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Demonstration of the Need for Meson Exchange Currents in the Beta Decay of $^{16}N(0^-)$

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The $^{16}N(0^-, 120\text{ keV}) \rightarrow {}^{16}O(0^+, \text{g.s.}) + e^- + \bar{\nu}_e$ beta decay rate is remeasured. The present result, $\Lambda_\beta = 0.41 \pm 0.06\text{ sec}^{-1}$, agrees with recent realistic calculations of this rate only when pion exchange currents are included in the axial-vector time component. The impulse approximation underestimates this rate by more than a factor of 3. This result may be combined with the muon capture rate for the inverse reaction to obtain $g_P/g_A = 10 \pm 2.5$.

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No nuclear decay has attracted as much theoretical attention over the past few years[1-10] as the beta decay of the 120-keV, $J^\pi = 0^-$ first excited state of ^{16}N:

$$^{16}N(0^-, 120\text{ keV}) \rightarrow {}^{16}O(0^+, \text{g.s.}) + e^- + \bar{\nu}_e. \quad (1)$$

This beta decay is expected[10] to receive a large enhancement from meson exchange effects and its rate may be combined[11] with the measured muon capture rate on ^{16}O to determine the induced pseudoscalar coupling constant g_P in finite nuclei. The large role to be played by meson exchange currents was first noted by Kubodera, Delorme, and Rho.[10] They pointed out that the time component of the axial-vector–current $\bar{N}N$ vertex is $O(p/M)$, while that of the $\bar{N}N\pi$ vertex is $O(1)$. Thus, in $0^- \leftrightarrow 0^+$ transitions, where the time component dominates, the two-body, pion-exchange matrix element is expected to be comparable to the one-body matrix element. Recent detailed calculations by Towner and Khanna[8] (TK) confirm this expectation. They find that pion-exchange contributions enhance the beta decay rate by a factor of ~ 4. It has long been known that the muon capture rate between 0^+ and 0^- states is particularly sensitive to g_P. This has prompted several measurements[12] of the partial muon capture rate Λ_μ:

$$\mu^- + {}^{16}O(0^+, \text{g.s.}) \rightarrow {}^{16}N(0^-, 120\text{ keV}) + \nu_\mu. \quad (2)$$

Maksymowicz[11] noted that analyzing Λ_μ to determine g_P requires detailed understanding of nuclear structure effects in the $A = 16$ system, while the ratio $\Lambda_\mu/\Lambda_\beta$ of the muon capture rate to the beta decay rate in the inverse reaction provides a measure of g_P that is less sensitive to nuclear structure uncertainties.

The only measurement of Λ_β to date was carried out by Palffy *et al.*[13] They found[14] $\Lambda_\beta = 0.46 \pm 0.10\text{ sec}^{-1}$. The result is suggestive of the important role of meson exchange currents, but the large experimental uncertainty and the lack of confirmation reduce one's confidence in this conclusion. We have remeasured Λ_β in order to resolve these issues.

Figure 1 shows the various levels[15] involved in the beta decay of low-lying levels of ^{16}N. Because of strong competition from the normal $E2$ γ decay of the 120-keV state, its beta-decay branching ratio R_β is very small ($R_\beta \sim 3 \times 10^{-6}$). The 0^- beta-decay signal must be extracted from the large background inevitably present from ^{16}N

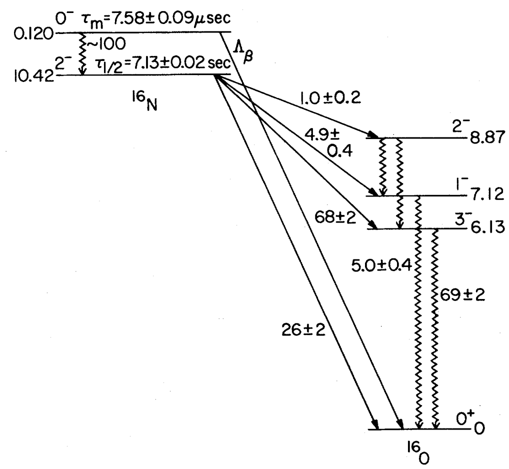

FIG. 1. The levels and transitions of the $A = 16$ system relevant to ^{16}N beta decay. The branching ratios listed are per disintegration and include the effects of cascades from higher levels.

ground-state beta decays. The lifetime of the 0^- state provides a characteristic signature for β rays emitted in the $0^- \rightarrow 0^+$ transition. The background intensity is minimized by changing the target continuously to minimize the effects of ^{16}N buildup. The electron energy threshold is placed beyond the end point for $^{16}N(2^-) \rightarrow {}^{16}O(3^-)$ decays for three reasons: (1) An analytic expression may be obtained for the background shape. (2) Electrons from the allowed decay $^{16}N(0^-) \rightarrow {}^{16}O(1^-)$ will not be incorrectly assigned to ground-state decays. (3) The $^{16}N(2^-)$ background is suppressed by an additional factor of 4.

The ^{16}N activity is produced in the reaction $^{15}N(d,p)^{16}N$, utilizing a 30-μA, 3.4-MeV D_2^+ beam from the Argonne National Laboratory dynamitron. The target consists of $^{15}NH_4{}^{15}NO_3$, enriched to 99% ^{15}N, melted into eight concentric circular grooves, 6.4 mm wide by 1.6 mm deep, cut in a 50-cm-diam by 3.2-mm-thick aluminum disk. The disk is rotated continuously at a rate of 3 Hz. The deuteron beam is pulsed onto the target for 10 μsec, after which time it is electrostatically deflected onto a collimator located outside the target room. A 63-μsec-long counting period follows, during which time β and γ rays from ^{16}N decays are separately multiscaled. β rays are detected with a telescope consisting of four thin plastic scintillators operated in coincidence. Beryllium inserted between the second and third scintillators ranges out all electrons except those from decays to the ^{16}O ground state. The 120-keV γ rays are detected with a Ge(Li) detector. The motion of the target during the bombardment and counting periods has a negligible effect upon the beta and gamma detector efficiencies. After the counting period, the target rotates 1.2 cm before the next bombardment begins. This guarantees that the previous beam spot is outside the beta telescope solid angle, reducing the background due to ^{16}N ground-state decays. The cycle is repeated until the target has undergone one complete revolution. The target disk is moved to bring the next groove into the deuteron beam and the process repeats. After all eight grooves have been measured, the target returns to its original position and a new circuit begins. A full circuit requires 17 sec, allowing the ^{16}N produced at a particular target location to decay away before that section is reused.

The beta detector efficiency is calibrated by observing ^{16}N ground-state decays with the wheel stopped. A 10-cm-diam by 10-cm-thick NaI detector, whose efficiency has been measured to 3.0% with the reaction $^{19}F(p,\alpha)^{16}O(3^-)$, observes 6.13-MeV γ rays from $^{16}N(2^-)$ decays to $^{16}O(3^-, 2^-)$, while the thin scintillators observe electrons from decays to $^{16}O(0^+, \text{g.s.})$. The detector efficiency is thus determined from the known beta-decay branching ratios of the $^{16}N(2^-)$ decay. A small correction is applied for the different spectrum shapes and end points in the $2^- \rightarrow 0^+$ and $0^- \rightarrow 0^+$ decays. The detector calibration will be discussed at greater length in a later publication. The efficiency of the Ge(Li) detector for 120-keV γ rays is determined with calibrated radioactive sources.

Figure 2 shows the measured beta rate as a function of time. A three-parameter fit to the data of the form $A\exp(-t/\tau_m) + C$ gives a mean life $\tau_m = 7.98 \pm 0.93$ μsec, in good agreement with the accepted value. A two-parameter fit, with the mean life fixed at 7.58 μsec, finds 638 ± 43 0^- counts, with a $\chi^2 = 51$ for 58 degrees of freedom. The observed signal-to-background ratio is consistent with that expected if the only source of background is due to the ^{16}N ground-state beta decay. It is important to note that this background is not time independent. Nearly 30% of the ^{16}N present at the end of the counting period is in the 0^- state at the beginning of the counting period. These ^{16}N nuclei must undergo gamma decay before they may contribute to the background rate. Therefore, the ^{16}N ground-state intensity during the counting period actually has the form

$$N(2^-) = B_2 + B_0(1 - e^{-t/(7.58\ \mu\text{sec})}). \quad (3)$$

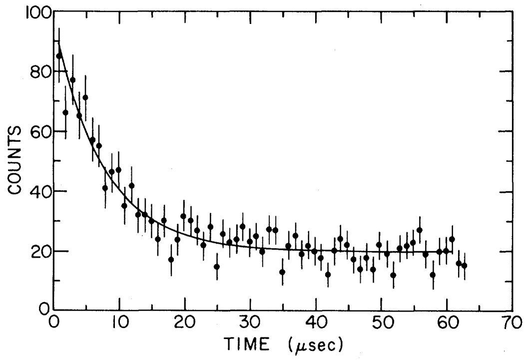

FIG. 2. The observed beta-decay rate as a function of time. The smooth curve is a fit of the form $A\exp(-t/\tau_m)+C$, with $\tau_m=7.58$ μsec ($\chi^2=51$ for 58 degrees of freedom). The background is consistent with the rate expected from ^{16}N ground-state beta decays.

Because the signal and background lifetimes are the same, the fitted form used is correct, but the apparent number of 0^- electrons found by the fit is less than the true number. The true 0^- beta-decay branching ratio is larger than the "measured" value by an amount

$$\Delta R_\beta = R(2^-\to 0^+)\frac{\lambda_{2^-}}{\lambda_{0^-}}\frac{\epsilon(2^-\to 0^+)}{\epsilon(0^-\to 0^+)}, \quad = (0.19\pm 0.02)\times 10^{-6}, \tag{4}$$

where R stands for the branching ratio and ϵ for the detector efficiencies for the detectors indicated. This expression is more complex, with much greater uncertainty, if an electron energy threshold that admits $^{16}N(2^-)$ decays to excited states is used. Tests with a $^{14}NH_4{}^{14}NO_3$ target confirm that all other background sources are time independent.

We find $R_\beta=(3.13\pm0.43)\times10^{-6}$, and $\Lambda_\beta=(0.41\pm0.06)$ sec^{-1}, in good agreement with the previous result. The uncertainty in the ^{16}N ground-state beta-decay branching ratios used in the beta telescope calibration dominates the error, contributing 0.29×10^{-6}. The calibration procedure of Palffy *et al.* was similar to ours, and so this uncertainty is common to the two measurements. The present measurement actually represents a factor of 3 reduction of the independent error sources and, thus, supersedes the previous one. A measurement to determine R_β to better than 5% is under consideration by the authors.

Figure 3 shows the experimentally allowed regions for Λ_μ and Λ_β along with recent calculations of these quantities by TK. The calculations differ from earlier ones in that a complete two-particle, two-hole basis is used for the ^{16}O ground state and Λ_μ and Λ_β are calculated separately, rather than only calculating $\Lambda_\mu/\Lambda_\beta$. It can be seen that the impulse-approximation calculations underestimate Λ_β by at least a factor of 3, independent of the choice of residual interaction used to fix the nuclear wave functions. By contrast, the calculations with meson exchange effects included reproduce the magnitude of Λ_β and, in one case, the one-boson-exchange potential model of TK, obtain quantitative agreement. Meson exchange currents have also proven necessary to obtain agreement with measurements of the axial-vector time component in the $A=12$ system.[16,17] These researches confirm the important role of pion exchange as prescribed by Kubodera, Delorme, and Rho.[10]

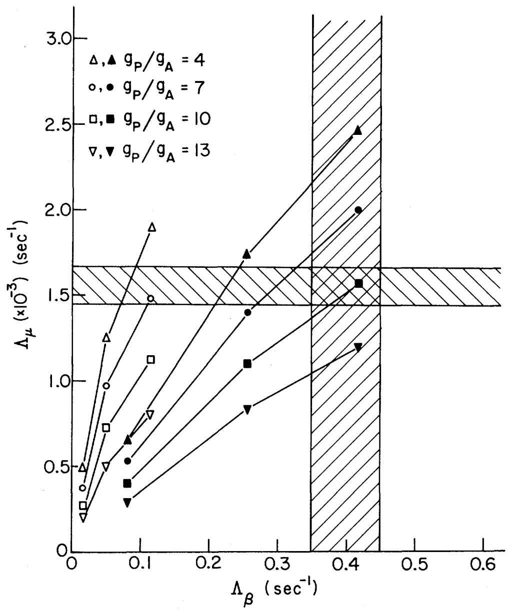

FIG. 3. The measured values of Λ_μ from Ref. 12 and Λ_β from the present work, along with calculated values from Ref. 8. The open points are impulse-approximation calculations. The closed points include meson exchange currents in the weak Hamiltonian. In each case, the calculation is done with three different residual interactions—a δ function plus π and ρ exchange, a G matrix, and a one-boson exchange potential. Details regarding the residual interactions are specified in Ref. 8. The lines connecting the points are only meant to guide the eye.

It has been noted[18] that the isovector parity-nonconserving force in nuclei may be obtained from the pion-exchange potential in $0^-\to0^+$ beta decay by isospin rotation. Recent shell-model calculations[19,20] of parity nonconservation in s-d shell nuclei that failed to include $2\hbar\omega$ excitations in the nuclear wave functions predicted effects a factor of 3 larger than observed. Haxton[18] argues that inclusion of $2\hbar\omega$ excitations removes this discrepancy in the case of ^{18}F. The present result confirms that this conclusion is more generally true. TK find values of Λ_β a factor of 2 to 3 larger than observed when they perform the calculation with a closed-shell ^{16}O wave function.

Using the calculation of TK, we find that $g_P/g_A = 10 \pm 2.5$. This result is model dependent. Further work on the correctness of the nuclear structure model is necessary. For example, the wave functions could be applied to calculate the ^{16}N ground-state decay. Our result is consistent with recent determinations[21,22] of g_P/g_A from muon capture measurements on H and ^{12}C.

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