Search for a nonzero triple-correlation coefficient and new experimental limit on T invariance in polarized-neutron beta decay*

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A detailed description of an experimental test of time-reversal invariance in the β decay of the polarized free neutron is presented. The experiment consists of a measurement of the triple-correlation coefficient D between the neutron polarization vector and the electron and antineutrino momentum vectors. A nonzero value for this coefficient would imply T violation, since final-state interactions and other corrections may be neglected at the present level of precision. The experiment was performed using a cold-neutron beam at the High Flux Reactor of the Institut Laue-Langevin, Grenoble. A polarizing neutron guide tube yielded a beam intensity of 10^9 neutrons/sec with a polarization of 70%. Our result, based upon observation of approximately 6×10^6 decays, is $D=(-1.1\pm1.7)\times10^{-3}$, consistent with time-reversal invariance in the $\Delta S=0$ weak interaction. In terms of the relative phase angle between axial-vector and vector coupling constants, the result may be expressed as $\phi=180.14\pm0.22°$.

I. INTRODUCTION

We present a detailed description of an experimental test[1] of time-reversal invariance in the β decay of the polarized free neutron. The primary motivation for this test lies in the occurrence[2] of CP and T violation in the K^0 system. Although many theoretical speculations have been made, at the present time there exists no clear understanding concerning the origin of these symmetry violations. The various theories which have been proposed can in general be categorized as either millistrong, electromagnetic, milliweak, or superweak. Wolfenstein[3,4] has reviewed many of the possibilities and their experimental consequences. Unfortunately, the experimental measurements are quite difficult, and the available data are not of sufficient precision to determine uniquely the origin of CP violation. In this situation, it is clear that more precise experimental tests in a wide variety of physical systems are necessary.

The present experiment provides a new upper limit on the possible presence of a direct milliweak T violation in the $\Delta S=0$ semileptonic weak interaction. Furthermore, even if the observed symmetry violations in the K^0 system are due to a CP-violating superweak $|\Delta S|=2$ interaction, a considerably larger ($\approx10^{-3}$) T violation in the $\Delta S=0$ sector would not in general be excluded. The present experiment is also sensitive to this indirect type of T violation.

Further motivation for the experiment lies in the possibility of uncovering a T violation whose physical origin is independent of the symmetry violations observed in the K^0 system. Contributions to β decay from a T-noninvariant second-class current provide one example of such a possibility.[5]

The decay probability for a polarized neutron can be written in the form[6]

$$W\propto 1+a\frac{\vec{p}_e\cdot\vec{p}_{\bar\nu}}{E_eE_{\bar\nu}}+\vec{P}\cdot\left(A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_{\bar\nu}}{E_{\bar\nu}}+D\frac{\vec{p}_e\times\vec{p}_{\bar\nu}}{E_eE_{\bar\nu}}\right),\tag{1}$$

where $\vec{p}_e$, $\vec{p}_{\bar\nu}$, E_e, and $E_{\bar\nu}$ are the lepton momenta and total energies, respectively, $\vec{P}$ is the neutron polarization vector, and a, A, B, and D are coefficients which depend on the values of the β decay coupling constants and of the Fermi and Gamow-Teller nuclear matrix elements. Explicit expressions for these coefficients are presented in Ref. 6.

The present experiment consists of a search for the three-vector correlation term

$$D\vec{P}\cdot\frac{\vec{p}_e\times\vec{p}_{\bar\nu}}{E_eE_{\bar\nu}}\tag{2}$$

in the decay of the polarized free neutron. The coefficient D is given by

$$D=\frac{2}{\sqrt3}\,\frac{|g_V||g_A||M_F||M_{G\text{-}T}|}{|g_A|^2|M_{G\text{-}T}|^2+|g_V|^2|M_F|^2}\sin\phi,$$

where M_F and $M_{G\text{-}T}$ are the Fermi and Gamow-

Teller nuclear matrix elements and where ϕ is the phase angle between axial-vector (g_A) and vector (g_V) coupling constants. For neutron decay $|M_F|=1$, $|M_{G-T}|=\sqrt{3}$, and ϕ is known to be near 180°. Time-reversal noninvariance would appear as a departure of ϕ from 180° and a consequent nonzero value for D.

Since final-state-interaction corrections and nuclear-recoil terms in the β-decay transition amplitude can also contribute to D, it must be shown that these contributions are insignificant in order to have a valid test of T invariance. Neglecting nuclear-recoil terms for the moment, the most significant final-state interaction in neutron β decay is the Coulomb scattering of the decay electron by the daughter proton. The lowest-order contribution to D from this process is given by[7]

$$D_{\text{Coul}}^{(1)}=\frac{2}{\sqrt{3}}\left|\frac{\alpha Z m}{p_e}\right| |M_F||M_{G-T}|\,\text{Re}\left[\left|\frac{g_S g_A^* - g_V g_T^*}{(|g_S|^2+|g_V|^2)|M_F|^2+(|g_T|^2+|g_A|^2)|M_{G-T}|^2}\right|\right],$$

in which α is the fine-structure constant, Z is the atomic number of the residual nucleus, and g_S and g_T are the coupling constants for scalar and tensor interactions, respectively. In a pure V-A theory of weak interactions, $D_{\text{Coul}}^{(1)}$ thus vanishes. However, since small deviations from a pure V-A theory are not ruled out by existing experimental evidence, the Coulomb correction to D may differ from zero. Upper limits on possible S and T terms in the effective weak Hamiltonian may be determined from experimental upper limits on the Fierz terms in allowed β decay. Following Calaprice *et al.*[8] and using present limits[9] on the Fierz terms, the first-order Coulomb correction to D for the neutron is at most 2×10^{-4} and is thus insignificant for the present measurement. Higher-order Coulomb correction terms are believed to be less important.

Now turning to recoil effects, the two most significant contributions to D arise from weak magnetism and possible induced-tensor couplings. The first of these has been calculated by Callan and Treiman,[10] who, assuming the existence of first-class currents only together with the CVC (conservation of vector current) hypothesis, find a contribution of order 2×10^{-5} to the D coefficient for neutron decay. Holstein[11] has calculated the contribution from induced tensor couplings. His result is of order $(E_0/M)\,\text{Im}(a^*d)$, where $a=g_V M_F$ and where d is the form factor for the induced-tensor contribution to the hadronic weak current. For mirror transitions such as neutron decay, d is a purely second-class form factor. Since $E_0/M \approx 10^{-3}$, a value near unity for $\text{Im}(a^*d)$ would be required in order to contribute significantly to D at the level of precision of the present experiment. Such a contribution would, of course, indicate the presence of a T-violating second-class current, and would therefore be of great interest. At present, however, there is no evidence for the existence of such a current.

From this discussion we conclude that a measurement of D in neutron β decay provides a test of the time-reversal invariance of the semileptonic $\Delta S=0$ weak interaction valid at least to the level of 2×10^{-4}.

II. PREVIOUS MEASUREMENTS OF THE D COEFFICIENT

The coefficient D has been measured several times previously, both for neutron decay[12-15] and for the decay of ^{19}Ne.[8,16] The results of these measurements are summarized in Table I. For the case of ^{19}Ne it should be noted that the final-state Coulomb correction to D is larger than for neutron decay by a factor of about 4 due to the $(\alpha Z/p)$ dependence of this term. Although this correction vanishes for a V-A theory, the possi-

TABLE I. Measurements of the D coefficient in β decay.

Decaying nucleus	D	ϕ	Reference
^{19}Ne	0.002 ± 0.014	$(180.2\pm1.6)°$	Calaprice *et al.* (Ref. 8)
	0.002 ± 0.004	$(180.2\pm0.4)°$	Calaprice *et al.* (Ref. 16)
neutron	-0.14 ± 0.20	$(198\pm27)°$	Clark *et al.* (Ref. 12)
	0.04 ± 0.05	$(175\pm6)°$	Burgy *et al.* (Ref. 13)
	-0.01 ± 0.01	$(181.3\pm1.3)°$	Erozolimsky *et al.* (Ref. 14)
	-0.0027 ± 0.0033	$(180.35\pm0.43)°$	Erozolimsky *et al.* (Ref. 15)
	-0.0011 ± 0.0017	$(180.14\pm0.22)°$	This work, see also Ref. 1

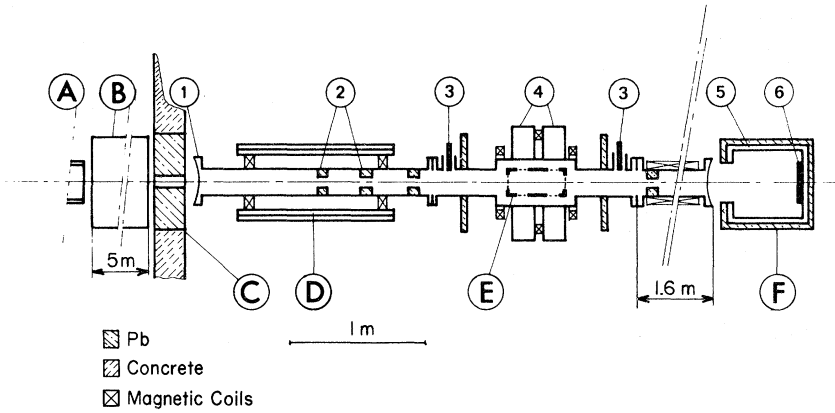

FIG. 1. Schematic diagram of the experimental setup: A—curved neutron-guide tube $H14$, B—polarizing guide tube, C—shielding, D—spin flipper, E—detection chamber, F—beam catcher, 1—Al entrance window to vacuum chamber, 2—beam collimators (^{6}LiF and Pb), 3—gate valves, 4—detectors, 5—LiF, 6—^{6}LiF.

bility of S and T couplings may complicate the interpretation of the ^{19}Ne measurements as tests of T invariance, at least below the level of 2×10^{-3}.

For the neutron, the principal limitation on the precision of the measurements has been the low neutron densities obtainable with existing polarized neutron beams. In addition, the measurement requires detection of coincidences and therefore inevitably suffers from a low detection efficiency. The low counting rates which result have led to rather large statistical errors.

For ^{19}Ne it has been possible to increase the intensity of the source by storage of the polarized atoms in a nearly closed vessel for periods of several seconds (see Ref. 16). This approach, however, does not appear to be feasible at present for the neutron.

III. EXPERIMENTAL METHOD

The improved precision of the present experiment with respect to previous measurements has been obtained by the availability of a high-intensity beam of cold neutrons, by the use of neutron guide tubes[17] both for reduction of background and for polarization of the beam, and by substantial improvements in the detection chamber. The experiment was performed at the High Flux Reactor (central flux $= 1.5 \times 10^{15}$ neutrons/cm^{2}sec) of the Institut Laue-Langevin in Grenoble.

A. The polarized neutron beam

A schematic diagram of the experiment is presented in Fig. 1. An unpolarized cold-neutron beam was obtained from the curved neutron-guide tube $H14$ (A in the figure), one of five guide tubes at this reactor which view a liquid-deuterium cold-neutron moderator. The cross section of this guide tube is a rectangle 20 cm high and 3 cm wide. Slow neutrons propagate through the guide tube by multiple total internal reflection from its nickel-coated inner surfaces. The tube is 27 m in length and has a radius of curvature of 2.7 km, corresponding to a neutron cutoff wavelength of 2.8 Å. Since this curvature is sufficient to prevent reflectionless transmission through the guide, γ rays from the reactor core and virtually all fast neutrons are removed from the beam, thereby eliminating what otherwise would constitute intense sources of background. The flux of the cold-neutron beam leaving $H14$ was 3×10^9 neutrons/cm^{2}sec.

The beam was subsequently polarized by passage through a magnetized FeCo curved guide tube (B) 5 m long with a rectangular cross section 57 mm high and 5 mm wide. Because of constructive interference between magnetic scattering and nuclear scattering of the neutrons by the FeCo walls of this guide tube, those neutrons with spin parallel to the magnetization direction of the FeCo underwent total reflection and were therefore transmitted by the guide tube with high efficiency. For neutrons with antiparallel spins, however, the interference between magnetic and nuclear scattering is destructive. These neutrons therefore were not reflected and consequently were poorly transmitted by the guide tube. The neutron beam leaving the guide tube was therefore polarized. Using a second similar magnetized guide tube as analyzer, the mean polarization of the beam was measured to be $(70 \pm 7)\%$. Upon leaving the polarizer, the beam intensity was 10^9 neutrons/sec with a mean neutron velocity of 1100 m/sec. For a complete description of the polarizer, see Ref. 18.

The beam then passed through a two-coil spin flipper (D).[19] As shown in Fig. 2, for both the spin-transmission mode and the spin-flip mode,

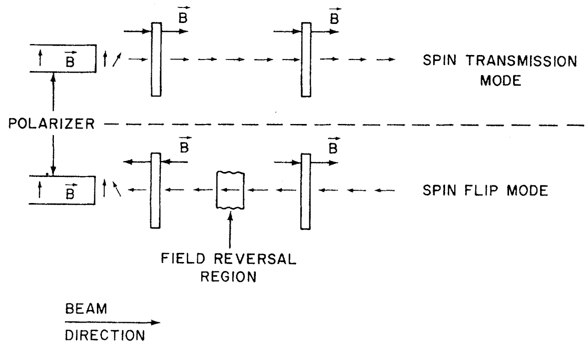

FIG. 2. The method of operation of the two-coil spin flipper.

the neutron polarization vector is initially in the upward direction. For spin transmission, the two coils generate parallel magnetic fields. In the region between the polarizer and the first coil the neutron spins are turned adiabatically into the beam direction. There are no nonadiabatic transitions and the spins remain oriented parallel to the beam direction after leaving the spin flipper.

For the spin-flip mode, the current in the first coil is reversed. In the region between the polarizer and the first coil the neutron spins are now turned adiabatically into the direction antiparallel to the beam direction. The neutrons then encounter a field-reversal region, where they undergo a nonadiabatic transition. The neutron spins remain fixed in space while the magnetic field is reversed. The net effect of these processes is that in the region beyond the spin flipper, the neutron spins are now antiparallel to the beam direction, and hence have undergone a spin flip with respect to the orientation they would have had in the spin-transmission mode. Depolarization of the beam in the field-reversal region was minimized by surrounding the entire two-coil spin flipper with a three-layered magnetic shield to reduce stray fields. The spin-flipping efficiency was measured by the shim method[20,21] to be 97%. This device is fully described elsewhere.[22] During the experiment, the neutron polarization was reversed every second.

The 3-G guide field in the decay region (E of Fig. 1) was obtained from a 3-coil system and was maintained parallel to the beam direction within an error of 1° by cancellation of the perpendicular components of the ambient magnetic field using large rectangular Helmholtz coils (not shown in Fig. 1). In this region the beam, collimated by slits (2) of ^{6}LiF and Pb, had a width of 5 cm and a height of 8 cm. The Pb served to reduce the background of neutron-capture γ rays from the polarizer and from the Al entrance window (1).

After the decay region, the beam passed through a 1.6-m-long drift tube into the beam catcher (F). In order to minimize background from the beam catcher, the beam was stopped by ^{6}LiF (6).

B. The detection chamber

The aluminum detection chamber and drift tubes were evacuated to a pressure of about 2×10^{-6} Torr by a 10-cm oil diffusion pump with a water-cooled baffle and liquid-nitrogen-cooled trap. Aluminum entrance and exit windows of 0.1 mm thickness allowed passage of the neutron beam with a minimum of undesirable neutron-capture γ radiation.

A cross section of one section of the decay chamber is shown in Fig. 3. The beam direction was perpendicular to the plane of the paper. The decay chamber consisted of two such sections in series, for a total of 8 detectors. Since the momentum of the neutron may be neglected, conservation of linear momentum allows the term (2) to be written

$$\frac{D\vec{P}\cdot(\vec{p}_p\times\vec{p}_e)}{E_eE_{\bar{\nu}}},$$

where $\vec{p}_p$ is the momentum of the recoil proton. The experimental geometry maximized this triple

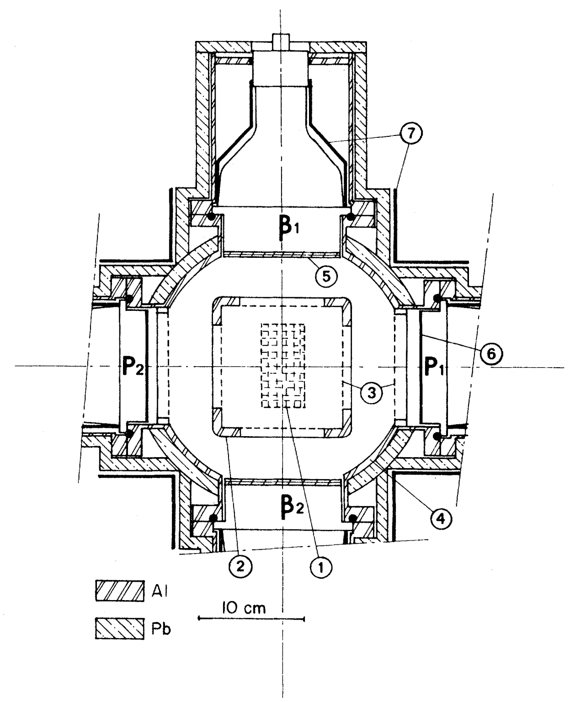

FIG. 3. Cross section of one section of decay chamber: 1—polarized neutron beam, 2—high-voltage box (20 kV), 3—proton-acceleration gap, 4—vacuum-chamber wall, 5—plastic scintillation β detector, 6—vacuum-evaporated 8000-Å layer of NaI(Tl) for proton detection, 7—magnetic shielding.

product by arranging the average directions of the three vectors to be mutually perpendicular. At the same time the symmetrical arrangement greatly reduced systematic errors, as will be made clear in Sec. IV.

For each section, decay electrons originating from the beam (1) were detected by means of two plastic scintillation detectors (5) located above and below the beam axis. The recoil protons, after drifting through the field-free region inside the high-voltage box (2), were accelerated to 20 keV in the 4 cm gap (3) and were counted by specially made scintillation detectors (6). These proton detectors were fabricated by methods similar to those suggested by Bauer and Weingart[23] and by Afonin and Bondarenko.[24] An 8000-Å layer of NaI (Tl) was evaporated under vacuum onto Lucite light pipes. After the evaporation, air at 10–20% relative humidity was admitted into the chamber for about 30 sec in order to allow recrystallization of the scintillator. Subsequent handling of the detectors was done under a dry argon atmosphere because of the hygroscopic behavior of NaI. The extreme thinness of the detectors allowed reduction of background. More details concerning the proton detectors can be found in Ref. 25.

All detectors used RCA-4525 photomultiplier tubes protected by magnetic shielding against the 3-*G* guide field and by Pb shielding against the ambient radiation background of about 1 mR/h.

C. Electronics

A schematic diagram of the electronics is shown in Fig. 4. The electronics was based upon a single multiplexed time-to-pulse-height converter which was started by pulses from the β detectors and stopped by pulses from the proton detectors. The β channel was biased to accept electron energies between 100 and 500 keV. The calibration was

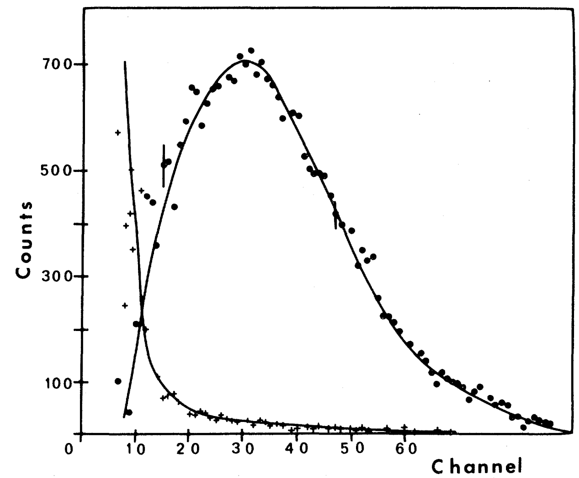

FIG. 5. Pulse-height spectrum of protons from neutron decay after acceleration to 20 keV. The plus signs show the background, while the circles represent proton pulses after background subtraction.

made from a ^{137}Cs source introduced into the chamber. Using the neutron beam itself as a source of protons, the proton energy windows were determined using a delayed-coincidence method. A typical proton energy spectrum obtained by this method is shown in Fig. 5. The 16 time-delay spectra (4 coincidence pairs for each sign of the neutron spin and for each of the two detector sections) were routed into separate regions of the memory of a 4096-channel analyzer. Figure 6 shows a time-delay spectrum for the coincidence pair $\beta_2 p_1$. The peak at channel 31 corresponding to $t=0$ is caused by background radiation scattered from one detector into another. The broad peak at 0.4 μsec delay is due to the recoil protons. This delay corresponds quite well with calculation of the transit

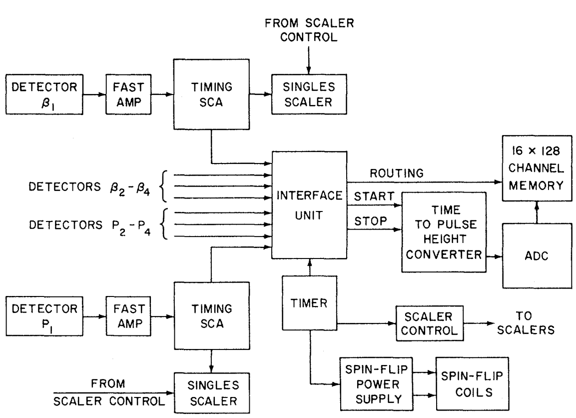

FIG. 4. Schematic diagram of the electronics.

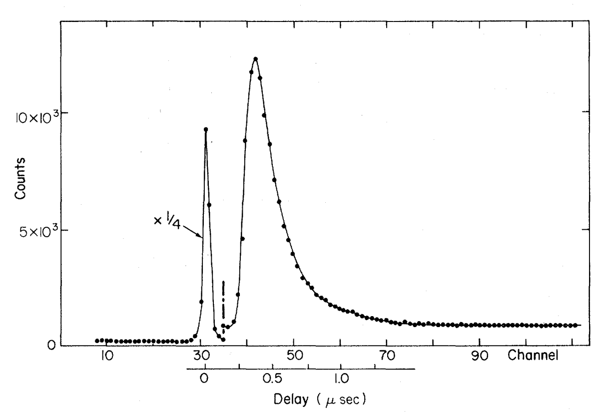

FIG. 6. Time-delay spectrum for the typical coincidence pair $\beta_2 p_1$ for one of the two spin states. These data represent about two weeks of running time.

time of the recoil protons from the decay volume through the field-free region and into the proton detectors. Events with delay times between 0.3 and 1.0 μsec were accepted. The flat background is caused by accidental coincidences. The average value of the signal-to-background ratio was approximately equal to 4. The number of true coincidences was determined by simple subtraction of the flat background from the integrated recoil proton peak. The over-all rate of true coincidences for the 8 coincidence channels amounted to 1.5 counts/sec.

Ion currents sometimes appeared between the high-voltage box and the walls of the chamber. The size of the currents depended critically on the surface finish of the aluminum high-voltage box as well as on its state of conditioning. Good results were usually obtained after treatment by a 1 mA glow discharge in a 200 mTorr argon atmosphere for 15 min. To prevent these ion currents from degrading the signal-to-background ratio, an electronic gate stopped the recording of data each time the proton counting rate exceeded a preset level. Typically, the time during which ion currents appeared above this level was about 2 min per day.

IV. DATA ANALYSIS AND DISCUSSION OF ERRORS

The data were analyzed in the following way. For each of the two independent detector sections, let $N^{\uparrow}_{\beta_i p_j}$ and $N^{\downarrow}_{\beta_i p_j}$ be the numbers of true coincidences between β detector i and proton detector j for the two directions of the polarization vector. Thus

$$\begin{aligned} N^{\downarrow}_{\beta_1 p_1} &= c^{\downarrow}\Omega^{\downarrow}_{\beta_1}\Omega^{\downarrow}_{p_1}e^{\downarrow}_{\beta_1}e^{\downarrow}_{p_1}(1+KPD)\,, \\ N^{\uparrow}_{\beta_1 p_1} &= c^{\uparrow}\Omega^{\uparrow}_{\beta_1}\Omega^{\uparrow}_{p_1}e^{\uparrow}_{\beta_1}e^{\uparrow}_{p_1}(1-KPD)\,, \end{aligned} \tag{3}$$

etc., where c is a constant proportional to the beam intensity, the Ω's are the solid angles subtended by counters β_1 and p_1, and the e's are the detection efficiencies. The possibility of shifts in these parameters as a function of the polarization direction has been explicitly allowed for. P is the mean value of the polarization and K is an instrumental coefficient which describes the reduction of the measured asymmetry due to finite detector solid angles and other kinematic effects. Forming the combination

$$R = \frac{N^{\downarrow}_{\beta_1 p_1}}{N^{\uparrow}_{\beta_1 p_1}}\,\frac{N^{\uparrow}_{\beta_1 p_2}}{N^{\downarrow}_{\beta_1 p_2}}\,\frac{N^{\uparrow}_{\beta_2 p_1}}{N^{\downarrow}_{\beta_2 p_1}}\,\frac{N^{\downarrow}_{\beta_2 p_2}}{N^{\uparrow}_{\beta_2 p_2}}\,, \tag{4}$$

we obtain

$$R = \frac{(1+KPD)^4}{(1-KPD)^4}\,, \tag{5}$$

independent of variations and shifts in counter efficiencies, solid angles, and beam intensity. The value of D is then determined from

$$D = \frac{1}{KP}\,\frac{R^{1/4}-1}{R^{1/4}+1} \tag{6}$$

and the total error in D is given by

$$\Delta D = \left\{\left[\frac{1}{KP}\,\frac{R^{1/4}}{2(R^{1/4}+1)^2}\,\frac{\Delta R}{R}\right]^2 + \left(D\,\frac{\Delta P}{P}\right)^2 + \left(D\,\frac{\Delta K}{K}\right)^2\right\}^{1/2}, \tag{7}$$

where we have assumed that the individual errors can be added in quadrature. The principal contributions to these individual errors are the following:

A. Errors in K:

(1) Determination of detector positions and solid angles, including uncertainties due to nonuniform detection efficiency.

(2) Determination of the decay volume, including nonuniformity of the neutron flux over the beam cross section.

(3) Penetration of electric fields into the field-free region through the grids, thereby distorting the particle trajectories.

(4) The effects of finite-energy resolution of the β detectors and finite-timing resolution of the electronics.

(5) Statistical error of the Monte Carlo evaluation of K.

(6) β and proton backscattering corrections.

B. Errors in P:

(1) Drifts in polarization and spin-flipping efficiency between the times of their measurement and the actual neutron-decay data taking.

(2) Lack of uniformity of polarization and spin-flipping efficiency over the beam cross section.

(3) Departure of spin-flipping efficiency from 100% and consequent inequality of the polarization for the two spin states.

(4) Inequality of the polarizing efficiency of the polarizer and the analyzing efficiency of the analyzer.

(5) Departure of the neutron detection efficiency of the ^{3}He gas proportional counter used for measurements of polarization from a $1/v$ relation.

C. Errors in R:

(1) Beam intensity, detection efficiency, and detector-solid-angle fluctuations and shifts.

(2) Inequality of counting times for the two spin states.

(3) Misalignment of the polarization axis with respect to the beam direction thereby introducing an asymmetry due to the A and B coefficients [see

Eq. (1)].

(4) Subtraction of random coincidences.

(5) Detection efficiency nonuniformities.

Since the D coefficient is known from previous measurements to be quite small, it is clear from Eq. (7) that errors in K and P are relatively unimportant. These errors contribute only if D differs from zero and thus cannot introduce a false nonzero value of D. Nevertheless, for completeness, we give a brief discussion of these errors.

The geometrical coefficient K was calculated using the Monte Carlo method to simulate the experiment. Many calculations were performed, in which the parameters involved in errors A(1), A(2), and A(4) were varied within reasonable limits. The effect on the value of K of these variations was invariably less than ±0.02. The statistical error of the Monte Carlo calculation [error A(5)] was ±0.01. We were not able to evaluate errors A(3) and A(6) with precision. Nevertheless, it is estimated that their effect on K cannot exceed 10%. We therefore conclude that $K = 0.45 \pm 0.05$.

The polarization measurement was performed both before and after the experiment as well as at approximately 2-week intervals during the $2\frac{1}{2}$-month period of data collection. No variations in the polarization or spin-flipping efficiency were observed. Error B(1) is therefore negligible.

The uniformity of the polarization and spin-flipping efficiency over the beam cross section [error B(2)] was checked by scanning the beam with a thin slit (1 mm) machined in fused ^{6}LiF. The variations observed between the central region of the beam and its outer regions were about 2%.

The mean value of the spin-flipping efficiency as mentioned above was found to be 97%. This effect leads to different values of the neutron polarization ($P^\uparrow$ and $P^\downarrow$) for the two spin directions [error B(3)]. In this case Eq. (5) becomes

$$R = \frac{(1 + KP^\uparrow D)^2 (1 + KP^\downarrow D)^2}{(1 - KP^\uparrow D)^2 (1 - KP^\downarrow D)^2}.$$

Neglecting terms of order D^2, this gives

$$D = \frac{1}{K(P^\uparrow + P^\downarrow)} \left(\frac{R^{1/2} - 1}{R^{1/2} + 1} \right).$$

Defining $\overline{P} = \frac{1}{2}(P^\uparrow + P^\downarrow)$,

$$D = \frac{1}{2K\overline{P}} \left(\frac{R^{1/2} - 1}{R^{1/2} + 1} \right). \tag{8}$$

Since the D coefficient is small, R may be written as $1 + \Delta$, where $\Delta \ll 1$. Applying the binomial expansion to the right-hand side of Eq. (8) gives

$$D \cong \frac{\Delta}{8K\overline{P}}.$$

A similar procedure applied to Eq. (6) yields

$$D \cong \frac{\Delta}{8KP} = \frac{R - 1}{8KP}. \tag{9}$$

Thus the error caused by imperfect spin-flipping efficiency can be eliminated by using $\overline{P}$ instead of P in Eq. (6).

Error B(4) is difficult to evaluate since the method used for measuring the polarization in fact measures the product of the efficiencies of polarizer and analyzer. Since the analyzer is very similar to the polarizer, we assume that these two efficiencies are equal to within several precent.[26]

Error B(5) is important because of the known[18] strong energy dependence of the polarizing efficiency. We believe that 5% is an upper limit for this error.

Taking into account all errors, the mean value of the polarization in the detection chamber is $P = 0.70 \pm 0.07$.[27]

Errors of type C deserve closer attention since such errors apparently can lead to a false nonzero D coefficient. However, as the following analysis will demonstrate, the symmetrical arrangement of the detectors together with the present method of analyzing the data virtually eliminates such errors.

By looking at Eqs. (3), (4), and (5), it can be seen that variations and shifts in counter efficiencies and solid angles as well as in beam intensity undergo exact cancellation. Thus error C(1) is eliminated. Error C(2) is negligible to the accuracy of the experiment, since the counting times for positive and negative polarization are equal to within 1 part in 10^5.

Let us estimate the effect of error C(3). The coincidence counting rate is given by [see Eq. (1)]

$$N \propto 1 + \vec{P} \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + D \frac{\vec{p}_e \times \vec{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} \right).$$

Since $|B|$ (≈ 1) is known to be much larger than $|A|$ (≈ 0.1), we will consider explicitly effects due to B only. The eight different coincidence rates are given by

$$N^\downarrow_{\beta_1 p_1} = c^\downarrow \Omega^\downarrow_{\beta_1} \Omega^\downarrow_{p_1} e^\downarrow_{\beta_1} e^\downarrow_{p_1} (1 - K_B P B + KPD),$$

$$N^\uparrow_{\beta_1 p_1} = c^\uparrow \Omega^\uparrow_{\beta_1} \Omega^\uparrow_{p_1} e^\uparrow_{\beta_1} e^\uparrow_{\beta_1} (1 + K_B P B - KPD),$$

etc.,

where K_B is proportional to the sine of the angle of misalignment between the polarization axis and the beam direction. The experimental ratio R [Eq. (4)] becomes

$$R = \left(\frac{(1 + KPD)^2 - (K_B P B)^2}{(1 - KPD)^2 - (K_B P B)^2} \right)^2.$$

Since the misalignment angle is known to be smaller than 1°,

$$|K_B PB| \leq 0.01.$$

Keeping only terms to first order in KPD, and making use of Eq. (9), we obtain

$$D' = \frac{1}{8KP}(R-1)[1-(K_B PB)^2] = D[1-(K_B PB)^2].$$

The effect of a 1° misalignment of the polarization direction with respect to the beam axis is therefore a reduction in the observed value of D by about 1 part in 10^4. Such an error is of no importance for the present measurement. In Sec. V we present an experimental verification of this conclusion.

Another possible source of systematic error is the subtraction of random coincidences. The distribution of such coincidences has been checked to be flat and to have the same value before the prompt peak and after the broad proton peak within the statistical uncertainty. No systematic error can therefore be introduced by the subtraction of false coincidences [error C(4)].

The remaining source of systematic error is the possibility that certain types of nonuniformity in the detection efficiencies [error C(5)] can lead to a false nonzero value of the D coefficient, as has been pointed out in Ref. 15. This effect is caused by changes in the trajectories of the recoil protons upon reversal of the spin due to the strong correlation ($B \simeq 1$) between the antineutrino momentum and the polarization vector. We have investigated this source of error and find that an upper limit for the contribution to D is 0.3×10^{-3}.

We therefore conclude that in this measurement the limiting factor remains the statistical error.

V. RESULTS AND COMMENTS

Figure 7 shows the results of the 61 runs, each approximately 24 h long, together with the corresponding statistical errors. The data for detector sections 1 and 2 have been calculated separately. The runs marked "Set A" in the figure were performed with the polarization axis misaligned by 8° with respect to the beam direction as a check of possible false asymmetries due to this misalignment. The resulting value of D for these runs is $D = (-4.9 \pm 4.2) \times 10^{-3}$. Since the main set of runs ("Set B") was performed with a misalignment angle of less than 1°, we conclude that the error due to misalignment is less than 10^{-3} and, therefore, negligible.

Set B, upon which we base our results, consisted of 5.9×10^6 events. For detector section 1, the result was $D_1 = (-1.3 \pm 2.2) \times 10^{-3}$, while for section 2, we obtained $D_2 = (-0.7 \pm 2.8) \times 10^{-3}$. The average of these two values and thus our final result for D is

$$D = (-1.1 \pm 1.7) \times 10^{-3},$$

where the quoted error is one standard deviation and is dominated by counting statistics. The value of χ^2 per degree of freedom for the 100 data points is 1.16. In terms of the phase angle between axial-vector and vector coupling constants, our result corresponds to

$$\phi = 180.14° \pm 0.22°,$$

which is consistent with T invariance in the strangeness-conserving semileptonic weak interaction.

In conclusion we would like to point out that a substantial improvement in the precision of the present test of T invariance would be possible by extension of the present techniques. Using a polarizer with a larger aperture and perhaps higher polarization, increasing the number of detectors, further improving the detection chamber, and doubling the measurement time would allow, by our estimate, an increase in the number of events observed by a factor of approximately 25 with a consequent 5-fold improvement in the statistical precision of the experiment. Systematic errors should remain manageable. However, the Coulomb correction to D would begin to become troublesome at this level and better experimental limits on scalar and tensor contributions to β decay would be desirable in order to interpret the improved measurement as a test of T invariance.

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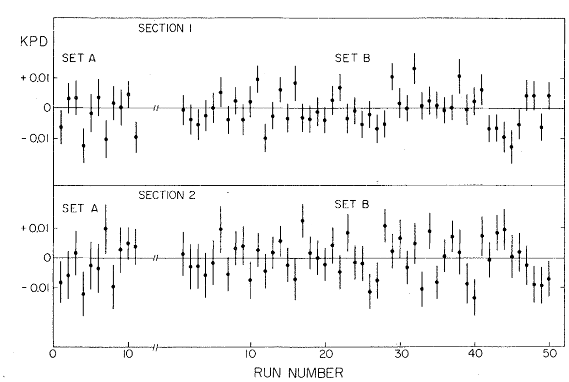

FIG. 7. Experimental results for the quantity KPD together with error bars. Each point represents about 24 h. of data taking. The runs marked "Set A" were used to verify the absence of systematic errors due to polarization axis misalignment. Only the runs of "Set B" were included in the final data analysis.

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