[(a)]Present address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87545.
[(b)]Present address: Centre des Recherches Nucleaire, F-67037 Strasbourg, France.

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Parity Nonconservation in ^{18}F, ^{19}F, and ^{21}Ne

W. C. Haxton[(a)] and B. F. Gibson
Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545

and

E. M. Henley
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 July 1980)

Parity nonconservation has been studied in ^{18}F, ^{19}F, and ^{21}Ne for the Weinberg-Salam model. After careful treatment of nuclear structure aspects, values are predicted for the γ-ray asymmetry and circular polarizations in good agreement with experiment provided one employs meson-nucleon coupling constants somewhat weaker than the "best values" recently suggested by Desplanques, Donoghue, and Holstein.

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Parity nonconservation (PNC) in the nucleon-nucleon interaction is apparent in the left-right asymmetry in p-p scattering,[1] in the parity-forbidden α decay of the 2^- (8.8 MeV) state in ^{16}O,[2] and in the circular polarization[3,4] or asymmetry[5] (for a polarized nucleus) of radiation emitted in nuclear γ decay. An understanding of these effects is extremely important since PNC provides a unique opportunity for studying the strangeness-conserving hadronic weak interacttion. In the case of nuclear phenomena the connection between experiment and the parameters of the weak interaction cannot be made without reliable microscopic calculations of the parity mixing induced by the PNC interaction. Unfortunately, it is extremely difficult to perform such calculations for many heavy nuclei, while existing work on the lighter nuclei is generally unsatisfactory because of oversimplified treatments of the shell-model structure and PNC potential. We have thus begun a program to calculate carefully the PNC transitions in ^{16}O, ^{18}F, ^{19}F, and ^{21}Ne using powerful shell-model techniques and a very general PNC potential arising from the exchange of π, ρ, and ω mesons. We believe that this work, in combination with the PNC results for few-body systems ($A = 2$–4), will allow us to extract stringent constraints on the parameters of the PNC NN interaction from experiment. In this Letter we provide the first results of this program: calculations of the γ-ray circular polarization in ^{18}F and ^{21}Ne and of the γ-ray asymmetry in ^{19}F. The results are encouraging since the calculated PNC effects, using Weinberg-Salam weak interaction meson-nucleon coupling constants somewhat weaker than those recently determined by Desplanques, Donoghue, and Holstein,[6] are in good agreement with experiment.

The circular polarization of the γ rays emitted in the $J^\pi, T=0^-, 0$ (1.08 MeV) $\to 1^+, 0$ (0.0 MeV) transition in ^{18}F has been measured by Barnes *et al.*[3] They found $P_\gamma(1.08 \text{ MeV}) = (-0.7 \pm 2.0) \times 10^{-3}$. This upper limit constrains the strength of the isovector components of the PNC interaction responsible for the mixing of the initial state with the nearby $0^+, 1$ (1.04 MeV) level. In a two-level mixing approximation

$$P_\gamma = \frac{2}{\Delta E} \operatorname{Re}\left[\frac{\langle 1^+ || M1 || 0^+\rangle}{\langle 1^+ || E1 || 0^-\rangle} \langle 0^+, 1 | V_{\text{PNC}} | 0^-, 0\rangle\right] \quad (1)$$

with $\Delta E = 39$ keV and with the electromagnetic operators evaluated at a momentum transfer $k = 1.08$ MeV/c. (Our multipole operators are those of deForest and Walecka[7]; all equations have been derived without assumptions on wave-function phases or reality of matrix elements.) The magnitude of the reduced-matrix-element ratio $|M1/E1| = 107^{+9}_{-11}$ can be determined from the lifetimes of the 0^+ and 0^- states.[8]

Adelberger *et al.*[5] determined the asymmetry A_γ, measured with respect to the polarization direction, of the 110-keV γ ray emitted in the decay of the $\frac{1}{2}^-$ first excited state in polarized ^{19}F. The result is $A_\gamma(110 \text{ keV}) = -(0.85 \pm 0.26) \times 10^{-4}$, where $d\omega/d\Omega_\gamma \sim 1 + A_\gamma \cos\theta$ for a completely polarized $\frac{1}{2}^-$ state. Assuming that a two-level mixing approximation is valid, this asymmetry tests a combination of $T=0$ and $T=1$ components of the PNC interaction responsible for the mixing of the $\frac{1}{2}^-, \frac{1}{2}$ level with the $\frac{1}{2}^+, \frac{1}{2}$ ground state. We find

$$A_\gamma = \frac{2}{\Delta E} \operatorname{Re}\left[\frac{\langle \frac{1}{2}^+ || M1 || \frac{1}{2}^+\rangle - \langle \frac{1}{2}^- || M1 || \frac{1}{2}^-\rangle}{\langle \frac{1}{2}^+ || E1 || \frac{1}{2}^-\rangle} \langle \tfrac{1}{2}^+, \tfrac{1}{2} | V_{\text{PNC}} | \tfrac{1}{2}^-, \tfrac{1}{2}\rangle\right] \quad (2)$$

with $\Delta E = 110$ keV and with the operators evaluated at $k = 110$ keV/c. The $M1$ matrix element for the $\frac{1}{2}^+$ state is determined from the measured magnetic moment, 2.6289,[8] and the magnitude of the reduced $E1$ matrix element from the lifetime of the $\frac{1}{2}^-$ level. The magnetic moment of the $\frac{1}{2}^-$ level is not known and thus must be taken from a calculation.

The circular polarization of the γ rays from the $\frac{1}{2}^-, \frac{1}{2}$(2.789 MeV) $\to \frac{3}{2}^+, \frac{1}{2}$(0.0 MeV) transition in ^{21}Ne has been measured by Snover *et al.*[4] The upper limit obtained is $P_\gamma(2.80 \text{ MeV}) = (2.4 \pm 2.9) \times 10^{-3}$. As in the ^{19}F case, this experiment measures a combination of the $T=0$ and $T=1$ components of the PNC matrix element governing the mixing of the $\frac{1}{2}^-, \frac{1}{2}$ and nearby $\frac{1}{2}^+, \frac{1}{2}$ (2.796 MeV) levels. However, one expects this combination to be quite different from that tested in ^{19}F, since ^{21}Ne is an odd-neutron rather than odd-proton nucleus. The experimental limit is significant in that it indicates a PNC matrix element much smaller than that found in ^{19}F. The theoretical expression for P_γ is, in the two-level mixing approximation,

$$P_\gamma = -\frac{2}{\Delta E} \frac{1 + \delta_-^* \delta_+}{1 + |\delta_-|^2} \operatorname{Re}\left[\frac{\langle \frac{3}{2}^+ || M1 || \frac{1}{2}^+\rangle}{\langle \frac{3}{2}^+ || E1 || \frac{1}{2}^-\rangle} \langle \tfrac{1}{2}^+, \tfrac{1}{2} | V_{\text{PNC}} | \tfrac{1}{2}^-, \tfrac{1}{2}\rangle\right] \quad (3)$$

with $\Delta E = 7.6 \pm 0.7$ keV, $\delta_- = \langle \frac{3}{2}^+ || M2 || \frac{1}{2}^-\rangle / \langle \frac{3}{2}^+ || E1 || \frac{1}{2}^-\rangle$, and $\delta_+ = \langle \frac{3}{2}^+ || E2 || \frac{1}{2}^+\rangle / \langle \frac{3}{2}^+ || M1 || \frac{1}{2}^+\rangle$. All multipole operators are evaluated at $k = 2.789$ MeV/c. Although the $\frac{1}{2}^- \to \frac{3}{2}^+$ and $\frac{1}{2}^+ \to \frac{3}{2}^+$ transition rates are known, the two mixing ratios are not. The uncertainty this introduces in the comparison of theory to experiment will be discussed later.

In our calculations we have employed a general two-body PNC potential which arises from single π, ρ, and ω exchange:

$$\begin{aligned} V_{\text{PNC}}(r) = {} & (i/M) F_\pi (\vec{\tau}_1 \times \vec{\tau}_2)_z (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{u}_\pi(r) \\ & + M^{-1}\{[F_0 \vec{\tau}_1 \cdot \vec{\tau}_2 + \tfrac{1}{2} F_1 (\vec{\tau}_1 + \vec{\tau}_2)_z + \tfrac{1}{2} F_2 (3\tau_{1z}\tau_{2z} - \vec{\tau}_1 \cdot \vec{\tau}_2)/\sqrt{6}] \\ & \qquad \times [(1+\mu_v) i (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{u}_\rho(r) + (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{v}_\rho(r)] \\ & + [G_0 + \tfrac{1}{2} G_1 (\vec{\tau}_1 + \vec{\tau}_2)_z][(1+\mu_s) i (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{u}_\rho(r) + (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{v}_\rho(r)] \\ & + \tfrac{1}{2} K_1 (\vec{\tau}_1 - \vec{\tau}_2)_z (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{v}_\rho(r) + H_1 i (\vec{\tau}_1 \times \vec{\tau}_2)_z (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{u}_\rho(r)\}, \end{aligned} \quad (4)$$

TABLE I. Weak-coupling constants as determined from the "best-value" results of Ref. 6 for the Weinberg-Salam model. We take $g_{\pi NN} = 13.45$, $g_\rho = 2.79$, $g_\omega = 8.37$, and $K_1 = G_1 - F_1$.

Coefficient	Ref. 6 equiv.	Value (10^{-6})
F_π	$g_{\pi NN} f_\pi/\sqrt{32}$	1.084
F_0	$-g_\rho h_\rho^0/2$	1.590
F_1	$-g_\rho h_\rho^1/2$	0.027
F_2	$-g_\rho h_\rho^2/2$	1.325
G_0	$-g_\omega h_\omega^0/2$	0.795
G_1	$-g_\omega h_\omega^1/2$	0.477
H_1	$-g_\rho h_\rho'^1/4$	0.0

where $r = |\vec{r}_1 - \vec{r}_2|$, $\vec{u} = (\vec{p}, e^{-mr}/4\pi r)$, $\vec{v} = (\vec{p}, e^{-mr}/4\pi r)$, $\vec{p} = \vec{p}_1 - \vec{p}_2$, $\mu_v = 3.70$, and $\mu_s = -0.12$. We caution that a relative momentum equal to $\vec{p}/2$ appears frequently in the literature. The radial functions depend on the π and ρ masses, as indicated (we set $m_\omega = m_\rho$). The coupling coefficients in this meson-exchange potential are independent, apart from the constraint $K_1 = G_1 - F_1$. In this Letter we have taken numerical values for these coefficients from the realistic treatment of the Weinberg-Salam model of Ref. 6. The resulting coefficients are given in Table I. Despite the large uncertainties in the theoretical estimates of these coefficients,[6] we think use of these "best values" will provide a measure of our present understanding of the PNC *NN* interaction. Ultimately, of course, we would like to derive stringent bounds on these coefficients directly from experiment. In a more detailed publication[9] we will present matrix elements of $V_{\rm PNC}$ decomposed into the various terms in (4), thus helping to prepare the way for such a determination.

The key to our present effort is the use of state-of-the-art shell-model techniques to derive realistic nuclear wave functions for the positive and negative parity states in ^{18}F, ^{19}F, and ^{21}Ne. We treat these three nuclei on the same footing: Full $0\hbar\omega$ and $1\hbar\omega$ calculations were performed with exact projection of spuriosity using the Los Alamos Scientific Laboratory version[10] of the Glasgow shell-model code.[11] The matrix elements for the *sd* shell were taken from Kuo and Brown,[12] while we used the cross-shell *p-sd* and *sd-fp* interactions of Millener and Kurath[13] and Kuo,[14] respectively. The effects of short-range correlations are included by multiplying the shell-model two-particle wave functions by a correlation function $f(r) = 1 - \exp(-\alpha r^2)(1 - \beta r^2)$, with $\alpha = 1.1$ f^{-2} and $\beta = 0.68$ f^{-2}.[15] This simple procedure yields results remarkably similar to those obtained in more sophisticated treatments of correlations.[16] In Ref. 9 we will discuss this approximation and the wave-function tests we have made by calculating various electromagnetic transitions.

Our results are summarized in Table II. For ^{18}F we find $|P_\gamma| = (5.94^{+0.50}_{-0.62}) \times 10^{-3}$ with the errors reflecting experimental uncertainties in the lifetimes of the 1.04 and 1.08 MeV states. A previous calculation employing the Weinberg-Salam model and the factorization approximation had obtained a value for $|P_\gamma|$ of 5.7×10^{-3},[17] in good agreement with the result we have obtained. The $E1$ transition strength is so strongly hindered, the leading term being isospin forbidden, that we cannot provide the sign of P_γ; indeed, we believe that the most important contributions to this decay may come from small isospin impurities in the nuclear states. We predict a lifetime for the $0^+, 1$ level of 2.98 fs, in good agreement with the experimental value of $2.7^{+0.6}_{-0.4}$ fs,[8] encouraging some confidence in the wave functions.

To predict the asymmetry in ^{19}F we must calculate both the PNC matrix element and the magnetic moment of the $\frac{1}{2}^-$ state. We find $\mu(\frac{1}{2}^-) = -0.23$ and $|A_\gamma| = 2.62 \times 10^{-4}$. The calculated moment of the ground state, $\mu(\frac{1}{2}^+) = 2.87$, agrees well with the experimental value 2.63. The sign of A_γ is determined by that of $\langle \frac{1}{2}^+ || E1 || \frac{1}{2}^- \rangle$, which must be calculated. Though this transition is weak (1.2×10^{-3} Weisskopf units) the suppres-

TABLE II. Comparison of calculated P_γ and A_γ to experiment using the weak interaction couplings of Table I.

	$|\langle\|V_{\rm PNC}\|\rangle|$ (eV)	Theory (10^{-3})	Exp (10^{-3})
^{18}F	1.080	$|P_\gamma| = 5.94^{+0.50}_{-0.62}$	$P_\gamma = -0.7 \pm 2.0$
^{19}F	1.338	$A_\gamma = -0.262$	$A_\gamma = -0.085 \pm 0.0026$
^{21}Ne	0.018	$|P_\gamma| = 1.41^{+0.16}_{-0.17}$	$P_\gamma = 2.4 \pm 2.9$

sion is much less severe than in the cases of the regular transitions in ^{18}F and ^{21}Ne, where consequently calculations of the signs of the circular polarizations are not feasible. We find a negative A_γ, in agreement with experiment. We have repeated our calculation of $\langle||E1||\rangle$ for two additional sets of wave functions, which we describe elsewhere,[9] and each of these also yields a negative asymmetry. An additional check is provided by the calculated magnitude of $\langle||E1||\rangle$ of 1.7 times the experimental value. Previously, Box, Gabric, and McKellar found $A_\gamma = -3.1\times10^{-4}$ using the Weinberg-Salam model and the factorization approximation.[18]

To provide a value for $|P_\gamma|$ in ^{21}Ne we must determine δ_+ and δ_-. Our calculated value for $\delta_+ = i0.026$ is credible in view of the $\frac{1}{2}^+$ lifetime estimate of 4.6 fs, compared to the experimental result 7.9 ± 1.0 fs.[19] However, the extreme weakness of the $\frac{1}{2}^- \to \frac{3}{2}^+$ decay discourages any attempt to calculate δ_- or the sign of the $\langle\frac{3}{2}^+||E1||\frac{1}{2}^-\rangle$ matrix element. The most stringent constraint on theoretical estimates of $\langle|V_{\rm PNC}|\rangle$ is obtained by assuming $\delta_-^* = \delta_+$. $|P_\gamma|$ then depends only on the ratio of lifetimes and the PNC matrix element. We find $|P_\gamma| = (1.41^{+0.16}_{-0.17})\times10^{-3}$, a value well within the experiment bound. This result depends on a strong cancellation between the F_π and F_0 contributions to the PNC matrix element, which in turn depends on the stronger damping of the ρ-exchange term by correlations. This cancellation persists under modest changes in our wave functions, though projection of spuriosity is essential in obtaining reliable results.[9] Previously, Brandenburg, McKellar, and Morrison[20] and Millener *et al.*[21] concluded that the inclusion of weak neutral currents, which enhance the $T=1$ parity mixing, leads to $|P_\gamma| \gtrsim (2-3)\%$, in strong disagreement with experiment and with our calculation. This comparison underscores one of the most significant results of Ref. 6, the sign change with respect to the factorization approximation in the "best value" for the isoscalar ρ coupling, which leads to the cancellation discussed above.

In summary, we have completed a careful analysis of PNC in three light nuclei, ^{18}F, ^{19}F, and ^{21}Ne. We believe that our unified approach to these three nuclei will prove valuable in future attempts to determine weak interaction parameters directly from experiment. Using a recent set of "best values" for the PNC potential parameters in the Weinberg-Salam model, we have obtained values for the matrix elements of the PNC potential which appear too strong in the cases of ^{18}F and ^{19}F and yet which correctly yield the strong suppression found in ^{21}Ne. To a very good approximation the couplings that determine these matrix elements are simply F_π and F_0. Thus, in view of the cancellation occurring between these two terms in ^{21}Ne, we conclude that the "best values" of Ref. 6 correctly give the relative but not the absolute strengths of these couplings. Agreement between theory and experiment in these light nuclei would be excellent if we weaken the corresponding couplings of Ref. 6, f_π and h_ρ^0, by two-thirds to 4 and -10, respectively, where these are given in units of $g_\pi = 3.8\times10^{-8}$. We recommend that such couplings be used as a starting point in future investigations, and emphasize that these values still lie well within the broad "reasonable range" specified in Ref. 6. This choice of couplings indicates that P_γ in ^{18}F may be close to the present experimental upper limit, and thus should encourage attempts to sharpen this bound. In addition, we believe that possibilities for measuring the mixing ratios δ_- and δ_+ in ^{21}Ne and the magnetic moment of the $\frac{1}{2}^-$ level in ^{19}F should be thoroughly explored. Knowledge of these parameters will eliminate present uncertainties in relating calculated PNC matrix elements to A_γ and $|P_\gamma|$. Finally, in the one case we have considered where a realistic calculation of the sign of a PNC observable is possible, our treatment yields the observed negative asymmetry in ^{19}F.

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[a]Present address: Department of Physics, Purdue University, West Lafayette, Ind. 47907.

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Nuclear-Structure Effects on Parity Nonconservation in Light Nuclei

B. A. Brown, W. A. Richter, and N. S. Godwin

Nuclear Physics Laboratory, Oxford University, Oxford OX1 3RH, England

(Received 27 August 1980)

The nucleon-nucleon parity-nonconserving potentials given by Desplangues, Donoghue, and Holstein (DDH) are used to calculate matrix elements between states of opposite parity in ^{10}B, ^{16}O, ^{18}F, ^{19}F, ^{20}Ne, and ^{21}Ne. The sensitivity of the parity-nonconserving matrix elements to various approximations in the microscopic shell-model wave functions is investigated. The final results using the DDH estimates for the weak meson-nucleon coupling constants based on the Weinberg-Salam theory are several times larger than experiment.

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Gauge theories of weak interactions predict nonleptonic weak interactions between quarks which are manifest in the well-known strangeness-changing ($\Delta S = 1$) decays of hadrons. All observed $\Delta S = 1$ decays involve only charged weak currents but both charged and neutral weak currents are expected to contribute to $\Delta S = 0$ weak interactions. Nonleptonic $\Delta S = 0$ weak interactions give rise to parity mixing in the energy levels of hadrons and nuclei which can be experimentally investigated by measuring small parity nonconservation in their electromagnetic and strong decays.[1]

The investigation of parity nonconservation in the decay of light nuclei has been extensively pursued because fairly reliable many-body wave functions exist for those nuclei and because there are several situations where the mixing between particular low-lying levels gives rise to measurable effects.[1] A theoretical interpretation of these data is important for the extraction of $\Delta S = 0$ nonleptonic weak-interaction coupling constants.

In this paper we report on the results of the first systematic calculation of parity-nonconserving (PNC) matrix elements for light nuclei using microscopic nuclear wave functions. Our emphasis is on the reliability and sensitivity of the results to the approximations which must be made in order to construct shell-model wave functions with finite degrees of freedom. For the nucleon-nucleon weak interaction we use the PNC potential given by Desplanques, Donoghue, and Holstein[2] (DDH) in Eq. (115) of their paper together with the "best-value" parameters from Table VII of their paper (we have used $h_\rho'^{(1)}=0$). This potential is equivalent to most of the other PNC potentials which have been proposed.[1] Our matrix elements will be given as a sum of all terms in the DDH potential but we note that the isoscalar and isovector matrix elements are dominated by about a factor of 10 by the potential terms proportional to h_ρ^0 and f_π, respectively. More com-

