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# Parity Mixing in $^{19}$F†

E. G. Adelberger,* H. E. Swanson,‡ M. D. Cooper, J. W. Tape,§ and T. A. Trainor
*Department of Physics, University of Washington, Seattle, Washington 98195*
(Received 5 November 1974)

The parity-nonconserving asymmetry of the 110-keV de-excitation radiation emitted by a polarized ensemble of $^{19}$F nuclei in the first excited state is found to be $\delta = -(1.8 \pm 0.9) \times 10^{-4}$.

The study of parity-nonconserving (PN) nucleon-nucleon forces provides a unique opportunity to observe the weak hadronic current interacting with itself.[1,2] At present most experimental evidence for the size of parity admixtures in nuclear states comes from circular polarization (CP) measurements in heavy nuclei. In these nuclei the complexities of the nuclear structure tend to obscure the properties of the basic PN interaction. It is, therefore, highly desirable to study parity mixing in light nuclei where the nuclear physics is relatively tractable and where one can elucidate the isospin structure of the PN forces.

Prior to this work there existed only two positive measurements of PN transitions in light nuclei—a CP measurement of the radiation from capture of thermal neutrons by hydrogen[3] and a measurement[4] of the PN $\alpha$ decay of the 8.8-MeV $2^-$ level of $^{16}$O. The $\alpha$-decay width in $^{16}$O is roughly in accord with theory, while the CP measurement in H$(n,\gamma)$ is about 100 times larger than expected with current theories.[2] The apparent strong discrepancy between these two examples is not understood.

We have measured parity mixing in the ground $(J^\pi = \frac{1}{2}^+)$ and 110-keV $(J^\pi = \frac{1}{2}^-)$ excited states of $^{19}$F. In this instance the nuclear physics is unusually simple but unlike the cases of $^{16}$O and $p+n$ which are sensitive only to the $\Delta I = 0$ or $\Delta I = 2$ PN interactions,[1,2] the $\Delta I = 1$ PN interaction is also involved. It is particularly interesting to study the $\Delta I = 1$ interaction since it may be sensitive to neutral weak currents. The mixing in $^{19}$F is well approximated by simple two-state theory because the next $J = \frac{1}{2}$ level occurs at $E_x = 5.34$ MeV and the irregular transition is $M1$.[5] Since the PN interaction is a small perturbation we have

$$|\text{g.s.}\rangle = |+\rangle - \epsilon|-\rangle,$$

$$|110\rangle = |-\rangle + \epsilon|+\rangle,$$

where $\epsilon = \langle - |H_{\text{PN}}|+\rangle/(110\text{ keV})$. The electromagnetic matrix element connecting the states contains regular ($E1$) and irregular ($M1$) components:

$$\langle \text{g.s.}|E1 + M1|110\rangle = \langle + |E1|-\rangle + \epsilon[\langle + |M1|+\rangle - \langle - |M1|-\rangle] + O(\epsilon^2),$$

where we have ignored PN exchange contributions. The PN $M1$ amplitudes are completely determined by $\epsilon$ and the magnetic moments of the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ levels. Our experiment measures $\epsilon$ by detecting the $M1$-$E1$ interference which produces a pseudoscalar anisotropy $\sigma(\theta) = \sigma_0(1 + \delta\vec{P}_F \cdot \vec{k}_\gamma)$ in the 110-keV de-excitation radiation from a polarized ensemble of $^{19}$F* ($\vec{P}_F$ represents the $^{19}$F* polarization vector and $\vec{k}_\gamma$ a unit vector along the $\gamma$-

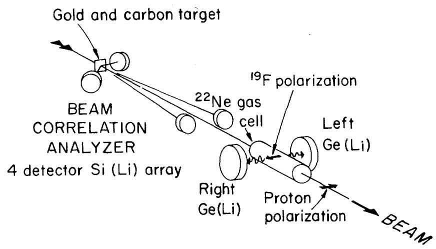


FIG. 1. The experimental geometry is shown. The beam first passes through the beam correlation analyzer which detects changes in beam position, angle, and spin direction associated with the proton-polarization state. Then the beam enters the $^{22}$Ne gas cell where the $^{19}F^*$'s are produced with spins opposite to those of the protons. De-excitation $\gamma$ rays are detected by the two matched Ge(Li) counters.

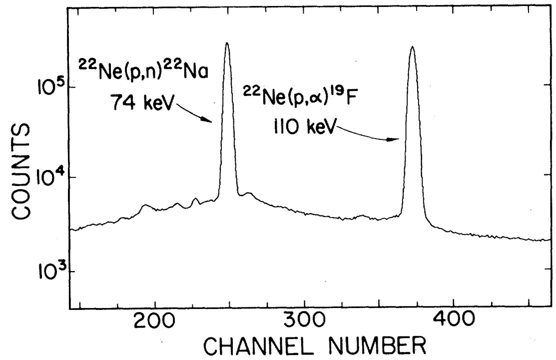


FIG. 2. A spectrum from one of the thin-window Ge(Li) counters showing the good peak-to-background ratio. The smooth background is primarily the Compton plateau of 1.275-MeV $\gamma$ rays from the $(p,p')$ reaction.

ray momentum).

The experimental geometry is shown in Fig. 1. Polarized $^{19}F^*$ nuclei are produced in the reaction $^{22}Ne(p_{pol}, \alpha)^{19}F$ by a 4.93-MeV transversely polarized proton beam from the University of Washington Lamb-shift polarized-ion source and FN tandem Van de Graaff accelerator. The simple spin structure of this reaction $(\frac{1}{2}^+ + 0^+ \to 0^+ + \frac{1}{2}^-)$ leads to a large polarization transfer, $K$, even if one sums over all $\alpha$ angles and employs a very thick target. For example, if the outgoing $\alpha$'s are $s$ wave, $K = -1$ ($\vec{P}_F$ opposite to $\vec{P}_p$). The coefficient $K$ is defined by $\vec{P}_F = K\vec{P}_p$, where $\vec{P}_p$ is the proton-beam polarization vector. In our experiment, the $^{19}F^*$ polarization must be retained for a time of approximately or more than the 850-psec lifetime of the 110-keV level. This is achieved by choosing the $^{22}$Ne target-gas pressure so that the recoiling $^{19}F^*$ nuclei decay before they come to rest—the rapidly fluctuating magnetic fields which occur during the slowing-down process do not cause a net precession of the magnetic moment. The beam is polarized alternately left or right and $\gamma$ rays are detected in two 10 $cm^2 \times 7$ mm planar thin-window Ge(Li) detectors mounted 5.8 cm from the beam axis on the left- and right-hand sides of the gas cell. Signals from the Ge(Li) detectors are digitized in two 100-MHz pulse-height analyzers which are under computer control. A $\gamma$-ray spectrum is shown in Fig. 2 demonstrating the excellent peak-to-background ratio. In order to reduce spin-correlated beam modulation the polarized-ion source is operated according to the adiabatic field-reduction scheme[6] with a typical beam polarization $P_p = 0.42$. Axial magnetic fields in the ion source produce a beam which is initially polarized longitudinally. The spin is rotated $\approx 90°$ by crossed $\vec{E}$ and $\vec{B}$ fields so that it will be transversely polarized at the target. The polarization state of the proton beam is switched every 0.31 sec by rapidly reversing the axial magnetic fields.[7] Ge(Li)-detector spectra are routed into separate halves of the analyzer memories according to the spin state of the beam. The PN anisotropy is obtained from the ratio $A = (R^+L^-)/(L^+R^-) \approx 1 + 4P_p\bar{K}\delta$. Here $\bar{K}$ is the net polarization transfer appropriately averaged over the lifetime of the 110-keV state, $R$ and $L$ denote counting rates in the right and left counters, and the superscripts + and − refer to the sign of the axial fields in the ion source. Note that in the expression for $A$ both polarization states as well as the counters $L$ and $R$ appear in numerator and denominator. Therefore many instrumental asymmetries cancel.

We employ two configurations, $a$ and $b$, of the crossed $\vec{E}$ and $\vec{B}$ fields. In configuration $a$, the axial state indicated by + corresponds to spin right at the target; in configuration $b$, the axial state indicated by + corresponds to spin left. In order to reduce spurious effects, we always acquire data in both configurations. The PN anisotropy is associated with the spin direction at the target. On the other hand, many instrumental asymmetries are correlated with the sign of the axial fields. We obtain $\delta$ from the expression

$$\bar{K}\delta = [A_a/A_b - 1]/(8P_p)$$

which cancels instrumental asymmetries associated directly with the sign of the axial fields.

Since $\delta$ is expected to be very small, it is necessary to demonstrate that instrumental asymmetries are either negligible or correctable. We have identified five important sources of such asymmetries. These arise because the ion source and accelerator introduce undesired correlations between the proton-beam properties and the spin state. The effects we consider are spin-correlated modulations of the beam intensity, position, angle, and energy, as well as misalignment of the spin direction. Our experiment is designed to minimize these asymmetries. We have chosen a beam energy such that in addition to 110-keV radiation from $^{22}$Ne($p$, $\alpha$) we also produce 74-keV radiation from the reaction $^{22}$Ne($p,n$). The 74-keV radiation comes from the decay of a $J=0$ level and hence is rigorously isotropic. By taking the ratio of the intensities of the 110- to 74-keV $\gamma$ rays in each spectrum we correct very accurately for spin-correlated beam intensity and position changes. Beam-angle modulation can produce asymmetries because the effective source of the 74-keV $\gamma$'s in the gas cell is separated by 1.3 cm from the source of 110-keV $\gamma$'s because of differing excitation functions for the ($p,n$) and ($p$, $\alpha$) reactions. Such asymmetries are reduced by operating the ion source in a mode which gives very small angle modulation. Asymmetries due to beam-energy modulation are suppressed by the use of two $\gamma$ counters—one on each side of the beam. Asymmetries are also produced if the left-right axis between the Ge(Li) counters does not lie exactly along the proton-polarization axis. Then the $\vec{L}\cdot\vec{S}$ force can produce $^{19}$F* ions which preferentially recoil toward one counter or the other and create an asymmetry correlated with the proton-spin direction which mimics a parity nonconservation. Of course, if the outgoing $\alpha$'s are purely $s$ wave this does not occur. The effect of the recoiling nuclei is minimized by positioning the counters to an accuracy of 0.1°. This is done by locating the effective centers of the counters with 122- and 70-keV $\gamma$ rays from radioactive sources.

The proton-beam properties are measured online during the experiment. Before the beam enters the $^{22}$Ne gas cell it passes through a foil consisting of 10 $\mu$g/cm$^2$ of C and 5 $\mu$g/cm of Au. This foil is viewed by four solid-state particle detectors—two at $\theta = \pm 3.9°$ and two at $\theta = \pm 55°$ (see Fig. 1). The yields of the unresolved scattering from Au and C at ±3.9°, as well as the scattering from Au at ±55°, and the scattering from C at ±55° are scaled. From these yields we compute the beam angle and position modulation as well as any small vertical component of the proton spin. Typical values are as follows. When the proton spin is flipped the beam intensity changes by ~2%, its average position shifts by $\pm 2.5\times10^{-4}$ cm, and its mean angle changes by $\pm 6\times10^{-4}$ deg. A typical variation of the proton-spin angle is ≈1°.

In separate experiments we have measured the sensitivity of our apparatus to each of the five effects listed above. This was done by measuring $A$ while the proton-beam properties were deliberately modulated with an amplitude between 10 and 100 times greater than that encountered in the main experiment. For these measurements the signal which normally controlled the polarization state was used to modulate the beam intensity, position, angle, or energy. The angle and position of an unpolarized beam from a direct-extraction ion source were modulated in both the horizontal and vertical planes with an electromagnet placed 1.75 m before the gas cell. Energy modulations were induced by varying the current in the 90° analyzing magnet. Intensity modulations were produced by varying the quenching voltage in the polarized-ion source while leaving the spin direction unchanged. In each of these tests the asymmetries $|A-1|$ were zero within statistics. When translated into modulations of the size encountered in the measurement of $\delta$ they correspond to upper limits on systematic errors in $\delta$ of less than $3\times10^{-5}$. This is smaller than the statistical uncertainty (see below) and will be neglected. The sensitivity to spin misalignment was determined by rotating the spin of the polarized beam 90° out of the reaction plane, where PN effects vanish and apparent asymmetries due to $\vec{L}\cdot\vec{S}$ forces are maximum. In this geometry we measured $|A-1|=(6.5\pm1.3)\times10^{-3}$. From this measurement we can correct $A$ with negligible error for the "fake" asymmetry due to misalignment of the spin near 0°. This correction changes our value for $\delta$ by 6%. No other corrections to the raw data are required.

Five independent measurements of the PN anisotropy are used in obtaining our result. The different runs are all internally consistent $[\chi^2=1.6, P(\chi^2 \geq 1.6)=0.8]$ and lead to a value of $\bar{K}\delta=(13.1\pm5.8)\times10^{-5}$ where the error is a statistical standard deviation. To demonstrate that the method of extracting $\gamma$-ray peak areas does not introduce artificial asymmetries we employ two different background-subtraction techniques and obtain similar results in both cases. With no background subtraction we obtain $\bar{K}\delta = (10.2 \pm 5.8) \times 10^{-5}$ which indicates that the background asymmetry is negligible.

We determined the net polarization of the $^{19}F^*$'s at the time of $\gamma$-ray emission, $\bar{K}$, by measuring the CP of the 110-keV radiation. For a $J = \frac{1}{2} \to J = \frac{1}{2}$ transition the CP of the photon is equal to the linear polarization of the initial state along the photon axis. The CP was measured by using the spin dependence of Compton scattering from magnetized iron. From this measurement the Ge(Li) counters were moved back an additional 5.0 cm from the beam axis and a symmetrical transmissiontype polarimeter inserted between the gas cell and the counters. The magnetization was reversed every second, while the beam polarization was held constant. Data were taken in both proton-spin directions and in two symmetrical magnet positions. The analyzing efficiency of our Compton polarimeter was computed using Monte Carlo methods and found to be $-(2.3 \pm 0.2) \times 10^{-3}$. The quoted error is dominated by uncertainties in the coherent cross sections. This leads to a polarization transfer $\bar{K} = -0.73 \pm 0.15$.

Combining our results, we obtain $\delta = -(1.8 \pm 0.9) \times 10^{-4}$ which corresponds to $|\langle - | H_{PN} | + \rangle| = 0.90 \pm 0.45$ eV. [We cannot infer the sign of $\langle - | \boldsymbol{H}_{PN} | + \rangle$ from our data since we do not know the sign of the regular $E1$ matrix element and do not trust a calculation to give the sign for a highly retarded transition ($\sim 10^{-3}$ Weisskopf units).] Several calculations of $\delta$ have been performed. Maqueda[5] used a single-body PN potential and uncorrelated nuclear wave functions to predict that $|\delta| = 4.3 \times 10^{-4}$. Gari *et al.*[8] and Box and McKellar[9] have recently calculated $\delta$ using two-body PN $N$-$N$ interactions and correlated wave functions. The two calculations agree very well. In these the $\Delta I = 0$ interaction gives $|\delta| \sim (0.4-0.9) \times 10^{-4}$, while the $\Delta I = 1$ interaction gives $|\delta| \sim (0.1-0.2) \times 10^{-4}$. Although the parity nonconservation in $^{19}F$ is somewhat greater than predicted by calculations based on charged weak currents and correlated wave functions the discrepancy is much less than in the $n+p$ system.

A complete account of this work will appear later. We would like to acknowledge a very ingenious attempt by Moline and Barnes[10] to do this experiment by a different technique. We learned a great deal from their work. We thank Dr. Gari and Professor McKellar for sending us their results before publication.

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†Work supported in part by the U.S. Atomic Energy Commission.

*Alfred P. Sloan Foundation Fellow.

‡Present address: Niels Bohr Institute, Copenhagen, Denmark.

§Present address: Bell Laboratories, Murray Hill, N. J. 07974, and Rutgers University, New Brunswick, N. J. 07192.

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