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Radiative muon capture on oxygen and the induced pseudoscalar coupling

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The photon spectrum from radiative muon capture in ^{16}O has been measured using a time projection chamber as a large acceptance pair spectrometer. The integrated partial branching ratio for photons of $E_\gamma > 57$ MeV, relative to the ordinary muon capture rate, is $(2.2 \pm 0.2) \times 10^{-5}$. When compared to a calculation using a phenomenological nuclear response function the data indicate a value for the induced pseudoscalar coupling in ^{16}O of $g_p/g_a = 7.3 \pm 0.9$; however, when compared to a microscopic nuclear-model calculation the value $g_p/g_a = 13.6^{+1.6}_{-1.9}$ is obtained.

Radiative muon capture (RMC) on a nucleus, $\mu^- Z \to (Z-1)\nu_\mu \gamma$, is a weak semileptonic process which is particularly sensitive to the induced pseudoscalar coupling constant g_p of the weak hadronic current. Through the use of the partially conserved axial-vector current hypothesis (PCAC), one obtains the familiar Goldberger-Treiman estimate $g_p/g_a = 6.8$ for the nucleon,[1] at the momentum transfer corresponding to ordinary muon capture (OMC). The average of several recent measurements of the rate of OMC on hydrogen yields a value for g_p/g_a of 6.9 ± 1.5,[2] although each of the experiments contributing to this average has an error in excess of 40%. In ^{16}O however, the ratio of the $^{16}O(\mu^-, \nu_\mu)^{16}N(0^-)$ capture rate to the $^{16}N(0^-)$ β-decay rate gives a significantly larger value, $g_p/g_a \sim 12$.[3,4]

In contrast to OMC, the momentum transfer is not fixed in the RMC process, but varies between $q^2 = -0.9m_\mu^2$ and $q^2 = +m_\mu^2$. This enhances the effect of the pseudoscalar coupling near the pole in the pion propagator, i.e., near the high-energy end of the photon spectrum. This increased sensitivity to g_p is the main reason why RMC has long been considered the preferred method for investigating g_p. The low capture probability in hydrogen ($\sim 10^{-3}$) combined with the expected low radiative branching ratio ($\sim 10^{-5}$) have thus far precluded a measurement of the elementary radiative capture process $\mu^- p \to n \nu_\mu \gamma$, although such an experiment is now underway at TRIUMF.[5]

RMC measurements are more feasible for heavier nuclei where the muon capture probability ($\propto Z^4$) is greatly enhanced, but RMC measurements on nuclei suffer the disadvantage that the nuclear response function must be properly included, since the final nuclear states are not resolved experimentally. Efforts to date have largely concentrated on the well-understood nucleus ^{40}Ca. Additional interest in nuclear RMC arises from the possibility of observing modifications of the elementary process by non-nucleonic degrees of freedom in the nucleus, which could manifest themselves as a renormalization of g_p.

There have been two previous measurements of RMC on ^{16}O, and their results for the branching ratio are in disagreement. Döbeli *et al.*[6] obtained an integrated branching ratio for photons of greater than 57 MeV, relative to the total muon capture rate of $R_\gamma = (2.44 \pm 0.47) \times 10^{-5}$, in contrast with the value of $(3.8 \pm 0.4) \times 10^{-5}$ recently reported by Frischknecht *et al.*[7] Much larger preliminary results for R_γ were reported by both these groups [$(6.2 \pm 0.8) \times 10^{-5}$ (Ref. 8), $(6.5 \pm 1.3) \times 10^{-5}$ (Ref. 9)] and were discussed in the literature,[10-12] but these results have since been found to be in error.[6,7]

For the present measurement the TRIUMF time projection chamber (TPC)[13,14] was used as a large solid angle (2.5 sr), medium resolution (~10% full width at half maximum) pair spectrometer to detect the γ rays from RMC. A 73 MeV/c μ^- beam (with e^- and π^- contamination of 10^{-2} and 10^{-3}, respectively) was stopped in a 3.0-cm-thick target of liquid D_2O (99.96% isotopically enriched), contained in a polyethylene bag. Heavy water was chosen in order to minimize the rate of photons from the decay of π^0's produced on hydrogen via charge exchange of the pions in the muon beam. A lead photon converter surrounded the target inside the inner diameter of the TPC. The converter consisted of two cylindrical layers of charged-particle veto scintillators, a 1.0-mm-thick lead sheet, and a segmented layer of 18 trigger scintillators. The innermost layer, along with four beam-defining scintillators in front of the target and one scintillator behind the target, served to define the muon stops, which were counted individually. The typical muon stopping rate was 4×10^5 s^{-1}. After each muon stop, a time gate of 4.0 μs was opened and photon events were accepted. The hardware photon trigger required the following: a valid trigger from the converter scintillators (i.e., no hits inside the converter cylinder and a hit after the converter layer); a minimum number (≥ 6) of wire hits in the TPC; and also at least two hits in the outer scintillator counters which surrounded the TPC. This ensured that both tracks from the e^+e^- conversion pair passed through the TPC, and provided an extremely clean photon signature.

The photon acceptance over the energy range of interest was measured using both radiative pion capture on carbon, and π^0-decay γ rays from $\pi^- p \rightarrow \pi^0 n$. The latter were obtained from a suitably normalized subtraction of spectra from π^- stopping in CH_2 and C. The GEANT Monte Carlo routines[15] were used to simulate the detector; Fig. 1 shows the data compared to Monte Carlo for $^{12}C(\pi^-,\gamma)$. The detector acceptance was normalized using the known $^{12}C(\pi^-,\gamma)$ branching ratio.[16,17]

A significant dependence of the measured acceptance on the rate in the chamber was observed (see Fig. 2). This was primarily due to space charge and positive ion effects in the TPC. At high rates, the flux of primary particles, impinging on the proportional wire regions in the end caps of the detector, caused a reduction of the observed signal amplitude. This in turn reduced the amplitude of the induced signals on the TPC cathode pads [from which the (x,y) coordinates of the track are determined], and some of the signals fell below threshold; consequently, fewer valid points were found for the track reconstruction, thereby reducing the event reconstruction efficiency. This rate effect was reproduced in the Monte Carlo simulation by reducing the cathode pad amplitudes in the same manner as observed in the data, and an identical reduction in acceptance was observed. The rate effect could be accounted for either by using the acceptance determined from pion capture taken at the same rate as the RMC data, or by normalizing the RMC data to Monte Carlo data with equivalent cathode pad amplitudes; both methods yielded mutually consistent results. The rate effect was much more important in the present work than in previous experiments with the TPC (Refs. 13 and 14) due to the lower magnetic field used (2.5 kG compared to 9.0 kG). The lower field was dictated by the photon trigger and resulted in a much larger charged-particle flux in the chamber. This rate effect contributed the largest (5.8%) error to the extracted branching ratio; it is discussed in more detail elsewhere.[18]

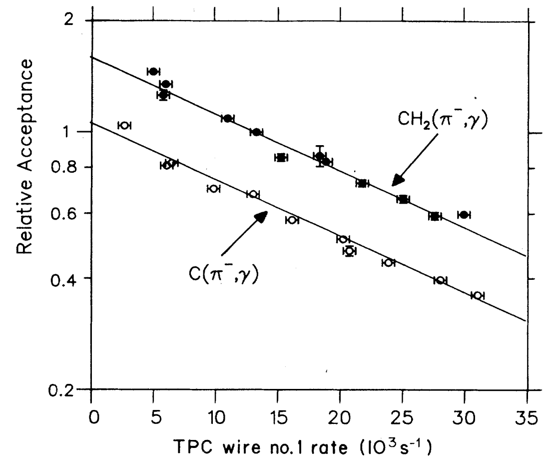

FIG. 2. Rate dependence of the photon acceptance, shown as a function of the rate of the innermost TPC anode (wire No. 1). The RMC data was taken at a wire No. 1 rate of 20×10^3 s^{-1}.

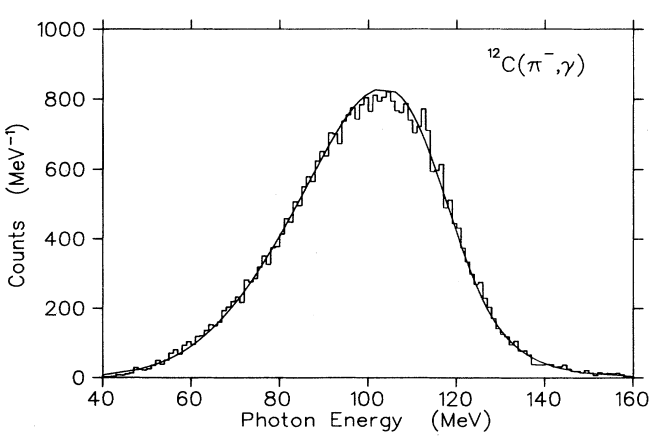

FIG. 1. Photon energy spectrum from radiative pion capture on ^{12}C, data (histogram) and Monte Carlo (curve).

RMC measurements in the past have often been plagued by backgrounds due to neutrons and radiative pion capture, neither of which is a difficulty in the present experiment. The TPC is by its nature insensitive to neutrons; pions are rejected by (i) an rf separator,[19] and (ii) rejection of any photon event in prompt coincidence with a signal in the beam counters. The overall pion rejection factor was measured to be better than 10^7. The remaining pion-induced events contributed $<0.1\%$ to the observed RMC signal.

The contribution to the photon energy spectrum due to cosmic-ray background was determined from data taken during beam-off periods with the muon stop requirement removed from the hardware trigger. The cosmic-ray background rate was measured to be 0.8 ± 0.1 events per day, contributing $(1.2 \pm 0.1)\%$ to the observed photon spectrum.

Muons that stop in materials surrounding the target can also undergo RMC. This background can be estimated from the measured muon stopping rate in the scintillators surrounding the target, and it can also be determined by fitting the time distribution of the photon events (exploiting the different muon lifetimes in different materials). These two methods yielded consistent results for this nontarget background, giving a $(2.5 \pm 0.8)\%$ contribution to the measured RMC spectrum.

Finally, there is the copious background from radiative muon decay and bremsstrahlung from muon-decay electrons in the target. For free muon decay, the spectra from both processes have an upper limit of 53 MeV. The distortion in the electron spectrum due to the muon being bound in an atomic orbit is negligible for ^{16}O. RMC experiments typically use only the portion of the spectrum with $E_\gamma > 57$ MeV (allowing for finite detector resolution). In the case of a magnetic spectrometer, however, there is often a high-energy tail in the detector response function which could cause bremsstrahlung photons to appear well above 57 MeV. Rather than rely only on the Monte Carlo to determine the high-energy tail in the detector response, it was explicitly measured, using a μ^+ beam. A μ^+ stopping in a target does not undergo nuclear capture; however, the radiative muon decay and bremsstrahlung processes occur much the same as for μ^-'s. The additional process of positron annihilation in flight does not modify the shape of the photon spectrum significantly. Consequently, any event above $\sim$53 MeV is due to the high-energy tail. Figure 3 shows the measured μ^+ energy spectrum, exhibiting the small high-energy tail which is consistent with the Monte Carlo prediction. The effect on the RMC spectrum was determined by normalizing the μ^+ to the μ^- data below 57 MeV, after subtracting the contribution from RMC below 57 MeV. This background contributed $(7.6 \pm 1.1)\%$ to the ^{16}O spectrum above 57 MeV.

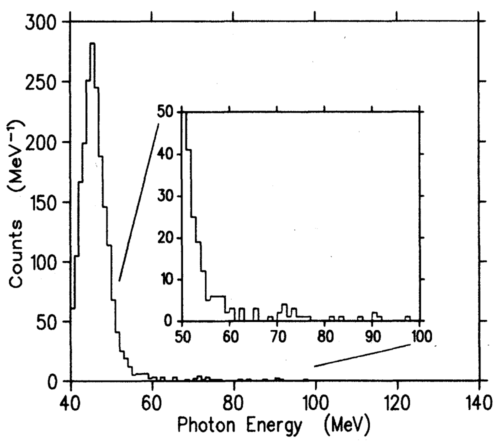

FIG. 3. Spectrum of radiative muon decay and external bremsstrahlung of decay positrons from μ^+ stopping in the D_2O target. The events above 53 MeV are due to the high-energy tail in the detector response function.

The RMC data shown in Fig. 4 yield an experimental branching ratio for $E_\gamma > 57$ MeV of $R_\gamma = (2.2 \pm 0.2) \times 10^{-5}$. This is in good agreement with the result $R_\gamma = (2.44 \pm 0.47) \times 10^{-5}$ reported by Döbeli *et al.*,[6] but it is a factor of 2 more precise. However, it disagrees by $> 3\sigma$ with the value $R_\gamma = (3.8 \pm 0.4) \times 10^{-5}$ given by Frischknecht *et al.*[7]

RMC in ^{40}Ca was also measured in the present experiment and a branching ratio of $R_\gamma = (2.18 \pm 0.16) \times 10^{-5}$ was obtained. This is in excellent agreement with several previous measurements[6,20,21] and adds confidence in the accuracy of the present technique. The ^{40}Ca results will be presented in detail in a subsequent publication.

Two calculations of the nuclear response for RMC in ^{16}O are available. The first is that of Christillin and Gmitro[10] in which a phenomenological approach is adopted. A realistic nuclear excitation spectrum is used, including low-lying individual states in the final ^{16}N nucleus, along with giant dipole and quadrupole resonances of Lorentzian form. The second is the microscopic calculation of Gmitro, Ovchinnikova, and Tetereva[11] in which meson-exchange effects at the electromagnetic vertex are included ("modified impulse approximation"). For the ^{16}O ground-state n-particle, n-hole ($n = 0,1,2$) shell model wave functions were used; only the leading negative parity levels of ^{16}N were included in the final state. Figures 4(a) and 4(b) show the theoretical spectra for different values of g_p from the calculations of Christillin and Gmitro[10]

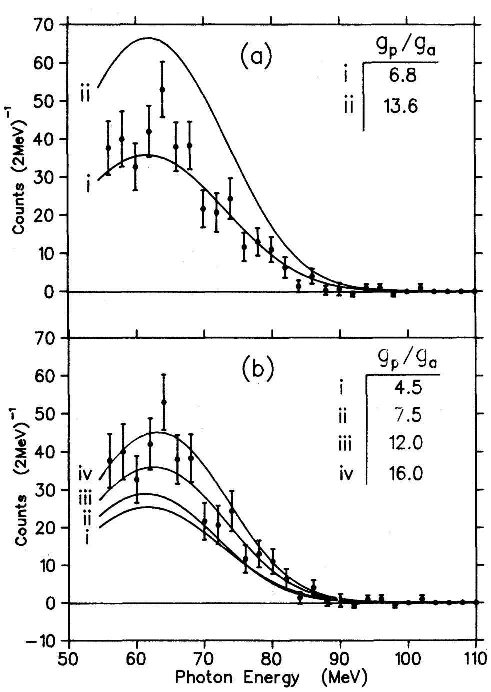

FIG. 4. Photon energy spectrum from RMC on ^{16}O (D_2O target) compared to (a) the spectra calculated by Christillin and Gmitro (Ref. 10) and to (b) the spectra calculated by Gmitro, Ovchinnikova, and Tetereva (Ref. 11) for different values of g_p. The theoretical spectra have been convoluted with the detector response function.

and Gmitro, Ovchinnikova, and Tetereva[11] respectively, convoluted with the detector response function and superimposed on the measured photon spectrum. The background from lower-energy photons due to the high-energy tail in the detector response function has been subtracted from the data.

Using the present value for R_γ, the calculation of Christillin and Gmitro[10] yields the value of $g_p/g_a = 7.3 \pm 0.9$. However, the very different value $g_p/g_a = 13.6^{+1.6}_{-1.9}$ is extracted if, instead, the calculation of Gmitro, Ovchinnikova, and Tetereva[11] is used. Contrary to the assertions made in Refs. 6 and 7, the two models predict very different dependences of R_γ on g_p/g_a for ^{16}O. The lower result obtained using the theory of Christillin and Gmitro[10] is in good agreement with the PCAC estimate for the nucleon ($g_p/g_a = 6.8$). However, the higher value obtained using the theory of Gmitro *et al.* [11] is in good agreement with the result $g_p/g_a \sim 12$ determined from the ratio of the $^{16}\mathrm{O}(\mu^-, \nu_\mu)^{16}\mathrm{N}(0^-)$ capture rate to the $^{16}\mathrm{N}(0^-)$ β-decay rate.[3,4] This would imply a substantial enhancement of g_p in the ^{16}O nucleus.

It is apparent that further theoretical work is now required to resolve the question of whether or not there is an enhancement of the pseudoscalar coupling strength in ^{16}O.

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