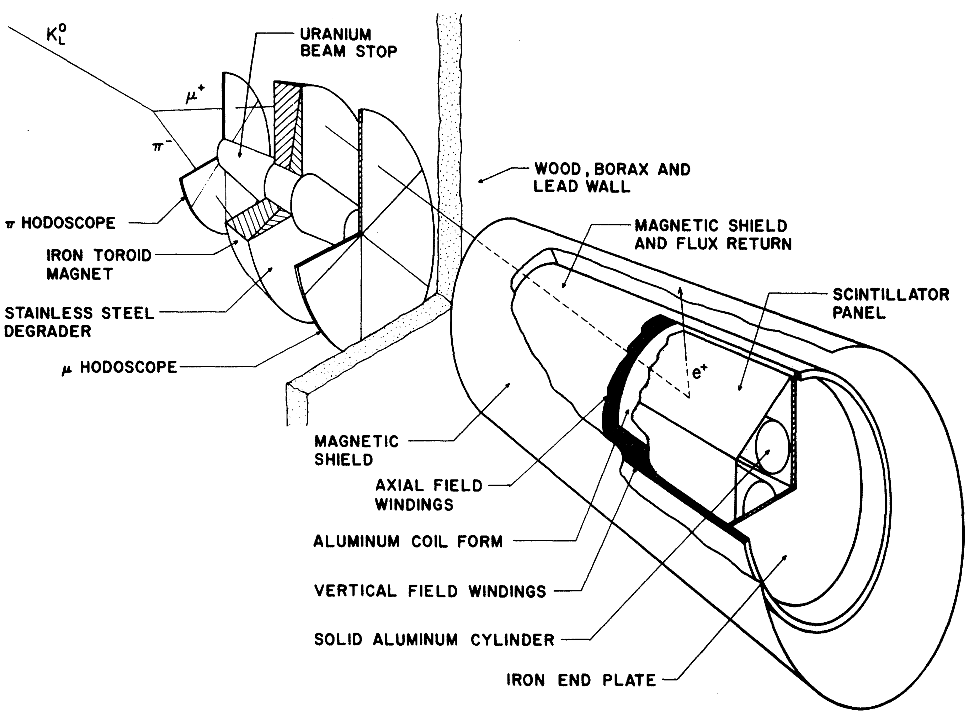

FIG. 1. Perspective view of the experimental apparatus. Drawing not to scale; see text for approximate dimensions.

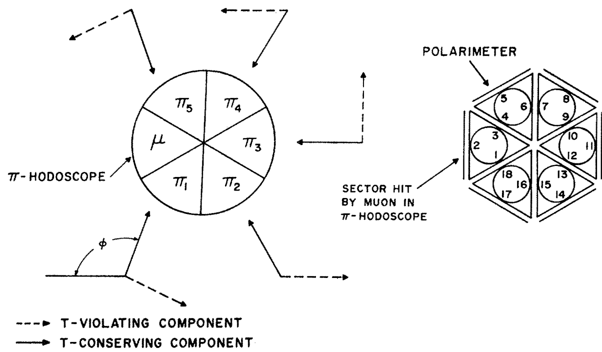

FIG. 2. (a) The five inequivalent $K_L{}^0 \rightarrow \pi^- \mu^+ \nu_\mu$ event types and schematic illustration of T-invariant and T-noninvariant components of μ^+ polarization transverse to the $K_L{}^0$ beam axis. (b) e^+ counters in the polarimeter.

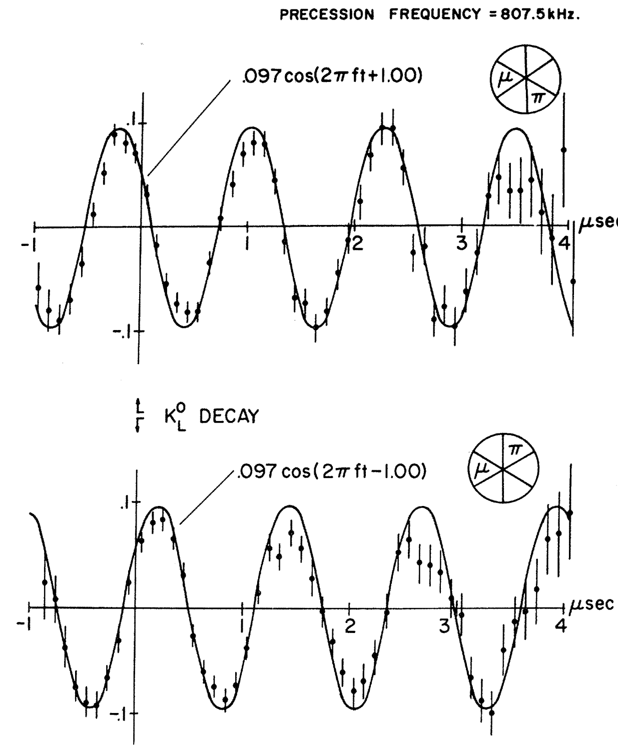

FIG. 3. Muon spin precession signals for the π_2 and π_4 event types. Some data points appear earlier in time ($t<0$) than the $K_L{}^0$ decay ($t=0$) because the histograms for different e^+ counters have been shifted forward in time to line up the phases of oscillation before summation. The raw histograms have relative phases offset by differences of outward pointing counter normals to respective scintillation panels.

In the sector hit by the pion we have indicated schematically the T-invariant and T-noninvariant components of transverse polarization. Comparing the five event types, the T-invariant components have a reflection symmetry in the horizontal plane, while the T-noninvariant ones have a screwlike symmetry about the $K_L{}^0$ axis. These sharply contrasting behaviors provide a clean separation of the T-invariant and T-noninvariant components of polarization.

The recorded event sequences have been histogrammed in time bins according to the time elapsed between $K_L{}^0$ and μ^+ decays. With all events rotated to the orientation shown in Fig. 2(a), there are 180 time-bin histograms corresponding to the five event types, eighteen e^+ counters [as labeled in Fig. 2(b)], and two polarities of precession field (half the data were recorded with $\vec{B}$ pointing upstream and half downstream).

Each of the 180 time-bin histograms has been parametrized by the distribution function

$$P_n(t) = C_n \exp(-\lambda_B t)\{\exp(-\lambda_\mu t)[1+\alpha|\vec{S}_\perp|\cos(2\pi f t+\varphi_n)]+B_n\}. \qquad (1)$$

In this formula t is the time elapsed between $K_L{}^0$ and μ^+ decays; C_n is a normalization constant; λ_μ is the muon decay rate; λ_B is the background rate in a sector of the polarimeter; B_n is the amplitude of nonmuonic delayed event background; α is the effective e^+ decay asymmetry from polarized μ^+; $|\vec{S}_\perp|$ is the magnitude of muon polarization projected into the precession plane; f is the muon Larmor frequency; and φ_n is the angle between the muon polarization at $t=0$ and the outward normal to the nth scintillation panel of the polarimeter. It can be shown[4] that formula (1) is the most general parametrization which is consistent with the construction symmetries of the experiment.

In Table I we present the mean muon precession asymmetry (represented by $\alpha|\vec{S}_\perp|$ and φ) for each event type. Within the approximate statistical errors the precession asymmetry vectors obey the reflection symmetry expected for T invariance, and we conclude from this that *there is no significant violation of T invariance in our data.* As a by-product of this analysis we have manipulated the data to obtain a single "raw" muon precession curve for each event type, isolated from the nonprecessing muon signal and background. The results obtained for π_2 and π_4

TABLE I. Fitted muon precession asymmetry for each event type.

Event type	No. of events	$\alpha\lvert\vec{S}\rvert$	φ^{a} (rad)	χ^2 for 2767 degrees of freedom
π_1	229 709	0.0860 ± 0.0038	1.842 ± 0.044	2804
π_2	483 829	0.0880 ± 0.0025	1.021 ± 0.028	2831
π_3	780 332	0.0730 ± 0.0019	-0.010 ± 0.026	2734
π_4	483 558	0.0840 ± 0.0025	-1.041 ± 0.029	2832
π_5	229 821	0.0950 ± 0.0038	-1.892 ± 0.040	2830

[a]See the π_1 event type in Fig. 2(a) for the definition of φ.

are shown in Fig. 3. For no T noninvariance the phase of oscillation of π_2 should be equal in magnitude, opposite in sign to π_4, and that is the way the theoretical curves have been drawn. The data do not depart significantly from the theoretical curves. The actual resolution in phase is $\pm 1.7°$ for the precession curves in Fig. 3.

The time-bin histograms have been fitted with Monte Carlo calculations assuming a vector matrix element[5]

$$M = [f_+(q^2)(P_K + P_\pi)_\alpha + f_-(q^2)(P_K - P_\pi)_\alpha]\,\bar{u}_\nu\gamma_\alpha(1+\gamma_5)v_\mu, \qquad (2)$$

$$q^2 = |P_K - P_\pi|^2 = M_K{}^2 + M_\pi{}^2 - 2M_K E_\pi$$

in the $K_L{}^0$ c.m. for the decay $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$. The muon polarization for a vector interaction has been given in convenient forms by Cabibbo and Maksymowicz[6] and is a sensitive function of the form-factor ratio $\xi(q^2) = f_-(q^2)/f_+(q^2)$. The result of our measurement for the form-factor ratio $\xi(q^2)$ is

$$\left.\begin{aligned} \mathrm{Re}\,\xi(0) &= -0.385 \pm 0.105 - 6.0\lambda_+, \\ \mathrm{Im}\,\xi &= -0.060 \pm 0.045, \end{aligned}\right\} \lambda_- = 0.0. \qquad (3)$$

The momentum-dependence parameters $\lambda_\pm$, defined by $f_\pm(q^2) = f_\pm(0)[1 + \lambda_\pm(q^2/m_\pi{}^2)]$, have not been determined by our analysis. The result for $\mathrm{Im}\,\xi$ again indicates no significant violation of T invariance. In the $K_L{}^0$ c.m. the error 0.045 in $\mathrm{Im}\,\xi$ corresponds to a maximum T-noninvariant component of muon polarization $= 0.045$ at any point on the Dalitz plot, and $\cong 0.009$ averaged over the Dalitz plot weighted by the decay intensity corresponding to Eq. (2) above.

The effective e^+ decay asymmetry ($= \alpha$) from polarized μ^+'s was estimated as a free parameter in the maximum-likelihood calculation leading to (3) and found to be 0.253 ± 0.005. We emphasize that with α determined by a free fit, the error obtained for $\mathrm{Im}\,\xi$ is an entirely experimental quantity and not dependent on a calculated analyzing power for the polarimeter.

The calculations leading to (3) include background corrections for (1) $K_L{}^0$ decay modes other than $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ contributing to the data sample, (2) events due to random coincidences, (3) events due to neutron interactions with material in the decay volume, and (4) events originating outside the decay volume. Each of these background contaminations contributes fewer than 10% of the recorded events. An estimated systematic error of 0.035 has been added to the statistical error for $\mathrm{Re}\,\xi(0)$ to account for imperfect knowledge of the $K_L{}^0$ momentum spectrum. $\mathrm{Im}\,\xi$ is not sensitive to a reasonable variation of the $K_L{}^0$ spectrum, and the error for $\mathrm{Im}\,\xi$ is purely statistical.

The result given in (3) for $\mathrm{Re}\,\xi(0)$ can be compared with existing measurements of the charged K decay $K^+ \to \pi^0 \mu^+ \nu_\mu$. In an overall fit to 25 $K^+ \to \pi^0 \mu^+ \nu_\mu$ experiments, Gaillard and Chounet[4] obtained $\mathrm{Re}\,\xi(0) = -0.85 \pm 0.20$, $\lambda_+ = 0.045 \pm 0.012$ with $\lambda_- \equiv 0.0$. Inserting $\lambda_+ = 0.045 \pm 0.012$ into (3) above yields $\mathrm{Re}\,\xi(0) = -0.655 \pm 0.127$. Our data are therefore in agreement with K^+ experiments. Previous measurements of muon polarization in $K_L{}^0 \to \pi^- \mu^+ \nu_\mu$ have tended toward a value of $\mathrm{Re}\,\xi$ far more negative than K^+ experiments: Auerbach *et al.*, $\mathrm{Re}\,\xi = -1.2 \pm 0.5$,[7] Abrams *et al.*, $\mathrm{Re}\,\xi = -1.6 \pm 0.5$,[8] Longo, $\mathrm{Re}\,\xi = -1.81 + 0.50$.[3]

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Correlation of Reported Gravitational Radiation Events with Terrestrial Phenomena

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We report here the results of a statistical cross-correlation study between 262 of Weber's gravitational radiation events and various geophysical, meteorological, and other phenomena. A correlation at the 2.7 standard-deviation level is found between the gravitational radiation events and the measure of the magnetospheric ring-current intensity, and at the 3.0 standard-deviation level with sidereal time. The results imply that some of the reported gravity events could be caused by processes other than gravitational radiation.

The reported observations of bursts of gravitational radiation[1,2] with a source in the direction of the galactic center[3] (or anticenter) has sparked intense scientific interest in the astrophysical implications of the measurements. Recent measurements also appear to rule out a scalar component for the radiation.[4] The current rate of detection of these events suggests a galactic mass-loss rate $\sim 10^4 M_{\odot}/\text{yr}$, a loss rate $\sim 10^2$ times larger than the upper limit allowed by current astronomical data.[5] Because of the important implications of the observations, Weber has conducted subsidiary measurements, apparently ruling out seismic, electromagnetic, and cosmic-ray disturbances on the detectors[1-3,6] as possible sources of the measured effects.

A recent publication[7] has suggested that there might be a significant correlation between the seventeen original events reported by Weber[1] and solar activity, terrestrial geomagnetic activity, and galactic cosmic rays. Correlation with a 2-day time lag at the >99.9% confidence level between two solar indicators and the seventeen events was reported. Correlation with no time lag at the 99% confidence level was found with the geomagnetic activity index K_p and with cosmic rays. Because of the difficulty of obtaining reliable statistical results based upon the small data sample of Ref. 7, it is desirable to use a much larger set of Weber's data.

We have examined the relationship of various geophysical, meteorological, and other phenomena to a body of 262 gravitational radiation events observed between 22 August 1969 and 22 December 1969. Most data were selected for their global nature; no assumptions as to physical causes were made. All of our correlation studies are reported here. The gravity data were kindly supplied to us by Professor Weber. We have coded each gravity event as unity. For daily averages if more than one event occurred within a day, the units were summed. The correlation coefficients between the coded events and indices of geomagnetic, meteorological, and other terrestrial activity were calculated using daily time lags between the two sets of data ranging from