where n is the number of resonances observed; the sample is presumed to be random.

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DIRECT MEASUREMENT OF μ^--MESONIC MOLECULE FORMATION RATES IN LIQUID HYDROGEN

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It has been shown[1] that if a few parts per million of Ne are dissolved in deuterated hydrogen, the following reactions are likely to occur:

$$(\mu p) + \mathrm{Ne} \rightarrow (\mu\ \mathrm{Ne}) + p, \qquad (1a)$$

$$(\mu d) + \mathrm{Ne} \rightarrow (\mu\ \mathrm{Ne}) + d. \qquad (1b)$$

The (μp) [or (μd)] binding energy is much smaller than the $(\mu$ Ne) ground-state binding energy. Therefore, transfer to an excited $(\mu$ Ne) state may occur. Mesonic de-excitation x rays characteristic of the Ne mesonic atom are then expected.

We are reporting experimental evidence here for $2p$ - $1s$ transition mesonic x rays of 214 keV from Reactions (1a) and (1b) obtained by dissolving neon in deuterium-free hydrogen and deuterium-hydrogen mixtures, respectively. Our results indicate that Reaction (1) leading to excited states is compatible with 100% of the cases.

The time distribution of these γ rays makes possible a direct measurement of the speed of $(p\mu p)$ and $(p\mu d)$ molecule formation.

The experimental apparatus is shown in Fig. 1. Negative muons (~3000/sec) from the μ^- channel[2] are brought to rest in an 8-liter liquid hydrogen target made out of Mylar. The synchrocyclotron was operated with stochastic extraction[3] and duty cycle ~30%. Hydrogen was purified by passing it through cold traps, silica gel, and Deoxo purifiers, before entering in a palladium leak purifier.[4]

Total capture rate experiments performed in a liquid hydrogen bubble chamber[5] have shown that the over-all contamination of gases with $Z > 2$ obtained with such a purifier is certainly less

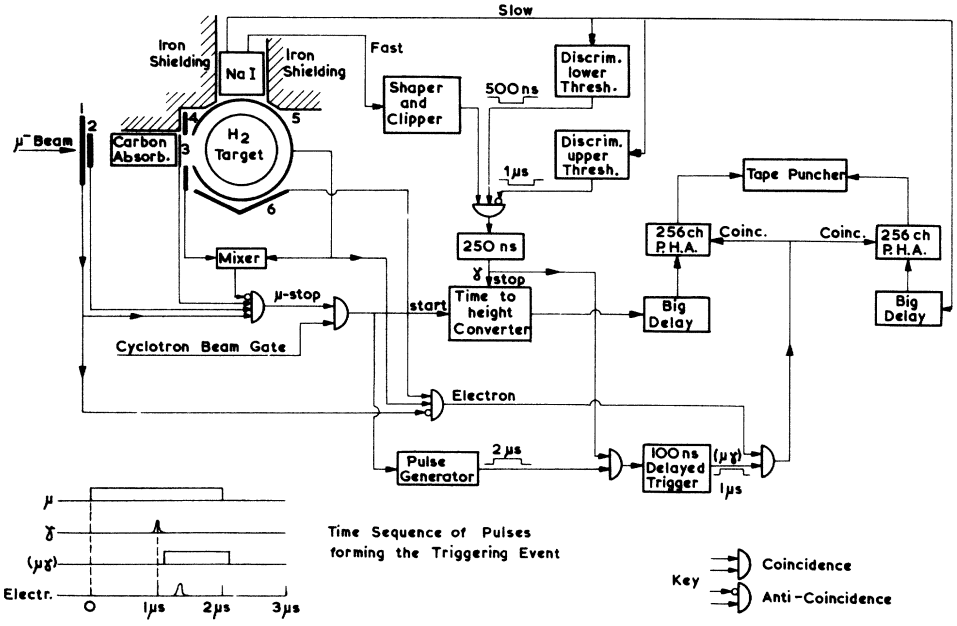

FIG. 1. Schematic layout of experimental arrangement and simplified block diagram of the electronics.

than 10^{-8}, assuring negligible perturbation of the (μp) and (μd) lifetimes due to transfers to impurities. In order to prevent neon from freezing (melting point 24°K), it was greatly diluted with purified hydrogen before being injected into the target. For such a reason we cannot state how much of the injected neon has actually been dissolved into the liquid hydrogen.

The 214-keV mesonic x rays from neon are detected by a 12-cm long, 12-cm diameter NaI crystal. The energy lost in the NaI crystal as well as the time interval between the arrival of the muon and the emission of the γ ray were analyzed by two 256-channel TMC pulse-height analyzers and punched in digital form on paper tape. The tapes were then read by an electronic computer and events ordered in a 128×256 matrix. In order to reject γ rays from captures and from decay-electron bremsstrahlung, a late decay electron was required in counter 6.

To determine the over-all probability of detection as well as the energy calibration and the energy and time resolution of the apparatus, a separate measurement of $2p$ - $1s$ mesonic x rays from Ne was made, by replacing the liquid hydrogen of the target with neon gas at liquid nitrogen temperature. Frequent further checks were made with mesonic x rays from Al and radioactive sources.

Measurements were taken in the following sequence:

(i) With the target full of neon-free hydrogen, data were taken in order to determine eventual structure of the background.

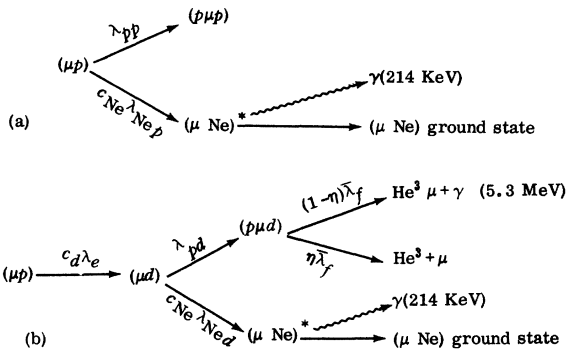

FIG. 2. Schematic representation of possible reaction paths after formation of (μp): (a) in deuterium-free hydrogen-neon mixture; (b) in hydrogen-neon mixture containing deuterium.

(ii) Then various amounts of neon were added, monitoring the fraction of negative muons transferred from the (μp) [or (μd)] atom to the neon both by the decrease of the number of decay electrons and by the change of the μ^- lifetime. In fact, the capture probability of a μ^- is negligibly small for hydrogen, and (0.33 ± 0.05) in the case of neon.[6]

For the (μp) lifetime, the target was filled up with deuterium-free liquid hydrogen. The sequence of events occurring after adding neon are as follows[7]: (i) The negative muon is slowed down and captured in a $1s$ orbit. Exchange collisions rapidly convert all the (μp) system into the singlet

Table I. Summary of results.

Process	D_2 concentration	Amount of neon added	Measured fraction of μ^- transferred to neon[a]	Rate of mesonic-molecule formation[b]	$2p$ - $1s$ mesonic x ray per transfer to neon[c]
$(\mu p)+p \rightarrow (p\mu p)$	≤ 8 ppm[d] ~ 3 ppm[e]	28.5 ppm	(5.1 ± 1.0) %	$\lambda_{pp} = (2.4 \pm 0.6) \times 10^6$ sec^{-1}	0.85 ± 0.26
	≤ 8 ppm[d] ~ 3 ppm[e]	114 ppm	(14 ± 2.5) %	$\lambda_{pp} = (2.04 \pm 0.12) \times 10^6$ sec^{-1}	1.07 ± 0.29
$(\mu d)+p \rightarrow (p\mu d)$	4060 ppm	15.75 ppm	(17 ± 3) %	$\lambda_{pd} = (4.96 \pm 0.35) \times 10^6$ sec^{-1}	1.03 ± 0.28
	460 ppm	31.5 ppm	(32 ± 5) %	$\lambda_{pd} = (5.46 \pm 0.52) \times 10^6$ sec^{-1}	0.83 ± 0.22
	10 060 ppm	31.5 ppm	(32 ± 5) %	$\lambda_{pd} = (5.90 \pm 0.60) \times 10^6$ sec^{-1}	1.01 ± 0.26

[a]The fraction of μ^- transferred to Ne is evaluated from the decrease of decay electrons assuming that the probability of a μ^- nuclear capture in Ne is 0.33 ± 0.05. See reference 6.

[b]Rates are obtained from experimental decay times (see Fig. 2) correcting for Ne and D_2 presence.

[c]Yields are calculated from the known value of the over-all efficiency $(4.6 \pm 0.9) \times 10^{-4}$ as measured filling up the target with Ne gas.

[d]This upper limit has been obtained by looking for fusion γ rays from reaction $(p\mu d) \rightarrow He^3 + \mu + \gamma$.

[e]Result of spectroscopic analysis of the manufacturer.

state. (ii) The thermal neutronlike (μp) atom then either forms a hydrogen molecular ion (rate λ_{pp}) or loses the μ^- to neon (rate $c_{Ne}\lambda_{Ne p}$). No transfer from the meson-molecule to neon is possible owing to its positive charge. These processes are represented symbolically in Fig. 2(a).[1]

For the (μd) lifetime, the target was filled with "natural" liquid hydrogen to which 0.5% of deuterium was added. Here we can sketch the sequence shown in Fig. 2(b).

Results are summarized in Table I and Fig. 3. Our direct measurement of λ_{pp} and λ_{pd} confirms the values obtained by comparing the time dependence of fusion γ rays at different D_2 concentrations.[8] Such time dependence remains unchanged under the exchange of the value of λ_{pd} and λ_f. In a recent work, Dzhelepov et al.,[9] with the help of a diffusion cloud chamber at room temperature, have indicated the solution $\lambda_f \gg \lambda_{pd}$. Our results indicate instead that $\lambda_{pd} \gg \lambda_f$ in agreement with liquid deuterium bubble chamber results.[10] In fact, the alternative $\lambda_f \gg \lambda_{pd}$ would imply that[8] $\lambda_{pd} = (0.26 \pm 0.03) \times 10^6$ sec^{-1}, in clear disagreement with our results.

Combining our value of $\lambda_{pp} = (2.04 \pm 0.14) \times 10^6$ sec^{-1} with the known[9] ratio $(\lambda_{pp} + \lambda_0)/\lambda_e = (1.06 \pm 0.11) \times 10^4$ (λ_0 = muon decay rate), we can deduce $\lambda_e = (2.34 \pm 0.28) \times 10^{10}$ sec^{-1} to be compared with the theoretically predicted value[7] $\lambda_e = 1.4 \times 10^{10}$ sec^{-1}.

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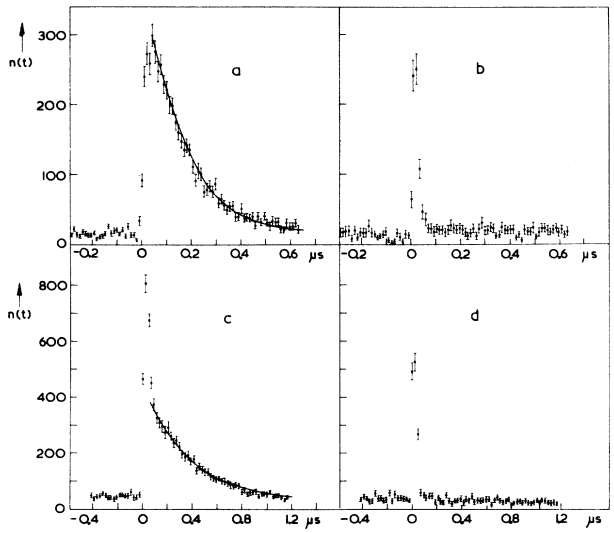

FIG. 3. (a) Counting rate $n(t)$ as a function of time relative to muon stopping of 214-keV mesonic x rays from the reaction $(\mu d) + \mathrm{Ne} \rightarrow (\mu\ \mathrm{Ne}) + d$. Data are for a fraction of μ^- transferred to Ne equal to (17 ± 3)%. The solid line represents the result of a least-squares fit of the experimental points [decay time = (153 ± 10) nsec]. (b) The same time distribution as in (a) before adding Ne. (c) Time distribution and least-squares fit for the reaction $(\mu p) + \mathrm{Ne} \rightarrow (\mu\ \mathrm{Ne}) + p$. Fraction of μ^- transferred to Ne equal to (14 ± 2.5)% [decay time = (340 ± 15) nsec]. (d) The same time distribution as in (c) before adding Ne. Data have been normalized, but otherwise uncorrected.

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