er possibility is that neutrons emitted at the scission stage may be directed preferentially along the fission axis. Recent studies[12] of the analogous[13] process of light charged particle emission in ternary fission have indicated an unexpectedly large axial component and it would therefore not be surprising if the same were true for scission neutrons. On the evidence now available however it is not possible to do more than speculate as to the origin of the enhanced axial emission of neutrons.

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Experimental Study of Weak Magnetism and Second-Class Interaction Effects in the β Decay of Polarized ^{19}Ne†

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The angular distribution of positrons emitted in the decay of polarized ^{19}Ne has been measured as a test for the second-class weak interaction. The β asymmetry parameter varies linearly with the β energy with slope $(dA/dE)_{\rm exp} = (-0.65 \pm 0.15)\%\ {\rm MeV}^{-1}$. This result requires a second-class form factor comparable to the weak-magnetism term.

It has been emphasized that a favorable way to detect the second-class weak interaction[1] is by means of angular correlation measurements in nuclear β decay.[2] With this motivation in mind we have investigated the energy dependence of the angular correlation between the initial nuclear spin and the positron direction in the decay $^{19}{\rm Ne} \rightarrow {}^{19}{\rm F} + e^+ + \nu$ ($T_{\rm max} = 2.2$ MeV, $t_{1/2} = 17.3$ sec).[3] This is a transition between members of a $\frac{1}{2}^+$ isospin doublet and such a decay is specified, to first order in recoil, by just four nuclear form factors, each of which is uniquely first or second class in origin.

Following Holstein and Treiman[2] the nuclear form factors are denoted as a, b, c, and d. The a and b terms arise from the vector interaction and correspond to the Fermi matrix element and weak-magnetism form factor, respectively. According to the conserved-vector-current (CVC) theory they are solely first class and, at zero momentum transfer, have the values $a(0) = 1.00$ and $b(0) = -148.60 \pm 0.03$.[4] The c and d terms originate from the axial-vector interaction; c is essentially the Gamow-Teller matrix element and is first class, whereas d, the tensor form factor, is second class.

With a and b fixed, both c and d are determined from a measurement of the asymmetry parameter, A, defined by the following rate formula for polarized nuclear decay[2]:

$$d\lambda = \frac{2G^2\cos^2\theta_C}{(2\pi)^4} F(Z,E)pE(E_0-E)^2 f_1(E)(1+AP\hat{I}\cdot\vec{p}/E)\,dE\,d\Omega_e. \tag{1}$$

The asymmetry parameter is given by $A(E)=f_4(E)/f_1(E)$, and for the $\frac{1}{2}\to\frac{1}{2}$ spin sequence

$$f_4(E)=\sqrt{\tfrac{1}{3}}\,[2ac-\tfrac{2}{3}(E_0/M)(ac-ab-ad)+\tfrac{2}{3}(E/M)(7ac-ab-ad)] + \tfrac{2}{3}[c^2-\tfrac{2}{3}(E_0/M)(c^2-cb-cd)+\tfrac{1}{3}(E/M)(11c^2-5cb+cd)], \tag{2}$$

$$f_1(E)=a^2+c^2-\tfrac{2}{3}(E_0/M)(c^2-cb-cd)+\tfrac{2}{3}(E/M)(3a^2+5c^2-2cb)-\tfrac{1}{3}(m_e^2/ME)(2c^2-2cb-cd). \tag{3}$$

In the above, $F(Z,E)$ is the usual Fermi function for a point nuclear charge, p and E are the momentum and total energy of the positron, M is the average nuclear mass, and P is the nuclear polarization which points in the direction $\hat{I}$.

The b and d terms cause the asymmetry parameter to depend on β energy and, with b determined by CVC theory, the energy dependence, or slope dA/dE, thus determines d. The c term has a strong effect on the energy independent part of the asymmetry because of destructive interference between a and c: $A\approx 2(\sqrt{3}ac+c^2)/3(a^2+c^2)\approx -4\%$ for $c\approx -1.6$.[5] The intercept therefore provides a sensitive way to determine c, the result being only weakly dependent on d. Alternatively, c can be obtained from the total decay rate for unpolarized decay, again with slight sensitivity to d: With $\lambda_{\text{exp}}=0.039\,93(5)$ sec^{-1} we obtain $c_\lambda=-1.584(3)$ and $-1.604(3)$ for $d=0$ and $d=+250$, respectively.[6] For $d=0$ and with the above values of a, b, and c we calculate, for comparison with the experimental result, the value $(dA/dE)_{\text{exp}}=(-0.34\pm0.01)\%$ MeV^{-1}. Finite-nuclear-size Coulomb corrections and the q^2 dependence of the form factors, as given by Holstein,[7] have been added to Eqs. (2) and (3) in obtaining the slope with $d=0$; the corrections are small and amount to -0.007% MeV^{-1} and -0.01% MeV^{-1}, respectively.

The asymmetry parameter was measured using the atomic-beam method of nuclear polarization which has been described in earlier studies of the ^{19}Ne decay.[8] Briefly the method is as follows (see Fig. 1). ^{19}Ne is produced by the reaction $^{19}\text{F}(p,n)^{19}\text{Ne}$ by bombarding a 200-mg/cm^2 gas target of SF_6 with a 20-μA beam of 12-MeV protons from the Princeton University cyclotron. Gas flows continuously from the target to a liquid-nitrogen–cooled trap, which removes the SF_6, and the purified ^{19}Ne is then pumped into the source cavity, or "oven," of the atomic-beam apparatus. By recirculation of unused ^{19}Ne atoms in the source chamber we gain an enhancement in the beam intensity of about two orders of magnitude.

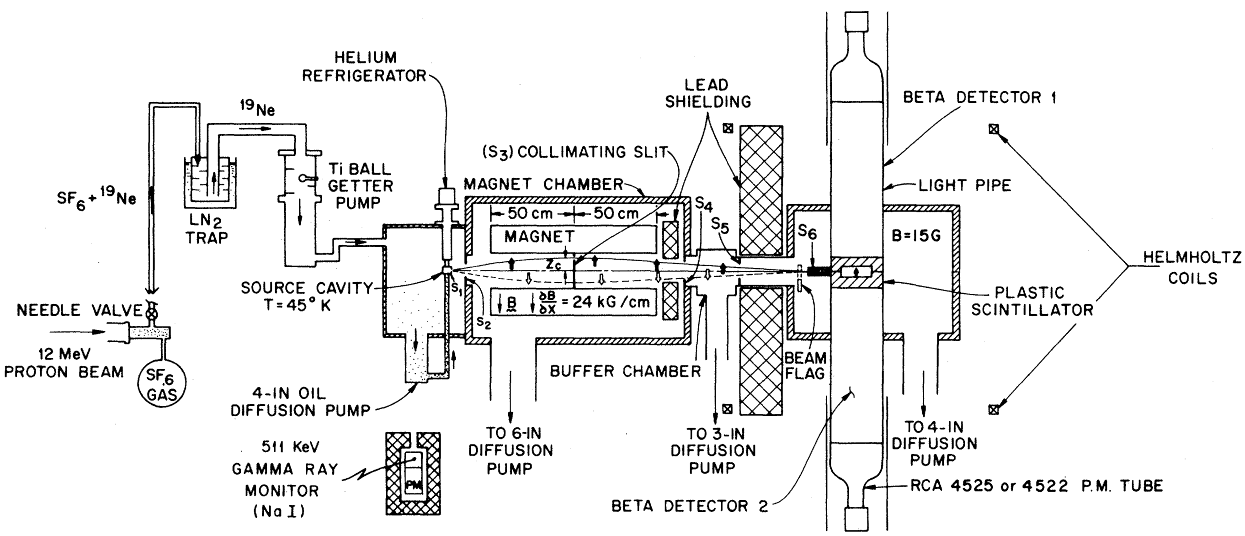

FIG. 1. The atomic-beam apparatus used to polarize ^{19}Ne. The solid line through the orbit-defining slits S_1, S_3, and S_6 illustrates the path of a typical atom with spin up. Slits S_2, S_4, and S_5 are used for differential pumping.

The ^{19}Ne atoms in the $^1S_0$ electronic ground state effuse from the source at thermal energies (45°K) and selection of either nuclear magnetic substate, $m_I = \pm\frac{1}{2}$, is achieved by three orbit-defining slits (S_1, S_3, and S_6) and a 100-cm-long Stern-Gerlach magnet (field gradient ~24 kG/cm). Slit S_3 is displaced from the line joining S_1 and S_6 sufficiently far to assure that the polarization of atoms passing through S_6 is 100%; the polarization is reversed by moving S_3 to the opposite side of the S_1-S_6 line.

The polarized atoms enter a storage cell constructed of two disks of plastic scintillator sealed to each other and to S_6. The disks are partially hollowed to form a cell 10.2 cm in diameter and 0.64 cm wide. The scintillators serve as the β detectors, having together a 4π solid angle, and are arranged to measure the "up-down" β asymmetry. Because of the small conductance of S_6 (a long narrow channel) atoms remain trapped in the cell for a few seconds and with an applied field of 15 G the polarization is essentially maintained despite perturbations due to wall collisions and field nonuniformity. A depolarization rate of 5% per second of storage is measured by varying the sitting time with an adjustable leak in the cell; the relaxation correction introduces an error in the polarization of 1%. No evidence is found for in-flight depolarization between the magnet and the cell and we estimate that the overall error in the polarization is no more than 2%.

The scintillators are optically decoupled from each other with coatings of aluminum 90 μg/cm^2 thick. Light pipes 50 cm long couple the scintillators to RCA 4525 photomultiplier tubes. The energy scale of the detectors is calibrated using the ^{19}Ne end point (2.216 ± 0.001 MeV) and a combination of the conversion lines of ^{207}Bi and ^{137}Cs and the γ-ray Compton edges of ^{22}Na and ThC′; the error in the energy scale is less than 5%. The full width at half-maximum energy resolution is 20% at 1 MeV and the pulse-height uniformity across each detector is better than 5%.

Data are taken in cycles consisting of measurements of both energy spectra with polarization "up" and "down" as well as the corresponding background spectra. The background is measured by inserting a flag in front of S_6 thus blocking the atomic beam but allowing randomly scattered ^{19}Ne to enter the cell. The total background summed over the energy spectrum is 2% of the true counts. Singles and coincidence events are both observed, the latter being due to backscattered positrons and to positron-annihilation γ coincidences. Singles rates are typically 1000 counts/sec and with the 4π detector geometry about 30% of all events are coincidences.

The singles spectra, corrected for background and coincidences, are combined to calculate the ratio

$$R_i(E) = \frac{[N_i(E)/N_T]^{\rm up} - [N_i(E)/N_T]^{\rm down}}{[N_i(E)/N_T]^{\rm up} + [N_i(E)/N_T]^{\rm down}} .$$

Here, N_T is the total counts in both detectors summed over energy and $N_i(E)$ is the energy spectrum for the ith detector ($i = 1, 2$). The relationship between R and the asymmetry parameter A is

$$R(E) = PG(v/c)A(E),$$

where P is the polarization and $G = \langle\cos\theta\rangle$ is the average of the cosine of the angle between the polarization and the positron directions; for the 4π geometry, a Monte Carlo calculation yields $G = 0.49 \pm 0.01$.

The asymmetry parameter obtained from the average of R_1 and R_2 for one of the runs is illustrated in Fig. 2 (only the statistical errors are

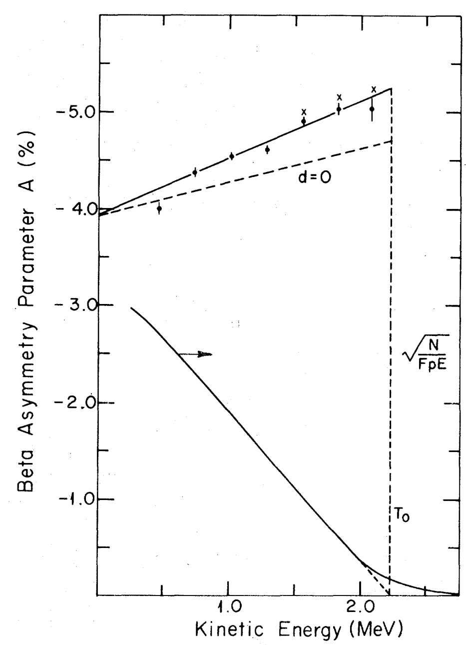

FIG. 2. The energy dependence of the β asymmetry parameter for ^{19}Ne decay. The dashed line illustrates the expected asymmetry with no second-class interaction ($d = 0$). Data points corrected for detector resolution and absorption of annihilation γ rays are shown as crosses, where the correction is large enough to be plotted. The lower portion of the figure shows the Kurie plot.

shown). The points marked by an X give the asymmetry after a correction for detector resolution and γ-ray absorption. The asymmetry parameter for positron energies less than 0.5 MeV is strongly affected by the background, due mostly to the 511-keV γ background, and coincidences. An error in these corrections probably accounts for the noticeably lower asymmetry for this energy but the mechanism is not completely understood at present. We choose to avoid this region and make a fit for energies 0.7–2.2 MeV where the background is small (less than 1%). The slope in this region for the points without the resolution correction[9] is $(dA/dE)_{\rm exp} = (-0.59 \pm 0.07)\%\ \text{MeV}^{-1}$, with reduced χ^2 for six points of 2.0. The statistical error, $0.04\%\ \text{MeV}^{-1}$, has been added in quadrature with errors in the polarization, calibration, and geometry factor to yield the above error. Other less tractable sources of error associated with detector nonuniformity, coincidence rejection, phototube-gain shifts, and pulse pile-up are not yet included. These effects were studied by measuring the asymmetry under the following conditions.

Detector nonuniformity or biased coincidence rejection may cause the geometry factor G to depend on the β energy. To assess the importance of this effect a different cell-detector system was constructed consisting of a thin-wall Mylar cell and two separated scintillators located outside the cell. Only 10% of the events are coincidences and the geometry factor is larger, $G = 0.7$. The resulting slope is $(-0.68 \pm 0.07)\%$ MeV^{-1}, consistent with the result for the 4π geometry, and we conclude that G is not strongly dependent on the β energy.

A consistent shift in the gain of the phototubes, correlated with the polarization state, is possible because of the asymmetry in count rates. This effect was judged to be small after obtaining consistent measurements of A with two different phototube and base types (using either anode or dynode energy signals) as well as a separate measurement with a special gain-stabilization circuit which yielded $(dA/dE)_{\rm exp} = (-0.65 \pm 0.07)\%\ \text{MeV}^{-1}$ (statistical).

Other measurements involve changing the direction of the magnetic field, using an alternate electronics and data-acquisition system, varying the detector uniformity and changing the count rate by a factor of 3. All of the data are consistent within $0.10\%\ \text{MeV}^{-1}$ and we take $(dA/dE)_{\rm exp} = (-0.65 \pm 0.15)\%\ \text{MeV}^{-1}$ for the best value of the slope and $A(0) = -3.91 \pm 0.14\%$ for the intercept.

With the values of a, b, and c noted above we find from the slope the value $d = +250 \pm 100$. That is, a sizable second-class form factor is needed to explain the energy dependence of the asymmetry. From the intercept and with $d = +250$ we also determine[10] $c = -1.609(2)$ in excellent agreement with the corresponding value specified above from the total decay rate.

An alternative explanation of the large slope is a violation of the weak-magnetism prediction of the CVC theory with $b_{\rm exp}/b_{\rm CVC} = 1.9 \pm 0.4$, but such a large breakdown is inconsistent with the measurements of weak magnetism in the $A = 12$ triad which confirm CVC theory to 20%.[11] We conclude that a more likely explanation of the ^{19}Ne asymmetry data is the presence of a second-class weak interaction.

Sugimoto, Tanihata, and Göring[12] have recently reported that similar angular correlation measurements on the mass-12 system favor a second-class d term comparable to the weak-magnetism term. In contrast we note that no second-class term is detected in the correlation data on the mass-8 system[13] nor in the ft asymmetries of mirror Gamow-Teller decays.[14] An analysis of the nuclear state dependence, taking into account meson exchange and off-mass-shell effects,[15] is needed before all these results can be judged for consistency.

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private communication). The b term is $19\sqrt{3}\mu$ (Ref. 2), where $\mu=\mu(^{19}\mathrm{Ne})-\mu(^{19}\mathrm{F})$ is the isovector magnetic moment and where the ^{19}Ne-^{19}F moments are $-1.887(2)\times\mu_N$ and $+2.628\mu_N$, respectively [G. H. Fuller and V. W. Cohen, Nucl. Data. Sect. A 5, 433 (1969)].

[5]Note that the small overall asymmetry makes the slope a relatively large fractional effect and thus reduces the importance of many systematic errors.

[6]The sign of c is taken from the asymmetry data. The decay rate is based on recent half-life measurements including $t_{1/2}=17.30\pm0.03$ sec (F. Calaprice, S. Freedman, and V. Narayanaswami, to be published). The determination of c is also discussed in this reference.

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Effects of the Triton D State in (d,t) Reactions

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Measurements of the tensor analyzing powers for (d,t) reactions on ^{118}Sn and ^{208}Pb are presented. It is shown that the measured quantities are sensitive to the D-state components in the triton wave function. The magnitudes of the observed analyzing powers are in good agreement with predictions obtained from a triton D-state wave function calculated in first-order perturbation theory.

It is well known that the deuteron D state can produce marked effects in (d,p) reactions.[1,2] The D state has very little influence on the reaction cross section, but can produce large changes in the observables for reactions induced with a polarized beam. In particular, the deuteron D state is primarily responsible for the large tensor analyzing powers[3] which are observed in (d,p) reactions on intermediate and heavy nuclei.

In this Letter, we argue that similar effects should be present in (d,t) reactions. In this case, however, the effects arise primarily from the D-state components in the triton wave function,[4] rather than from the deuteron D state. Measurements of the tensor analyzing powers for (d,t) reactions on ^{118}Sn and ^{208}Pb are presented, and the measurements are compared with the results of distorted-wave calculations.[5] A simple triton wave function, in which the D-state components are calculated from first-order perturbation theory, is used to predict the magnitude of the effects of the triton D state.

The reaction calculations presented in this Letter are based on the distorted-wave Born approx-