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RADIATIVE MUON CAPTURE ON HYDROGEN

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ABSTRACT

The induced pseudoscalar coupling constant, g_P, of the weak hadronic current can be determined from the measurement of the branching ratio of Radiative Muon Capture on hydrogen. This rare process is being investigated in the TRIUMF RMC experiment which is now taking data. This paper describes the experiment and indicates the status of the data analysis.

1. INTRODUCTION

The weak hadronic current in semileptonic reactions is not purely $V - A$,

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because the strong force induces additional couplings. One of these, the induced pseudoscalar coupling constant, g_P, is still very poorly determined experimentally. Better precision than that obtained in previous Ordinary Muon Capture (OMC) experiments on hydrogen is possible by investigating Radiative Muon Capture (RMC) on hydrogen, i. e. the reaction

$$\mu^- p \rightarrow \nu_\mu n \gamma.$$

Compared to OMC, RMC offers the possibility of varying the momentum transfer, leading to more sensitivity to the induced weak pseudoscalar form factor. On the other hand, RMC is experimentally more difficult than OMC since the rate is four to five orders of magnitude smaller and the various backgrounds are much more important.

2. THEORETICAL CONSIDERATIONS

Assuming Lorentz invariance, semileptonic weak interactions between nucleons and leptons are parameterized by six complex form factors (functions of the momentum transfer q). Assuming time-reversal invariance these form factors are real. The explicit form of the weak hadronic vector and axial-vector current is[1]:

$$< n|J_V^\alpha|p > = \bar{u}_n \left[F_V(q^2)\gamma^\alpha + iF_M(q^2)\sigma^{\alpha\nu}q_\nu + F_S(q^2)q^\alpha\right] u_p$$
$$< n|J_A^\alpha|p > = \bar{u}_n \left[F_A(q^2)\gamma^\alpha\gamma_5 + iF_T(q^2)\sigma^{\alpha\nu}q_\nu\gamma_5 + F_P(q^2)\gamma_5 q^\alpha\right] u_p\,.$$

The vector F_V and axial-vector F_A form factors reflect the basic $V-A$ structure of the weak charged current; the induced weak magnetism F_M and pseudoscalar F_P are first-class form factors; the induced scalar F_S and tensor F_T are second-class form factors. Theoretical arguments can be used to restrict the number of these form factors. For instance, one generally assumes that second-class currents do not exist since they do not occur naturally in gauge theories and because there is experimental evidence against a tensor interaction.[2,3] The Conserved Vector Current (CVC) hypothesis is a natural consequence of the Standard Model and it is well supported by experimental evidence. CVC can be used to relate the vector and weak magnetism form factors to the electromagnetic form factors.

There remain the axial-vector and pseudoscalar form factors. The hypothesis of Partial Conservation of Axial Current (PCAC) and the Goldberger-Treiman relation lead to a relation for these two form factors. It is usually stated in terms of the "coupling constants" $g_A \equiv F_A(q^2)$ and $g_P \equiv m_\mu F_P(q^2)$, and it is evaluated at $q^2 = 0.88m_\mu^2$, corresponding to the momentum transfer in OMC. Thus the "Goldberger-Treiman" estimate for the nucleon is:

$$\frac{g_P}{g_A} = \frac{2Mm_\mu}{m_\pi^2 + q^2}\bigg|_{q^2=0.88m_\mu^2} = 6.78\,.$$

The axial-vector coupling constant has been measured to great accuracy in neutron decay[4] and good agreement with theory is found. The pseudoscalar coupling constant is not well determined experimentally. Several measurements of OMC on hydrogen lead to values of g_P/g_A. The world average is[5]:

$$g_P/g_A = 6.9 \pm 1.5.$$

The theoretical prediction for g_P should be accurate to about 6 % since the Goldberger-Treiman relation which gives g_A is verified to this level of accuracy.[6] It is therefore very desirable to measure g_P to a similar level of precision. The present experiment aims for a measurement of the RMC branching ratio in hydrogen to 8 % accuracy which should yield g_P to $\approx$ 10 %.

3. THE EXPERIMENTAL SETUP

The principal features of the detector are shown schematically in figure 1. A 65.5 MeV/c μ^- beam from the TRIUMF M9 channel is stopped in a liquid hydrogen target. The emerging photons which are converted in a thin lead sheet into e^+e^- pairs create a specific trigger pattern in the scintillator system. The e^+e^- pairs are detected in an inner wire chamber and a large drift chamber. A large magnet provides an axial field of 0.24 T and counters are installed on the top and sides in order to veto cosmic ray events.

Since RMC on hydrogen has a branching ratio of the order of 10^{-8}, the experiment must contend with large backgrounds. Photons associated with the frequent ordinary and radiative muon decays (external and internal bremsstrahlung) make any measurement below $E_\gamma = 53$ MeV impossible and, due to the finite energy resolution of the detector, can even produce a photon background above this threshold. Therefore good energy resolution is needed to separate this background without losing too much efficiency. There is also a large neutron background from OMC (about 10^5 times as frequent as RMC) to which the detector has to be completely insensitive. In addition, the detector should provide an unambiguous signature for a photon with good efficiency over a large solid angle. This is achieved with a large solid angle ($\approx 2\pi$) photon pair-spectrometer consisting of a cylindrical photon converter (1.08 mm lead) and a 4 layer cylindrical drift chamber[7] surrounding the converter. The drift chamber provides the xy information on electron and positron tracks with a spatial resolution of up to 120 μm(σ). A layer of stereo wires in combination with a small inner wire chamber determines the z component of a track.

A dangerous background comes from the pions present in the beam (since every pion stopping in hydrogen will create at least one photon in the relevant energy range). A radio-frequency separator in the beamline reduces the pion contamination to about 10^{-6}. Residual pion reactions can be eliminated by a timing cut because they are prompt as opposed to the non-prompt RMC reactions. The lifetime of a muon in a hydrogen orbital (τ_μ^H = 2195 ns) is almost that of the free particle. The fact that the capture pro bility rises rapidly for heavier nuclei ($\sim Z^4$) helps to eliminate another background arising from muons which stop in the target walls. Since the target cell is made out of gold, muon capture in the wall proceeds very quickly and these events can be vetoed by a timing cut. Furthermore, even a very small contamination (10^{-9}) of the hydrogen target with elements of higher atomic number Z would be detrimental because of the very large rate at which muons are transfered. Even the fraction of deuterium in natural hydrogen (140 ppm) would produce ^{3}He via muon-induced fusion and provide a RMC rate larger than that from protium. Therefore isotopically ultra-pure protium ^{1}H with a deuterium component of approximately 0.5 ppm is used.

Because of the enormous backgrounds an efficient trigger system is necessary for rejection of the host of non-RMC type events. Three segmented inner layers of scintillators (A, A', B) surround the target and veto the copious flux of charged particles from normal muon decay. A fourth segmented scintillator layer (C) is located just outside the lead converter and a fifth layer (D) is positioned outside the drift chamber. The trigger requires signals in each of the C and D layers. The drift chamber information is also available for on-line event selection: a trigger card[8] using the postamplifier signals provides the hit pattern, which has to be appropriate for an e^+e^- pair. In total a fraction of roughly 10^{-4} of all muon stops will fulfill all the on-line trigger conditions for an RMC-type event and get recorded onto 8 mm video tape.

The detector has been commissioned and has recorded the first hydrogen data in a 3-week beam period in August 1990. An example of a photon event is shown in figure 2.

4. STATUS OF DATA ANALYSIS

In the August 1990 run period 21.4×10^{10} muon stops ($\equiv$ 4.5 days livetime) were examined. Before any cuts are applied the resulting photon energy spectrum (see figure 3) is obviously dominated at higher energies by the π^- induced photons. Below approximately 50 MeV the background spectrum from bremsstrahlung from ordinary muon decay rises steeply and then falls off again as the spectrometer acceptance decreases very rapidly at very low energies.

Next a timing cut against prompt pions, a cosmic ray cut and several cuts on tracking parameters are applied to the data. The time spectrum of the remaining events with energies between 56 MeV and 100 MeV (see figure 4) has, as a very prominent feature, an exponentially decaying RMC component from muon stops in the gold target walls ($\tau_\mu^{Au} = 73ns$). The events occuring later than $5\,\tau_\mu^{Au}$ are considered to be hydrogen RMC events. The combination of this timing cut with the other cuts results in the RMC spectrum shown in figure 5. Between 56 MeV and 100 MeV there are 27 protium RMC candidates.

This result can be confirmed by the analysis of data taken with a μ^+ beam. Positive muons produce no RMC signal since the positive particles are not captured by the nucleus, and thus the photon spectrum from μ^+ stops in the detector shows mainly the background effects present in the μ^- data. The μ^+ photon spectrum does not have a pion background and additional photons from positron annihilation in flight show up. Nevertheless the bremsstrahlung spectrum and its high energy tail due to the detector resolution can be investigated in this way. In that part of the August beam time dedicated to measurements with positive muons 5.17×10^{10} stops ($\equiv$ 1.2 days livetime) were examined. The final photon energy spectrum (see figure 6) shows only three events above 56 MeV. Two of them are just above the limit and may very well belong to the tail from the bremsstrahlung spectrum. The event near 100 MeV is consistent with an expected cosmic ray background leaking through all cuts (see below).

The comparison with the μ^+ data strengthens the confidence in the RMC candidates of the μ^- photon spectrum. However, additional corrections are necessary. The cosmic ray background cannot be completely suppressed due to its small neutral component. A long study in October 1990 showed that 0.3 ± 0.1 cosmic ray events per day remain in the 56 MeV to 100 MeV range of the photon spectra after all cuts. Therefore one of the RMC candidates is expected to be a cosmic ray event. Corrections of similar order are also necessary for the gold RMC events which survive the timing cut and the ^3He RMC events due to the small deuterium component in the target. The final number of hydrogen RMC events is 23.

The photon acceptance is verified by detecting photons which are produced by a negative pion beam stopping in the hydrogen target. Through charge exchange (60 %) or pion capture reactions (40 %) photons are created which are uniformly distributed between 55 MeV and 83 MeV or monoenergetic at 129 MeV, respectively. Figure 7 shows the measured spectrum and the results of a Monte-Carlo simulation using GEANT. The experimental acceptance for photons from the charge exchange reaction is 0.53 % and agrees very well with the value obtained from the simulation.

5. CONCLUSION

The first measurements with the RMC detector are very encouraging: approximately 23 events (after background subtraction) from the previously unobserved Radiative Muon Capture reaction on hydrogen have been collected. In a 3-week period in December 1990 and in a 4-week period in January–February 1991 the detector has examined an additional 108×10^{10} μ^- stops. The data from these two recent runs are currently being analyzed. It is estimated that 400 RMC events will be required to obtain the value of g_P to 10 % accuracy.

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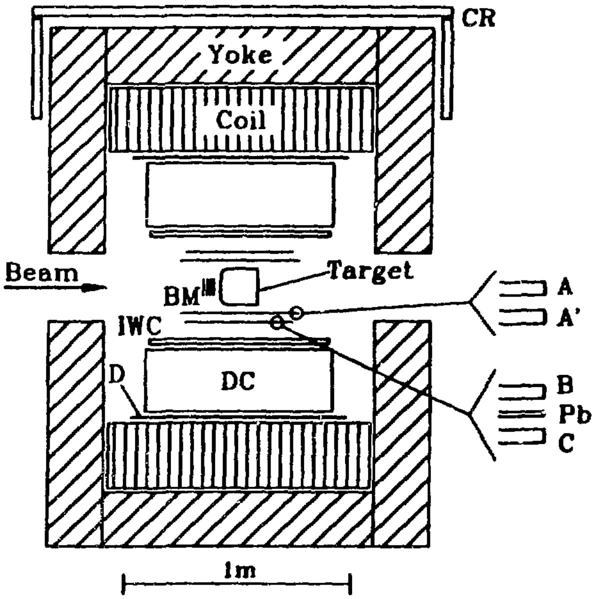

Figure 1: The detector (BM, A, A', B, C, D: scintillators; Pb: lead converter; IWC: Inner Wire Chamber; DC: Drift Chamber; CR: Cosmic Ray anti-counter)

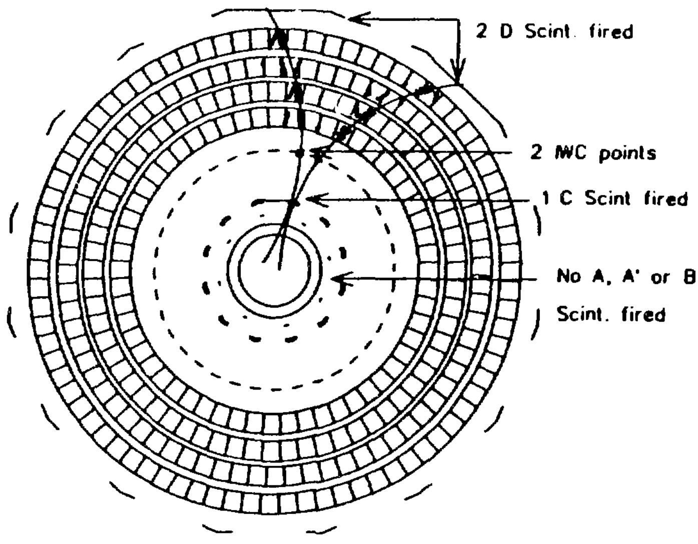

Figure 2: A photon pair conversion in the RMC detector. The position of the fired scintillators and wires at the middle plane ($z = 0$) is shown. Drift chamber hits appear twice due to the left-right ambiguity. The hits of the third drift chamber layer (stereo layer) appear displaced from the fitted tracks in this on-line display.

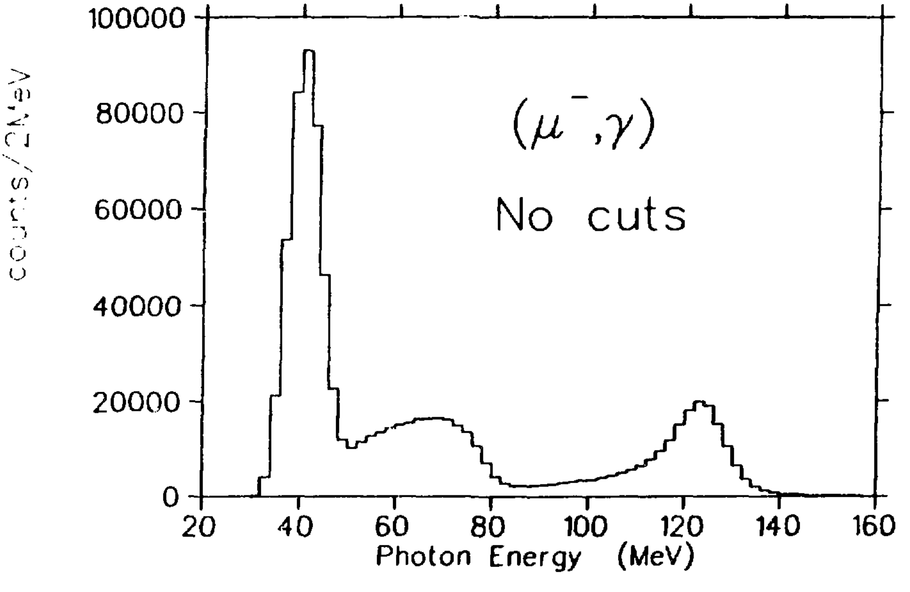

Figure 3: Photon energy spectrum obtained from μ^- data sample without cuts.

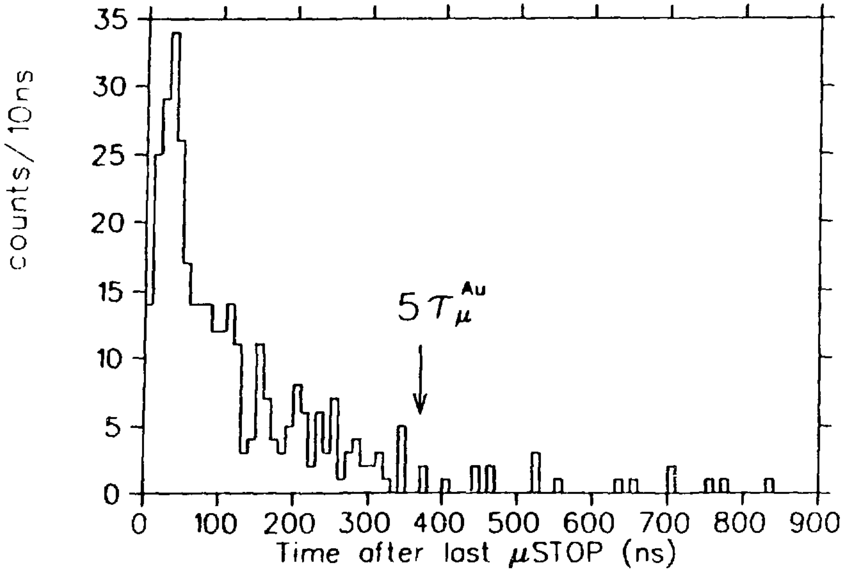

Figure 4: Time spectrum of photon events after cuts (56 MeV < E_γ < 100 MeV).

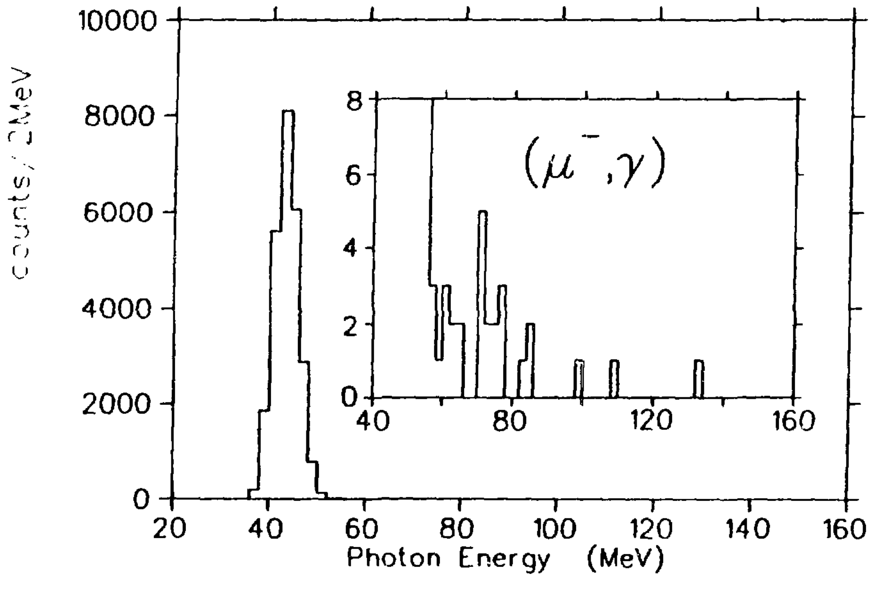

Figure 5: μ^-p photon energy spectrum after all cuts.

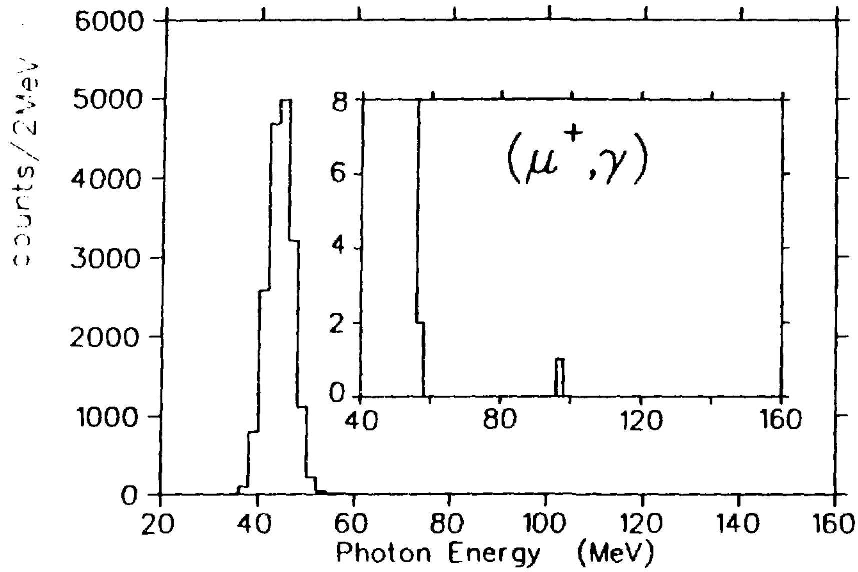

Figure 6: μ^+p photon energy spectrum after all cuts.

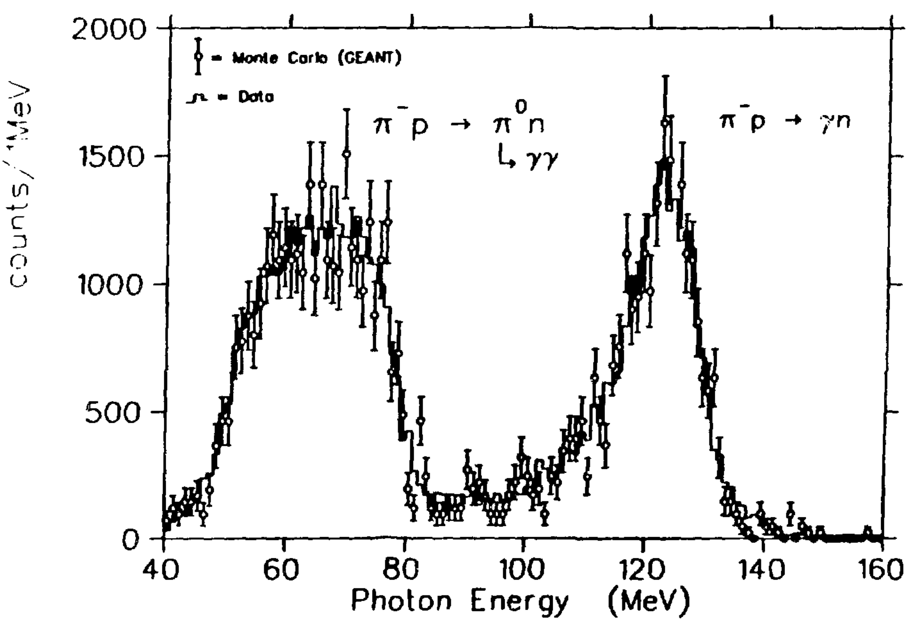

Figure 7: Photon energy spectrum obtained from π^- data sample and from Monte-Carlo detector simulation.