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Proposed new experimental case to investigate the weak parity nonconserving couplings in ^{20}F

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A new experiment to investigate the isospin sensitivity of the parity nonconserving (PNC) interaction in light nuclei is proposed. The observable is the PNC asymmetry for the emitted gamma rays from the 1^-1 state in ^{20}F ($E_x=0.983$ MeV) partially polarized in the reaction ^{22}Ne($\vec{d},\alpha_3$)^{20}F, which is predicted in the range $(2.4-5.8\ )\times 10^{-5}$. The structure parts of the components of the PNC matrix elements have been carefully calculated for the analysis of the experimental result in terms of the weak coupling constants. A new class of diagrams contributing to the PNC matrix elements has been included for the first time.

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Parity nonconserving (PNC) phenomena in purely hadronic processes are under increasing investigations from both theoretical and experimental points of view [1]. The calculation of the weak meson-nucleon coupling constants f_π, h_ρ^0, h_ρ^1, h_ρ^2, h_ω^0, h_ω^1 in different quark models (see Refs. [1,2,3,4], abbreviated as AH, DDH, DZ, and KM) indicate a relatively large range for these values. Moreover, the topological soliton model of Ref. [4] strongly suppresses the contribution of the weak neutral currents dominated by f_π. Such a controversy between different models stimulate the search for new reliable experimental cases in order to extract relevant information on the weak couplings. In light nuclei the PNC effects are enhanced for excitation energies, where two nearby levels of the same spin but opposite parties exist [parity mixed doublet (PMD)]. For this mass region the existing models of nuclear structure can reasonably describe the data and the accuracy of their results is increasing [1,13,22]. In special cases (e.g, the ^{18}F and ^{19}F), the PNC structure calculations can be normalized to other experimental investigations, like the first forbidden beta decay [1], processes sensitive to the same components of the wave function. Only a few experimental cases with nonzero results and small errors can be taken into consideration to extract the weak coupling constants for different isospin transfer: (i) the longitudinal analyzing power (A_z) in the $\vec{p}p$ [5] and $\vec{p}+\alpha$ [6] elastic scattering; (ii) the PNC asymmetry (A_γ^1) of the gamma rays emitted by the partially polarized $\frac{1}{2}^-$ state of the ^{19}F ($E_x=110$ keV) obtained in the reaction [7] ^{22}Ne($\vec{p},\alpha_1$)^{19}F. Two other possible cases are under investigation: the measurement of the longitudinal analyzing power in the ^{13}C($\vec{p},p$)^{13}C elastic scattering [8,9] and in the ^{15}N($\vec{p},\alpha_0$)^{12}C nuclear reaction [10]. In this paper another case for measuring the PNC asymmetry is proposed; the considered nucleus is ^{20}F with a PMD 1^-1, 1^+1 (see Fig. 1). It is similar to the ^{19}F case in both the analysis and concerning the expected result. The first excited state ($1/2^-$) of the ^{19}F nucleus can be polarized effectively ($\sim 70\%$) [1,7] by the transfer reaction ^{22}Ne($\vec{p},\alpha_1$)^{19}F, mainly because this reaction has a simple spin structure: $0+\frac{1}{2}\rightarrow\frac{1}{2}+0$. A similar reaction, ^{22}Ne($\vec{d},\alpha_3$)^{20}F, could be used to transfer the deuteron polarization to the first 1^-1 excited state in ^{20}F ($E_x=0.9837$ MeV), which forms a parity doublet with the nearby 1^+1 level, $E_x=1.0568$ MeV (see Fig. 1). The PNC observable is the forward-backward asymmetry of the emitted γ rays, $A_\gamma(\theta)$. A typical $e1,m1$ PNC mixing decay scheme is described in Ref. [1]. Using the standard formalism [11] it can be shown that

$$A_\gamma(\theta)\equiv\frac{W(\theta)-W(\pi-\theta)}{W(\theta)+W(\pi-\theta)}=2\frac{\langle V_{\rm PNC}\rangle}{\Delta E}\frac{m_1}{e^1}\left[\frac{E^-}{E^+}\right]^{3/2}$$
$$\times\frac{\sum_{\nu\,\rm odd}P_\nu(\cos\theta)B_\nu(I)\{F_\nu(11)+F_\nu(22)\delta_+\delta_-+F_\nu(12)(\delta_++\delta_-)\}}{1+\delta_-^2+\sum_{\nu\,\rm even>0}P_\nu(\cos\theta)B_\nu(I)\{F_\nu(11)+F_\nu(22)\delta_-^2+2F_\nu(12)\delta_-\}}\ , \tag{1}$$

where $\delta_+=e_2/m_1$ and $\delta_-=m_2/e_1$ are the mixing ratios, e_λ, m_λ are the multipolar electromagnetic transition amplitudes, F_ν are geometric coefficients defined in Ref. [11],

$$B_\nu=\sum_M\sqrt{2\nu+1}C^{I\ \nu I}_{M0M}p(M)\ , \tag{2}$$

$p(M)$ is the probability for the emitting state to have the spin projection M on the quantization axis defined by the polarization of the incident particles, I and I' represent the spin of the initial and final states respectively, and P_ν are the Legendre polynominals of the angle θ between the

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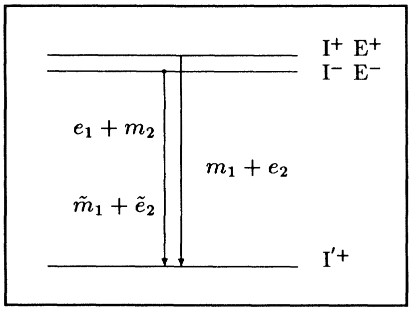

FIG. 1. Typical level scheme for an e_1, m_1 mixing doublet. The decay under observation is from the I^-E^- level and $\tilde{m}_1$, $\tilde{e}_2$ are parity forbidden electromagnetic amplitudes.

emitted photon and the quantization axis. The negative parity state must have a much longer lifetime as compared to the positive parity state (see Fig. 1) in order to obtain an amplification of the effect [1]. Equation (1) can be rewritten

$$A_\gamma(\theta) \equiv A_\gamma^1 R(\theta) , \tag{3}$$

where A_γ^1 is the PNC asymmetry, which is roughly equal to the PNC circular polarization P_γ^{PNC} for small mixing ratios. This quantity contains the PNC information and the PC part of it can be extracted from the regular data by

$$\left| \frac{A_\gamma^1}{\langle V_{\mathrm{PNC}} \rangle} \right| = \frac{2}{|E^+ - E^-|} \left[\frac{\tau_- b_+ (1+\delta_-^2)}{\tau_+ b_- (1+\delta_-^2)} \left[\frac{E^-}{E^+} \right]^3 \right]^{1/2} , \tag{4}$$

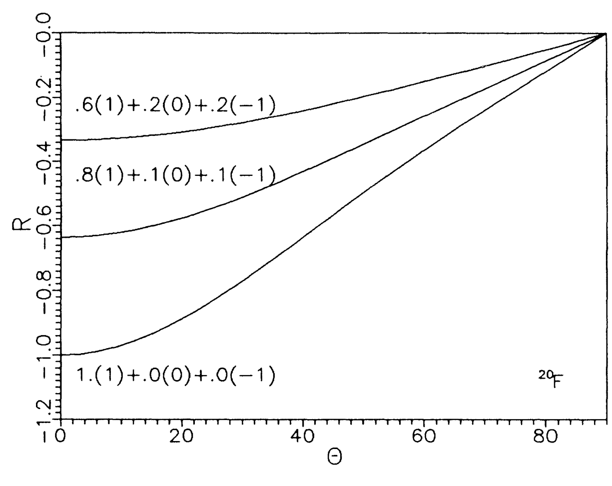

FIG. 2. Angle-dependent part R of the forward-backward asymmetry. The curves describe different M populations of the decaying 1^- state. In parenthesis are the M values and in front are the population probabilities $p(M)$.

where $E^\pm$, $\tau_\pm$, $b_\pm$ are the excitation energies, the lifetimes, and the branching ratios, respectively. The values obtained for this quantity are 1.92×10^{-4} and 1.64×10^{-4} eV^{-1} for ^{19}F and ^{20}F, respectively, when the experimental information from Ref. [12] is used (the small mixing ratio $\delta_- = -0.02$ for ^{20}F has been calculated). The coefficients B_ν in Eq. (1) contain all the information for the polarization probabilities $p(M)$. They can be extracted from the circular polarization which, for a partially polarized emitting state, is dominated by the parity conserving contribution [11]

$$P_\gamma^{\mathrm{PC}}(\theta) = \frac{\sum_{\nu\,\mathrm{odd}} P_\nu(\cos\theta) B_\nu(I) \{F_\nu(11) + F_\nu(22)\delta_-^2 + 2F_\nu(12)\delta_-\}}{1+\delta_-^2 + \sum_{\nu\,\mathrm{even}>0} P_\nu(\cos\theta) B_\nu(I) \{F_\nu(11) + F_\nu(22)\delta_-^2 + 2F_\nu(12)\delta_-\}} . \tag{5}$$

This expression is very similar to the angle-dependent part R of the forward-backward asymmetry [see Eqs. (1) and (3)]. In fact it is not necessary to extract the B_ν from the P_γ^{PC} data because for $\delta_+, \delta_- \ll 1$ one can approximate $R(\theta) \approx P_\gamma^{\mathrm{PC}}(\theta)$. The calculations of $R(\theta)$ for different combinations of the M state population for the 1^-1 state in ^{20}F are shown in Fig. 2. It can be concluded from the results in Fig. 2 that $P_\gamma^{\mathrm{PC}}(0°) \approx 0.4$ can be obtained from 50% polarization of this state. It also turns out that the angular distribution has a maximum at 0° and in particular

$$R(0°) \approx P_\gamma^{\mathrm{PC}}(0°) , \quad A_\gamma(0°) \approx A_\gamma^1 P_\gamma^{(\mathrm{PC})}(0°) . \tag{6}$$

In order to determine the magnitude of the PNC asymmetry A_γ^1, a shell model calculation of the PNC matrix element has been performed using the OXBASH code [14]. These calculations have been performed in the ZBM model space using the F and Z interactions (abbreviated as REWIL and ZWM, respectively) from Ref. [15]. There are two types of contributions to the PNC matrix element: one is from two-body transition densities (TBTD), if all four orbitals entering the two-body matrix elements (TBME) are in the valence space [13]; another one arises from the one-body transition densities (OBTD) [14], if two orbitals are in the core

$$\langle J^\pi T | V_{\mathrm{PNC}} | J^{-\pi} T' \rangle_{\mathrm{ob}} = \sum_{n_1 l_1 j_1, n_2 l_2 j_2, t} \frac{C_{M'\tau M}^{T' t T}}{\sqrt{(2J+1)(2T+1)}} \langle n_1 l_1 j_1 \| U_{\mathrm{s.p.}}^{(0t)} \| n_2 l_2 j_2 \rangle \mathrm{OBTD}((n_1 l_1 j_1)(n_2 l_2 j_2);0t) \tag{7}$$

TABLE I. Calculated PNC matrix elements for different weak coupling models and nuclear interaction models; (r) means rescaled.

Nuclear model	Nucleus	DDH	AH	DZ	KM	Adopt value	$10^5 A_\gamma^1$
		$\lvert\langle V_{\rm PNC}\rangle\rvert$ (eV)					
REWIL	^{19}F	1.35	0.86	0.78	0.41	0.38	−7.4
	^{20}F	1.28	0.80	0.70	0.36		
	$(r)^{20}$F	0.36	0.35	0.34	0.33	0.35	5.8
ZWM	^{19}F	1.49	0.94	0.83	0.43		
	^{20}F	1.04	0.64	0.55	0.27		
	$(r)^{20}$F	0.27	0.26	0.25	0.24	0.25	4.1

where the single particle (s.p.) PNC potential $U_{\rm s.p.}$ can be obtained as a Hartree-Fock (HF) trace of the two body PNC potential with the core s.p. density. The only contribution of this type in the ZBM model space comes from the $(1p_{1/2}2s_{1/2})$ one-body matrix element which turns out to be more than 60% from the total matrix element for all the discussed cases. The TBME have been calculated with harmonic oscillator wave functions ($\hbar\omega=13$ MeV is appropriate for $A=20$ [14]). Short range correlations have been implemented with the correlation function [16]:

$$g(r)=1-\exp[(-ar^2)(1-br^2)]\ , \tag{8}$$

$a=1.1$ fm^{-2}, $b=0.68$ fm^{-2}, which give similar results with a much more elaborated treatment [17]. This procedure results in a suppression of the pion exchange matrix element by 20%–30% and a decrease for ρ and ω exchange by a factor of 3–4.

In Table I the PNC matrix elements for ^{19}F and ^{20}F are analyzed in terms of the same weak coupling models as in Ref. [8]. The experimentally extracted value [1,7] is indicated on the first row of the column "adopt value." A rescaling procedure to this experimental value has been performed for every weak couplings model and every nuclear structure model. Based on the REWIL calculations, a 0.35 eV PNC matrix element can be safely predicted for the parity mixed states in ^{20}F. For the analysis of the experimental result it is useful to express the PNC asymmetry in terms the weak coupling constants [1,7]

$$A_\gamma^1=C_\pi f_\pi+C_\rho^0h_\rho^0+C_\omega^0h_\omega^0+C_\omega^1h_\omega^1+C_\rho^1h_\rho^1+C_\rho^2h_\rho^2\ , \tag{9}$$

where the C coefficients are presented in Table II. The values of these coefficients are based on a rescaling of the DDH PNC matrix element for ^{19}F to the 0.46 eV value calculated in Ref. [1]. The 0.46 eV value has been obtained by normalization of the calculated results for the first forbidden beta decay of the ^{19}Ne (whose structure part are similar to the PNC calculations) to the corresponding experimental value. Unfortunately, a similar beta decay does not exist for the ^{20}F case and a direct normalization is not possible.

The effects of other possible corrections have been carefully checked. Due to the derivative structure of the PNC interaction [2,1] sensible modification of the PNC matrix elements are expected when Woods-Saxon (WS) wave functions instead of harmonic oscillator wave functions (w.f.) are used. These effects have been checked with approximate WS w.f. obtained after a diagonalization of the WS single particle potential in the harmonic oscillator (h.o.) basis [18]. For the WS s.p. potential the neutron parametrization of Ref. [19] has been used. The removal of the spurious components of the shell model wave function due to center of mass (c.m.) motion was also taken into account with an approximate procedure described in Ref. [20]. The WS procedure being very time consuming, the calculations have been restricted to two components of the PNC potential, which contributes more than 80% to the PNC matrix element: V_π is the one pion exchange contribution to the isovector part [8] of the $V_{\rm PNC}$ and V'_ρ is the main contribution to the isoscalar [proportional to $h_\rho^0(1+\mu_v)$ [1]] part. In the calculations the sum on the h.p. basis has been restricted to 7 major shells. In this sense, a large scale shell model calculation has been performed with the result that these corrections are rather small and uniform, as can be extracted from Table III. The total (WS+c.m.) corrections are 14% for ^{19}F and 13% for ^{20}F; they do not affect the final result, if the rescaling procedure is used.

Recently, a new class of diagrams has been introduced [21] as a one-body contribution to the PNC matrix element. Their actual form from Ref. [21] is not yet very useful due to the fact that the hard core effect has not been included in the intermediate states, between which the bosons are exchanged (see Fig. 5(c) from Ref. [21]).

TABLE II. Structure coefficients entering Eq. (9). The strong coupling constants considered have been taken from DDH and AH calculations.

	C_π	C_ρ^0	C_ω^0	C_ω^1	C_ρ^1	C_ρ^2
REWIL	89.67	−23.5	−14.7	−13.7	−8.38	0.32
ZWM	69.6	−15.7	−10.0	−10.5	−13.7	−0.78

TABLE III. Modifications of the largest contributions to the DDH PNC matrix element (bare) due to the (WS) wave functions and due to WS and center-of-mass spuriousity removal (WS+c.m.).

	Bare			WS			WS+c.m.		
	V_π	V'_ρ	V'_{tot}	V_π	V'_ρ	V'_{tot}	V_π	V'_ρ	V'_{tot}
^{19}F	0.69	0.56	1.25	0.66	0.54	1.20	0.65	0.42	1.07
^{20}F	0.73	0.47	1.19	0.69	0.42	1.10	0.67	0.37	1.04

One can approximate this effect using the decreasing factors obtained for the two-body PNC potential [see comments after Eq. (8)]. Another possibility is to use an approximate correlation function

$$\tilde{g} \approx 1-\exp(-\tilde{a}r)\ , \quad \tilde{a}=1.6\,\text{fm}^{-1}\ . \tag{10}$$

Multiplying the meson propagator with $\tilde{g}^2$ and having in mind the derivative action of the meson propagator for PNC processes one can replace the α constants in Eqs. (3.6), (3.14), and (3.20) from Ref. [21] by

$$\tilde{\alpha}_i=\alpha_i(m_i)-\frac{2m_i}{m_i+\tilde{a}}\alpha_i(m_i+\tilde{a})+\frac{m_i}{m_i+2\tilde{a}}\alpha_i(m_i+2\tilde{a})\ , \quad i=\pi,\rho,\omega\ . \tag{11}$$

The explicit calculations give $\tilde{\alpha}_\pi=0.2437$, $\tilde{\alpha}_\rho=-0.1699$, $\tilde{\alpha}_\omega=-0.1337$. Their decrease, when compared with the corresponding values from Ref. [21], is in very good agreement with the two-body PNC results obtained with a realistic correlation function [see Eq. (8) and the comments after it]. The contribution of the new class of diagrams calculated using Eq. (9), Eq. (2.17) from Ref. [21], and the neutron WS parametrization from Ref. [19] is additive to the PNC matrix element. The π contribution is less than 4% and the ρ and ω are 9–10 %. These results can be summarized as

$$A_\gamma^1(^{19}\text{F})=-104.3f_\pi+35.3h_\rho^0+21.2h_\omega^0+18.3h_\omega^1\ , \tag{12}$$

$$A_\gamma^1(^{20}\text{F})=93.7f_\pi-25.4h_\rho^0-15.9h_\omega^0-15.h_\omega^1\ . \tag{13}$$

They can be further used to analyze the eventual successful ^{20}F results in terms of the weak coupling constants. The accuracy of this analysis could be further improved with the new *s-p-sd-fp* interaction in preparation at Michigan State University [22].

The prediction of the measured forward-backward asymmetry is rather difficult, because it must be based on the mechanism of the polarization transfer reactions, which is poorly known. The ^{22}Ne$(d,\alpha_3)^{20}$F reaction can be observed for small deuteron energies ($Q_3=1.72$ MeV [12]) and with relatively high yields ($\sigma\approx 5$ mb for $E_d=2$ MeV [23]). Moreover, the angular distribution in Fig. 3 from Ref. [23] indicate that relative waves up to $l=1$ are mainly contributing. However, this kinematical information is not enough to predict the magnitude of the P_γ^{PC}. Dynamical information is necessary to know how much of the p wave contribution is in the entrance channel as compared with the exit channel. A larger p wave contribution in the entrance channel could indicate a large s wave contribution in the exit channel leading to a large polarization transfer as in the ^{19}F case.

Based on this experiment information and on the results in Fig. 2 one can expect values between 20 and 50 % for the $P_\gamma^{(\text{PC})}(0°)$ in the proposed polarization transfer reaction. The experimental asymmetry [Eq. (6)] is expected to be in the range $(1.2\text{–}2.9)\times10^{-5}$; this is within the limits of accuracy for the actual experimental setup [1,7].

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