OBSERVATION OF μ^- CAPTURE IN LIQUID HYDROGEN*

Roger H. Hildebrand
Argonne National Laboratory, Argonne, Illinois and The University of Chicago, Chicago, Illinois
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The $(pn)(\mu\nu)$ interaction responsible for the basic capture process,

$$\mu^- + p \rightarrow n + \nu, \qquad (1)$$

is to date the least well investigated leg of the Puppi triangle which unites the three weak interactions that are supposedly governed by the universal Fermi interaction of the type V-A. We report here the observation of this process in a hydrogen bubble chamber, and a rough evaluation of the absolute capture rate. The results presented here are preliminary in character.[1]

In fact, reaction (1) has never before been observed directly. Our understanding of it is inferred from experiments on μ^- capture by complex nuclei, and from $\pi \rightarrow \mu(e)$ decay. Extensive measurements of μ-capture rates for nuclei from Be to U, such as those of the Chicago group,[2,3] can, in view of the complications of nuclear physics, at best be used to verify that "restricted universality" (i.e., the equality of the strengths) holds to ~20% in the comparison of β decay and μ capture. From the analogy of the vertices in $\pi \rightarrow \mu(e)$ decay and in $\mu(e)$ capture, and the excellent agreement between theory and experiment for the $(\pi \rightarrow \mu)/(\pi \rightarrow e)$ branching ratio,[4] we may reasonably conclude that the GT part of the $(pn)(\mu\nu)$ interaction is A, and of essentially the same strength as the A coupling in $(np)(e\nu)$. On the other hand, little is known about the F part of this interaction or about the relative phase of the GT and F couplings.

One can avoid the nuclear complications by studying reaction (1) directly, e.g., in a hydrogen bubble chamber. It is well known that new atomic and molecular problems appear when muons come to rest in liquid hydrogen,[5-8] but it can by now be shown that these problems are soluble. The questions we must answer before we can interpret the results have been clearly stated by Telegdi[9]:

"(1) What fraction of their lifetime do the μ^-'s spend as $(p\mu^-)$ atoms, and what fraction as $(p\mu p)$ 'molecules?'

(2) What are the populations, of specified relative μ-p spin orientations S $(S = S_\mu + S_p = 0, 1)$ in the relevant μ atoms and molecules, at the instant of capture?

(3) What are the exact probabilities, $|\psi(0)|^2$, for finding the muon at the proton(s) in the systems of interest?"

The first of these questions can be answered by experiment.[10,11] Preliminary measurements by a Columbia group[11] indicate that the μ's spend about $\frac{1}{4}$ of their lifetime in (μp) atoms and $\frac{3}{4}$ of their time in $(p\mu p)$ molecules. Weinberg estimates[12] that nearly all the $(p\mu p)$ molecules will be in the ortho, $L = 1$ state (proton spins parallel) at the time of capture. He shows that the answers to the second and third questions are perfectly calculable. The calculation has not yet been made but Weinberg has shown that for V-A interactions the ratio of the relevant molecular to atomic capture rates must lie between 0.44 and 0.88. For a $V+A$ theory it can be shown that this ratio is 1.16. We see that if the experimental problems can be solved the results will be meaningful.

The technique used in this experiment is an extension of that discussed by Wheeler in 1953.[13] A $99\frac{1}{2}$% pure muon beam from the Chicago cyclotron is brought to rest in an 8-liter hydrogen bubble chamber; the quoted purity is a limit inferred from the fraction of nondecaying stopping particles. The incoming particles are identified as muons by their residual range vs curvature in the 20-kilogauss field of the chamber. Reaction (1) is identified by the absence of a decay electron and by the appearance of a recoil proton created by the neutron.

Since the expected capture rate is very low (of order one capture to 1000 decays), our method of identification must exclude pion captures, or μ captures in elements of $Z > 1$, both of which produce nondecaying meson tracks and emit neutrons. Furthermore, we must in no case associate nondecaying meson tracks with recoil protons due to the general background of low-energy neutrons near the meson beam. The success of the experiment thus depends on one's ability to determine with adequate precision the energy of a neutron emitted from the end of a meson track by measuring the range and direction of a recoil proton it is supposed to have caused. This technique has been critically investigated with the same bubble chamber by Pyka[14] by studying the neutrons from radiative π^- capture [see Fig. 1(a)]. He obtains a Panofsky ratio 1.53 ± 0.10 and a neutron energy $E_n = (8.86 \pm 0.05)$ Mev, both of which are in excellent agreement with accepted values. We may thus be confident that the bubble chamber can be used as

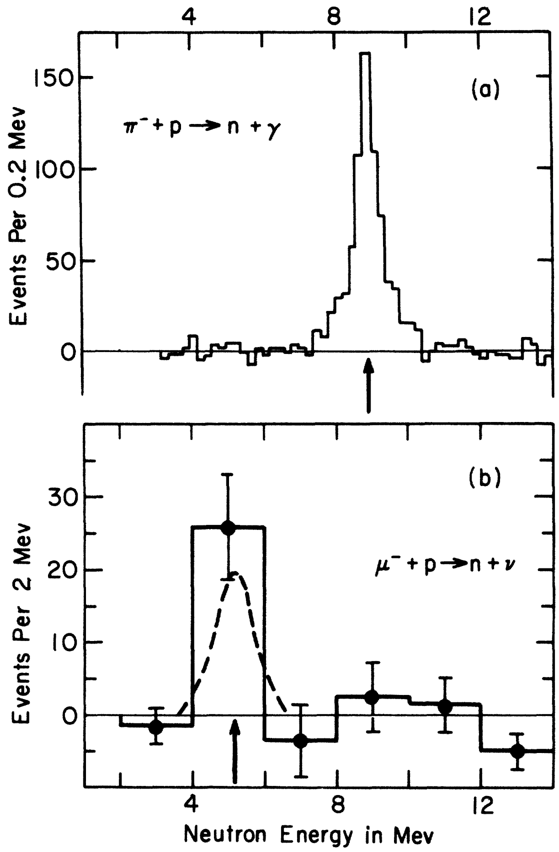

FIG. 1. Neutron spectra obtained from π^- captures (a) (Pyka, reference 14) and μ^- captures (b). The arrows indicate the predicted energies of the neutrons for the two reactions (8.88 Mev and 5.22 Mev). The dashed curve shows the expected resolution for the μ-capture experiment. The background (Fig. 2) has been subtracted.

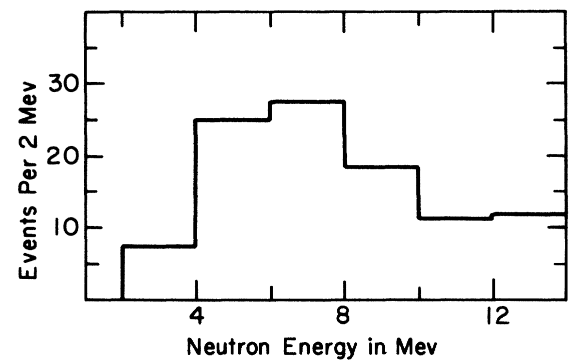

FIG. 2. Background neutron spectrum determined by connecting decaying μ's by hypothetical neutron paths to recoil protons appearing in the same pictures.

a low-energy neutron spectrometer of known efficiency and adequate resolution.

Our preliminary data for the μ-capture experiment yield the neutron spectrum shown in Fig. 1(b). An experimentally determined background has been subtracted. This background (Fig. 2) was obtained by connecting decaying muons by hypothetical neutron paths to all recoil protons appearing in the same pictures. Our background subtraction is hence an absolute one.

The capture rate may be obtained alternatively from the fraction of nondecaying muon tracks. This second method is valid only if captures in impurities can be excluded a priori. In experiments performed in this laboratory, Schiff[15] showed that in H_2 containing 100 ppm (parts per million) of Ne one half of the muons are transferred from hydrogen to Ne. We assume that other impurities would act similarly. Since the μ-capture rate in Ne or other impurities of $Z \gg 1$ is orders of magnitude faster than that expected for hydrogen, such contamination could be a serious problem even at 1 ppm—the upper limit set by our analysis for N_2 and O_2. A second possible source of error is that of confusing pions with muons. With our chamber (20-kgauss field) this is not serious. We know from studies of the residual range vs curvature of a large sample of identified pions that the π's can be excluded (to $< 5 \times 10^{-2}$). With a μ beam containing $< \frac{1}{2}\%$ π's, this corresponds to better than $3:10^4$ rejection. Failure to observe low-energy decay electrons is also found to be a negligible source of error. Our principal concern, therefore, is the problem of impurities. In any event, this second technique will yield an upper limit to the capture rate, and it has the advantage of being ~10 times more efficient.

For both of the techniques discussed above, one has to make an allowance for the presence of deuterium. If the recoil protons are measured, capture by D or He^3 will not be confused with capture by protons, but the rate of capture by protons will be lower than for isotopically pure hydrogen. The hydrogen used in this experiment had a deuterium concentration of 22 ± 2 ppm.[16] We estimate that this should reduce the observed capture rate by protons by somewhat less than 15%. If the recoil protons are not measured then capture by D and He^3 will roughly cancel the reduction in capture by protons. The deuterium correction need not be discussed in detail here since the statistical error attached to our present result is about 28% and since we shall soon use hydrogen of 5 times greater isotopic purity. No correction for the effect of deuterium has been made to the figures presented here. The only chemical impurity detected in the H_2 used in this experiment was He, with a concentration of 50 ppm. Schiff[15] has shown that the transfer rate of μ's to helium is so low that we should not expect this He contamination to introduce a measurable error.

Our preliminary results may be summarized as follows:

N_{rec} = (net number of 5.2-Mev neutrons identified by recoils of length $\geq$0.8 mm) = 26 ± 7.2.

ϵ = (efficiency of bubble chamber as a detector for 5.2-Mev neutrons counting recoils $\geq$0.8 mm) = 0.120.

E = (scanning efficiency for recoils $\geq$0.8 mm in pictures with nondecaying μ's) > 0.99.

N_{cap} = (number of captures determined by recoil proton method) $= N_{rec}/(\epsilon E) = 217 \pm 58$.

N_{nd} = [number of nondecaying μ's (we expect $N_{nd} = N_{cap}$ if no capture by impurities)] = 385 ± 40.

N_s = (number of stopping μ's) = 235×10^3.

From these figures and the mean life of the muon ($\tau_\mu = 2.203 \times 10^{-6}$),[17] we obtain the capture rate shown in Table I.

From this work we conclude:

A. (1) Reaction (1) does occur in liquid hydrogen as expected. (2) There are no fundamental obstacles to prevent considerable improvement of this experiment. We comment below on this.

B. Accepting Weinberg's arguments[12] about the molecular aspects of the problem, then (1) the capture rate is consistent with the "universal" V-A capture theory[18]; (2) the $V+A$ variant of that theory can be excluded.

Although the statistical accuracy of the bubble chamber approach to the μ-capture problem is thus far limited, this approach has the advantage that the detection efficiency and the background can be readily and accurately determined. Furthermore, we are improving this experiment in the following respects: 1. The statistical accuracy is being increased by reducing the neutron background and by accumulating more events. 2. Hydrogen of 5 times greater isotopic purity will be used in future runs. This should essentially eliminate all allowance for deuterium. 3. By using hydrogen of greater chemical purity (such as can be obtained with commercial palladium leak purifiers), method 2 will be made more reliable.

I acknowledge with gratitude the encouragement, stimulation, and enlightenment I have received from V. L. Telegdi during the long preparation of this experiment. I also wish to thank Professor H. Primakoff, Professor S. Weinberg, Professor L. Lederman, and Dr. S. Cohen for helpful discussions. The bubble chamber was constructed in collaboration with Professor S. C. Wright. The experiment could not have succeeded without the cooperation of the cyclotron crew and the bubble chamber group. In particular, I wish to thank E. Denton, J. Doede, R. Handler, H. Kobrak, P. Kloeppel, S. Lucero, M. Pyka, A. Saulys, and S. C. Wright for their help in operating the chamber. I also wish to thank J. Berryhill, L. McDonnell, and K. Richey for directing the scanning and measuring, respectively, and M. Schiff and B. Garbow for developing the track analysis system. I am grateful to J. Doede for help with the analysis of events and to C. Stevens for analyzing the hydrogen. I wish to emphasize the dependence of this work on the experiments by Pyka[14] and Schiff[15]

Table I. μ-capture rate in liquid hydrogen (density 0.056 g/cm^3). The theoretical figures were obtained assuming $\Lambda(\frac{1}{2},-\frac{1}{2};{}_1H^1) = 636$ sec^{-1}, $\Lambda(\frac{1}{2},+\frac{1}{2};{}_1H^1) = 13$ sec^{-1} (Primakoff[a]).

Experiment[b]	
Method 1: Events identified by nondecay of muons and by recoil protons. $\Lambda = N_{cap}/(\tau_\mu N_s)$	$\Lambda = 420 \pm 120$ sec^{-1}
Method 2: Events identified only by nondecay of muons. $\Lambda \leq N_{nd}/(\tau_\mu N_s)$	$\Lambda \leq 710 \pm 75$ sec^{-1}
Theory[c]	
$V-A$: (Weinberg[d] limits correspond to $\xi = \frac{1}{2}$ and $\xi = 1$)	$300 < \Lambda < 565$ sec^{-1}
$V+A$: (Wolfenstein[e])	$\Lambda < 200$ sec^{-1}

[a] See reference 5.

[b] The experimental figures are not corrected for the deuterium contamination (22 ± 2 ppm). We assume that method 2 gives a higher value because of the presence of impurities.

[c] The theoretical figures were computed assuming that the μ's spend all their lifetime in $p\mu p$ molecules.

[d] See reference 12.

[e] L. Wolfenstein, Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester (Interscience Publishers, Inc., New York, 1960), pp. 529-537. See also Ya. B. Zel'dovich and S. S. Gershtein, J. Exptl. Theoret. Phys. (U.S.S.R.) 35, 821 (1959) [translation: Soviet Phys.-JETP 8, 570 (1959)]. These authors emphasize the strong spin dependence, but they do not discuss the molecular case.

using the same bubble chamber. The muon exposure and event measurement were done at the Enrico Fermi Institute for Nuclear Studies, and the scanning and analysis at Argonne National Laboratory.

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[18]By "universal" we mean that the coupling constants for muon capture are those equivalent to, and derived from, the β-decay coupling constants; see Primakoff, reference 6.

LOW-ENERGY CHARGED MESON PHOTOPRODUCTION

J. K. Walker and J. P. Burq
Ecole Normale Supérieure, Laboratoire de l'Accélérateur Linéaire, Orsay, Seine et Oise, France
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Recently the discrepancies which still exist in the study of low-energy π-meson photoproduction have been discussed.[1] It was emphasized that a new and rather precise experiment by Adamovich et al.[2] on the reaction $\gamma + p \rightarrow \pi^+ + n$ at a gamma-ray energy of 185 Mev was in sharp disagreement with the old results of Beneventano et al.[3] Both these experiments were performed using nuclear emulsions to detect the positive pions and it seemed strange that such a wide disagreement should have been found. In particular, the disagreement was not in the form of absolute normalization (which has usually been the source of greatest error in photon-induced experiments), but rather it seemed to exist as an energy or angular dependence.

In an attempt to resolve this discrepancy, we have measured the angular distribution of π^+ mesons from hydrogen at 185-Mev gamma-ray energy using a bremsstrahlung beam of maximum energy of 220 Mev produced by the electron linear accelerator of the Ecole Normale Supérieure.

In this reaction, pions produced at backward angles have energies of the order of 12 Mev, whereas at forward angles energies of 40 Mev are reached. Due to the long path length (2.6 meters) from source to image of the double-focusing magnetic spectrometer which was used, the percentage of mesons which decay varies from 60% to 40% between the above two energies. If a detection system at the focal plane of the spectrometer can distinguish pions from muons of the same momentum, then this large energy-dependent correction can be made to the data. However, as the experiment depended critically on the fact that there should be no systematic energy-dependent error present, we adopted an alternative approach which required no energy-dependent correction at all, but relied on the analysis of several experimental sets of data at fixed momentum