Limit on Im($C_S C_A^*$) from a Test of T Invariance in ^{19}Ne Beta Decay

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An investigation of the time-reversal–odd angular correlation $\hat{\sigma}\cdot(\hat{J}\times\vec{p}/E)$ in ^{19}Ne β decay is reported. In this correlation, $\hat{\sigma}$, $\vec{p}$, and E are the β spin, momentum, and energy, respectively, and $\hat{J}$ is the initial ^{19}Ne spin. The sample was polarized by an atomic beam method and the β polarization was measured with four Mott-scattering polarimeters. The magnitude R of the angular correlation is found to be -0.079 ± 0.053, consistent with time-reversal invariance. This result also implies $\mathrm{Im}(C_S C_A^*)=0.19\pm0.13$.

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The violation of the discrete combined symmetry of charge conjugation and parity (CP) was discovered nearly two decades ago by Christenson *et al.*[1] in the decay of neutral K mesons. Since then, much effort has gone into searches for CP and the associated time-reversal (T) noninvariance in many systems.[2] No positive results have been found outside the neutral K system. The K meson and other data cannot distinguish among several viable theoretical mechanisms for CP nonconservation. Furthermore, gauge theories which include CP nonconservation allow observable effects in β decay without conflict with the K meson data.

The tests of T invariance in nuclear β decay depend on the measurement of T-odd angular correlations.[3,4] These correlations are composed of products of the momenta and angular momenta of the decay. The partial decay rate ω is

$$\omega(\hat{J},\hat{\sigma},Q_e,Q_\nu)dE\,dQ_e\,dQ_\nu \propto [1+A(\vec{p}\cdot\hat{J}/E)+D\{\hat{J}\cdot(\vec{p}\times\vec{q})/EE_\nu\}+N(\hat{\sigma}\cdot\hat{J})+R\{\hat{\sigma}\cdot(\hat{J}\times\vec{p}/E)\}]dE\,Q_e\,dQ_\nu.$$

In this expression $\hat{J}$ is the nuclear spin direction, $\vec{p}$ and E are the beta momentum and energy, $\hat{\sigma}$ is the beta spin direction, $\vec{q}$ is the neutrino momentum, and Q_e and Q_ν refer to the two sets of angular coordinates. The coefficients D and R should be zero if time reversal is a good symmetry (in the absence of final-state corrections). Previous beta-decay time-reversal tests have focused principally on the correlation given by the D coefficient, which is sensitive to an imaginary interference term between the vector and axial vector weak coupling constants, $\mathrm{Im}(C_V C_A^*)$. The R coefficient is sensitive to an imaginary interference between the scalar and axial vector couplings, $\mathrm{Im}(C_S C_A^*)$. This term is present in the Higgs-exchange mechanism of CP violation, and it has been noted that values of R as large as ~0.1 are not ruled out by any available data.[5]

We measured the R coefficient for the beta decay $^{19}\mathrm{Ne}\rightarrow{}^{19}\mathrm{F}+\beta^+ +\nu_e$ ($E_{k,\,\max}=2.2$ MeV, $t_{1/2}=17.2$ sec). The expression for the R coefficient, with Coulomb corrections ignored, is[6]

$$R\xi = 2\,\mathrm{Im}\{-\tfrac{2}{3}M_{\mathrm{GT}}^2(C_T C_A'^* C_T' C_A^*)+\tfrac{1}{3}\sqrt{3}\,M_{\mathrm{F}}M_{\mathrm{GT}}(C_S C_A'^* + C_S' C_A^* - C_V C_T'^* - C_V' C_T^*)\},$$

where

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

For ^{19}Ne, neglecting C_T, assuming C_S is small, and using 1.0 and -1.28 for the Fermi and Gamow-Teller matrix elements, $C_V=1$, and $C_A=-1.25$, we find $R=-0.207\,\mathrm{Im}[(C_S+C_S')C_A^*]$.

One expects a nonzero value for the R coefficient due to T-conserving electromagnetic interactions between the emitted beta and the final nucleus. The electromagnetic term was calculated to first order for a point nucleus by Jackson, Treiman, and Wyld[6] with the result

$$R_{\mathrm{em}} = (\alpha Z m/p)A \simeq -2.6\times10^{-3} m/p.$$

The average value for this correction over the energy range from 0.5 to 1.5 MeV is 1×10^{-3}. This term has been recently calculated by Vogel and Werner[7] including finite nuclear size, screening of atomic electrons, and second forbidden and radiative terms. They find that R_{em} is still proportional to A (the beta asymmetry parameter), although about 7% larger than the point-nucleus approximation. This effect is much smaller than the sensitivity of this experiment. We note that ^{19}Ne is a particularly suitable candidate for a test of invariance since R_{em} is fortuitously small. In other beta decays, $R_{em} \sim 0.1$.

The details of the Princeton rare-gas atomic-beam machine have been given elsewhere,[4, 8] and so the device will be described only briefly. A schematic diagram of the machine is shown in Fig. 1. A 12-MeV proton beam incident on a continuous-flow SF_6 gas target produces ^{19}Ne through the reaction $^{19}F(p,n)^{19}Ne$. The ^{19}Ne is separated in a liquid-nitrogen cold trap and then pumped to the cryogenic source of the atomic beam. The spin states are selected in a two-pole "Stern Gerlach" magnet, and the resulting polarized beam is caught in a holding cell. This beam is virtually 100% polarized, and is held in the cell for a mean time of 6.5 sec. Typical decay rates in the cell are 10^4 decays/sec. The ^{19}Ne polarization is maintained with a 16-G field from a pair of Helmholtz coils 20 cm in radius. Depolarization of this sample over the period of residence in the cell appears to be less than 5%. To monitor the polarization of the sample as well as total activity, the cell has gas proportional counters built into each end. The polarization is monitored with use of the beta asymmetry A by looking for a counting-rate asymmetry as the ^{19}Ne polarization is changed.

To measure the R correlation, we analyze the beta particles emitted perpendicular to the ^{19}Ne spin direction for a transverse spin component that is also perpendicular to the original ^{19}Ne spin (see inset in Fig. 1). Beta polarimetry is performed in air, and so the cell has four thin (0.013 cm) Kapton windows on the sides perpendicular to the polarization axis. Multiple scattering in the Kapton is very nearly the same in magnitude as the multiple scattering in the air between the cell and the beta polarimeters, an rms angle of about 8° at 1 MeV.

The method of polarimetry chosen in this experiment is that of large-angle Mott scattering off thin foils of a high-Z material, in this case gold.[9] A beam of positrons transversely polarized in an up-down sense will show a small (typically about 5%) asymmetry in left-right Coulomb scattering. The analyzing power is very small for small-angle scattering, and so plural scattering in the gold foils can significantly reduce this sensitivity. Calculation has indicated that the probability of plural scattering from multiple foils spaced apart a distance comparable to the width of the foils is less than that from a single foil as thick as the sum of the thicknesses. In this experiment, two foils with areal densities of 2 and 3 mg/cm^2 were chosen to make use of the bulk of the spectrum from roughly 0.5 to 1.5 MeV. Four identical polarimeters were positioned symmetrically around the cell; two polarimeters are shown

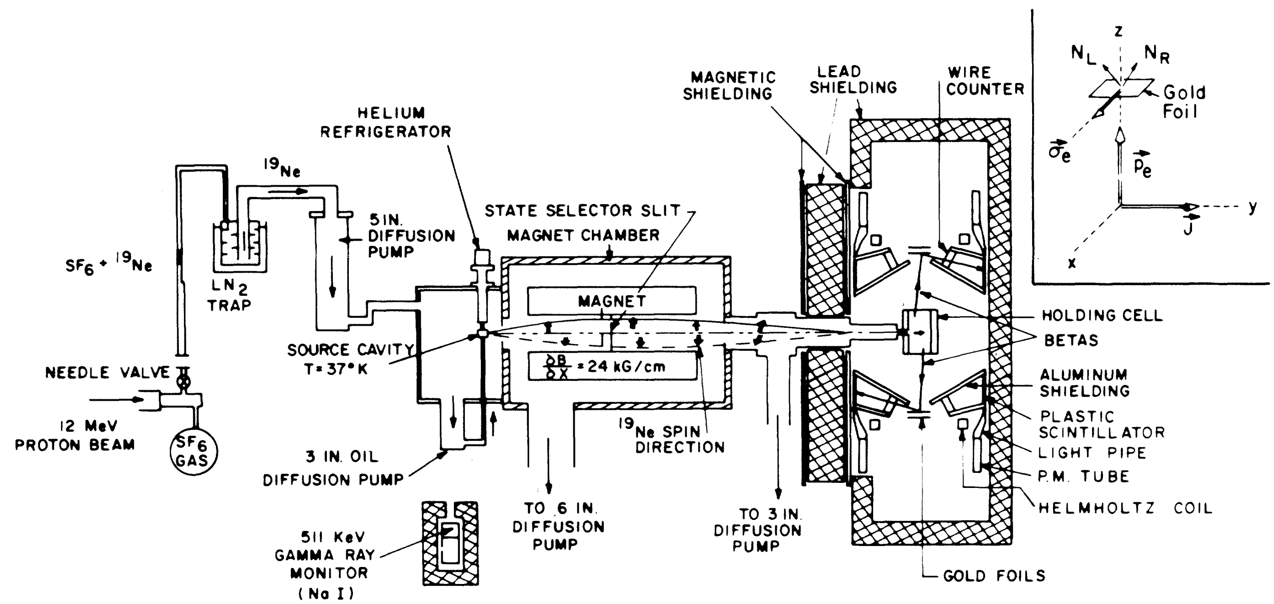

FIG. 1. Schematic illustration of the apparatus. The ^{19}Ne is produced with 12 MeV protons incident on an SF_6 target. A thermal beam of ^{19}Ne atoms is polarized by deflection in a "Stern-Gerlach" magnet. The polarized beam is captured in a holding cell surrounded by four Mott-scattering polarimeters. Each polarimeter is arranged to measure the positron polarization $\vec{\sigma}_e$ normal to the plane $\vec{p}_e$ and $\vec{J}$ (see inset).

in Fig. 1.

Arranged symmetrically on either side of the gold foils were beta detector telescopes. Each consisted of a transmission gas-filled proportional counter backed by a plastic scintillator and photomultiplier tube (Hamamatsu R1166). Scintillator signals from 1-MeV monoenergetic electrons yielded a spectrum with a full width at half maximum of 30% of the peak value. To reduce the background of true coincidences from external sources, a lead house with 10-cm-thick walls was constructed around the cell/polarimeter assembly. The typical counting rate in each detector telescope was about ten counts per minute above 0.4 MeV. During operation the background rate was about one quarter of the rate in the vicinity of 1 MeV.

The eight digitized beta-energy signals were stored in a computer for both nuclear polarization states. The computer was activated whenever a gas counter signal was detected. The rate of gates generated was typically 100 Hz; the ratio of true to accidental coincidences was greater than 10:1 for all energies above 0.2 MeV.

The scattering asymmetry Δ was calculated as follows:

$$\Delta = (x^{1/2} - 1)/(x^{1/2} + 1),$$

where

$$x = N_{1L}N_{2R}/N_{2L}N_{1R}$$

and the N's are the counts in the left and right telescopes for the polarization states labelled 1 and 2. This combination cancels out differences in detector efficiencies, and any variations in activity in the cell, under the assumption that the polarization is the same in each case. The subtraction of background was not done explicitly, but was incorporated in terms of a washed-out polarimeter analyzing power, as described below. The asymmetry is related to R by $\Delta = \alpha PR$ where P is the ^{19}Ne polarization and α is the analyzing power.

To calibrate the polarimeter, one would like to use transversely polarized positrons of the same energy range as emitted by ^{19}Ne. The T- and P-conserving correlation $N\hat{\sigma}\cdot\hat{J}$ provides this; for ^{19}Ne, $N = (m/E)A \approx 0.02$ at 1 MeV. This is smaller than the sensitivity afforded by our decay rate, so that we chose to estimate the analyzing power with a Monte Carlo computer simulation. This simulation included the actual geometry, and multiple scattering in the cell windows, intervening air, and gold foils. Mott-scattering data were taken from published compilations.[10,11] These results were corrected for finite detector resolution, tabulated for nine different energy windows, and then washed out by the observed ratio of scattering to background. The anaylzing powers are given in Table I. The observed asymmetries for six days of running are given in the next column. These asymmetries are corrected for a systematic effect due to the beta asymmetry, which results in a nonuniform flux of beta radiation from the cell. This can mock an asymmetry in scattering either directly or through the resulting annihilation radiation from the stopped positrons. The former has been calculated using a Monte Carlo program; the results are included in Table I. The annihilation effect can be identified by the energy signal in the scintillators; this effect was found to be much smaller than the statistical uncertainties. Since these systematic effects both scale with the beta asymmetry, they are particularly small in ^{19}Ne. The weighted average of resulting R values (under the assumption that the dependence of R on beta energy is negligible) is $R = -0.079 \pm 0.053$, which translates to $\mathrm{Im}(C_S C_A^*) = 0.19 \pm 0.13$, on the assumption $C_S = C_S'$. We consider these values consistent with time-reversal invariance.

Previous limits on $|C_S|$ from the electron-neutrino angular correlation[12] imply that $|C_S|^2 + |C_S'|^2 < 0.2$. If we use again the assumption that $C_S = C_S'$, this implies $\mathrm{Im}(C_S C_A^*) < 0.4$. For comparison, we note that the lowest limit for $\mathrm{Re}(C_S C_V^*)$ is obtained from the constancy of the ft values of pure Fermi decays.[13,14] It is found that the pure Fermi Fierz interference term is $b_{\mathrm{Fierz}}{}^{\mathrm{F}} = \mathrm{Re}(C_S + C_S')C_V^* = -0.001 \pm 0.006$.

TABLE I. Measured asymmetries and implied R values. δE is the window in the scintillator spectrum, α is the polarimeter analyzing power, Δ is the measured asymmetry, Δ_β is the beta-asymmetry correction, and the final column gives the implied R values, where $R = (\Delta - \Delta_\beta)/\alpha$.

δE (MeV)	α (%)	Δ(%)	Δ_β(%)	R
0.1 – 0.2	0.2	0.0 ± 0.3	– 0.02	0.21 ± 0.72
0.2 – 0.3	0.7	0.1 ± 0.3	0.01	0.10 ± 0.39
0.3 – 0.4	1.5	– 0.2 ± 0.4	0.06	– 0.18 ± 0.24
0.4 – 0.5	2.1	0.2 ± 0.4	0.10	0.50 ± 0.17
0.5 – 0.7	3.1	0.2 ± 0.5	0.14	0.01 ± 0.14
0.7 – 0.9	3.9	– 0.5 ± 0.4	0.17	– 0.16 ± 0.11
0.9 – 1.2	4.5	0.0 ± 0.5	0.19	– 0.05 ± 0.10
1.2 – 1.5	3.9	0.0 ± 0.6	0.17	– 0.05 ± 0.15
1.5 – 2.2	2.3	– 0.7 ± 0.5	0.11	– 0.34 ± 0.23

This work represents a first direct measurement of the R correlation. Polarized ^{19}Ne appears to be the nucleus of choice for this measurement because of the very small systematic errors and final-state corrections associated with it. Improved methods of polarizing ^{19}Ne are being investigated; proposed optical pumping of ^{19}Ne could increase the source strength by as many as four orders of magnitude. This would allow a careful calibration of the polarimeter with the N correlation, and a more sensitive measurement of R. A final uncertainty of better than 10^{-3} might be possible, at which point the understanding of the final-state effects becomes an important factor.

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

[2]For a recent review, see J. W. Cronin, Rev. Mod. Phys. 53, 373 (1981).

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

[4]R. M. Baltrusaitis and F. P. Calaprice, Phys. Rev. Lett. 38, 464 (1977); R. M. Baltrusaitis, Ph.D. thesis, Princeton University, 1977 (unpublished).

[5]P. Herczeg, Bull. Am. Phys. Soc. 27, 717 (1982), and to be published.

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

[7]P. Vogel and B. Werner, Nucl. Phys. A404, 345 (1983). Our attention has also been drawn to the work on this subject by B. Holstein, Phys. Rev. C 28, 342 (1983).

[8]F. P. Calaprice, E. D. Commins, and D. C. Girvin, Phys. Rev. D 9, 519 (1974); M. B. Schneider, Ph.D. thesis, Princeton University, 1983 (unpublished).

[9]J. G. Wilson and S. A. Wouthuysen, *Progress in Elementary Particle and Cosmic Ray Physics* (North-Holland, Amsterdam, 1960), Vol. 5, pp. 67ff.

[10]J. A. Doggett and L. V. Spencer, Phys. Rev. 103, 1597 (1956).

[11]P. Uginčius and H. Überall, Nucl. Phys. A198, 494 (1972).

[12]J. Allen, R. Burman, W. Hermannsfeldt, P. Stahelin, and T. Braid, Phys. Rev. 116, 134 (1959).

[13]J. C. Hardy and I. Towner, Nucl. Phys. A254, 221 (1975).

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