Test of Time-Reversal Symmetry in the β Decay of ^{19}Ne

A. L. Hallin,[a] F. P. Calaprice, D. W. MacArthur,[a] L. E. Piilonen
M. B. Schneider, and D. F. Schreiber
Princeton University, Princeton, New Jersey 08544
(Received 12 September 1983)

With a new detection method, the upper limit on the time-reversal–noninvariant triple angular correlation $\vec{J}\cdot(\vec{p}_e\times\vec{p}_\nu)/E_eE_\nu$ in the nuclear decay $^{19}\mathrm{Ne}\to{}^{19}\mathrm{F}+e^++\nu$ has been reduced. Polarized ^{19}Ne atoms from an atomic beam are captured in a holding cell, where the decay positrons and recoil ions are observed. The new value for the asymmetry parameter for this correlation is $D=0.004\pm0.0008$, which is consistent with time-reversal symmetry.

PACS numbers: 23.40.Bw, 11.30.Er, 27.20.+n

Several tests of time-reversal invariance have been made since the 1964 discovery of CP noninvariance in the decay of the $K_L{}^0$ meson.[1] In nuclear physics, limits for T-odd amplitudes relative to T-even amplitudes are now $\lesssim 10^{-3}$ for strong, electromagnetic, and weak interaction processes, with no evidence for a violation of T invariance.

The most precise tests of T invariance in nuclear beta decay have been made by measuring the angular correlation $D\hat{J}\cdot(\vec{p}_e\times\vec{p}_\nu)/E_eE_\nu$, where $\hat{J}$ is the initial nuclear-spin direction, and p_e, E_e and p_ν, E_ν are the momenta and energies of the electron and neutrino, respectively. Since this correlation is odd under T, a nonzero value for the parameter D signifies a violation of T invariance, if final-state interactions are negligible. Previous values for the asymmetry parameters for the beta decays of the free neutron and ^{19}Ne are $D=-0.0011\pm0.0017$[2] and $D=-0.0005\pm0.0010$,[3] respectively. It has been shown recently[4] that gauge theories with left-right symmetry[5] can accommodate, in first order, a nonzero time-reversal–noninvariant contribution to the coefficient D, and that values of the order 10^{-3}–10^{-4} cannot be ruled out. Motivated by the general need for improving tests of T invariance where possible, we have developed a new method for measuring the above triple correlation and report here a new result for ^{19}Ne decay.

The expression for D, including final-state electromagnetic terms to order αZ involving the Fermi (M_F) and Gamow-Teller (M_GT) matrix elements, is given for $\frac{1}{2}^+\to\frac{1}{2}^+$ decays as follows[6]:

$$D\xi=\frac{2}{\sqrt{3}}M_\mathrm{F}M_\mathrm{GT}\,\mathrm{Im}(C_SC_T{}^*-C_VC_A{}^*+C_S{}'C_T{}'^*-C_V{}'C_A{}'^*)$$
$$+\frac{2}{\sqrt{3}}\frac{\alpha Zm_e}{p_e}M_\mathrm{F}M_\mathrm{GT}\,\mathrm{Re}(C_SC_A{}^*-C_VC_T{}^*+C_S{}'C_A{}'^*-C_V{}'C_T{}'^*),$$

where

$$\xi=M_\mathrm{F}{}^2(|C_S|^2+|C_V|^2+|C_S{}'|^2+|C_V{}'|^2)+M_\mathrm{GT}{}^2(|C_T|^2+|C_A|^2+|C_T{}'|^2+|C_A{}'|^2).$$

The first term in the expression for D is nonzero only if T invariance is violated. The second term, proportional to αZ, is due to final-state interactions and is present even if T invariance is valid. However, in a pure VA interaction this final-state term vanishes and D is sensitive to a violation of T invariance through the term $\mathrm{Im}(C_VC_A{}^*)$. For ^{19}Ne decay we have $M_\mathrm{F}=1.00$, $M_\mathrm{GT}=-1.28$ and with $C_V=1$, $C_A=-1.25$ we obtain $D=0.518\sin\varphi_{VA}$, where φ_{VA} is the phase angle between C_V and C_A.

The real part of the coupling constants C_S and C_T are known to be small from limits on Fierz interference terms. Present limits[7] are such that their contribution to D through the above αZ term could be no more than ~10^{-4}. We note that higher-order terms have been considered in the final-state effect by Callan and Treiman.[8] They find a nonzero contribution to D which is due mainly to the weak magnetism matrix element. However, the effect is small and for ^{19}Ne the contribution to D is $2.6\times10^{-4}p/p_\mathrm{max}$. In summary, the final-state effects permitted by limits on C_S and C_T and the expected final-state effect due to weak magnetism are smaller than current experimental limits for D and do not yet affect conclusions regarding the T-noninvariant term

$\mathrm{Im}(C_V C_A^*)$.

The ^{19}Ne isotope was produced with the Princeton cyclotron and polarized by an atomic-beam apparatus. A description of the production and polarization method are published elsewhere.[3] We summarize here only the pertinent details of this method and the new features of the detection system.

An atomic-beam apparatus with a "Stern-Gerlach" magnet state selector produces a thermal polarized beam of ^{19}Ne with an intensity of about 40 000 atoms/sec. The beam terminates in a special cell which houses the detectors. The entrance to the cell is a long channel with a high flow impedance for atoms exiting from the cell so that about 25% of the atoms which enter the cell decay there. Depolarization during the dwell time is insignificant. The cell is a long thin-wall cylinder with radius 1 cm and length 20 cm. The axis of the cell, the beam axis, and the polarization axis are collinear (see Fig. 1).

Since $\langle \vec{p}_e + \vec{p}_\nu + \vec{p}_R \rangle = 0$ for atoms in the cell, the angular correlation $\vec{J}\cdot(\vec{p}_e \times \vec{p}_\nu)$ is equivalent to $-\vec{J}\cdot(\vec{p}_e \times \vec{p}_R)$, where $\vec{p}_R$ is the momentum of the recoil daughter nucleus. We therefore measure the angular correlation by detecting the directions of the positrons and the associated recoil F^- ions. The positrons are detected outside the cell by an array of four plastic scintillators. The recoil F^- ions have a maximum energy of 200 eV and thus must be detected within the cell. To provide efficient detection we preaccelerate the ions before they impact on the detector. A novel feature of our method is the application of an electric field along the cell axis (polarization axis). This allows recoil ions to drift across the cell with the transverse momentum acquired in the decay while accelerating along the cell axis. When the ion reaches the wall it has sufficient energy to knock out several secondary electrons; the secondary electrons are accelerated along the cell axis from the hit site to a segmented microchannel-plate electron multiplier. The four segments of the electron multiplier provide the azimuthal position of the ion hit site in the cell. This azimuthal position is correlated with the azimuthal position of the beta particle to determine the angular correlation. The acceleration of the ions does not affect their momentum transverse to $\hat{J}$ thus leaving the angular correlation $\vec{J}\cdot(\vec{p}_e \times \vec{p}_R)$ unaffected.

The electric field within the cell was produced by evaporating a thin semiconducting layer (100 MΩ/sq) of germanium on the inner surface, and then applying a voltage of 10–14 kV across the length. To ensure azimuthal symmetry of the electric field, conducting rings of gold (0.05 cm wide) were evaporated over the germanium every centimeter. Finally, a thin layer of MgO was fumed on the surface to enhance secondary-electron emission.

The polarization was maintained by a magnetic

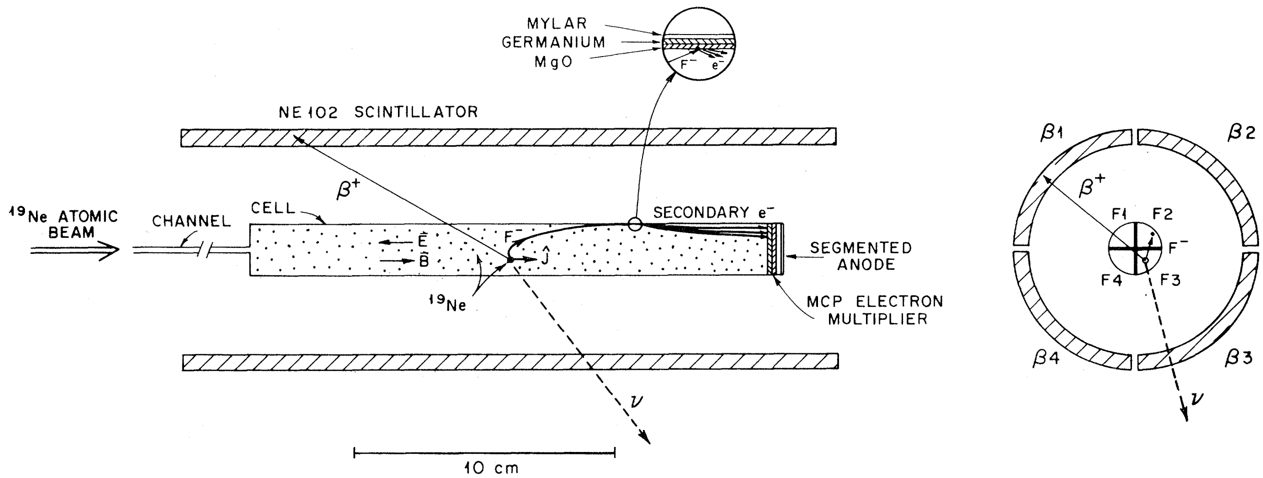

FIG. 1. Schematic illustration of the cylindrical cell and the detector system. Polarized ^{19}Ne, which enters the cell through a long narrow channel, fills the entire cell (dots). A uniform magnetic field maintains the polarization along the cell axis. In a typical decay the positron passes through the thin wall of the cell to one of four plastic scintillators (β_1 through β_4). The F^- recoil ion is accelerated along the cell axis by an electric field. The ion strikes the inside surface emitting secondary electrons which are accelerated into an electron multiplier segmented in four parts (F_1 through F_4).

field of ≈ 1 G which was produced by a solenoid inside a magnetic shield made of three layers of high-permeability material. A uniform field was important to reduce systematic asymmetries[9] and to prevent depolarization of the ^{19}Ne in the channel. For diagnostic purposes, a pair of coils was placed inside the detector chamber to generate a transverse magnetic field. Under these conditions of transverse polarization, we were able to observe a large neutrino asymmetry $BJ\cdot p_\nu$, where $B=-1$, and determine the sensitivity of the apparatus.

Pulses from the microchannel-plate anodes and photomultiplier tubes were processed to generate signals corresponding to four beta energies, the ion anode number, and the ion time of flight. Coincidence events for each ion-beta detector pair were sorted by beta energy and ion time of flight into computer arrays. Data were taken for approximately 130 h in cycles each of 20 min. The nuclear polarization was reversed halfway through each cycle. In addition, the detectors were periodically rotated 180° with respect to the detector chamber. The axial magnetic field was also reversed for each configuration. As a sample of the quality of the data we illustrate a time-of-flight spectrum in Fig. 2. The prompt peak corresponds to betas in coincidence with

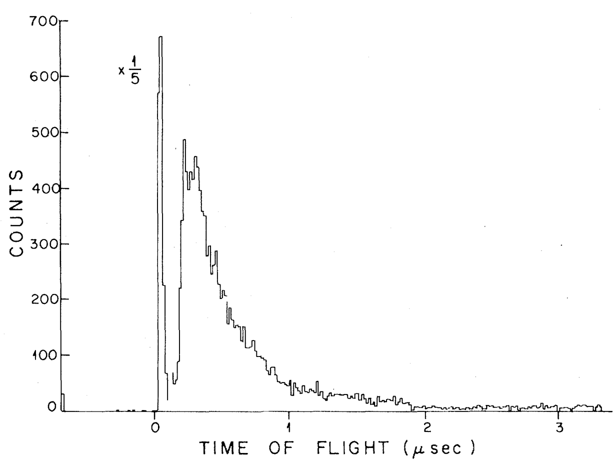

FIG. 2. Typical beta-ion time-delay spectrum for one cycle of data (20 min). The spectrum was acquired with a time-to-amplitude converter which is started with one beta signal and stopped with an ion signal. The sharp prompt peak, scaled down by 5, is due to positron–shakeoff-electron coincidences. The broad delayed peak is due to positron-F^- delayed coincidences. The latter are used for the angular-correlation measurements. Accidental coincidences are infrequent, as can be noted from the few counts to the left of the prompt peak.

shakeoff electrons. The broad delayed bump is due to beta-ion coincidences. The flat part of the spectrum before the prompt peak is due to accidental coincidences. Typical beta and ion singles rates in each detector were 2 and 1.5 kHz, respectively, while the total coincidence rate was 2.5 kHz.

There are three types of detector coincidence pairs that are used to determine D: (1) A single beta counter in coincidence with only one ion counter with relative angle 90°. (2) A single beta in coincidence with two ion signals, one in an ion counter in the same quadrant as the beta (0°) and the other in an ion counter at 90°. This multiple-ion-counter events is denoted as a "45°" event. (3) A single beta in coincidence with two ion signals, one at 90° and the other at 180°. These are called "135°" events. A single ion can produce multiple signals because of the multiplicity of secondary electrons and because of finite position resolution in the microchannel-plate–anode geometry. The latter was found to be the dominant cause of multiplicity.

For each type of event, and for each cycle, an asymmetry was calculated by defining the ratio

$$R=\frac{N_{12}^{\uparrow}N_{23}^{\uparrow}N_{34}^{\uparrow}N_{41}^{\uparrow}N_{14}^{\downarrow}N_{21}^{\downarrow}N_{32}^{\downarrow}N_{43}^{\downarrow}}{N_{12}^{\downarrow}N_{23}^{\downarrow}N_{34}^{\downarrow}N_{41}^{\downarrow}N_{14}^{\uparrow}N_{21}^{\uparrow}N_{32}^{\uparrow}N_{43}^{\uparrow}}.$$

Here $N_{ij}^{\uparrow}$ refers to the number of β_i-F_j coincidence events observed with polarization "up." All N's in the numerator are increased by a positive D while all N's in the denominator are decreased. This ratio explicitly cancels any differences in detector efficiencies and count rates between the two halves of each cycle. The experimental count rate asymmetry Δ is determined by the relationship

$$\Delta=(1-R^{1/8})/(1+R^{1/8}),$$

which is then related to the asymmetry parameter D by

$$\Delta=DGWP.$$

Here P is the nuclear polarization, W is a washout factor, and G is the average of the vector product $\vec{J}\cdot(\vec{p}_e\times\vec{p}_\nu)/E_eE_\nu$ over the acceptance of the detector. The quantity G as computed by a Monte Carlo program is given for all pairs in Table I. The factor W allows for additional washout of the asymmetry not included in the factor G. Some causes of extra washout are (1) collisions of the ions with residual gas atoms in the cell and (2) irregular motion of secondary electrons from the ion hit site to the microchannel plate.

TABLE I. Summary of time-reversal asymmetry data. Final result: $D = +0.0004 \pm 0.0008$.

Event	Δ	G	W	P	D
90°	$(3.1 \pm 1.5) \times 10^{-4}$	0.233 ± 0.005	0.6	1.0	$(2.2 \pm 1.1) \times 10^{-3}$
45°	$(-3.8 \pm 2.0) \times 10^{-4}$	0.204 ± 0.008	0.6	1.0	$(-3.1 \pm 1.6) \times 10^{-3}$
135°	$(-0.2 \pm 1.6) \times 10^{-4}$	0.149 ± 0.005	0.6	1.0	$(-0.2 \pm 1.8) \times 10^{-3}$

The washout factor was determined experimentally by two methods: (1) comparison of the measured neutrino asymmetry $B\vec{J} \cdot \vec{p}_\nu$ with that expected with $B = -1$ and Monte Carlo calculations (see above) and (2) comparison of the observed beta-ion count rates for 0°, 45°, and 135° pairs with the Monte Carlo program. Both methods indicated that the washout is $W \approx 0.6$. We rotated the polarization 90° (aligning on the β_2-β_4 axis) and measured the beta asymmetry $A\vec{J} \cdot \vec{p}_e/E$ with beta detectors β_2-β_4. This yielded an asymmetry consistent with 100% polarization, confirming that the washout $W = 0.6$ was not due to depolarization.

The values for Δ, G, W, P, and D are summarized in Table I for the three sets of detector pairs. Combining all detector pairs we find from the present data the value

$$D = +0.0004 \pm 0.0008.$$

Thus, our results are consistent with time-reversal invariance. In previous work[3] on ^{19}Ne decay we obtained the result $D = -0.0005 \pm 0.0010$. We combine this with our present result to give a slightly better limit of $D = +0.0001 \pm 0.0006$. The measurements on ^{19}Ne decay are thus now significantly below the characteristic K_2^0 CP violation of $\sim 2 \times 10^{-3}$ with no evidence for T violation.

An important feature of the present design is the small accidental coincidence rate (see Fig. 2). This is the result of having a detector geometry which enables detection of nearly all betas and recoil ions. The low accidental rate demonstrates that a large increase in source strength is useful. An improvement in the statistical error on D to a level of $\sigma_D \cong \pm 1 \times 10^{-4}$ seems possible. At this level final-state effects and spurious instrumental effects become important. New methods of producing an intense source of polarized ^{19}Ne by laser optical pumping are under investigation.

[a]Present address: Los Alamos National Laboratory, Los Alamos, N. Mex. 87544.

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

[2]R. I. Steinberg, P. Liand, B. Vignon, and V. W. Hughes, Phys. Rev. Lett. 33, 41 (1974).

[3]R. M. Baltrusaitis and F. P. Calaprice, Phys. Rev. Lett. 38, 464 (1977).

[4]P. Herczeg, Phys. Rev. D 28, 200 (1983).

[5]R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 566 (1975).

[6]J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Phys. Rev. 106, 519 (1957), and Nucl. Phys. 4, 206 (1957).

[7]B. R. Holstein, Phys. Rev. C 16, 753 (1977).

[8]C. G. Callan and S. B. Treiman, Phys. Rev. 162, 1494 (1967).

[9]A. L. Hallin, Ph.D. thesis, Princeton University, 1983 (unpublished).