Parity Mixing of 0^+ and 0^- Levels in ^{18}F

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The circular polarization of the γ rays emitted in the transition from the 1.081-MeV state to the ground state in ^{18}F has been measured to be $(1.6 \pm 5.6)\times 10^{-4}$, corresponding to a parity-nonconserving (PNC) matrix element $|\langle 0^+, I=1 | V^{\mathrm{PNC}} | 0^-, I=0\rangle| = 0.03 \pm 0.10$ eV. The weak pion-nucleon coupling constant deduced from the weighted average of all recent ^{18}F measurements is $(0.28^{+0.89}_{-0.28})\times 10^{-7}$. This result, together with PNC matrix elements in other experiments, suggests that the isovector weak *NN* interaction may be strongly suppressed compared with the isoscalar weak *NN* interaction.

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Parity-nonconserving (PNC) effects in nuclear processes provide a unique opportunity to investigate the relative strength of the $\Delta I = 0, 1$, and 2 components of the nonleptonic weak interaction. At low energies, these effects are calculated in terms of a weak nucleon-nucleon potential, V^{PNC}, derived from meson-exchange interactions in which the meson (π, ρ, or ω) is coupled to one nucleon through the weak interaction and to the other through the strong interaction.[1] The strengths of the different isospin components are defined by the weak meson-nucleon coupling constants f_π^1, h_ρ^0, h_ρ^1, h_ρ^2, h_ω^0, and h_ω^1 for π, and ρ, and ω exchange potentials, respectively. Desplanques, Donoghue, and Holstein[2] (DDH) have recently evaluated these weak coupling constants from standard electroweak theory and different quark models for the mesons and nucleons. They have deduced a reasonable range and a "best" value for each of the coupling constants. The PNC observables predicted from their "best" values are in reasonable agreement with experimental data from few-nucleon systems[3] and light nuclei.[4] In most cases, the PNC effects are due to a mixture of different isospin contributions. It is highly desirable to be able to measure the different weak meson-nucleon coupling constants separately. The weak pion-nucleon coupling constant f_π^1 is of particular interest because the long-range pion-exchange potential, the best understood potential in nuclear physics, can be separated from other short-range potentials and is expected to have significant contributions from weak neutral currents.[5]

A favorable way to study the weak pion-exchange potential is to measure the mixing amplitude of the $J^\pi = 0^+$, $I=1$ level at 1.042 MeV and the 0^-, $I=0$ level at 1.081 MeV in ^{18}F (see Fig. 1). The parity impurities in these levels lead to a circular polarization of the γ rays from these levels to the ground state given by[8]

$$P_\gamma(1042) = \frac{2\langle 0^+, 1 | V^{\mathrm{PNC}} | 0^-, 0\rangle}{\Delta E} \, \frac{\langle 0^- \| E1 \| 1^+\rangle}{\langle 0^+ \| M1 \| 1^+\rangle},$$

and

$$P_\gamma(1081) = -\frac{2\langle 0^+, 1 | V^{\mathrm{PNC}} | 0^-, 0\rangle}{\Delta E} \, \frac{\langle 0^+ \| M1 \| 1^+\rangle}{\langle 0^- \| E1 \| 1^+\rangle},$$

where the energy splitting, ΔE, is 39.20 ± 0.11 keV,[6] $\langle 0^- \| E1 \| 1^+\rangle$ and $\langle 0^+ \| M1 \| 1^+\rangle$ are the reduced matrix elements for the $E1$ and $M1$ transitions from the 1.081- and 1.042-MeV levels, and $\langle 0^+, 1 | V^{\mathrm{PNC}} | 0^-, 0\rangle$ is the parity-mixing matrix element. From the measured lifetimes[9] of these levels, the ratio $|\langle 0^+ \| M1 \| 1^+\rangle / \langle 0^- \| E1 \| 1^+\rangle|$ is deduced to be

109 ± 12. Thus $P_\gamma(1081)$ is strongly enhanced, whereas the suppression of $P_\gamma(1042)$ provides a sensitive test of possible systematic asymmetries in our measurement. In the meson-exchange model, the pion-exchange contribution to the PNC matrix element is related to the two-body pion-exchange matrix element in the forbidden β^+ decay ${}^{18}\mathrm{Ne} \to {}^{18}\mathrm{F}(1081) + e^+ = \nu$ (see Fig. 1), and the calculated ratio of these two matrix elements is reasonably independent of the shell-model wave functions.[6,10] It has also been shown by Adelberger *et al.*[6] that the calculated ratio of one- and two-body pion-exchange matrix elements for the β^+ decay is insensitive to the choice of shell-model wave functions. Thus the observed forbidden β^+ decay rate[6,7] can be used in the evaluation of the pion-exchange PNC matrix element. Since the contributions from heavier mesons are small ($\sim 5\%$) and add constructively in the PNC matrix element as discussed in Ref. 6, an upper limit for f_π^1, which is assumed to be positive,[2] is given by

$$|P_\gamma(1081)| = (4.33 \pm 0.87) \times 10^3 f_\pi^1,$$

where the uncertainty includes both experimental and theoretical uncertainties added in quadrature.

In this favorable case, ambiguities in the interpretation of the experimental data are largely removed and a firm value for f_π^1 can be determined from an accurately measured value of the circular polarization of the γ rays from the 1.081-MeV level. The measurement described in this paper and an independent experiment by Bini *et al.*[11] have significantly reduced the limit on f_π^1 reported in previous publications.[4]

The ^{18}F was produced in the reaction ${}^{16}\mathrm{O}({}^3\mathrm{He},p){}^{18}\mathrm{F}$ with 10 to 15 μA of a 4.05-MeV ${}^3\mathrm{He}^+$ beam from the 4-MV Van de Graaff accelerator at Queen's University. The recirculating water target was isolated from the beam-line vacuum by ~ 1.0 mg/cm^2 thick Ti window foils ($\Delta E \approx 0.5$ MeV). The foils were changed after every 2 to 3 d of beam bombardment. The circular polarization of the γ rays was measured by four magnetic transmission-type Compton polarimeters with Permendur alloy cores 7.2 cm long. The internal magnetization of the cores was estimated to be 2.3 ± 0.1 T, and the analyzing power, η, of the polarimeters at 1.08 MeV was deduced to be $1.62 \pm 0.08\%$ from measurements with a ^{60}Co source. The polarimeters were placed symmetrically around the target at 90° to the beam direction, and each polarimeter was backed by a 150-cm^2 intrinsic n-type Ge detector.

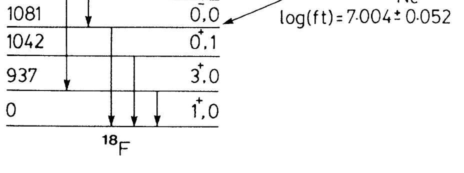

FIG. 1. The energy levels (not to scale) in ^{18}F and the β^+ decay of ^{18}Ne. Only levels and transitions relevant to this experiment are shown. The log(ft) value is deduced from the weighted average of β^+-decay rates from Adelberger *et al.* (Ref. 6) and Hernandez and Daehnick (Ref. 7).

The magnetic fields in vertical and horizontal pairs of polarimeters were in opposite directions with respect to the target to minimize the beam deflection by stray fields. A switching circuit reversed all the internal magnetic fields every 7.5 to 10 s, a time period which was set differently for each block of runs. Data collection was blocked for 0.1 s during field switching, although the fields stabilized in ~ 0.05 s.

The counting rate at each detector was maintained at $\sim 60 \times 10^3$/s for pulses greater than 50 keV. To reduce pileup loss, the time constants of the ORTEC model 673 gated integrators were set at 0.25 μs, corresponding to an output pulse width of ~ 3 μs. The energy resolution was typically 3.3 keV FWHM at 1.08 MeV. Linear gates were used to select the 800 keV $\le E_\gamma \le$ 1400 keV portion of the γ-ray spectra ($\sim \frac{1}{4}$ of all γ-ray events) to be analyzed. A four-channel analog routing controller was built to reduce the effective dead-time loss of the analog-to-digital converters (ADC's) to less than 4%. However, the total peak losses were $\sim 35\%$. In our setup, each of the three ADC's accepted linear signals from all four detectors, and the spectra were routed into different memory locations according to detector, ADC, and magnet current state.

Figure 2(a) shows a γ ray spectrum from one detec-

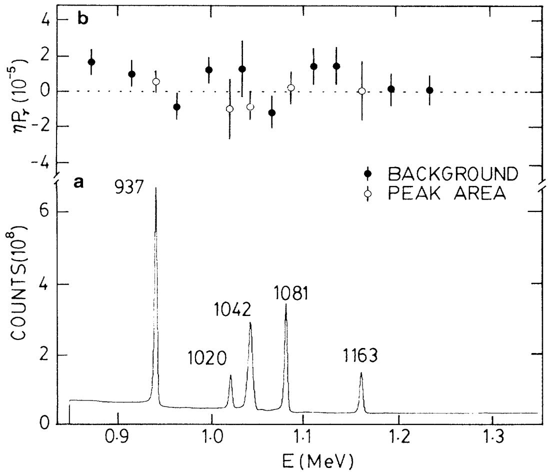

FIG. 2. (a) A portion of the γ-ray spectrum of all the data from one detector. The numbers labeling the peaks are γ-ray energies in kiloelectronvolts. (b) The measured asymmetry from different background-subtracted peak areas (open circles) and background regions (solid circles).

tor. In addition to the 1.042- and 1.081-MeV peaks, the spectra contain peaks from 0.937-, 1.020-, and 1.163-MeV γ-rays from ^{18}F which are expected to have negligible circular polarizations. For each run, data were collected for ~ 800 s and the 24 spectra (3 ADC's $\times 2$ magnet current states $\times 4$ detectors) were written on magnetic tape. After 180 runs, the polarity of the magnet-power supply was reversed at the input to the polarimeters to check systematic bias associated with logic levels. A total of 2560 h of data was collected. The total number of counts in the 1081-keV peak is $\sim 1.5 \times 10^{10}$, and the ratio of peak area to background is ~ 3.7.

From the counts in a region of the up (U), right (R), down (D), and left (L) polarimeter spectra, the circular polarization is deduced from the asymmetry, ηP_γ:

$$\eta P_\gamma = \frac{1-[U(0)D(0)R(1)L(1)/U(1)D(1)R(0)L(0)]^{1/4}}{1+[U(0)D(0)R(1)L(1)/U(1)D(1)R(0)L(0)]^{1/4}},$$

where in magnet current states 0 (1) the magnetizations of the D and U polarimeters are parallel (antiparallel) to the photon propagation direction, and the magnetizations of L and R polarimeters are antiparallel (parallel) to the photon propagation direction. This quadrupole ratio is insensitive, in first order, to beam motion and differences in total charge collected in the two magnet-current states. Figure 2(b) shows the asymmetries in different regions of the γ-ray spectrum. The asymmetries of all the γ-ray background-subtracted peak areas are consistent with zero, which indicates that false asymmetries introduced by our experimental arrangement are negligible. The circular polarization of the γ rays from the 1.081-MeV level is found to be $(1.6 \pm 5.6) \times 10^{-4}$. The value of f_π^1 is deduced to be $(0.37{}^{+1.29}_{-0.37}) \times 10^{-7}$.

Tests have been undertaken to determine the sensitivity of our apparatus to a variety of systematic effects that could influence the experimental results. The stray magnetic fields from the polarimeters along the beam line have been measured, and the contribution due to beam motion correlated with magnetic field reversal is estimated to be $\delta P_\gamma < 10^{-6}$. The double ratios $U(0)D(1)/U(1)D(0)$ and $L(0)R(1)/L(1)R(0)$, which are sensitive to beam motion, are $1.000\,023 \pm 0.000\,024$ and $1.000\,005 \pm 0.000\,025$, respectively, which indicates no significant beam-steering effects. From dead-time and auxiliary measurements, the second-order effect due to counting rate differences is estimated to be $\delta P_\gamma < 10^{-5}$. For all the peaks, the distributions of asymmetries of individual runs have standard deviations which are $\sim 0.6\%$ larger than would be given by the statistical uncertainties; this corresponds to a reduced χ^2 of ~ 1.01. The average of the circular polarization of the background regions is positive. This may be due to circularly polarized γ rays produced by positron bremsstrahlung [e.g., from ^{15}O produced by ^{16}O(^{3}He, α)^{15}O].

Table I is a summary of all experimental results on the measurement of $P_\gamma(1081)$. The value of f_π^1 deduced from the weighted average of $P_\gamma(1081)$ is $(0.28{}^{+0.89}_{-0.28}) \times 10^{-7}$, which is substantially less than the "best" value of 4.6×10^{-7} given by DDH. Figure 3 shows the range of possible values of f_π^1 and $h_\rho^0 + 0.58 h_\omega^0$ based on observed PNC effects in light nuclei, where the experimental results are expressed as $A f_\pi^1 + B(h_\rho^0 + 0.58 h_\omega^0)$. The coefficients A and B are deduced from measurements and nuclear-structure calculations.[3,6] A discrepancy in the interpretation of different experiments is indicated by the lack of a common overlapping region in Fig. 3. The β^+-decay measurements for ^{18}F and ^{19}F have shown that the coefficients for f_π^1 calculated with $0 + 1\hbar\omega$ shell-model wave

TABLE I. Summary of recent measurements of $P_\gamma(1081)$.

Barnes *et al.* (Ref. 4)	$(-7 \pm 20) \times 10^{-4}$
Ahrens *et al.* (Ref. 4)	$(-10 \pm 18) \times 10^{-4}$
Bizzeti *et al.* (Ref. 4)	$(-4 \pm 30) \times 10^{-4}$
Bini *et al.* (Ref. 11)	$(2.7 \pm 5.7) \times 10^{-4}$
This work	$(1.6 \pm 5.6) \times 10^{-4}$
Weighted average	$(1.2 \pm 3.8) \times 10^{-4}$

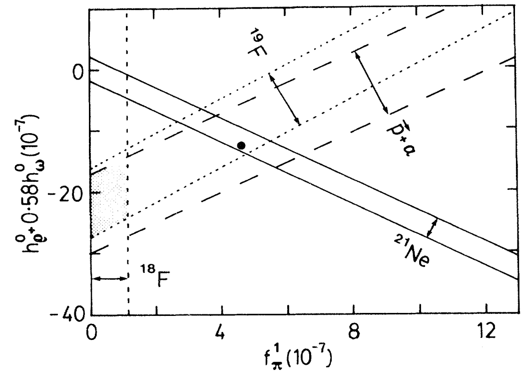

FIG. 3. Constraints on the weak isovector f_π^1 and isoscalar $h_\rho^0 + 0.58 h_\omega^0$ NN interaction strengths. The coefficients are deduced from Refs. 3 and 6. The small isovector contributions from heavier mesons have been ignored. The parallel lines are 1σ limits on experimental results. The closed circle indicates the "best" value of DDH. The darkened region indicates the preferred area allowed by the measurements (see text).

functions have to be reduced by a factor of 3. For the case of ^{18}F, such a correction is shown to be necessary to compensate for $2\hbar\omega$ contributions which have been neglected. For ^{21}Ne, the β-decay measurement is not possible, and calculations including $2\hbar\omega$ wave functions have not been done. However, the β^+-decay measurements cited suggest that the coefficients A and B for ^{21}Ne should also be reduced by a factor of 3. From the measured value of P_γ for ^{21}Ne, with its assigned error, one therefore obtains the enlarged permissible region shown in Fig. 3.

Based on the $p_{\text{pol}}+\alpha$, ^{19}F, and ^{18}F PNC results, the short-range isoscalar weak NN interaction is in reasonable agreement with the "best" value of DDH, but the long-range isovector weak NN interation appears to be suppressed. This does not contradict the PNC effects observed in $p_{\text{pol}}+p$ experiments as they are not sensitive to the value of f_π^1. Earlier calculations of PNC effects in medium and heavy nuclei, which indicate that there are substantial pion-exchange contributions, have been shown to be uncertain because of the inadequacy in the shell-model wave functions used.[12] Because the ranges of the ρ- and ω-exchange potentials are roughly the size of a nucleon, a more realistic treatment of nuclear PNC effects may require calculation of the short-range isoscalar weak NN interaction from the exchange of weak-interaction vector bosons between quarks, as in the hybrid model of Kisslinger and Miller.[13] Whether such calculations will yield better predictions of nuclear PNC effects than models incorporating only meson exchanges remains to be studied.

Through the combined efforts of many laboratories, the value of f_π^1 is now well established and excludes a significant portion of the reasonable range estimated by DDH. This provides a severe constraint[5] on the strong-interaction models used in evaluating the weak pion-nucleon coupling constant from fundamental electroweak theory.

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