INFLUENCE OF THE $\Lambda\pi$ RESONANCE ON CORRELATIONS IN THE REACTION $K^- + d \to \Lambda + \pi^- + p$†

Orin I. Dahl, Nahmin Horwitz,* Donald H. Miller, Joseph J. Murray, and Paul G. White
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received January 9, 1961)

When K^- mesons are absorbed in deuterium, two possible reactions are

$$K^- + d \to \Lambda + \pi^- + p, \qquad (1a)$$

$$K^- + d \to \Sigma^0 + \pi^- + p, \quad \Sigma^0 \to \Lambda + \gamma. \qquad (1b)$$

We have examined in detail a group of events of types (1a) and (1b) obtained in an exposure of the 15-in. deuterium bubble chamber to a 450-Mev/c separated K^- beam.[1] Application of an energy-momentum balance at the interaction vertex leads to an unambiguous separation of the Λ and Σ^0 events except for a small fraction of those cases in which the recoil proton is too short for measurement.[2] The fitting constraints also ensure a high degree of accuracy (~1%) in the determination of the momenta of the reaction products. Figure 1 shows the distribution of the kinematic variables T_p and T_{π^-} (proton and pion kinetic energy, respectively) for 282 events which (a) were produced by absorption of stopped K^-'s as determined by the fitting procedure and (b) did not result from the decay of a Σ^0 [reaction (1b)]. In addition, the pion and proton spectra for these events are plotted separately in Figs. 2 and 3.

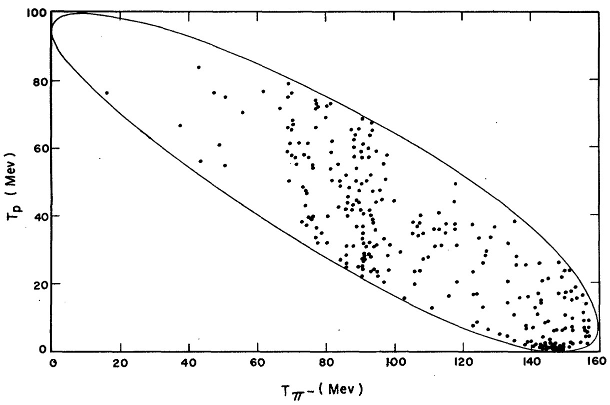

FIG. 1. Distribution of proton and pion kinetic energies in the reaction $K^- + d \to \Lambda + \pi^- + p$ (282 events).

Two prominent features of this absorption reaction are reflected in the pion peaks at $T_{\pi^-} = 92$ and 147 Mev. We consider the higher momentum peak first. Because of the loose structure of the deuteron, it is expected that a group of Λ's will appear as a result of K^- absorptions on single nucleons. This group of events may be described by an impulse model which includes the effects of interactions in the final state. In reaction (1a) the situation is particularly favorable: since the pion-nucleon system is produced in the weakly interacting isotopic spin $I = 1/2$ state, only the Λp interaction need be taken into account. The appropriate modifications of the impulse model have been developed by several authors.[3,4] They point out that for stopped K^-'s captured from

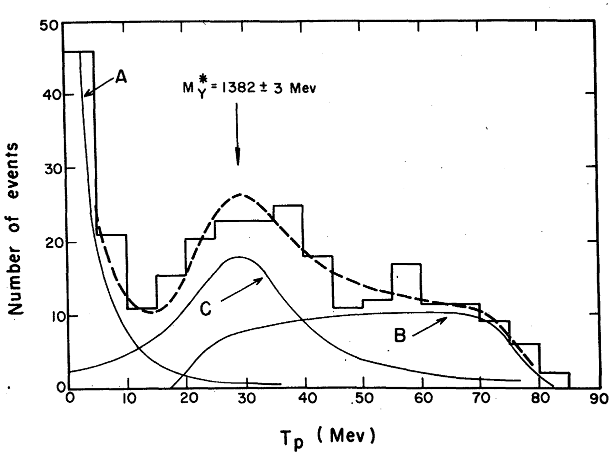

FIG. 2. Proton energy spectrum for the reaction $K^- + d \to \Lambda + \pi^- + p$. A: direct production. B: Σ-Λ conversion. C: resonance events (half-width ±20 Mev).

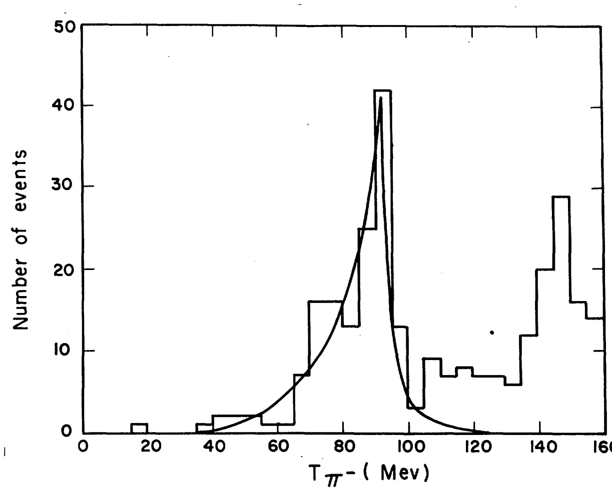

FIG. 3. Pion energy spectrum for the reaction $K^- + d \to \Lambda + \pi^- + p$.

atomic S orbitals,[5] the YN (hyperon-nucleon) system is produced predominantly with relative angular momentum $L=0$, so that interactions in other than S waves of the YN system may be neglected. Using the formulas given by Kotani and Ross,[4] we find that while the angular correlations in the final stage depend sensitively on the strength of the Λp interaction, the total production rate for given T_p is only slightly affected. It is apparent from Fig. 2 that this model qualitatively accounts for absorptions with $T_p<10$ Mev; however, it predicts that less than 20% of the directly produced events will have $T_p>10$ Mev.

The lower energy peak occurs at pion energies expected for production of Σ's in the K^- absorption reaction. Since a Λ rather than a Σ emerges from the absorption vertex, a two-step process is suggested: the K^- interacts with one nucleon to form a Σ and π^-, and then the Σ interacts with the other nucleon and converts to a Λ via the reaction $\Sigma+N\rightarrow\Lambda+p$.[3,4,6] For K^- capture from atomic S orbitals, it may be shown that the observed conversion rate is readily accounted for by reasonable choice of parameters in the zero-effective-range theory for the S-wave ΣN interaction. A typical prediction of the theory for the conversion-pion spectrum is shown in Fig. 3.[7] Since conversion occurs predominantly in the S wave of the ΣN system, the angular distribution of the Λp relative momentum will be isotropic with respect to the direction of the recoil π^-. For such a distribution, the frequency of events along lines of constant T_{π^-} in Fig. 1 will be independent of T_p. The calculated proton spectrum is shown in Fig. 2. Again, although the theory accounts qualitatively for the main features of the conversion process, there remains a group of events with $T_p>10$ Mev and $T_{\pi^-}>100$ Mev which are not readily associated with either direct absorption or internal conversion.

Alston et al. have recently presented strong evidence for the existence of a resonance in the $\Lambda\pi$ system (hereafter called Y^*) at a total mass of $M_{Y^*}=1380\pm5$ Mev and with a half-width less than ±32 Mev.[8] More recent data support the existence of this resonance and suggest that the width may be as little as ±15 Mev.[9] Production of this state in the K^-d absorption reaction would result in a peak in the proton spectrum in the region near $T_p=30.5$ Mev. Examination of Figs. 1 and 2 indicates that the anomalous events may readily be attributed to production of the resonant $\Lambda\pi$ system.[10] Under this assumption, we have attempted to estimate the relative importance of the processes contributing to this reaction by folding together the three distributions in Fig. 2 appropriately normalized to reproduce the observed proton spectrum. Possible interference effects have been neglected. The resonance curve used corresponds to $M_{Y^*}=1382$ Mev, with a half-width of ±20 Mev. From this we estimate that of the 282 events examined, roughly 87 are direct Λ's, 102 are internal conversions, and 93 are associated with the resonant channel.[11]

The spin of the resonant $\Lambda\pi$ state has not yet been established definitely. In the absence of final-state interactions, the resonant channel will result in the $\Lambda\pi$ being produced in a pure angular-momentum state. For $J=1/2$, the distribution of the c.m. $\Lambda\pi$ relative momentum will be spatially isotropic. For $J=3/2$, the distribution is not uniquely determined by conservation of angular momentum alone, but must still be symmetric about a plane perpendicular to the direction of the recoil proton.[12] However, in the region (large T_p) where the effect of the Λp interaction is likely to be small, the angular distribution is distorted by overlap with the internal-conversion events.

A region of particular interest is $5<T_p<20$ Mev, where both the Y^* and direct production are important, while the contribution from internal conversion is negligible. The observed events show a marked tendency for the Λp system to be produced with low relative momentum (large T_{π^-} on Fig. 1). In particular, for the 48 events in this group we obtain

$$(N_f-N_b)/(N_f+N_b)=0.44\pm0.13,$$

where N_f (N_b) is the number of events for which the c.m. angle of the $\Lambda\pi$ system is less than (greater than) 90 deg with respect to the recoil proton direction. If the quantum numbers of the Y^* are the same as those of the zero-energy K^-p system ($S^{1/2}$ for odd $K\Lambda$ parity, $P^{1/2}$ for even), so that this is the resonance suggested by Dalitz and Tuan,[13] the distribution of events for $T_p<20$ Mev is readily understood in terms of an attractive S-wave Λp interaction. In using the final-state interaction theory, the $\Lambda\pi$ resonance was taken into account through an enhancement of the single-nucleon transition operator, $\langle K^-n|T|\Lambda\pi^-\rangle$, as the energy of the $\Lambda\pi$ system was decreased below the K^-n threshold. For a Λp potential of Gaussian form and range corresponding to two-pion exchange, the data suggest that the volume integral of the average potential is 280 ± 90 Mev-fermi^3.[14] A strong S-wave Λp interaction could also be present if the resonant state were $P^{3/2}$ and the $K\Lambda$ parity even. If J is one-half, but the parity of the Y^* differs from that of the zero-energy K^-p system, or if the Y^* state is $P^{3/2}$ and the $K^-\Lambda$ parity is odd, the recoil proton must be produced in an odd angular-momentum state with respect to the Y^*. Since the effect of S-wave Λp scattering will then be small, the angular distribution can probably be accounted for by an interference between the two production modes. In this case, the Λ will in general be polarized with respect to the production plane; however, the data are statistically inadequate to determine whether a significant effect is present.

It is of interest to compare the rate for Y^* production with the rate for the nonmesonic processes

$$K^- + d \rightarrow \Sigma^- + p;\ \Sigma^0 + n;\ \Lambda + n,$$

which occur with a combined frequency of $\sim 1.2\%$ when stopped K^-'s are absorbed.[15] Since reaction (1a) constitutes 21.5% of all zero-energy K^- absorption events,[15] we estimate that $\sim 6\%$ of the absorptions proceed through the resonant $\Lambda\pi^-$ channel. By charge independence, an additional 3% proceeds through the $\Lambda\pi^0$ channel. The suppression of nonmesonic absorption reflects the much smaller volume of the deuteron in which these events may occur because of the large momentum (> 500 Mev/c) present in the final state.

It is a pleasure to thank Professor Luis Alvarez for his advice and encouragement throughout this work, and the assistance of the bubble-chamber and scanning staffs of the Lawrence Radiation Laboratory.

†Work done under the auspices of the U. S. Atomic Energy Commission.

*Present address: Department of Physics, University of Syracuse, Syracuse, New York.

[1]A preliminary analysis of this reaction was presented in Bull. Am. Phys. Soc. 3, 363 (1958).

[2]The few ambiguous events with $T_p < 3$ Mev were assigned to the Σ^0 and Λ categories in proportion to the number observed in each group with $3 < T_p < 10$ Mev.

[3]R. Karplus and L. Rodberg, Phys. Rev. 115, 1058 (1959).

[4]T. Kotani and M. Ross, Nuovo cimento 14, 1282 (1959), Eqs. (50), (51), and (52).

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

[6]The existence of this reaction was first inferred from a study of K^- absorption stars in nuclear emulsion. See F. Webb, E. Iloff, F. Featherston, W. W. Chupp, G. Goldhaber, and S. Goldhaber, Nuovo cimento 8, 899 (1958).

[7]The presence of a cusp in the π^- rate as T_{π^-} is decreased through the threshold for the reaction $\Sigma + N \rightarrow \Lambda + p$ was emphasized in reference 4. [See also L. Fonda and R. Newton, Phys. Rev. 119, 1394 (1960).] The theoretical curve was calculated using Eqs. (59 through 62) of reference 4 and the S-wave effective-range parameters: complex scattering length $A_0 + iB_0 = (-0.005 + i\,0.005)$ Mev/c^{-1}; cutoff $\epsilon = 200$ Mev/c. Though the predictions are somewhat sensitive to ϵ, the data remain in disagreement with the choice of positive A_0, which would correspond to a diagonal $J = 1/2$, ΣN potential strong enough to produce a bound state. This was first noted in reference 3.

[8]M. Alston, L. W. Alvarez, P. Eberhard, M. L. Good, W. Graziano, H. Ticho, and S. Wojcicki, Phys. Rev. Letters 5, 520 (1960).

[9]M. Ferro-Luzzi, J. Berge, J. Kirz, J. Murray, A. Rosenfeld, and M. Watson, Bull. Am. Phys. Soc. 5, 509 (1960).

[10]R. Adair has suggested that part of the effect observed by Alston et al. (reference 4) may result from general constraints imposed on the reaction amplitudes by conservation of angular momentum and centrifugal barrier effects. [See Proceedings of the Conference on Strong Interactions, Berkeley, California, 1960; Bull. Am. Phys. Soc. 5, 516 (1960).] It is difficult to see how the mechanisms pointed out by Adair can be operative in the present reaction.

[11]The observed width of the resonance may be expected to vary, depending upon the reaction in which it is produced. The number of events attributed to the individual mechanisms depends somewhat upon the width assumed for the resonance. A sharper resonance leads to more events being assigned to the internal-conversion process, and conversely.

[12]We are indebted to T. Day, L. Rodberg, G. Snow, J. Sucher, and S. Claus for clarification of this point. See also L. C. Biedenharn, in Nuclear Spectroscopy, edited by Fay Ajzenberg-Selove (Academic Press, New York, 1960), Sec. Vc.

[13]R. H. Dalitz and S. F. Tuan, Ann. Phys. 3, 307 (1960).

[14]For odd $K\Lambda$ parity, the Λp system will be produced in the ^3S state. This potential is then directly comparable to that calculated by R. Downs and R. Dalitz [Phys. Rev. 114, 593 (1959)] from data on lambda-hypernuclear binding energies. Neglecting three-body forces they find 174 Mev-fermi^3 for the same volume integral. For even $K\Lambda$ parity, the potential is an appropriate average of both the ^1S and ^3S interactions.

[15]Data of O. I. Dahl, N. Horwitz, D. H. Miller, J. J. Murray, and P. G. White, reported by L. Alvarez at the Ninth International Conference on High-Energy Physics, Kiev, U.S.S.R., 1959 (unpublished); L. Alvarez, Lawrence Radiation Laboratory Report UCRL-9354, September, 1959 (unpublished).