$0^+ \to 0^-$ β^+ Decay of ^{18}Ne and the Determination of F_π

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The β^+ branch of ^{18}Ne to the 1081-keV $J^\pi = 0^-$, $I = 0$ level of ^{18}F is observed to have an intensity of $(1.71 \pm 0.41)\times 10^{-4}$ times that of the superallowed Fermi transition to the 1042-keV $J^\pi = 0^+$, $I = 1$ level. This result plus the previously measured upper limit on parity mixing in the $0^+, 0^-$ doublet of ^{18}F yields an upper limit of $\pm(0.5 \pm 1.3)\times 10^{-6}$ for F_π. This limit is largely independent of details of nuclear structure.

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It has been recognized for several years that pion exchange should play a large and calculable role in A_0, the time component of the nuclear axial current.[1,2] The effects will be especially large in $0^+ \to 0^-$ β decays where the one-body (impulse) contributions to A_0 are suppressed, being proportional to $\vec{\sigma}\cdot\vec{v}/c$ and $\vec{\sigma}\cdot\hat{r}k$. Both v (the nucleon velocity) and k (the momentum transferred to the leptons) are small in β decay. On the other hand, the π-exchange contribution to A_0 is not similarly suppressed since the π carries off the same quantum numbers ($\Delta J^\pi = 0^-$; $\Delta I = 1$) that A_0 brings in. Unfortunately, very little is known experimentally about $0^+ \rightleftharpoons 0^-$ β decay. The β decay[3] of ^{16}N^m is the only example in a light, well-understood nucleus.

In this Letter we describe a measurement of the decay rate of ^{18}Ne ($J^\pi = 0^+$, $I = 1$) to the 1081-keV ($J^\pi = 0^-$, $I = 0$) level of ^{18}F. This decay is particularly interesting for the following reasons:

(1) It is one of the rare cases of a $0^+ \to 0^-$ transition in a theoretically tractable nuclear system. Shell-model wave functions (see Haxton[4]) predict that pion-exchange currents increase the β-decay rate by a factor of approximately 2.5 compared with the impulse current alone.

(2) To the extent that exchange currents are important, knowledge of this β^+-decay rate removes most of the nuclear structure uncertainties in extracting F_π, the weak parity-nonconserving (PNC) πNN vertex.

The $\pi^\pm$-exchange component of the PNC NN force is pure $\Delta I = 1$. The most sensitive existing measurement of this force[5] examined parity mixing of the 1042-keV ($J^\pi = 0^+, I = 1$) and 1081-keV levels of ^{18}F. The $0^+ \to 0^-$ decay of ^{18}Ne connects these same levels (assuming isospin symmetry). Moreover the π-exchange contribution to the β^+-decay rate and the π-exchange contribution to the parity mixing have *identical* dependence on the nuclear coordinates.[4,6] The $0^+ \to 0^-$ $\beta^\pm$-decay exchange-current operator is

$$M_{\beta^\pm}{}^{(2)} = \mp i\left(\frac{m_\pi}{M_N}\right)^2 \frac{g^2}{4\pi}\frac{1}{2F_A}\frac{1}{2}\sum_{i\neq j}\left[\tau_i \otimes \tau_j\right]_{1,\pm 1}(\vec{\sigma}_i + \vec{\sigma}_j)\cdot\vec{r}_{ij}\,\varphi_\pi(r_{ij}),$$

while the $\pi^\pm$-exchange parity-mixing operator is

$$H_{\rm PNC} = iF_\pi\left(\frac{m_\pi{}^2}{M_N}\right)\frac{1}{\pi\sqrt{2}}\,\frac{1}{2}\sum_{i\neq j}\left[\tau_i \otimes \tau_j\right]_{1,0}(\vec{\sigma}_i + \vec{\sigma}_j)\cdot\vec{r}_{ij}\,\varphi_\pi(r_{ij})$$

(see Ref. 4). In these expressions,

$$\varphi_\pi(r_{ij}) = [\exp(-m_\pi r_{ij})/m_\pi r_{ij}](1 + 1/m_\pi r_{ij}),$$

g is the strong πNN coupling constant and $F_A = -1.23$.

F_π (the strength of the PNC π-exchange NN interaction) is poorly determined by existing data and analyses. The measured[5] circular polarization of the 1081-keV γ ray, $P_\gamma = (-0.7 \pm 2.0)\times 10^{-3}$, yields a value $|\langle 0^-|H_{\rm PNC}|0^+\rangle| = 0.13 \pm 0.36$ eV. $|F_\pi|$ has been inferred from this measured matrix element by relying on shell-model calculations of the nuclear wave functions. However, to the extent that $\alpha \equiv M_\beta{}^{(2)}/M_\beta{}^{(1)}$ (the ratio of the two-body to the one-body β-decay matrix elements) is known, $|F_\pi|$ can be obtained from P_γ and the β-decay rate ω in a way which is otherwise *completely independent* of the nuclear wave functions, i.e., $F_\pi = K[(\alpha+1)/\alpha]P_\gamma\sqrt{\omega}$, where K is a constant containing kinematic factors and known quantities such as F_A and g. We return to this point below.

We produced ^{18}Ne activity by bombarding natural O$_2$ gas with 12-MeV ^{3}He ions. The irradiated gas was transferred from the bombardment cell to a Lucite chamber placed in a heavily shielded counting station. β-delayed γ rays were

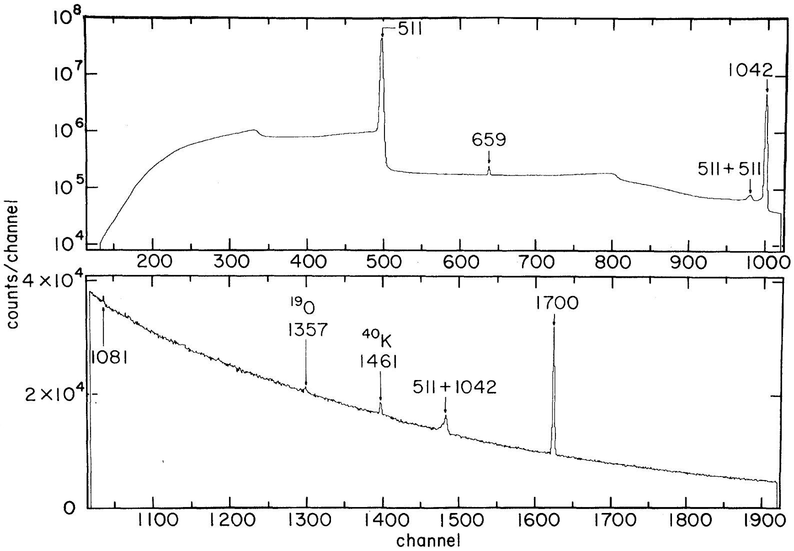

FIG. 1. Spectrum of γ rays following ^{18}Ne β^+ decays. This is a sum of data taken with two different detectors in order to improve statistics.

counted for 1.70 sec, beginning 0.10 sec, after each bombardment ended. γ rays were detected in Ge(Li) detectors equipped with pileup-rejection circuitry. The γ-ray spectrum was "hardened" by 1.27-cm-thick Pb absorbers placed in front of the detector. Our gas-transfer system, which operated on a 2.00-sec cycle, is similar to those described in Refs. 6 and 7. Contaminant activities, principally ^{18}F, ^{17}F, and ^{15}O produced by the reactions ^{16}O(^{3}He,p), ^{16}O(^{3}He, d), and ^{16}O(^{3}He, α), respectively, were largely removed by three liquid-nitrogen traps, one of which was filled with a molecular sieve material. By multiscaling the γ rays we determined that the dominant background activity was ^{18}F produced by ^{18}Ne decays within the counting chamber. In addition, a small amount of ^{15}O was transmitted through the traps.

A composite spectrum of γ rays taken with two different detectors is shown in Fig. 1. Previously observed γ rays of 511, 659, 1042, and 1700 keV are prominent. Low-intensity peaks (see Fig. 2, also), present in data taken with each detector separately, are observed at 1080.6 ±0.3, 1357, and 1461 keV. Sliding pulser spectra ruled out any possibility that the 1081-keV peak was due to differential nonlinearity in the analog-to-digital converter. We ascribe the 1357-keV peak to decays of ^{19}O produced in the reaction ^{18}O(^{3}He, 2p). In a subsidiary measurement with the gas-transfer system operating on an 80-sec cycle, we determined that the 1357-keV peak had a decay half-life of approximately 26 sec, in good agreement with the ^{19}O value of 26.8 sec. The 1461-keV peak arises from the ^{40}K background in the room. We conclude that the 1081-keV peak is from ^{18}Ne decay since its measured energy is in

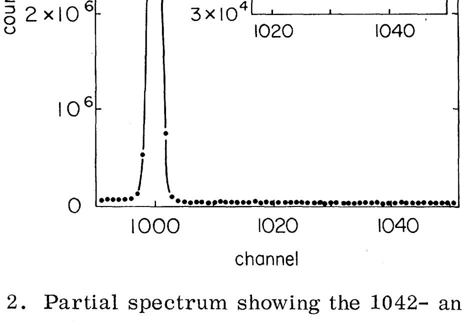

FIG. 2. Partial spectrum showing the 1042- and 1081-keV lines. The smooth curves are Gaussian peaks fitted to the data. The width of the 1081-keV peak was constrained to be identical to that of the 1042-keV line.

excellent agreement with the accepted value of 1080.5 ± 0.1 keV for the corresponding ^{18}F transition.

The relative efficiencies of our Ge(Li) detectors plus "hardeners" were measured with use of known decays[8] of ^{56}Co and ^{207}Bi sources. Relative intensities of the 659-, 1042-, 1081-, and 1700-keV γ rays are 1.75 ± 0.05, 100.0, $(1.92 \pm 0.32) \times 10^{-2}$, and 0.680 ± 0.011, respectively. These intensities (except for the previously unobserved 1081-keV γ ray) are in good agreement with the lower-statistics results of Hardy *et al.*[9] and of Yoshizawa *et al.*[10] In addition, our value $R = \Gamma(1700\text{-keV level} \to \text{g.s.})/\Gamma(1700\text{-keV level} \to \text{all}) = 0.280 \pm 0.007$ is in good agreement with the value $R = 0.298 \pm 0.013$ presented by Rolfs *et al.*[11] The weak 1081-keV γ ray cannot be due to deexcitation of the 1700-keV level via the 1081-keV level since[11] $\Gamma(1700\text{-keV level} \to 1081\text{-keV level})/\Gamma(1700\text{-keV level} \to \text{all}) < 2 \times 10^{-3}$. Therefore β^+ feeding of the 1700-keV level can account for at most 546 of the observed 2156 ± 355 counts in the 1081-keV peak. We assume that 273 ± 273 of the 2156 counts arise from decays of the 1700-keV level and ascribe the remaining 1883 ± 448 counts to direct feeding of the 1081-keV level in ^{18}Ne decay.

The resulting ^{18}Ne decay branching ratios (normalized to 100 for the superallowed transition to the 1042-keV level) are 100.0, $(1.71 \pm 0.41) \times 10^{-2}$, and 2.47 ± 0.05 for transitions to the 1042-, 1081-, and 1700-keV levels, respectively. Assuming that the superallowed Fermi transition has a partial half-life of 22.00 ± 0.61 sec and an ft value of 2977 ± 87 sec,[7] we obtain a partial half-life of $(1.29 \pm 0.31) \times 10^5$ sec and $ft = (1.60 \pm 0.39) \times 10^7$ sec for the $0^+ \to 0^-$ transition. We have computed f, assuming an allowed β- spectrum shape, which is reasonable since the matrix elements of the π exchange and the $\vec{\sigma} \cdot \vec{v}/c$ one-body currents are both independent of the momentum transferred to the leptons. In what follows we neglect all terms (they are small) which are momentum-transfer dependent. For a more complete discussion including the k dependence, see Ref. 4.

Now we turn to some implications of our result. In the following paper, Haxton[4] calculates the β^+-decay rate expected with use of the wave functions employed in a recent analysis[12] of the PNC circular polarization in ^{18}F. His predicted rate, $\omega_{\text{theor}} = 7.5 \times 10^{-5}$ sec^{-1}, is appreciably faster than our measured value, $\omega_{\text{expt}} = (5.4 \pm 1.3) \times 10^{-6}$ sec^{-1}. Similar disagreement would occur with other calculations[12] of the parity mixing in ^{18}F. Reasons for this deficiency are given in Ref. 4, along with a more realistic shell-model calculation, $\omega_{\text{theor}} = 4.8 \times 10^{-6}$ sec^{-1}, which is in much better agreement with experiment. To what extent should one expect similar problems in the calculation of parity mixing in ^{16}O, ^{19}F, and ^{21}Ne? Our result indicates that the predictions in these other systems must be reexamined and, wherever possible, subjected to independent experimental tests such as the one which we report here.

Haxton[4] argues that, although the absolute ^{18}Ne $0^+ \to 0^-$ β^+-decay rate $\omega_{\text{theor}} \propto |M_\beta^{(1)} + M_\beta^{(2)}|^2$ is sensitive to the shell-model configurations of the nuclear states, the ratio $\alpha = M_\beta^{(2)}/M_\beta^{(1)} \approx +0.67$ is not. If so, we can deduce $M_\beta^{(2)}$ from ω_{expt}. The expressions for H_{PNC} and $M_\beta^{(2)}$ given above yield

$$F_\pi = \frac{\langle 0^- | H_{\text{PNC}} | 0^+ \rangle}{M_N} \, \frac{\alpha + 1}{\alpha} \, \frac{g^2}{4\pi} \, \frac{\pi}{2F_A} \left[\frac{(ft)_{0^+ \to 0^-}}{(ft)_{0^+ \to 0^+}} \right]^{1/2}.$$

Inserting the values for $|\langle 0^- | H_{\text{PNC}} | 0^+ \rangle|$ and $(ft)_{0^+ \to 0^-}$ obtained from Ref. 5 and this work, respectively, and assuming that $\alpha \approx 0.67$, we find that $\pm F_\pi = (0.5 \pm 1.3) \times 10^{-6}$. This is quite consistent with the "best value," $F_\pi = 1.08 \times 10^{-6}$, deduced from an analysis[13] of hyperon decays with use of the Weinberg-Salam model of the weak interaction, and $[\text{SU}(6)]_W$ and the quark model of hadron structure. If we "correct" the prediction[12] for $P_\gamma(1081)$ by the factor $(\omega_{\text{expt}}/\omega_{\text{theor}})^{1/2}$, we obtain $|P_{\gamma\ \text{theor}}(1081)| = 1.6 \times 10^{-3}$. Therefore a modest improvement in the experimental error of $P_\gamma(1081)$ may produce a detectable effect and permit us to measure F_π in a manner remarkably free of uncertainties due to nuclear structure.

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Parity Nonconservation in ^{18}F and Meson-Exchange Contributions to the Axial Charge Operator

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A simple relationship between the one-body and exchange-current contributions to the axial charge operator may allow a separation of these amplitudes in the β-decay transition $^{18}\mathrm{Ne}(J^\pi I = 0^+1) \to {}^{18}\mathrm{F}(J^\pi I = 0^-0)$. Since the exchange-current operator is related by isospin rotation to the pion-exchange component of the parity-nonconserving nucleon-nucleon potential, this suggests that the parity-nonconserving pion coupling can be extracted, with minimal dependence on nuclear models, from circular-polarization measurements for the analog γ decay in ^{18}F.

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Strong arguments have been made for the importance, in the study of exchange currents in nuclei, of transitions between $J^\pi = 0^+$ and 0^- states. First, because of the weakness of "background" terms involving isobars and heavy mesons, soft-pion theorems provide a model-independent description of the leading exchange-current contribution to the axial charge operator.[1] Second, the range of the resulting pionic currents is sufficient so that conventional nuclear physics treatments, with the effects of short-range correlations included perturbatively, should be adequate. And third, since the single-nucleon contribution to the axial charge operator enters only in order $(\vec{p}/M)$, the exchange-current influence on observed $0^+ \to 0^-$ β decay and muon-capture rates can be unusually large.

In this Letter, I consider the β decay of the $J^\pi T = 0^+1$ ground state of ^{18}Ne leading to the 0^-0 1.08-MeV state in ^{18}F. A great deal of effort has been expended in searching for this weak-decay branch,[2] culminating in the measurement of Adelberger *et al.* reported in the preceding Letter.[3] The reason for this strong interest is that the dominant amplitude responsible for the parity-nonconserving (PNC) mixing of the 0^-0 and analog 0^+1 (1.04-MeV) levels in ^{18}F is related to the exchange-current contribution to the β-decay operator by isospin rotation. Thus, on the simplest level, this β-decay branch provides an important test of nuclear wave functions used in estimating PNC effects in ^{18}F. Wave functions used in recent calculations[4,5] fail this test for reasons that will be clarified in this Letter. More importantly, a simple relationship depending only on gross features of the nucleus is shown to exist between the strengths of the leading term in the one-body β-decay amplitude and the exchange current. The reported measurement[3] thus provides a direct estimate of the PNC potential matrix element. A constraint on the PNC pion coupling independent of nuclear models then follows from the current upper limit on the γ-ray circular polarization in ^{18}F.

The differential rate for a nucleus to β-decay via a $0^+ \to 0^-$ transition is determined by multipole matrix elements of the axial charge and longitudinal current operators.[6] These multipole