μ-MESONIC MOLECULES IN LIQUID HYDROGEN*

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We have undertaken a study of muon catalysis of the fusion reaction $p+d \rightarrow He^3+Q$ (5.4 Mev) in order to obtain information necessary to the unfolding of the molecular effects on the muon absorption reaction $\mu^-+p \rightarrow n+\nu$ taking place in liquid hydrogen. Such studies also serve as a useful method of observing the molecular systems $p\mu p$ and $p\mu d$ and of measuring the fusion rate initiated in an s state. The yield of fusion γ rays from pure hydrogen has been measured as a function of time relative to the muon stopping at six different deuterium concentrations. The present experiment is essentially an extension of the earlier work of Ashmore et al.[1]

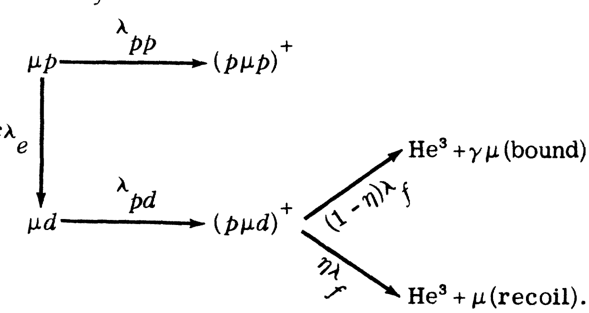
The sequence of events leading to the fusion process assuming dilute deuterium concentrations ($c \ll 1$) are as follows.[2]

(i) The μ^- is rapidly slowed down and captured into a $1s$ orbit about a proton. Exchange collisions result in a rapid (~5 nsec) depopulation of the triplet hyperfine level, leaving the μ^-p system entirely in the singlet state.

(ii) The thermal neutron-like μp atom then either forms a μ-hydrogen molecular ion (rate $=\lambda_{pp}$) or loses the muon to a deuteron ($c\lambda_e$).

(iii) The neutral μd atom can in turn form a $(p\mu d)^+$ molecule.

(iv) The latter, because of the small internuclear separation, can lead to $p+d$ fusion (λ_f). The Q value of 5.4 Mev can be given to a "rejuvenated" muon ($\eta\lambda_f$) via $E0$ internal conversion, or to an $M1$ γ ray $[(1-\eta)\lambda_f]$. Symbolically,



At each stage of the process, the muon can decay into $e+\nu+\bar{\nu}$ ($\lambda_0=0.45\times10^6$ sec^{-1}). Direct formation of $(p\mu d)^+$ from the μp system is negligible as are processes of higher order in c.

A schematic layout of the experiment is shown in Fig. 1. A purified 125-Mev/c muon beam [500 μ^-/sec with <0.5% (pions + electrons)] was brought to rest in a specially constructed target. This was initially filled with hydrogen having a deuterium content of 5 parts per million (ppm). Purity was obtained by careful outgassing of the completely closed "pure target" system, palladium filtering, and successive cold traps at near liquid hydrogen temperature.[3] Deuterium was later added in multiples of a standard concentration (c_0 = 110 ppm). The absence of pions and electrons was monitored by both range and time-of-flight measurements. A duty cycle of ~30% was obtained by electronically gating the optimum 75% of the synchrocyclotron vibrating target beam. The γ-ray pulses from the NaI counter were selected by a single-channel pulse-height window which was set at 4.0-6.0 Mev, using O^{16} (6.13 Mev) and C^{12} (4.43 Mev) γ rays as calibration standards. A large background of γ rays in this energy band arises from bremsstrahlung of μ-decay electrons; and capture γ rays and μ-mesonic x rays from the few percent of muons stopping in the high-Z target walls. These were almost completely eliminated by requiring a decay electron count in the 3.5 μsec subsequent to the detection of the fusion γ ray. The surrounding electron counters $\sum A_i$ subtended 60% of the total solid angle.

The data for 5-, 110-, and 8000-ppm D_2 concentrations appear in Fig. 2(a). Similar data for 220, 440, and 900 ppm were also obtained. Normalization was based on counts of decay electrons with muon stoppings as an additional check. Figure 2(b) shows the dependence of the time-integrated count on the D_2 concentration.

A solution for the coupled equations describing the population of the various states is readily obtained, if muon recycling is neglected.[4] A further simplification is the neglect of the hyperfine states in the $p\mu d$ molecule which influence the interpretation of λ_f.[2,5] The fraction of γ rays per stopped muon is

$$n(t)=(1-\eta)\lambda_f\lambda_{pd}c\lambda_e e^{-\lambda_0 t}\left(\frac{e^{-\alpha t}}{(\alpha-\lambda_{pd})(\alpha-\lambda_f)}+\frac{e^{-\lambda_{pd}t}}{(\alpha-\lambda_{pd})(\lambda_f-\lambda_{pd})}-\frac{e^{-\lambda_f t}}{(\alpha-\lambda_f)(\lambda_f-\lambda_{pd})}\right), \quad (1)$$

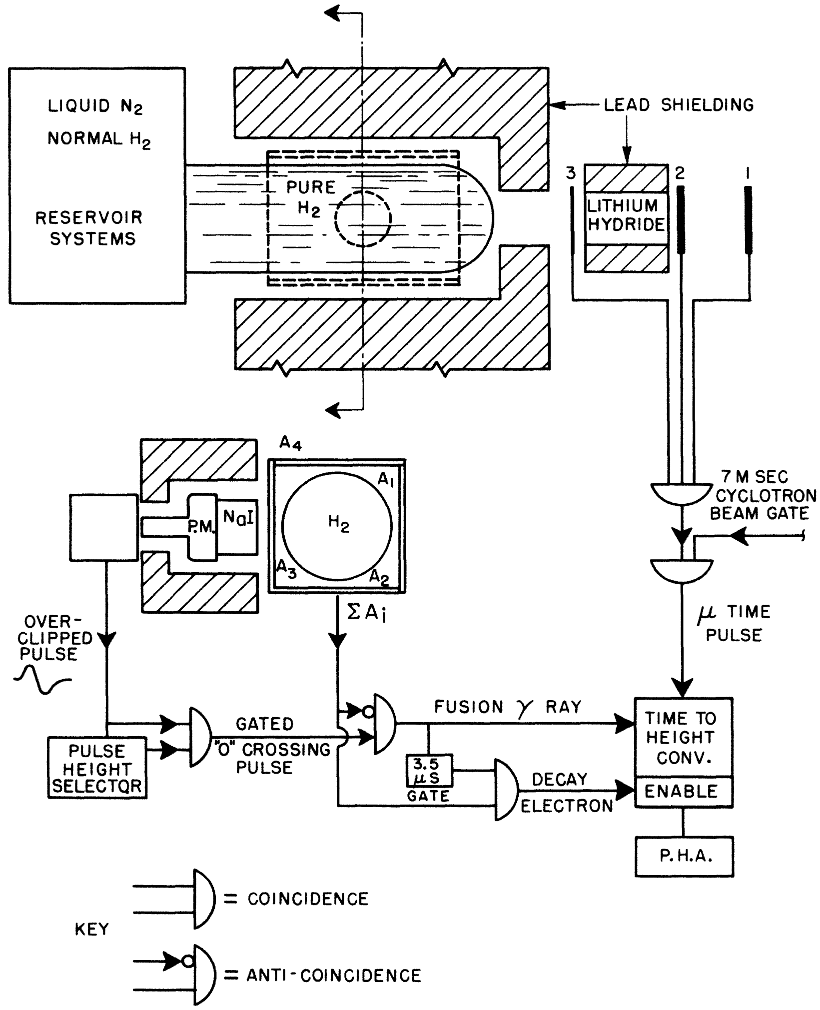


FIG. 1. Schematic layout of the experiment. Shielding details, beam optics, amplifier, delay, internal time-to-height converter logic, and other aspects have been omitted.

where $\alpha \equiv \lambda_{pp} + c\lambda_e$. Two time integrals are also used:

$$N_{\mathrm{I}} = \int_0^\infty n(t)dt$$

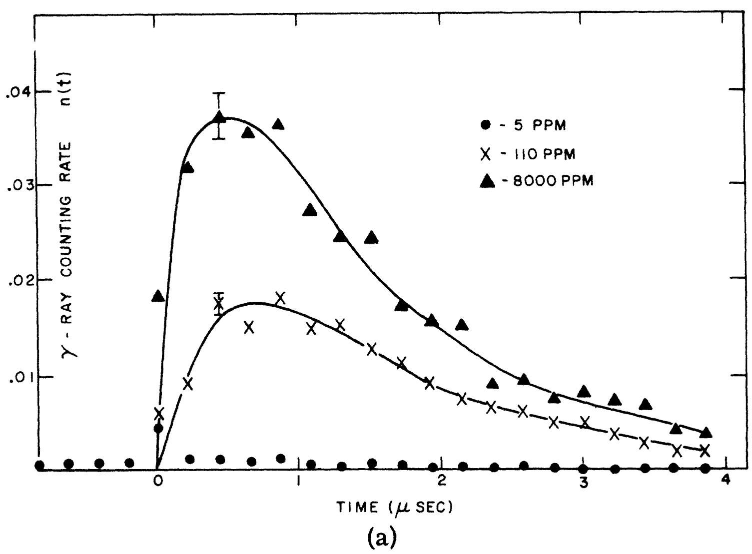
$$= (1-\eta)\left(\frac{\lambda_f}{\lambda_f+\lambda_0}\right)\left(\frac{\lambda_{pd}}{\lambda_{pd}+\lambda_0}\right)\left(\frac{c\lambda_e}{\lambda_{pp}+\lambda_0+c\lambda_e}\right), \quad \text{(1a)}$$

$$N_{\mathrm{II}} = \int_0^\infty n(t)e^{\lambda_0 t}dt = (1-\eta)\frac{c\lambda_e}{\lambda_{pp}+c\lambda_e}. \quad \text{(1b)}$$

Note that (1a) and (1b) become independent of c as $c\lambda_e \to \infty$. This condition of "saturation" was noted by Alvarez et al.[6] in their observation of rejuvenated muons.

The various rates were extracted from the data in a somewhat decoupled manner by the following steps: (i) The 8000-ppm curve is near saturation and hence depends only on λ_f and λ_{pd}, which were obtained by least-squares fitting using Eq. (1) in the limit $c\lambda_e \to \infty$. More precisely, only a "fast" and a "slow" rate are obtained. To identify the former with λ_{pd} and the latter with λ_f, appeal is made to the Carnegie experiment[7] which provides a lower limit for λ_{pd}. (ii) The ratio of slope to intercept of the straight-line fits in Fig. 2(b) is by Eq. (1a), $(\lambda_{pp}+\lambda_0)/c_0\lambda_e$ and by Eq. (1b), $\lambda_{pp}/c_0\lambda_e$. (iii) The lifetime of the atom $(\lambda_{pp}+c\lambda_e+\lambda_0)^{-1}$ can be inferred from the shift in time of the centroid of the yield curves as c is increased.

Table I lists the results along with pertinent previous measurements.[1,7,8] Space does not permit a detailed comparison with the large body of relevant theoretical calculations that have been



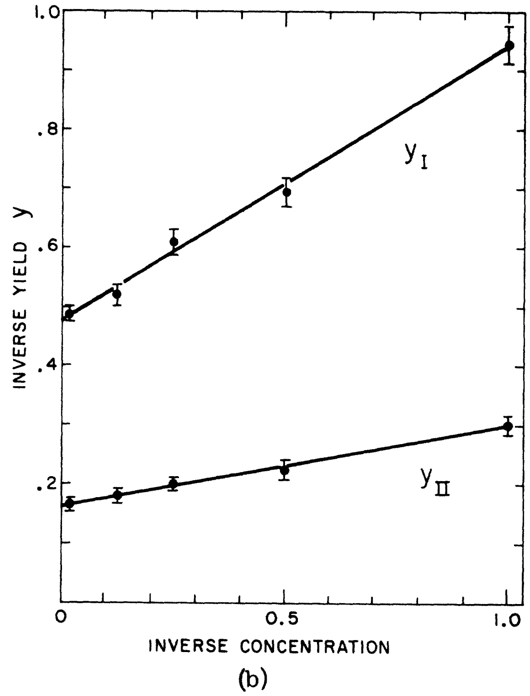


FIG. 2. (a) Normalized but otherwise uncorrected data for the γ-ray counting rate $n(t)$ as a function of time relative to muon stopping. (b) Integrated γ-ray counts vs D_2 concentration (line I). The ordinate is the reciprocal of the yield of γ rays per 1000 decay electrons. The abscissa is the inverse of the concentration in units of $c_0 = 110$ ppm. The points of curve II are obtained from the data of (a) weighted by exp $(\lambda_0 t)$. The straight lines represent the results of fitting the data to Eq. (1a) and to Eq. (1b).

published. The agreement between the theoretical and measured λ's are generally within a factor of 5. Perhaps it is significant that the best agreement is obtained in the case of λ_e, where λ_e (calculated) $\approx 1.4 \times 10^{10}$ sec^{-1} and λ_e (measured) $= 1.9 \times 10^{10}$ sec^{-1}. The calculation of this process might be less sensitive to the approximations employed than the processes which involve a three-body bound state.

The value of λ_{pp} is most significant for interpreting muon absorption data in liquid hydrogen.[9] In pure protium (H^1) the muons will spend 25% of their lifetime in the μp atom where absorption is from the singlet state exclusively.[2] The remainder of the absorption will take place from the $p\mu p$ system, involving a combination of singlet and triplet rates.[10,11] In an experiment[3] which has coordinated with the present one, we have made counter observations of neutrons from muon capture at times >1 μsec after the muon stopping, hence largely from the $p\mu p$ state. It may, however, be possible to measure μp capture by extending the observations to time $\lesssim \lambda_{pp}^{-1}$. Both hyperfine rates could then be extracted.

The data of Table I also permit an evaluation of the effects of deuterium on absorption experiments. For example, if muons stop in hydrogen containing 50-ppm deuterium, 16% interact from μp, 50% from $p\mu p$, 3% from μd, and 31% from $p\mu d$. Of the latter, 30% will actually interact from He^3, giving rise to a large number of muon absorptions by He^3. In fact, using $\Lambda_{He^3}{}^{capt} = 2500$ sec^{-1},[12] and $\Lambda_H{}^{capt} \sim 400$ sec^{-1},[11] ~40% of the aggregate absorptions will be from He_3.

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Table I. Experimental results.

	Present experiment	Others
λ_f (10^6 sec^{-1})	0.26 ± 0.03^a	<8.8, $>1.9^d$
λ_{pd} (10^6 sec^{-1})	5.5 ± 1.1	<20, $>0.55^d$ $\geqslant 6.5 \pm 2^{e,f}$
$(\lambda_{pp}+\lambda_0)/\lambda_e$ (10^{-4})	1.06 ± 0.11	$3.7^{g,h}$ $1.11^{+0.90}_{-0.47}{}^{i}$
λ_{pp} (10^6 sec^{-1})	1.4 ± 0.5	
Fusion γ rays per stopped muon at saturation (%), $N_I(c\lambda_e \to \infty)$	33 ± 8^b 31 ± 3^c	34 ± 6^d
Rejuvenated muons per stopped muon (%), $\eta N_I(c\lambda_e \to \infty)$		2.4 ± 0.2^g 2.64 ± 0.35^i

[a]This is the mean value over about 3 μsec of what is actually a composite lifetime. There is some arbitrariness in how one chooses to infer this mean.[2,5]

[b]This value is derived from an absolute calibration of the NaI counter system efficiency. A direct experimental calibration was carried out by measuring the yield of 5.4-Mev $2p \to 1s$ mesonic x rays produced by muons stopping in a tantalum foil.

[c]This is derived from $\lambda_f\lambda_{pd}(1-\eta)(\lambda_{pd}+\lambda_0)^{-1}(\lambda_f+\lambda_0)^{-1}$. See Eq. (1a).

[d]See reference 1.

[e]See reference 7.

[f]We have re-analyzed the Carnegie data[7] using a recent result of S. S. Gershtein [J. Exptl. Theoret. Phys. (U.S.S.R.) 40, 698 (1961); translation: Soviet Phys.—JETP 13, 488 (1961)] who calculates the intrinsic enhancement of the rejuvenation predicted to occur in large concentrations of deuterium. An increase, ~1.7, is due to the population of those $(p\mu d)^+$ hyperfine levels which are more favorable to internal conversion. This results from the exchange scattering process $(\mu d)_{J=3/2}+d \to (\mu d)_{J=1/2}+d$. This also lowers the deduced value of λ_{dd}. The inequality refers to the fact that there is a transfer of an unknown quantity of muons to impurities dissolved in the D_2.

[g]See reference 4.

[h]The Chicago group has pointed out that this value is proportional to the density of D_2 in normal hydrogen. Both the Chicago and Berkeley results for normal hydrogen agree. Whereas natural hydrogen (in water) has 150 ppm D_2, an assay of the Chicago hydrogen revealed (40 ± 14) ppm. Presumably a similar correction should be applied to the Berkeley data.

[i]See reference 8.

[4]The recycling of rejuvenated muons has a negligible effect on $c\lambda_e$, λ_{pp}, and λ_{pd} but does result in a correction of 7% to λ_f. This can be seen from the secular determinant of the coupled equations including recycling:

$$(\lambda-\lambda_f)(\lambda-\alpha)(\lambda-\lambda_{pd})+\eta\lambda_f c\lambda_e\lambda_{pd}=0.$$

This provides the first order corrections:

$$\delta\lambda_f=\left(\frac{c\lambda_e}{\alpha-\lambda_f}\right)\left(\frac{\lambda_{pd}}{\lambda_{pd}-\lambda_f}\right)\eta\lambda_f\ (\sim\eta\lambda_f \text{ for } c\lambda_e\to\infty).$$

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