TRI-PP-89-54

Invited paper presented at XIII Yamada Conference on Nuclear Weak Process and Nuclear Structure, Osaka, June 12-15

TRI-PP-89-54
Jun 1989

RADIATIVE MUON CAPTURE IN LIGHT NUCLEI

M.D. Hasinoff[1], S. Ahmad[1], D.S. Armstrong[1], G. Azuelos[2], W. Bertl[3], M. Blecher[4], R.A. Burnham[1], E.T.H. Clifford[5], C.Q. Chen[6], Z.H. Ding[6], P. Depommier[7], T.P. Gorringe[1], R. Henderson[8], A.J. Larabee[1], J.A. Macdonald[2], S.C. McDonald[8], H. Mes[9], T. Numao[5], J.-M. Poutissou[2], R. Poutissou[7], B.C. Robertson[10], A. Serna-Angel[4], J. Summhammer[5], G.N. Taylor[8], C.E. Waltham[1], D.H. Wright[4,1], N.S. Zhang[6].

[1] University of British Columbia, Vancouver, B.C., Canada V6T 2A6 [a,b]
[2] TRIUMF, Vancouver, B.C., Canada V6T 2A3[a,b]
[3] PSI/SIN, CH-5234, Villigen, Switzerland[b]
[4] Virginia Polytechnic Inst. and State U., Blacksburg, VA, USA 24061[a,b]
[5] TRIUMF and University of Victoria, Victoria, B.C., Canada V8W 2Y2[a]
[6] Institute of High Energy Physics, Academia Sinica, Beijing, China[b]
[7] Université de Montréal, Montréal, P.Q. Canada H3C 3J7[a,b]
[8] University of Melbourne, Parkville, Victoria, Australia, 3052[b]
[9] National Research Council of Canada, Ottawa, Ontario Canada K1A OR6[a]
[10] Queen's University, Kingston, Ontario, Canada K7L 3N6[a,b]
[a] RMC-I collaboration - Nuclear RMC in the TPC (TRIUMF Expt. 249)
[b] RMC-II collaboration RMC in Hydrogen (TRIUMF Expt. 452)

ABSTRACT

Radiative muon capture rates have been measured for carbon, oxygen and calcium targets. The carbon and oxygen rates yield large values for g_p when compared to detailed microscopic calculations but the conventional Goldberger-Treiman value when compared to phenomenological model calculations. A progress report on the TRIUMF RMC measurement on hydrogen is also given.

Radiative muon capture (RMC), $\mu^- Z \rightarrow \nu(Z-1)\gamma$, is a weak semileptonic process which is particularly sensitive to the induced pseudoscalar coupling constant, g_p, of the weak hadronic current. A programme is underway at TRIUMF to measure the energy spectrum and branching ratio for RMC on hydrogen, to determine g_p for a free nucleon. As a precursor to the hydrogen measurement, and also to investigate the possible renormalization of g_p in nuclei, RMC rates on ^{40}Ca, ^{16}O and ^{12}C were measured and are reported below.

Through the use of PCAC and the Goldberger-Treiman relation, one can obtain the estimate $g_p/g_a = 6.8$ for the nucleon. In a recent review article, Gmitro and Truöl[1)] examined the existing data for RMC, and claimed that the evidence points toward a renormalization of g_p in nuclei. The apparent effect is strongly dependent on the nuclear charge, Z, with g_p larger than the Goldberger-Treiman estimate for light nuclei, and reduced to near zero for heavy nuclei. There are also indications from ordinary muon capture measurements on light nuclei[2)] and recoil polarization measurements[3,4)] on ^{12}C that g_p may

CA9421015

be somewhat larger than the Goldberger-Treiman estimate. Such a Z-dependent renormalization would point toward a modification of the pion field in the nuclear medium.

The TRIUMF Time Projection Chamber (TPC)[5] was used as a large solid angle (2.5 sr), medium resolution (~10% FWHM) pair spectrometer to detect gamma rays from RMC. A lead photon converter package surrounded the stopping target inside the inner diameter of the TPC. The innermost scintillator layer, along with four beam scintillators in front of the target and one veto 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 (950 ns for ^{40}Ca, 4.0 μs for ^{16}O and ^{12}C) 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 in the 2 inner layers and a hit in the final converter layer); a sufficient number ($\geq$6) of wire hits in the TPC; and also at least 2 hits in the outer scintillator counters which surrounded the TPC. This ensured that both tracks from the e^+e^- 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 gamma rays from $\pi^- p \rightarrow \pi^0 n$. The latter were obtained from a subtraction (suitably normalized) of spectra from π^- stopping in CH_2 and C. At low rates the average acceptance in the region of the π^0 spectrum, including track reconstruction efficiency and software cuts, was 0.26% at a magnetic field of 2.7 kG using a 1.0 mm thick converter. The GEANT Monte Carlo routines were used to simulate the detector response function.

A significant rate dependence for the TPC acceptance was observed during the experiment. This was due to space charge and positive ion effects inside the TPC which caused a quenching of the observed amplitude on the TPC cathode pads (which determine the (x,y) coordinates of the track). This reduced the number of points available 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.

RMC measurements in the past have often been troubled by backgrounds due to neutrons and radiative pion capture, neither of which is a difficulty with the present detector. The TPC is by its nature insensitive to neutrons; pions are rejected by (i) an RF separator 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 $<$ 1% to the observed RMC rate.

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 $\pm$ 0.1) events/day, contributing $\leq$ 1.5% to the observed photon spectrum.

Two other backgrounds need to be considered: RMC photons from non-target stops and (internal and external) bremsstrahlung photons from decay electrons. The first background can be estimated from the μ^- stopping rate in the surrounding scintillators and it can also be determined by fitting the time distribution of the photon events. Both methods yielded consistent results and indicated a background of (6.0 $\pm$ 1.8)% in the worst case (^{12}C). Since the TPC response function has a high energy tail, some of the bremsstrahlung photons (E_γ <52.8 MeV) can be reconstructed with an energy > 57 MeV. This background was measured by stopping a μ^+ beam and observing the number of γ events with reconstructed energy > 57 MeV. For the Ca target this high energy tail contribution was totally negligible. However, it was 6% (14%) for ^{16}O (^{12}C), respectively and thus it would have been unacceptably high for the hydrogen experiment. Monte Carlo studies indicated that e^+ annihilation in-flight had little effect on the spectral shape.

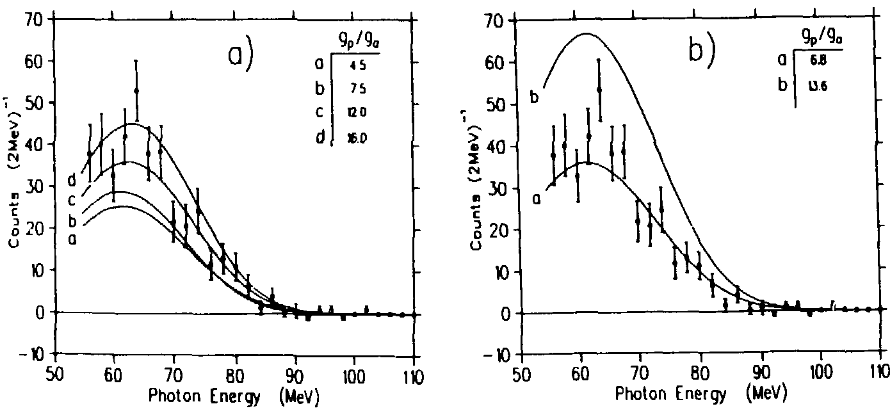

Figure 1: Photon energy spectrum from RMC on ^{16}O compared to the calculations of a) Gmitro et al.[14] and b) Christillin and Gmitro[16].

Results have been obtained for RMC on ^{40}Ca, ^{16}O (using a D_2O target) and ^{12}C, using both a 0.6 mm and a 1.0 mm lead converter. Figure 1 shows the ^{16}O data for the 1.0 mm converter compared to the two theoretical calculations for various values of g_p/g_a. The theoretical spectra have been convoluted with the acceptance and response function of the detector. Our final results for the branching ratios for RMC (E_γ >57 MeV) relative to ordinary muon capture are compared to previous measurements in Table 1. The branching ratio for ^{40}Ca agrees well with the several previous measurements[6-9] . Our results for ^{16}O and ^{12}C are much smaller than the values initially reported by the SIN group using NaI detectors[10] but agree well with their final results[8]. The preliminary results of the same group for ^{16}O using a pair spectrometer[11] have now been revised downwards[12]. However, they are still in disagreement with both their revised NaI result and our present value.

A comparison of our results with the most recent theoretical calculations allows us

Table 1: Results of recent experiments on RMC in light nuclei. BR refers to the branching ratio (E_γ >57 MeV) relative to ordinary muon capture. The values of g_p/g_a listed are extracted from the integrated branching ratio ("integral") and from fitting to the detailed shape of the theoretical energy spectrum ("spectral").

Target	# Events	BR ($E_\gamma > 57$ MeV)	g_p/g_a		Theory	Expt.
		($\times 10^{-5}$)	Integral	Spectral		
^{40}Ca	3458	2.18 ±0.16	5.7±0.8	5.4±0.8	13)	This Expt.
"	"	2.04 ±0.14	4.6±1.8	3.6±1.9	14)	"
	1229	2.11 ±0.14	-	6.5±1.6	15)	6)
	2450	1.96 ±0.20	-	4.6±0.9	13)	7)
	"	1.92 ±0.20	-	3.5±1.3	15)	"
	"	2.07 ±0.20	5.8±2.4	3.0±0.6	15)	"
	3234	2.30 ±0.21	-	$6.3^{+1.0}_{-1.5}$	13)	8)
	3133	2.35 ±0.31	7.6±1.6	7.3±1.6	13)	9)
	"	2.15 ±0.26	6.0±2.8	6.3±3.5	14)	"
^{16}O	361	2.22 ±0.23	7.3±0.9	7.1±0.9	16)	This Expt.
	"	2.18 ±0.21	$13.6^{+1.6}_{-1.9}$	$13.1^{+1.8}_{-2.0}$	14)	"
	325	2.44 ±0.47	-	8.4±1.9	16)	8)
	1459	3.80 ±0.40	13.5±1.5	-	16)	12)
^{12}C	613	2.34 ±0.23	7.8±0.9	-	16)	This Expt.
	"	2.27 ±0.18	14.3±1.5	-	14)	"
	75	2.7 ±1.8	-	9.5±7.2	16)	8)

to extract g_p/g_a, albeit in a model-dependent manner. For ^{40}Ca the integral rate method gives $g_p/g_a = 5.7 \pm 0.8$ using the phenomenological nuclear response calculation[13)] and 4.6 ± 1.8 using the microscopic calculation[14)]. However, a fit to the detailed spectral shape of the microscopic calculation produces a somewhat lower value (3.6 ± 1.8) in agreement with that observed by Frischknecht et al.[7)]. This difference between the integral rate and spectral fitting values in the microscopic calculation is possibly due to the neglect of the quadrupole contribution. For ^{16}O, our measured partial branching ratio gives $g_p/g_a = 7.3 \pm 0.9$ using the phenomenological calculation[16)] and $g_p/g_a = 13.6\,^{+1.9}_{-1.6}$ using the microscopic calculation[14)]. The lower result is in good agreement with the PCAC prediction. However, the higher value obtained using the microscopic calculation implies a substantial enhancement of g_p, in agreement with the value $g_p \sim 10-12\ g_a$ determined from exclusive μ capture and β decay rates[2)]. A similar enhancement of g_p/g_a in ^{12}C is also observed in the various recoil polarization experiments[3,4]. A calculation of the nuclear response for RMC in ^{12}C has not yet been done; consequently the ^{12}C data in Table 1 are compared with the theoretical results for ^{16}O. Similar results for g_p/g_a are obtained as for ^{16}O; however,this should be regarded with caution until a calculation specific to ^{12}C becomes available.

An improved pair spectrometer (with an increased acceptance and an improved response function) has been constructed for the Hydrogen experiment. The central detector is a large solid angle ($\sim 2\pi$) drift chamber with 4 layers of cells, each cell possessing 6 sense wires. The cells in layer 3 are wired in stereo to provide one axial coordinate; the second z point comes from a cylindrical wire chamber situated just inside the drift chamber. Three segmented layers of scintillators A,A′,B surround the liquid hydrogen target and veto the copious flux of charged particles from normal muon decay. Photons are converted in a 1.0 mm lead sheet exterior to the B ring and the resulting e^+e^- pair is detected in segmented C,D scintillators. The trigger requires a single C counter and at least two appropriate D counters. The drift chamber cell pattern appropriate for a pair is also incorporated into the trigger decision. The trigger rate is expected to be a few per second for a μ^- stopping rate of 10^6/s.

At a magnetic field of 2.4 kG the acceptance for 70 MeV photons is calculated to be 0.9 %. This acceptance will be measured experimentally using π^0 decay gammas from the reaction $\pi^- p \rightarrow \pi^0 n$. The expected photon energy resolution of the pair spectrometer is about 10 % FWHM, but the high-energy tail of the response function is significantly reduced when compared to the TPC. The liquid hydrogen will be contained in a Au flask (0.25mm thickness) surrounded by Ag heat shields and vacuum jackets. Although the RMC rate on Au and Ag is much larger than on ^1H the μ^- lifetime in the former materials is ≤ 80 ns as compared to 2.2 μs in ^1H. A software cut selecting events occurring at least 300 ns after the last μstop will reduce this non-target background to ~ 2.5 % of the expected signal. The main background will be capture from ^3He as a result of μ–induced fusion on the deuterium impurity in the liquid hydrogen. If ordinary hydrogen was used (140 ppm ^2H) this background would swamp the signal. By using enriched hydrogen (2.7 ppm ^2H) borrowed from Saclay we can reduce this background to ≤ 8 % of the signal. The pion contamination in the μ^- beam represents another formidable background problem. As with the nuclear measurements, this is reduced by an RF separator in phase with the cyclotron and the rejection of events in coincidence with any of the four beam counters. We expect to be able to reduce this pion contamination background to ≤ 2 % of the signal. Charged cosmic-ray events will be vetoed by wire chambers and scintillators mounted on the top and sides of the spectrometer magnet. However, a neutral cosmic-ray induced background of ~ 20 % is expected, based on data taken with the TPC. This can be subtracted with high accuracy by collecting data during beam-off periods.

The drift chamber is now installed in the magnet and preliminary acceptance mea-

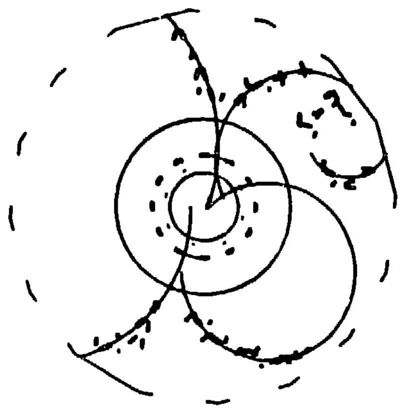

Figure 2: A $\pi^0 \to 2\gamma$ event with both γ's converted.

surements are underway. Fig. 2 shows a π^0 event in which both γ-rays have converted in the 1.0 mm lead sheet. The expected final error on the RMC branching ratio for hydrogen will be 8% leading to an error in g_p/g_a of 10%. RMC data on several nuclear targets will be collected before we mount the ^{1}H target. The final data-taking on the enriched ^{1}H target will begin early in 1990.

This work is supported by NSERC (Canada), the U.S. NSF (VPI & SU), PSI/SIN, and the Australian Research Council.

1) M. Gmitro and P. Truöl, Adv. Nucl. Phys. **18**(1987)241.

2) A.R. Heath and G.T. Garvey, Phys. Rev. C **31**(1985)2190; L.A. Hamel et al., Z. Phys. **A321**(1985)439.

3) Y. Kuno et al., Z. Phys. **A323**(1986)69.

4) L. Roesch et al., Phys. Lett. **107B**(1981)31.

5) C.K. Hargrove et al., N.I.M. **219**(1984)461; D.A. Bryman et al., N.I.M. **234**(1985)42.

6) R.D. Hart et al., Phys. Rev. Lett. **39**(1977)399.

7) A. Frischknecht et al., Phys. Rev. C **32**(1985)1506.

8) M. Döbeli et al., Phys. Rev. C **37**(1988)1633, M. Döbeli, Ph.D. thesis, Univ. Zurich (1987), unpublished.

9) C.J. Virtue, Ph.D. Thesis, Univ. of British Columbia (1987), unpublished.

10) M. Döbeli et al., Czech. J. Phys. **B36**(1986)386.

11) A. Frischknecht et al., Czech. J. Phys. **B32**(1982)270.

12) A. Frischknecht et al., Phys. Rev. C **38**(1988)1996.

13) P. Christillin, Nucl. Phys. **A362**(1981)391.

14) M. Gmitro, A.A. Ovchinnikova and T.V. Tetereva, Nucl. Phys. **A453**(1986)685.

15) H.P.C. Rood, A.F. Yano and F.B. Yano, Nucl. Phys. **A228**(1974)333.

16) P. Christillin and M. Gmitro, Phys. Lett. **B150**(1985)50.