the reaction $p+p\rightarrow\pi^++d$.

[8]It may be expected that final-state interactions will redistribute the reaction products among the available final states but will not seriously affect the absolute transition rate. T. B. Day, G. A. Snow, and J. Sucher, in University of Maryland Technical Report 167, March, 1960 (unpublished), have estimated the effects of multiple scattering on the absorption rate at 200 Mev/c K^- laboratory momentum and found them to be small.

[9]At zero and 200 Mev/c, the necessary parameters for the $T=0$ and $T=1$ absorption channels were taken from reference 2 for the experimentally preferred (a+) and (b+) solutions. At 300 Mev/c, we used the σ_0 and σ_1 absorption cross sections of P. Norden, R. Tripp, A. Rosenfeld, and F. Solmitz reported by L. Alvarez at the Ninth International Conference on High-Energy Physics, Kiev, Russia, 1959 (unpublished).

FORMATION OF μ-MESONIC MOLECULES IN H-D MIXTURES*

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Since the discovery by Alvarez et al.[1] of the catalysis of nuclear reactions by negative muons, first discussed by Frank,[2] there have been numerous estimates[3-5] of the rates of the many processes involved. The results of these calculations are disparate, even in some rather careful recent work.[6,7] Apart from the intrinsic interest in mesonic atomic and molecular systems, an additional stimulus to their study is the necessity of understanding these phenomena for the interpretation of future measurements of the rate of absorption of negative muons in hydrogen.

Herein we report new experimental data, which allow a determination of some of the reaction rates involved in the catalysis processes.

In the experimental work done previously, μ^- mesons were stopped in hydrogen containing small quantities of deuterium. The chain of events believed to lead to nuclear catalysis in that case is depicted in Fig. 1. Within this scheme, the number of nuclear reactions

$$p+d\rightarrow \mathrm{He}^3+Q \tag{1}$$

(where Q signifies a γ ray or a "regenerated" μ^-) per muon is given by

$$N_{pd}=[C_D\lambda_{pd}/(\lambda_{HH}+C_D\lambda_{pd}+\lambda_0)]\times[\lambda_{DH}/(\lambda_{DH}+\lambda_0)]f_{pd}, \tag{2}$$

where f_{pd} is the fraction of $(p\mu^-d)$ molecules which undergo nuclear reactions, and C_D is the deuterium concentration (the hydrogen concentration is $1-C_D\cong 1$ for these cases). In deriving Eq. (2) from Fig. 1 the branch labeled $C_D\lambda_{DD}$ is ignored, as is that labeled $C_D\lambda_{HD}$.[8] In addition, recycling of the muon is ignored since it is expected[4] to occur only for regenerations. This makes an error of ~3% in N_{pd}.

The data so far available consist of the (bubble chamber) measurement by the Berkeley group[1,9] of αN_{pd} [α is the fraction of all p-d nuclear reactions leading to a regenerated muon: $\alpha=k/(k+1)$, where k is the internal conversion coefficient], and the experiment of Ashmore et al.[10] measuring N_{pd} at $C_D=0.018$. The bubble chamber data show that αN_{pd} is saturated at $C_D\cong 0.01$ where $\alpha N_{pd}=0.024\pm0.002$. Furthermore, if one inserts the Berkeley data into Eq. (2), one obtains the relation[4,5]

$$\lambda_{pd}=(2.0\pm0.7)\times10^3(\lambda_{HH}+\lambda_0). \tag{3}$$

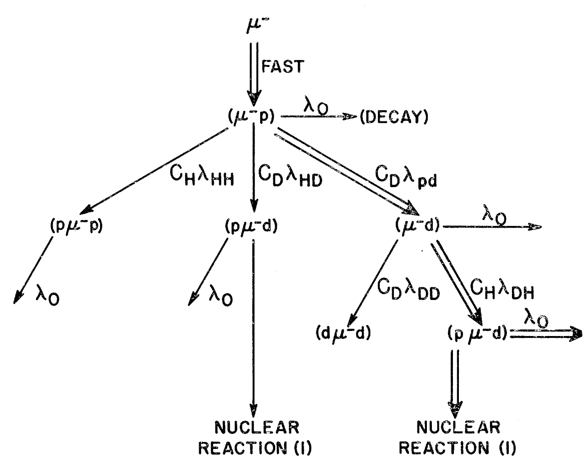

FIG. 1. Chain of events believed to lead to catalysis at low deuterium concentration. Note the scheme for labeling and ordering the reaction rate subscripts. The reaction rates are defined as those for pure hydrogen and deuterium, at bubble chamber conditions: $\rho_H=0.58$ g/cm^3, and $\rho_D=0.133$ g/cm^3. The double lines show those processes which are important at saturation. We neglect recycling, as mentioned in the text.

The experiment of Ashmore et al. indicates[11] that at saturation,

$$N_{pd} = 0.34 \pm 0.06,$$
$$0.55\times10^{6}\ \mathrm{sec}^{-1} < \lambda_{\mathrm{DH}} < 2\times10^{7}\ \mathrm{sec}^{-1},$$
$$0.30 < f_{pd} < 0.66. \qquad (4)$$

In the present experiment, we stopped negative muons in a bubble chamber containing 94.9 atomic % deuterium and 5.1 atomic % hydrogen. The expected chain of events in this case is shown in Fig. 2. Again the fraction f_{pd} of $(p\mu^- d)$ molecules undergo reaction (1), while the fraction f_{dd} of $(d\mu^- d)$ molecules undergo one of the reactions

$$d + d \rightarrow \mathrm{He}^3 + n, \qquad (5)$$
$$d + d \rightarrow \mathrm{H}^3 + p. \qquad (6)$$

Assuming complete recycling of the muon in reactions (5) and (6),[4] the number, N_{dd}, of nuclear reactions of type (5) or (6) per muon is

$$N_{dd} = f_{dd} C_{\mathrm{D}} \lambda_{\mathrm{DD}} / [C_{\mathrm{D}}(1-f_{dd})\lambda_{\mathrm{DD}} + C_{\mathrm{H}}\lambda_{\mathrm{DH}} + \lambda_0], \qquad (7)$$

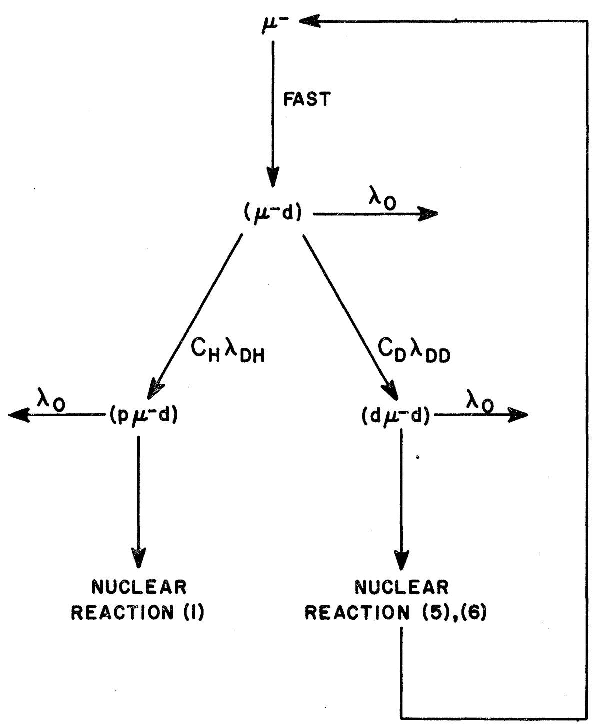

FIG. 2. Chain of events believed to lead to catalysis at low hydrogen concentration. Recycling from reaction (1) is neglected, while recycling in (5) and (6), expected to be 92% (see reference 4), is assumed to be complete.

while the number of regenerations per muon is

$$\alpha N_{pd} = \alpha f_{pd} C_{\mathrm{H}} \lambda_{\mathrm{DH}} / [C_{\mathrm{D}}(1-f_{dd})\lambda_{\mathrm{DD}} + C_{\mathrm{H}}\lambda_{\mathrm{DH}} + \lambda_0]. \qquad (8)$$

In this experiment we found that the number of regenerations per muon is nearly equal to the number found by Alvarez et al. at saturation, indicating that λ_{DH} is quite large. The events found were (including all necessary corrections) 96 ± 16 cases of reaction (6) [we cannot detect reaction (5)] and 33.8 ± 5.6 regenerations in pictures which contained a total of 2201 ± 50 μ - e decays. Reaction (6) and the regenerations were identified by the characteristic ranges of the proton and the muon, respectively. In addition to these events, 62 ± 8 mesons were absorbed in the chamber. We concluded from a counter investigation of the beam as well as curvature measurements in the chamber that these were not pions, and therefore must be attributed to muon capture on impurities in the chamber.

From the ratio of the number of cases of reaction (6) to the number of stopping muons we see that $f_{dd} \geq 0.1$ (it is expected[4] that $f_{dd} = 1$), where we have assumed, as we will throughout, a branching ratio of 1:1 between reactions (5) and (6).[12] We could in principle, by inserting our data into Eq. (8) and comparing this with Eq. (2), using the Berkeley saturation data, determine λ_{DH}. However, due to uncertainty in the Z of the impurity, we cannot definitely exclude $\lambda_{\mathrm{DH}} = \infty$. Nevertheless we can obtain a lower limit to λ_{DH} by assuming that all impurities have high Z, and by assuming that $f_{dd} = 1$. We thus obtain

$$\lambda_{\mathrm{DH}} > 1\times10^{7}\ \mathrm{sec}^{-1}\ (90\%\ \text{statistical probability}), \qquad (9)$$

$$\alpha f_{pd} = 0.024 \pm 0.002. \qquad (10)$$

Further, by dividing Eq. (7) by Eq. (8) we obtain

$$f_{dd}(\lambda_{\mathrm{DD}}/\lambda_{\mathrm{DH}}) = (8.5 \pm 3)\times10^{-3}, \qquad (11)$$

which is independent of the Z of the chamber contaminant. Equations (11) and (9) yield

$$f_{dd}\lambda_{\mathrm{DD}} > 8.5\times10^{4}\ \mathrm{sec}^{-1}. \qquad (12)$$

Inclusion of Ashmore's results, Eq. (4), indicates that $\lambda_{\mathrm{DH}} \cong 2\times10^{7}\ \mathrm{sec}^{-1}$ and $f_{pd} = 0.34$, and thus that $f_{dd}\lambda_{\mathrm{DD}} \cong 1.7\times10^{5}\ \mathrm{sec}^{-1}$. For comparison, a recent calculation[6] yields the values $\lambda_{\mathrm{DH}} = 2.5\times10^{6}\ \mathrm{sec}^{-1}$ and $\lambda_{\mathrm{DD}} = 5.9\times10^{4}\ \mathrm{sec}^{-1}$.

The large discrepancy between the calculated and experimental values is surprising. If the experiments are correct, something is wrong with the calculations of meson-molecular formation rates, or the mechanisms (Figs. 1 and 2) supposed to lead to nuclear catalysis are incorrect.

The analysis given here indicates that in liquid hydrogen containing >1% deuterium, all absorptions of μ^- by protons will be from a $(p\mu^-d)$ molecule. For liquid hydrogen containing <1% deuterium, it is not at present possible to know the molecular or atomic states from which muons are captured. However, even for absorptions from $(p\mu^-d)$ molecules, capture and absorption of the muon by the He^3 reaction product will seriously complicate the interpretation of experimental data.

Work is presently in progress on an extension of this experiment, with a smaller concentration of hydrogen, which should allow a more precise determination of λ_{DH} and λ_{DD}.

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HIGH-ENERGY BREMSSTRAHLUNG FROM A SILICON SINGLE CRYSTAL

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In a previous Letter[1] we reported the results relative to electron pair production from a silicon single crystal. In this Letter we give the results relative to several measurements on bremsstrahlung from a similar target. We also compare these results with the theoretical prediction by Überall[2] and Schiff.[3]

We used about the same experimental arrangement described in reference 1. The only differences are that the single crystal is now mounted within the synchrotron chamber and that the spectrometer converter is an aluminum one; moreover we added another counting channel, for measuring simultaneously at two different photon energies.

The silicon single crystal is in the form of a half-circular plate 15 mm in diameter and 2.7×10^{-3} radiation length in thickness; it is cut perpendicular to the axis [111] within ±4 mrad, as determined by a Laue x-ray back-reflection method.[4] A goniometric device allows the single crystal to be rotated both about a horizontal and a vertical axis; the precision in the measurement of the angles is ±0.5 mrad.

First we successively measure the numbers $N(\theta, k)$, $N(\theta, k_0)$ of symmetrical pairs per fixed number of monitor units (corresponding to 10^{10} equivalent quanta), as a function of the angle θ between the incident 1-Gev electron beam and the crystal axis, and for the central values k, k_0 of the photon energies. We subtract for delayed coincidences and for background as in the pre-