MUON CAPTURE IN LIQUID HYDROGEN*

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(Received February 21, 1962)

We are reporting an observation of the muon-proton capture reaction,

$$\mu^- + p \rightarrow n + \nu. \tag{1}$$

Negative muons were stopped in a liquid hydrogen target and the 5.2-Mev neutrons from (1) were detected in liquid scintillation proton recoil counters. The initial state in (1) may be either a μp atom in the $1s$ state or a $(p\mu p)^+$ molecular ion. A meaningful interpretation of the observed capture rate requires a knowledge of the relative muon-proton spin orientation and the muon-proton wave function overlap.

Our information concerning the initial state is derived from several sources. The μp atom reaches the singlet state in <1 nsec.[1] The mean transition time from μp to $(p\mu p)^+$ in pure liquid hydrogen was determined to be 0.7 ± 0.3 μsec in a related experiment.[2] The dominance of the $1s\sigma g$ ortho $(p\mu p)^+$ state at formation has been given by theory,[1,3] as has its stability against transition to the ground (para) state. The stability is confirmed by this experiment.

Neutron counting began 1 μsec after the incident muon pulse. This has the effect of weighting the $(p\mu p)^+$ state very strongly. The principal result then is a determination of the muon capture rate from the molecular state:

$$\Lambda_{p\mu p} = 515 \pm 85 \text{ sec}^{-1}.$$

Our result is in agreement with the bubble chamber capture rate of 420 ± 120 sec^{-1} reported by Hildebrand.[4] His muon initial state, predominantly $p\mu p$, includes known admixtures of μp, μd, and $p\mu d$, and should be scaled up (or our result down) by 10% for a direct comparison.

In this preliminary report we outline the main features of this experiment. A sketch of the geometry may be found in reference 2.

1. Data taking rate. The observed rate is ~10^{-3} of the muon decay rate: $\lambda_0 = 0.45 \times 10^6$ sec^{-1}. The real neutron rate was ~8 counts per hour. Pulses from all counters were photographed on two oscilloscopes. Accidental neutron events were 10% of the real rate.

2. Hydrogen target. A 15-liter cryogenic target was constructed and filled with liquid protium ($_1H^1$). High purity was achieved by the following steps: The target was outgassed by ionic pumping for 60 hours at 150°C, reaching an ultimate pressure of 3×10^{-6} mm. It was then cooled by filling a separate cold reservoir with commercial liquid hydrogen. Subsequent desorption rates from all sources were entirely negligible. Protium liquid was then formed by passing in hydrogen gas from which deuterium and other impurities, except He, had been removed via fractional distillation. The incoming gas passed through a palladium filter[5] and a cold trap at ~30°K. Reasonable estimates of the effect of these precautions lead to impurity concentrations of $\ll 10^{-9}$ except for $_1H^2$ which was measured to be $\lesssim 1$ ppm.[6] Since transfer rates to low-Z impurities have been measured[7] to be ~5×10^{10} sec^{-1}, our conditions preclude any significant transfer.[4] The possibility of counting neutrons from muons stopping in the walls is reduced by constructing the 8-in. diameter target exclusively of high-Z materials. The wall background is then short-lived and amounted to an 8% correction to the data taken after 1 μsec.

3. Muon beam. A purified 125-Mev/c muon beam, duty cycle ≈30% and containing less than 1% pions and electrons before moderation, was collimated to three inches in diameter at the thin entrance window of the target. The distribution of muon endings in the hydrogen was measured by scanning with a small counter in a Styrofoam dummy target.

4. Neutron detectors. Pulse shape discrimination along the lines developed by Brooks[8] was employed to distinguish neutrons and γ rays. A Monte Carlo calculation of the over-all detection efficiency was made using an IBM 7090. The code included the effects of neutron scattering in the hydrogen, target and counter walls, local shielding, carbon collisions, etc. The results of the calculation were confirmed by experiments carried out with the Nevis neutron velocity selector.

A background of 18% arises from photoneutrons produced by decay electron bremsstrahlung. These were directly observed by stopping positive muons in the hydrogen target.

The corrected neutron energy spectrum, together with the result of the Monte Carlo calculation, is shown in Fig. 1. The time distribution

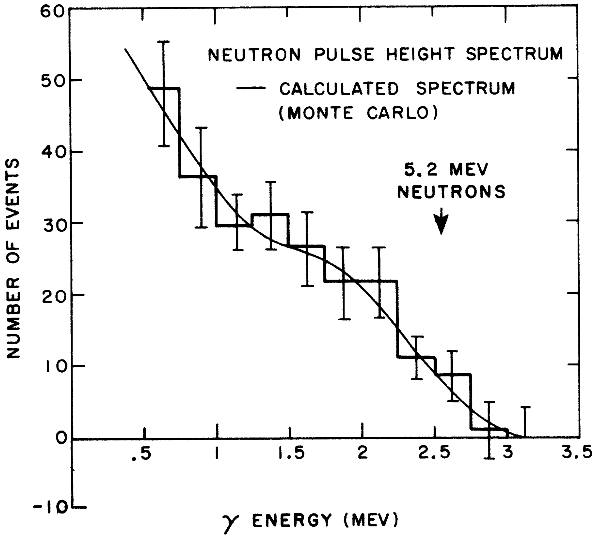

FIG. 1. Energy spectrum of neutrons from $\mu^- + p \to n + \nu$. The response of liquid scintillator to proton recoils is nonlinear and the energy scale is set by a series of γ-ray sources. The solid line is the expected neutron spectrum on the basis of a Monte Carlo calculation.

of the 279 real neutron counts is shown in Fig. 2.

Gershtein and Zeldovitch[9] and Weinberg[3] have discussed the properties of the $(p\mu p)^+$ system in relation to the capture process (1). Weinberg has expressed the $(p\mu p)^+$ capture rate as a linear combination of μp atomic capture rates appropriate to the singlet (Λ_0) and triplet (Λ_1) states:

$$\Lambda_{p\mu p}^{\text{theor}} = (2\gamma_0)[\eta\Lambda_0 + (1-\eta)\Lambda_t]. \qquad (2)$$

The factor $2\gamma_0 = 1.17$ is a measure of the enhanced muon density in the more tightly bound molecule and is calculated from the molecular wave function of Cohen et al.[1] The factor η is bounded by the values $\frac{3}{8}$ and $\frac{3}{4}$. It departs from the upper limit only in so far as the hyperfine interaction mixes states of total spin $\frac{3}{2}$ with those of spin $\frac{1}{2}$. However, an examination of the influence of the various spin-spin and spin-rotation interactions involved in the calculation of η indicates that the mixing is in fact small. This is confirmed by more detailed calculations performed in this laboratory[10] leading to the result $\eta = \frac{3}{4}$ with an uncertainty of a few percent.

The values $\Lambda_0 = 636\ \text{sec}^{-1}$ and $\Lambda_1 = 13\ \text{sec}^{-1}$ were calculated by Primakoff[11] using the V-A theory of weak interactions and the current conjectures concerning renormalized and induced couplings. Thus, from (2),

$$\Lambda_{p\mu p}^{\text{theor}} = 560\ \text{sec}^{-1}.$$

We conclude, as have others,[4,12,13] that the $V+A$ variant of the theory is ruled out since this theory predicts $\Lambda_{p\mu p} < 200\ \text{sec}^{-1}$. Beyond this, suppose one asks the question: What is actually known about the coupling constants in muon capture? The magnitude and universality of the axial vector contribution is established by $\pi \to \mu + \nu$ and $\pi \to e + \nu$, by the recently reported He^3 experiment,[14] and also by the analysis of various capture rate experiments in complex nuclei.[15] The recently observed spin dependence[12,13] also establishes the presence of G_A, but, as recently emphasized by Wolfenstein,[16] all these data give very little information concerning the vector interaction. Thus we can use the result of this experiment to evaluate the ratio of Fermi to Gamow-Teller couplings, $(g_V/g_A)_\mu$ (regarding all other parameters as correctly given by the theory and/or experiment).[17]

We obtain, including only our experimental uncertainty of 17%:

$$(g_V/g_A)_\mu = -0.70 \pm 0.21,$$

in accord with the hypothesis of bare-nucleon-lepton V-A coupling and muon-electron universality.

Two additional points can be inferred from our measurements. (a) The adequacy of the time fit of Fig. 2 shows that the ortho-para conversion rate in the $p\mu p$ system is less than 10% of the muon decay rate. (b) Since the environmental perturbations on the decay of muons in hydrogen are so very small, one can make a sensitive test of the validity of TCP invariance in weak interactions. This is the requirement of equality of particle and antiparticle lifetimes. Frequent monitoring of the time decay spectrum of the electrons and direct comparison with the positrons from positive muon decay show the equality of the lifetimes to ~2%.

Experiments are in progress to repeat and improve the present measurements. It may also be possible to observe process (1) initiated from the $(p\mu d)^+$ molecular ion. This ion has several interesting features; the population and nature of the four hyperfine states can be directly studied through the mechanism of muon-induced nuclear fusion.[2] If we write, in analogy to Eq. (2),

$$\Lambda_{p\mu d}^{\text{theor}} = \gamma'[\eta'\Lambda_0 + (1-\eta')\Lambda_t], \qquad (3)$$

it can be shown that η' is small and slowly time

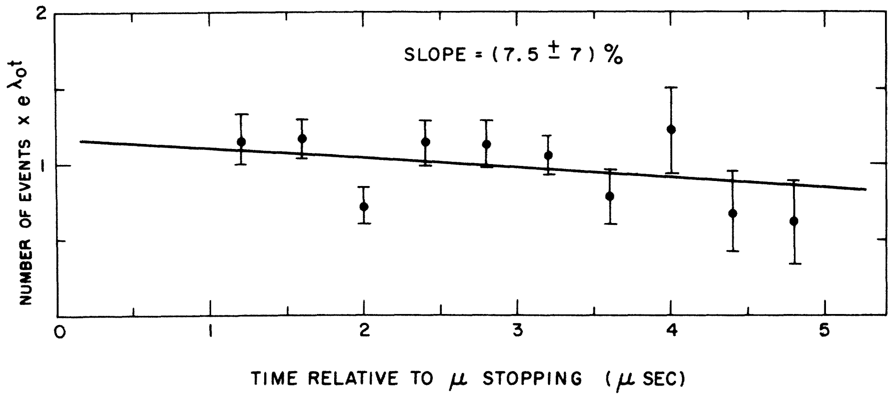

FIG. 2. The time distribution of neutrons following the muon stopping. The number of events in each time interval has been multiplied by $e^{\lambda_0 t}$ to remove the time dependence characteristic of electron decay.

dependent. This time variation is a result of the different fusion rates for the four hyperfine states. We have considered in detail the magnitude and variation of η'. We note here only that such a measurement may compete with the technically difficult observation of μp triplet capture in dilute hydrogen gas.

We would like to especially thank the following individuals: E. W. Anderson and I. T. Wang for participation in the latter phases of the experiment; Dr. M. Kalos of United Nuclear Corporation Development Division for valuable discussions concerning the Monte Carlo calculations; Yin Au for engineering of the hydrogen target; S. Meravy for construction and operation of the target; and A. Halpern and N. Kroll for discussions on the theory of molecules.

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*Research supported by the Office of Naval Research.

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[3] S. Weinberg, Phys. Rev. Letters 4, 575 (1960).

[4] R. H. Hildebrand, Phys. Rev. Letters 8, 34 (1962). An upper limit of 720 $\sec^{-1}$ is also given in this paper, based on the observed number of muon stoppings without electrons. Assuming the theoretical rate for He^3 capture,[11] the upper limit is reduced to 570 $\sec^{-1}$. The transfer to impurities is thus relatively small when reasonable precautions are taken.

[5] Our measured ratio of He to H_2 passage through palladium is $<10^{-6}$. This is determined by comparing leakage rates with the palladium thimble evacuated and pressurized. The inequality results because no difference is observed.

[6] We would like to thank Dr. R. Hildebrand and Mr. C. Stevens of Argonne National Laboratory and also Dr. D. Rittenberg and Dr. I. Sucher of Columbia Medical School for doing the hydrogen assays.

[7] M. Schiff, University of Chicago, Enrico Fermi Institute of Nuclear Science EFINS-61-33 Report 351, 1961 (unpublished); V. P. Dzhelepov, P. F. Yermalov, Ye. A. Kushnirenko, V. I. Moskalev, and S. S. Gershtein, Dubna Report D-812, 1961 [Nuclear Phys. (to be published)]. See also theoretical considerations of S. S. Gershtein and V. D. Krivchenkov, J. Exptl. Theoret. Phys. (U.S.S.R.) 40, 1491 (1961) [translation: Soviet Phys.–JETP 13, 1044 (1961)].

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[15] See, for example, Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester (Interscience Publishers, Inc., New York, 1960), in particular L. Wolfenstein and V. L. Telegdi.

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[17] We follow the notation of reference 11. Small g's refer to the intrinsic couplings. For β decay, $(g_V/g_A)_\beta = -0.80$ with an uncertainty of about 10%. Another way of viewing our data is as follows: If only a universal Gamow-Teller coupling is assumed, $\Lambda_{p\mu p} \sim 300 \sec^{-1}$.