MEASUREMENT OF THE NUCLEAR CAPTURE RATE OF MUONS BY FREE DEUTERONS

A. Placci and E. Zavattini
CERN, Geneva, Switzerland

and

A. Bertin and A. Vitale
Istituto di Fisica dell'Università di Bologna, and Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy
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We have measured the nuclear capture rate of negative muons by deuterons in μd atoms. The experiment was performed by stopping negative muons in a target of ultrapure gaseous hydrogen at 7.6 atm with 5.2% deuterium and looking at the outgoing neutrons. The result is $\Lambda_{\rm expt} = 451 \pm 70\ {\rm sec}^{-1}$.

We report here the results of a measurement of the nuclear capture rate of muons by free deuterons, according to the reaction

$$\mu^- + d \to n + n + \nu_\mu. \quad (1)$$

As pointed out by Uberall and Wolfenstein[1] and by Wang,[2] Reaction (1) is chiefly attractive because, due to the presence of two neutrons in the final state, the Pauli exclusion-principle effect gives an opportunity of measuring an almost pure Gamow-Teller coupling.

The experiment was performed at the CERN synchrocyclotron (SC). The 130-MeV/c negative muons from the SC muon channel were stopped in ultrapure gaseous hydrogen at 7.6 atm pressure and 293°K, contaminated by 5.2% deuterium. The incoming muon rate was about 13 000 sec^{-1} with a duty cycle of 35%; the rate of muons stopping in the gas was about 20 sec^{-1}. Reaction (1) was identified by detecting the outgoing neutrons by means of liquid scintillation detectors.

For our conditions, one can state the following:

(i) Because of the high rate of the transfer process[3-6]

$$\mu p + d \to \mu d + p + 135\ {\rm eV} \quad (2)$$

and the chosen contamination of deuterium, the muons are transferred from the initially formed μp atoms to deuterium atoms within about 150 nsec.

(ii) The formation of $p\mu d$[3,7] and $d\mu d$[8] molecules is sharply reduced due to the low density of the gaseous hydrogen.

(iii) Transfer reactions from the μd atoms to other nuclei[9] are avoided, since both gases were filtered through a palladium purifier to achieve a high degree of purity.

(iv) The μd atoms are initially formed in a statistical mixture of doublet ($F = \frac{1}{2}$) and quartet ($F = \frac{3}{2}$) states,[10] with an initial kinetic energy of 45 eV.[5,6] They are then rather rapidly slowed down to thermal energies by scattering against the surrounding hydrogen and deuterium molecules.[4-11]

Several predictions for the rate of process (1) are available[1,2,12]; the latest ones are those given by Cremmer[12]:

$$\Lambda_d = 452.3\ {\rm sec}^{-1}, \quad \Lambda_q = 31.7\ {\rm sec}^{-1}, \quad (3)$$

where Λ_d refers to the doublet and Λ_q to the quartet spin state of the μd system.[13]

The apparatus used for the present experiment is quite similar to the one used by Alberigi Quaranta et al.[14] to measure the nuclear capture rate of muons by free protons. Figure 1 shows a simplified view of the experimental setup. The stainless-steel vessel T filled with deuterated hydrogen also contained three wire proportional counters (counter α, β, and γ in Fig. 1). The α grid was working in fast coincidence with the telescope of counters 1 and 2 to define the incoming beam. The quasicylindrical counters β and γ supplied anticoincidence signals; the stopping time of a muon in the useful volume of gas was defined by a "mu-stop" anticoincidence signal $[1, 2, \alpha, \sim(\sum A_i, \beta, \gamma)]$ (where ~ means "not").

The target and the operation of the proportional counters and of the N_i neutron counters have been described in previous papers.[14-16] Since the neutrons from Reaction (1) have an energy distribution sharply peaked around 1.4 MeV,[2,12] to improve the energy resolution in the present experiment the chosen neutron counters had smaller size (12.5 cm diam) than those used by Alberigi Quaranta et al.[14]; the energy resolution was 9% at 3 MeV (electron equivalent energy). The background of gamma rays in the neutron detectors was eliminated by pulse-shape discrimination.

The electronic logic was also extensively described elsewhere[14]; we shall recall here its

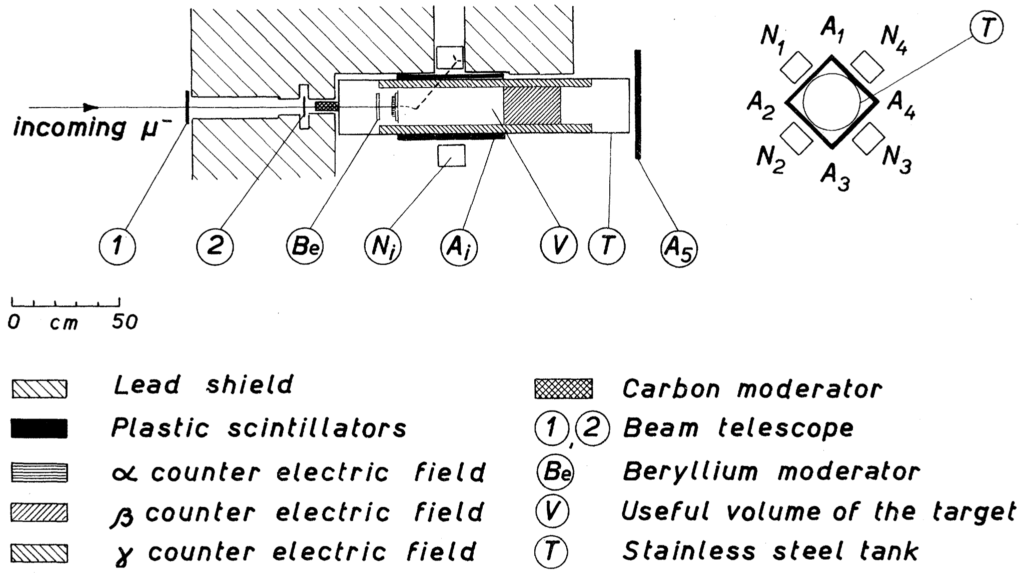

FIG. 1. Simplified scheme of the experimental apparatus.

main function. For every neutral event (i.e., a pulse in one of the neutron counters within a 9-μsec gate opened by the "mu-stop" signal) the electronics supplied a trigger (neutral trigger) which started recording the amplitude, the time, and the amplitude in the tail region of the pulse coming from the neutron counter. The last quantity was necessary to operate the neutron-gamma pulse-shape discrimination. The same information was photographed on the tracks of two double-beam oscilloscopes, together with the signals from counters β and γ.

To deduce the experimental rate Λ_{expt} for Reaction (1) it was necessary to know the number of muons stopped in hydrogen. With this aim, the measurements in the neutral trigger condition were alternated with measurements of the yield of the decay electrons coming from muons stopped in deuterated hydrogen, and separately detected by the four (A_i, N_i) telescopes (electron trigger).

In order to select the events due to process (1) from those collected in the neutral trigger condition, we went through the following steps:

(i) All events were rejected whose pictures showed a pulse within a time interval of 50 μsec on the oscilloscope tracks displaying the outputs of counters β and γ.

(ii) Only proton-recoil pulses corresponding to electron equivalent energies larger than 0.45 MeV and smaller than 2.55 MeV were finally accepted (proton energies ranging from 1.6 to 6.6 MeV).

(iii) Following the rules of pulse-shape discrimination, all the events for which the neutron-counter pulses located a point in the gamma region of the amplitude versus tail plot[16] were rejected.

(iv) A first selection in time was then performed accepting only those events having a delay larger than 0.4 μsec with respect to the muon stopping time.

The time distribution of the residual events was then fitted by an expression composed of the sum of two exponential terms plus a constant, in order to separate the neutrons due to process (1), to nuclear captures of muons by iron, and to the accidentials.

The time distribution of the events, after subtracting the accidentals, is shown in Fig. 2. The accidental counts turned out to be about 12% of the neutrons from process (1) counted in the first considered time channel. Besides the 2.2-μsec component, a contribution of neutrons having a time distribution characteristic of muon captures by iron nuclei is also present in Fig. 2: Such contribution is due to nuclear captures of muons directly stopping in the wires of the proportional counters α, β, and γ. The number of neutrons due to process (1) counted with a final lower time cut of 0.8 μsec was $N = 261 \pm 37$, where the error includes also the uncertainty with which the level of the accidentals was known.

To obtain the experimental rate Λ_{expt} it was necessary to know the efficiency of the neutron counters, which was determined by a Monte Carlo calculation, similarly to what was done,

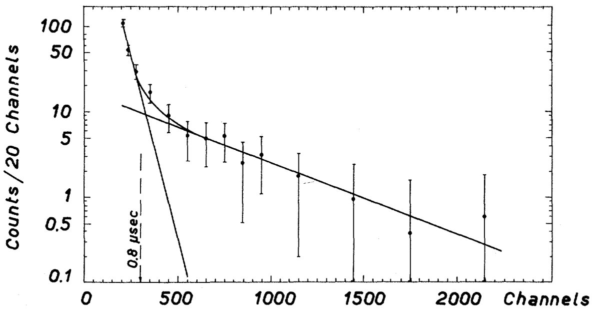

FIG. 2. Experimental time distribution of the neutron events after subtraction of the accidentals. The two straight lines correspond to the two components having 0.2 μsec (iron events) and 2.2 μsec (deuterium events) lifetimes. The arrow shows the time cut used in the analysis. Abscissa: 4.2 nsec/channel.

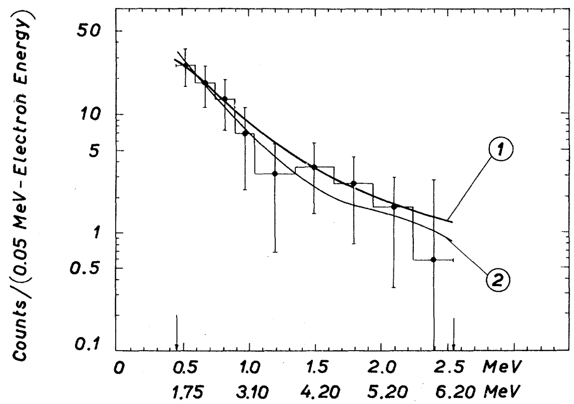

FIG. 3. Experimental energy spectrum of the pulses due to the 261 neutrons coming from Reaction (1). The energy cuts effected in the analysis are shown by the arrows. The solid lines represent the expected amplitude spectra (normalized to the number of events) calculated by the Monte Carlo method; curves 1 and 2 were obtained starting from the theoretical neutron energy spectra given by Cremmer (Ref. 12) and by Wang (Ref. 2), respectively. Upper scale, electron energies; lower scale, proton energies.

e.g., by Alberigi Quaranta et al.[14] The energy spectrum of the neutrons from Reaction (1) assumed in the Monte Carlo calculation was the one given by Cremmer[12]; however, calculations starting from the distribution given by Wang[2] gave only a small difference in the final results.

Figure 3 shows the experimental energy spectrum of the neutrons due to process (1). This distribution was obtained by subtracting from the total spectrum the energy spectra of the neutrons due to nuclear captures of muons by iron nuclei and to accidentals, which were observed in subsidiary measurements.

From the total number of neutrons N, the cal culated value of the overall efficiency of the neutron detectors, the number of decay electrons measured in correspondence to the N neutrons, and the efficiency of the apparatus for counting electrons, which was separately measured, the following value was extracted for the nuclear capture rate of muons by free deuterons:

$$\Lambda_{\text{expt}} = 451 \pm 70 \text{ sec}^{-1}. \qquad (4)$$

In order to compare our result (4) with the predictions given by Eq. (3), it is necessary to know what fraction of the μd atoms are in the doublet state at any given time, i.e., to know how the total spin of the μd systems evolves in time due to the process

$$(\mu d)_{F1} + p \to (\mu d)_{F2} + p, \qquad (5)$$

$F1$ and $F2$ are now two different values of the total spin of the μd system.[17]

Calculations of the cross section for scattering of μd atoms having a kinetic energy of the order of the thermal energies against protons were performed by Cohen, Judd, and Riddell[6] and by Belyaev et al.[4]; however, these authors neglect the spin interaction in their calculations.

For the present, then, we can say that, excluding large changes in the currently accepted values of the coupling constants g_A, g_V, and g_P, the result given by Eq. (4) is compatible with the predictions (3) if one assumes that the deexcitation process (5) (with $F1 = \frac{3}{2}$ and $F2 = \frac{1}{2}$) proceeds at a rate larger than $5 \times 10^5 \text{ sec}^{-1}$ in our experimental conditions.[18]

In this case, the value (4) is also in agreement with the corresponding result given by Wang et al.,[19] obtained by stopping negative muons in a target of liquid deuterated hydrogen, which is

$$\Lambda = 365 \pm 96 \text{ sec}^{-1}.$$

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[10]F is the total angular momentum quantum number of the μd system, which in the lowest orbital state ($L=0$) can be either $\frac{1}{2}$ or $\frac{3}{2}$. The energy difference between these two hyperfine states is 0.046 eV. In our conditions $KT=0.025$ eV, where K is the Boltzmann constant, and $T=293$°K.

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[17]The corresponding scattering reactions against deuterium molecules which produce a change in F occur to a negligible extent in our experimental conditions, as can easily be seen from the rates calculated by Gershtein (see Ref. 5) and measured by Doede (see Ref. 8).

[18]Among many other mechanisms, it is possible that the effect of the hyperfine mixing in the two total spin $J=1$ states of the colliding ($\mu d+p$) system may lead to this rate.

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PHOTOPRODUCTION OF RHO MESONS FROM HYDROGEN AND CARBON BY LINEARLY POLARIZED PHOTONS*

G. Diambrini-Palazzi†, G. McClellan, N. Mistry, P. Mostek, H. Ogren, J. Swartz, and R. Talman
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 12 June 1970)

The photoproduction of ρ^0 mesons from hydrogen and carbon has been measured at 3.5 GeV using polarized photons from coherent bremsstrahlung produced by 10-GeV electrons on a diamond crystal. Asymmetry ratios for carbon and hydrogen are measured and are consistent with the mainly diffractive nature of ρ^0 photoproduction. A small nondiffractive component is suggested in the case of hydrogen.

The photoproduction of ρ^0 mesons at 0° from hydrogen and carbon by linearly polarized photons of 3.5 GeV has been measured at the Cornell 10-GeV electron synchrotron. Coherent bremsstrahlung is produced by 9.7-GeV electrons striking a diamond crystal[1,2] mounted on a remotely controlled goniometer arrangement within the synchrotron. The photon beam is collimated to a divergence of 2×10^{-4} rad and is monitored by a thin-plate ion chamber, after which it passes through a 1-mil aluminum converter of a uniform-field electron-pair spectrometer system which measures the photon spectrum. The beam then passes through the rho-production target and is stopped in a uranium and lead plug in the first magnet of the rho-detection system. The rho apparatus is the same as described previously[3]; counter sizes and positions have been changed to obtain a narrower energy acceptance.

The diamond was aligned with the (110) crystal axis along the beam direction. It was then rotated to obtain a major peak in the bremsstrahlung spectrum at 4 GeV from the single reciprocal lattice point ($n_1=0$, $n_2=2$, $n_3=0$).[4,5] In the orientation labelled $D(V)$, the plane of polarization of the photons within the peak is approximately vertical, and thus perpendicular to the horizontal plane of detection of the $\pi^+\pi^-$ pair. The bremsstrahlung intensity spectrum measured by the electron-pair spectrometer (EPS) is shown