PHYSICAL REVIEW D VOLUME 14, NUMBER 1 1 JULY 1976

Test of the rotational invariance of the weak interaction*

Riley Newman† and Stephen Wiesner‡
Columbia University, New York, New York 10027
(Received 10 November 1975)

We consider the possibility that the weak interaction might recognize a preferred direction in space. We report a search for anisotropy in the β decay of unpolarized ^{90}Y nuclei. Our result may be expressed in terms of an expansion of the angular distribution of the decay electron: $\Gamma(\theta) \propto 1 + \epsilon_1\cos\theta + \epsilon_2\cos^2\theta + \cdots$, where θ is the angle between the direction of emission of the electron and any supposed asymmetry axis. We find for any axis that $|\epsilon_1| < 10^{-6.8}$ and $|\epsilon_2| < 10^{-5.7}$ (90% confidence limits).

I. INTRODUCTION

The weak interaction is known to violate at least one and probably two discrete space-time symmetries (parity and time reversal). One is led to ask if it might also violate a continuous symmetry of the Lorentz group, such as rotational invariance. Surprisingly, the experimental evidence for the rotational invariance of the weak interaction (RIWI) is very limited. This was pointed out by Lee and Yang at the same time that they suggested that parity might be violated in the weak interaction,[1] and the situation has changed little since then.

II. PRESENT EVIDENCE FOR ROTATIONAL INVARIANCE

Let us consider the extent to which present knowledge can be used to exclude the possibility that the weak interaction recognizes a preferred direction in space or violates angular momentum conservation.

It would seem that a limit on the breakdown of RIWI might be obtained from our knowledge of "forbidden" nuclear β decays—decays whose rate is suppressed by the requirement that the electron and neutrino carry off one or more units of orbital angular momentum in order to arrive at the spin-parity of the daughter nucleus. Since this suppression comes from the requirement of angular-momentum conservation, it would seem that a failure of angular-momentum conservation in the weak interaction should be reflected in a violation of these selection rules. However, as long as the weak coupling remains a point interaction, even with RIWI failure, its only effect on a nucleus in β decay can be to turn a neutron into a proton (or vice versa) and give it a limited momentum kick, with or without spin flip. This is just what happens normally, so that the selection rules for forbidden β decays must remain unaltered, and no test of RIWI is afforded.

Perhaps the best evidence for RIWI comes from the stringent test of present weak-interaction theory afforded by the branching ratio $\Gamma(\pi\to e\nu)/\Gamma(\pi\to \mu\nu)$. The electron decay mode of the pion is suppressed by a large factor on the order of m_e^2/m_μ^2—a result which is peculiar to any combination of V and A parts of a leptonic current in the usual (rotationally invariant) current-current Lagrangian. An anomalous part of the weak π decay amplitude of almost any kind would reveal itself sensitively in a deviation of this branching ratio from the $V-A$ prediction.

In fact, the branching ratio is measured[2,3] to be $(1.274\pm0.024)\times10^{-4}$, differing by less than 0.07×10^{-4} from the theoretical $V-A$ value[3,4] of 1.233×10^{-4}. Thus, we can put rough limits on the ratio ϵ of any anomalous amplitude for $\pi\to e\nu$ compared with the normal amplitude for $\pi\to\mu\nu$. (For example, ϵ might represent an amplitude for the π to decay into a $J=1$ state in which the electron and neutrino have opposite helicities, as preferred by a $V-A$ coupling.) We obtain $\epsilon \lesssim (0.07\times10^{-4})^{1/2}$ or $\lesssim m_\mu/m_e \times (0.07\times10^{-4})$ depending on whether the anomalous amplitude is assumed to be incoherent or coherent with the normal amplitude for $\pi\to e\nu$. Either assumption suggests a limit on ϵ on the order of 10^{-3}.

A weaker test of RIWI is provided by the ratio $\Gamma(K^+\to 2\pi)/\Gamma(K^0\to 2\pi)$, measured to be about 1/700. The K^+ decay into two pions in an $l=0$ state is forbidden by the $\Delta I=\frac{1}{2}$ rule. Assuming that the observed decay rate is due to a J-violating decay into an $l=1$ state yields a limit $\epsilon \lesssim (700)^{-1/2} = 4\times10^{-2}$ for the relative amplitude of a J-violating part of the weak interaction.

It may be noted that the decay $K_L^0\to 2\pi$ remains CP-forbidden even if the pions are produced in a state with $l\neq 0$.

Thus, prior to this experiment, there seems to have been no evidence excluding a violation of rotational invariance by the weak interaction with relative amplitude $\lesssim10^{-3}$ (roughly the amplitude of the CP violation observed in K decay).

III. THE EXPERIMENT

Our experiment was a search for anisotropy in the β decay of unpolarized nuclei, in a reference frame which was nonrotating with respect to the "fixed" stars. The experiment was designed to be sensitive to dipole or quadrupole anisotropy, by which we mean nonzero values of ϵ_1 or ϵ_2, respectively, in an expansion of the β decay distribution Γ as

$$\Gamma(\theta)=\Gamma_0[1+\epsilon_1\cos\theta+\epsilon_2\cos^2\theta+\cdots], \tag{1}$$

where θ is the angle between an asymmetry axis and the emission direction of the electron.

In this expression, ϵ may be interpreted roughly as the relative *amplitude* for a RIWI-violating transition which yields the same final-state particles as normal β decay, since the anisotropy would be expected to arise primarily from the interference between the normal decay amplitude and an anomalous amplitude.

Our apparatus is shown schematically in Fig. 1 and in detail in Fig. 2. A 10-Ci ^{90}Sr source was secured to an inside wall of an evacuated chamber, opposite an aluminum charge-collecting plate. Electrons leaving the source in the direction of the plate were collected, yielding a current (averaging 6.8 nA, or 4.3×10^{10} electrons/sec) which was a measure of the rate for β emission in that direction. The chamber rotated continuously about a vertical axis with rotation frequency 0.75 Hz. Thus, a β-decay anisotropy (not exactly parallel to the rotation axis) would be reflected in a modulation of the collected current with frequency 0.75 Hz, and/or at integral multiples of that frequency depending on the multipole moment of the anisotropy.

The collector plate subtended a solid angle of nearly 2π. The active part of the source was a mixture of strontium titinate and silver, 0.3 mm $\times$35 mm$\times$35 mm, covered by 0.07-mm silver and 0.075-mm steel windows. The β-decay chain is $^{90}\mathrm{Sr}\to{}^{90}\mathrm{Y}\to{}^{90}\mathrm{Zr}(0^+\to2^-\to0^+)$. The ^{90}Sr decay electrons have a maximum energy of 0.54 MeV and could not penetrate the source window. Of the electrons born in ^{90}Y decay (2.27-MeV end-point energy), 11.7% escaped the source and were collected.

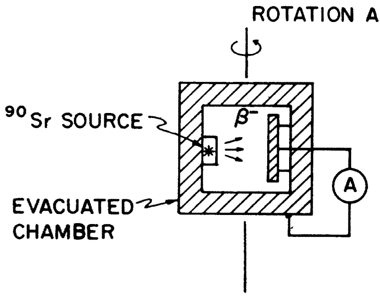

FIG. 1. Schematic representation of the experiment. Anisotropy in β decay would be reflected in a modulation of the current in the ammeter as the chamber rotates.

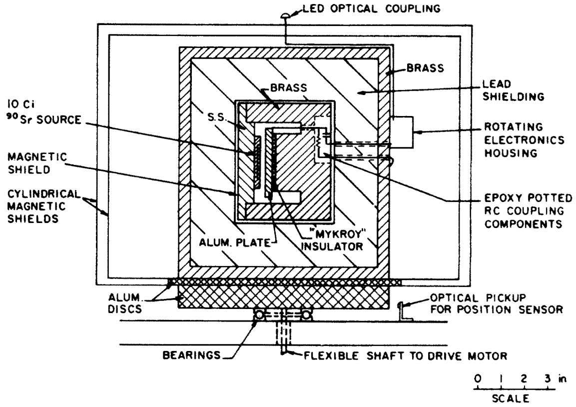

FIG. 2. Details of the rotating apparatus, seen in cross section.

Great care was exercised to minimize all effects which might define a lab-fixed direction inside the rotating chamber. The rotation axis was held vertical to within 10^{-4} rad. The magnetic field in the chamber was minimized by a set of three concentric high-permeability magnetic shields surrounding it, plus external Helmholtz coils which nulled the average horizontal component of the earth's field. The lab-fixed horizontal component of the magnetic field inside the chamber with these precautions was measured to be $<5\times10^{-5}$ G.

The phase-sensitive amplifier scheme used to search for modulation of the plate current is shown in Fig. 3. Briefly, the plate current controlled the frequency of a pulse generator in the

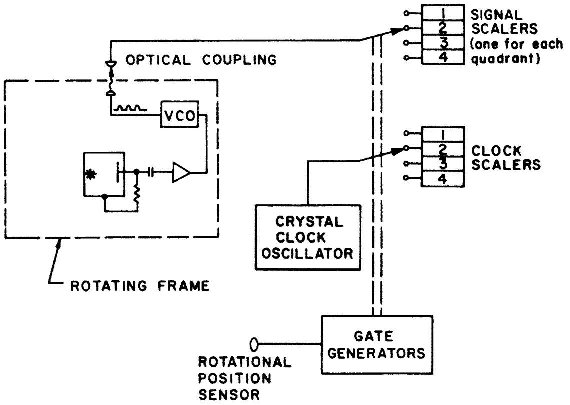

FIG. 3. Schematic representation of the phase-sensitive amplifier system. Anisotropy in β decay would be reflected in the inequality of the four ratios of counts in the signal scalers to counts in the corresponding clock scalers.

rotating system. This pulse frequency was communicated to the stationary lab frame via an light-emitting-diode phototransistor optical link on the rotation axis of the rotating assembly. In the lab frame the pulses were digitally analyzed for frequency modulation at multiples of the chamber rotation frequency.

The plate current was ac coupled to a two-stage amplifier with a bandpass of 0.02 to 3.0 Hz. The voltage output of the amplifier frequency modulated a 15.5-kHz pulse generator. Thus, the average frequency shift $\langle \Delta f \rangle$ from the central oscillator frequency over an angular region of the chamber's rotation was related to the corresponding average current variation $\langle \Delta i \rangle$ from the mean plate current by $\langle \Delta f \rangle = k \langle \Delta i \rangle$ where the modulation factor k was 1.26×10^{15} Hz/A at 0.75 Hz and 1.01×10^{15} Hz/A at 1.5 Hz. The frequency-modulated pulses were gated into one of four scalars according to the lab-fixed quadrant in which the instantaneous source-to-plate direction lay. The same gate signals gated clock pulses from a crystal controlled oscillator into a corresponding set of four clock scalers. The counts from all scalers were recorded at two-hour (2-h) intervals. Mean frequencies (ratios of pulses counted to elapsed time recorded in clock scalers) then yielded values for the mean current variation $\langle \Delta i \rangle$ associated with any quadrant or combination of quadrants over the time interval.

Data were collected almost continuously over a period of a month, with breaks every two days to pump down the chamber and change batteries, yielding a total of 232 good 2-h runs.

The data were analyzed in terms of the quantity $\delta \equiv 2(\langle i_A \rangle - \langle i_B \rangle)/(\langle i_A \rangle + \langle i_B \rangle)$, where $\langle i_A \rangle$ and $\langle i_B \rangle$ represent mean currents associated with lab-fixed angular regions A and B of the chambers rotation. Three values of δ were determined for each 2-h run: δ_{NS}, δ_{EW}, and $\delta_{2\nu}$ where NS and EW represent north-south and east-west angular divisions and $\delta_{2\nu}$ corresponds to a quadrupole combination of the four quadrants.

Now a statistically significant nonzero value for one of the current asymmetries δ could represent either a true anisotropy in β decay or a spurious effect due to lab-fixed influences such as magnetic fields or a tilt of the rotation axis of the spinning chamber. An important feature of this experiment is the ability to distinguish a "true" anisotropy. Suppose at 9:00 a.m. the β-decay electrons seem to prefer to go east, yielding a positive δ_{EW}. If at 9:00 p.m. when the earth has rotated 180° the electrons still prefer east, yielding the same positive δ_{EW}, we may conclude the effect is spurious, while if the electrons now prefer west we may suspect a true anisotropy of the kind for which we are searching. In general, a dipole type of asymmetry in β decay will reveal itself in a modulation of δ_{NS} and δ_{EW} with the earth's rotation frequency, while a quadrupole asymmetry will modulate $\delta_{2\nu}$ at twice the earth's rotation frequency.

TABLE I. Measured values of the coefficients in Eq. (2), representing variation with sidereal time of the lab current symmetries.

Asymmetry type	$10^8 a_0$	$10^8 a_1$	$10^8 a_2$
NS	-1.9 ± 1.0	3.2 ± 1.9	1.7 ± 1.9
EW	1.1 ± 1.0	2.9 ± 1.9	1.9 ± 1.9
2ν	-1.0 ± 1.0	0.5 ± 1.7	0.7 ± 1.7

The three types of current asymmetry δ were each fitted to distributions in sidereal time of the form:

$$\delta = a_0 + a_1 \sin(\omega t + \phi_1) + a_2 \sin(2\omega t + \phi_2) , \tag{2}$$

where ω is the angular frequency of the earth's rotation. Results of the fits are presented in Table I. The uncertainties presented are based on the experimentally observed fluctuations in the values of the δ for individual 2-h runs at the same sidereal time on different days. This method of determining the statistical fluctuation in the δ from run to run automatically includes the effects of all kinds of random noise in the experiment, such as amplifier noise and equipment vibration, as well as the statistical fluctuation in the number of β decays. The observed rms fluctuation in the δ was 1.4×10^{-7}, which was only 30% greater than that which we calculate assuming the fluctuation to be due only to the statistical uncertainty in the number of electrons collected in each 2-h run (an

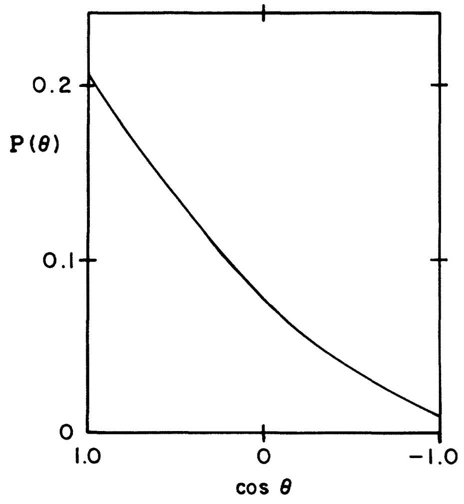

FIG. 4. The probability $P(\theta)$ of collecting a ^{90}Y decay electron emitted at an angle θ with respect to the normal direction from source-to-collector plate, as determined by a Monte Carlo calculation.

TABLE II. Expected values for the coefficients in Eq. (2) and Table I, in terms of the ϵ asymmetry parameters and the angle Ψ between asymmetry axis and the earth's polar axis.

Asymmetry type	a_0	a_1	a_2
NS	$0.36\epsilon_1\cos\Psi$	$0.39\epsilon_1\sin\Psi$	0
EW	$0.18\epsilon_1\cos\Psi$	$0.50\epsilon_1\sin\Psi$	0
2ν	$0.009(3\sin^2\Psi - 2)$	$0.016\epsilon_2\sin 2\Psi$	$0.024\epsilon_2\sin^2\Psi$

average of 3×10^{14} electrons/run).

The results in Table I show no significant evidence for anisotropy, spurious or otherwise. The χ^2 for a value of zero for all the parameters is 13.6, for nine degrees of freedom.

In obtaining a limit on the anisotropy of β decay from the data of Table I, the effect of multiple scattering of the decay electrons in the source material and covering window must be taken into account. Due to this scattering, a decay electron partially "forgets" the direction in which it was born by the time it leaves the source, so that any original anisotropy it may have had is partially washed out and the directional sensitivity of the apparatus is reduced. To determine the precise effect of this scattering, a Monte Carlo program was written to track electrons from birth as they scatter and slow, using the Moliére theory of multiple scattering and including the effect of both radiative and ionization energy losses. This program was used to evaluate the mean probability $P(\theta_n)$ of collecting electrons born with the energy distribution of ^{90}Y decay and originally emitted at an angle θ_n with respect to the chamber-fixed normal direction $\hat{n}$ from source to collector plate.

The resulting distribution, shown in Fig. 4, was well fitted by a parametrization

$$P(\theta_n) \propto 1 + C_1\cos\theta_n + C_2\cos^2\theta_n \tag{3}$$

with $C_1 = 1.26$, $C_2 = 0.39$. The program predicted the average collection probability for the electrons from all angles to be 0.088—somewhat lower than the observed collection efficiency of 0.117 based on the measured collected current and the manufacturers estimate of the source strength. Equation (3) is used in the following way to take multiple scattering into account in analyzing our data. Let us parametrize a hypothetical anisotropy in the original β-decay distribution in terms of parameters ϵ_1 and ϵ_2 as in Eq. (1). Then Eqs. (1) and (3) may be folded together to give an expression for the instantaneous collected current I in our apparatus as a function of the angle θ between the presumed asymmetry axis and the instantaneous direction of the collector plate, $\hat{n}$:

$$I(\theta) = I_0\left[1 + \frac{\epsilon_1 C_1}{3}\cos\theta + \frac{\epsilon_2 C_2}{15}\cos 2\theta\right]. \tag{4}$$

The last step in making contact with the data of Table I in order to put limits on ϵ_1 and ϵ_2 involves a rather intricate folding together of the rotation of the chamber about a lab-fixed vertical axis with the rotation of that axis about the earth's polar axis. This folding also takes into account a phase shift in the amplifier, such that for example the measured δ_{EW} was a mixture of the "true" δ_{EW} and δ_{NS}. This phase shift was −26° at 0.75 Hz and −45° at 1.5 Hz. The results of the folding depend on the angle Ψ that the presumed asymmetry axis in fixed space makes with the earth's polar axis. These results are tabulated in Table II.

Comparing Table II with Table I we may put limits on the ϵ which are independent of Ψ. Taking 90% confidence limits on the parameters in Table I to be 1.65σ above the most likely value, we obtain limits:

$$|\epsilon_1| < 10^{-6.8},$$

$$|\epsilon_2| < 10^{-5.7}.$$

ACKNOWLEDGMENTS

We appreciate helpful comments by Norman Christ, T. D. Lee, and Malvin Ruderman. The help of Richard Gonsalves and Espedito Ruggiero in preparing the experiment is gratefully acknowledged. We also thank Fred Andrews of Amersham/Searle Corporation for his help and advice with the Sr^{90} source. One of us (S.W.) would like to thank Don Eldridge for his hospitality.

---

*Research supported in part by the National Science Foundation.

†Present address: University of California, Irvine, Irvine, California 92664. Sloan Foundation Fellow, 1970–1973.

‡Present address: 32100 Page Mill Road, Los Altos, California 94022.

[1] T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956).

[2] E. DiCapua *et al.*, Phys. Rev. 133, B1333 (1964).

[3] D. Bryman and C. Picciotto, Phys. Rev. D 11, 1337 (1975).

[4] T. Kinoshita, Phys. Rev. Lett. 2, 477 (1959).