Rosenberg, Phys. Rev. 116, 1034 (1959); 117, 1095 (1960).

[2]Our units are lengths in Bohr radii, energy in rydbergs.

[3]B. H. Bransden, A. Dalgarno, T. L. John, and M. J. Seaton, Proc. Phys. Soc. (London) 71, 877 (1958) contains a fairly complete bibliography.

[4]A. Temkin, Phys. Rev. 116, 358 (1959). A. Temkin and J. Lamkin (to be published). Our scattering lengths are $a_s = 5.8$, $a_t = 1.9$.

[5]V. M. Martin, M. J. Seaton, and J. B. G. Wallace, Proc. Roy. Soc. (London) 72, 701 (1958).

[6]B. A. Lippmann, Bull. Am. Phys. Soc. 5, 119 (1960).

[7]A. Dalgarno and A. Stewart, Proc. Roy. Soc. (London) A238, 269, 276 (1956).

[8]G. Breit, Phys. Rev. 36, 383 (1930). P. J. Luke, R. E. Meyerott, and W. W. Clendenin, Phys. Rev. 85, 401 (1952).

[9]The method used is essentially that of Luke, Meyerott, and Clendenin (reference 8).

[10]P. M. Morse and W. P. Allis, Phys. Rev. 44, 269 (1933). The scattering lengths for this method are $a_s = 8.06$, $a_t = 2.35$.

METHOD FOR DETERMINING THE ORBITAL ANGULAR MOMENTUM IN K^--d CAPTURE*

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In a recent communication, Day, Snow, and Sucher predicted that K^- mesons when stopped in liquid hydrogen or deuterium would be captured from high-lying S atomic orbitals of the K^--p or K^--d system.[1] They found that the Stark-effect mixing of angular-momentum states induced by the strong electric fields experienced by the neutral K^--p or K^--d system as it passed within the Bohr orbitals of other atoms of the liquid allowed rapid capture through the S-wave K-nucleon interaction. Their prediction has been used to draw important conclusions about the properties of hyperons[1] and the nature of the low-energy, S-wave K-nucleon interaction.[2] In addition, estimates indicate that Stark-effect mixing determines the course of the antiproton annihilation reaction at rest.[3] Because of the wide applicability of the prediction, an experimental test is highly desirable. The obvious experiment of looking for K-shell x rays when K^- mesons are stopped in liquid H_2 or D_2 is technically difficult and probably will not be done in the near future.

It may be noted that several of the K^--d capture reactions are sensitive to the orbital angular momentum of the K^--d system. This is implied for example in the calculations of Pais and Treiman[4] and Day and Snow[5] on the $\Sigma^- n$-hyperfragment production rate. Their work shows that if the bound $\Sigma^- n$ system existed and its characteristics were known, the production rate for stopped K^- mesons would provide a clear determination of the orbital from which capture occurs. It is the purpose of this note to point out that the K^--d orbital angular momentum determines the rates for another class of reactions that is more accessible experimentally, the nonmesonic capture reactions in deuterium,

$$K^- + d \to \Sigma^- + p, \quad (1a)$$

$$K^- + d \to \Sigma^0 + n, \quad (1b)$$

$$K^- + d \to \Lambda + n, \quad (1c)$$

where the rate for reaction (1a) is twice that for (1b) by charge independence. We shall confine our attention to reaction (1a) since it is easily recognized in a deuterium-filled bubble chamber and is known to occur at a rate of $\sim 0.7\%$ when stopped K^- mesons are captured.[6] For K^- capture at rest, the center-of-mass momentum of the $\Sigma^- p$ system is 511 Mev/c, and production is inhibited unless the K^- is absorbed while the two nucleons are within a distance $\sim 0.4 \times 10^{-13}$ cm. The small size of this effective interaction volume implies that the rate for (1a) will be proportional to $|\phi_{nS}(r=0)|^2$ or to $|\nabla\phi_{nP}(r=0)|^2$ depending upon the atomic orbital from which capture occurs. On the other hand, mesonic absorption can occur over the entire volume of the deuteron and will proceed through the S-wave K^--nucleon interaction for capture from either S or P atomic orbitals.[5] Therefore, if capture occurs predominantly from S orbitals as predicted by Day, Snow, and Sucher, the fraction of nonmesonic absorptions observed at rest and in flight must be a continuous and slowly varying function of K^- momentum.

Making the explicit assumption that the behavior of the nonmesonic transition amplitude is determined by the centrifugal barrier in the initial state, and that only S- and P-wave absorption is important at low momentum, we have[7]

$$\Gamma_{nm}(q) = (A + Bq^2)pcN. \tag{2}$$

Here q is the center-of-mass momentum of the initial K^--d system in units of $\mu_{Kd}c$, where μ_{Kd} is the K^--d reduced mass and c the velocity of light; p is the final center-of-mass momentum measured in units of its threshold value, $p_0 = 511$ Mev/c; and N is the atomic density of liquid deuterium. The quantities A and B are to be determined from measurement of the in-flight production cross sections. The capture rate from nS or nP orbitals may then be estimated by using

$$\Gamma_{nm}{}^{nS} = cA\,|\phi_{nS}(r=0)|^2, \tag{3a}$$

$$\Gamma_{nm}{}^{nP} = cB(\hbar/\mu_{Kd}c)^2\,|\nabla\phi_{nP}(r=0)|^2. \tag{3b}$$

Since the absolute transition rate cannot be measured, Eqs. (3a) and (3b) must be compared with the mesonic absorption rate. To obtain the latter, we assume that the absorption rate in deuterium is essentially the sum of the absorption rates for the free neutron and proton.[8] The mesonic absorption rate from an nl orbital is then given by

$$\Gamma_n{}^{nl} = 4\pi c\left(\frac{\hbar}{\mu_{Kp}c}\right)\left(\frac{b_0 + 3b_1}{2}\right)\langle|\phi_{nl}(r)|^2\rangle_{\rm av}, \tag{4}$$

where μ_{Kp} is the reduced K^--p mass, and the average over the nucleon density distribution is evaluated by using the Hulthén form for the deuteron wave function. The quantities b_0 and b_1 are the imaginary parts of the $T=0$ and $T=1$ zero-energy scattering lengths evaluated by Dalitz and Tuan.[9] Dividing Eqs. (3a) and (3b) by Eq. (4), we obtain for the fraction of nonmesonic absorptions from S or P atomic orbitals:

$$R^S(0) = 0.123\times10^{26}\,A, \tag{5a}$$

$$R^P(0) = 0.0241\times10^{26}\,B. \tag{5b}$$

At present, only the fraction of nonmesonic absorptions occurring at rest is known. Since either Eq. (5a) or (5b) should essentially account for the observed value, $R(0) \simeq 0.007$, A or B may be determined and corresponding lower limits for $\Gamma_{nm}(q)$ estimated from Eq. (2). To obtain lower limits for the fraction of nonmesonic absorptions expected in flight, $\Gamma_{nm}(q)$ may be divided by the mesonic absorption rate as given by

$$\Gamma_m(q) \simeq qc\left(\frac{\sigma_0 + 3\sigma_1}{2}\right)N, \tag{6}$$

where σ_0 and σ_1 are the absorption cross sections for the $T=0$ and $T=1$ states of the K^--p system.[9] Typical results are listed in Table I for the two assumptions of S- or P-orbital capture at rest.

Table I. Lower limit for fraction of nonmesonic absorptions expected in flight when K^- capture at rest occurs from either S or P atomic orbitals.

K^- laboratory momentum (Mev/c)	S-orbital capture	P-orbital capture
50	0.007	0
200	0.019	0.016
300	0.017	0.032

The ease with which the experiment can yield a definitive result depends upon the extent to which A is not equal to B in Eq. (2). In the analogous reaction $\pi^+ + d \to p + p$, B is much greater than A because of the anomalously small S-wave, π-nucleon interaction. In the present case, the S-wave, K^--nucleon interaction is very large, and if A is much greater than B, a measurement of low statistical accuracy would indicate that ordinary collisional and radiative de-excitation mechanisms were inadequate to account for the observed nonmesonic rate at rest.

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[1] T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters 3, 61 (1959).

[2] R. H. Dalitz and S. F. Tuan, Ann. Phys. (to be published).

[3] Bipin Desai, Phys. Rev. (to be published).

[4] A. Pais and S. B. Treiman, Phys. Rev. 107, 1396 (1957).

[5] T. B. Day and G. A. Snow, Phys. Rev. Letters 2, 59 (1959).

[6] Data of N. Horwitz, D. Miller, and J. Murray, reported by L. Alvarez at the Ninth Annual International Conference on High-Energy Physics, Kiev, Russia, 1959 (unpublished).

[7] The general properties for such a transition amplitude have been discussed by K. A. Brueckner and K. M. Watson [Phys. Rev. 86, 923 (1952)] and K. M. Watson [Phys. Rev. 88, 1163 (1952)] in connection with

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]

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

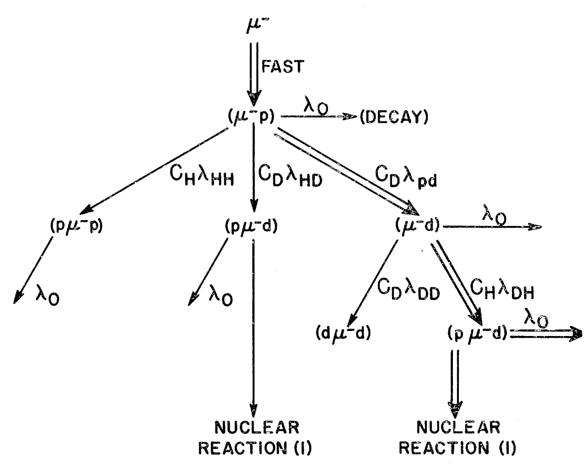

FIG. 1. Chain of events believed to lead to catalysis at low deuterium concentration. Note the scheme for labeling and ordering the reaction rate subscripts. The reaction rates are defined as those for pure hydrogen and deuterium, at bubble chamber conditions: $\rho_H=0.58$ g/cm^3, and $\rho_D=0.133$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