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

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and Paul C. White

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INFLUENCE OF THE Λπ RESONANCE ON
CORRELATIONS IN THE REACTION \( K^- + d \rightarrow \Lambda + \pi^- + p \)

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

\[
K^- + d \rightarrow \Lambda + \pi^- + p \\
\rightarrow \Sigma^0 + \pi^- + p \\
\rightarrow \Lambda + \gamma.
\]

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 \( \Lambda \) and \( \Sigma^0 \) 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
\((\sim 1\%)\) in the determination of the momenta of the reaction products. Figure 1
shows the distribution of the kinematic variables \( T_p \) and \( T_\pi^- \) (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 \( \Sigma^0 \) (reaction 1b). In addition, the pion and proton spectra
for these events are plotted separately in Figs. 2 and 3.

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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 $\Lambda$'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 $\Lambda p$ 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 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 state depend sensitively on the strength of the $\Lambda p$ 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 $\Sigma$'s in the $K^-$ absorption reaction. Since a $\Lambda$ rather than a $\Sigma$ emerges from the absorption vertex, a two-step process is suggested: the $K^-$ interacts with one nucleon to form a $\Sigma$ and $\pi^-$, and then the $\Sigma$ interacts with the other nucleon and converts to a $\Xi$ via the reaction $\Sigma + N \rightarrow \Lambda + p$. $^3,^4,^6$

For $K^-$ capture from atomic $S$ orbitals it is 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 $\Sigma N$ 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 Δp relative momentum will be isotropic with respect to the
direction of the recoil η−. For such a distribution, the frequency of events
along lines of constant T_{η−} 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_{η−} > 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 Δω system (hereafter called Y^*) at a total mass of
M_y^* = 1380 ± 5 Mev and with a half-width less than ± 32 Mev. More recent
data support the existence of this resonance and suggest that the width may
be as little as ± 15 Mev. 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 Δω system.

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 normalised to reproduce the observed
proton spectrum. Possible interference effects have been neglected. The
resonance curve used corresponds to M_y^* = 1382 Mev, with a halfwidth of
± 20 Mev. From this we estimate that of the 282 events examined, roughly
87 are direct Δω's, 102 are internal conversions, and 93 are associated with
the resonant channel.

The spin of the resonant Δω state has not yet been established
definitely. In the absence of final-state interactions, the resonant channel
will result in the Δω being produced in a pure angular-momentum state.
For J = 1/2, the distribution of the c.m. Δω 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. However, in the region (large $T_p$) where the effect of the $\Lambda p$ 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 $\Lambda p$ system to be produced with low relative momentum (large $T_\pi$ on Fig. 1). In particular, for the 48 events in this group we obtain

$$\left(\frac{N_f - N_b}{N_f + N_b}\right) = 0.44 \pm 0.13$$

where $N_f(N_b)$ is the number of events for which the cm angle of the $\Lambda \pi$ system is less than (greater than) 90 deg with respect to the recoil proton direction.

If the quantum number of the $Y^*$ are the same as those of the zero-energy $K^- p$ system ($S^{1/2}$ for odd $\Lambda \Lambda$ parity, $P^{1/2}$ for even), so that this is the resonance suggested by Dalitz and Tuan, the distribution of events for $T_p < 20$ Mev is readily understood in terms of an attractive $S$-wave $\Lambda p$ 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 $\Lambda p$ potential of Gaussian form and range corresponding to two-pion exchange, the data suggest that the volume integral of the average potential is $280 \pm 90$ Mev-fermi. A strong $S$-wave $\Lambda p$ interaction could also be present if the resonant state were $P^{3/2}$ and the $\Lambda \Lambda$ 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
\( \Lambda p \) 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 \( \Lambda \) 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 nonmesic processes

\[
K^- + d \rightarrow \Xi^- + p; \Sigma^0 + n; \Lambda + n,
\]

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 \( \Delta n^- \) channel. By charge independence, an additional 3\% proceeds through the \( \Delta n^0 \) channel. The suppression of nonmesic 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.
Footnotes


2. The few ambiguous events with \( T_p < 3 \) Mev were assigned to the \( \Sigma^0 \) and \( \Lambda \) categories in proportion to the number observed in each group with \( 3 < T_p < 10 \) Mev.


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


7. The presence of a cusp in the \( \pi^- \) rate as \( T_{\pi^-} \) is decreased through the threshold for the reaction \( \Sigma + N \rightarrow \Lambda + p \) was emphasized in Ref. 4. [See also L. Fonda and R. Newton, Phys. Rev. 119, 1394 (1960)]. The theoretical curve was calculated using Eqs. (59 through 62) of Ref. (4) and the S-wave effective range parameters: complex scattering length \( A_0 + iB_0 = (-0.005 + i.005) \) Mev/c\(^{-1}\); cutoff \( \epsilon = 200 \) Mev/c. Though the predictions are somewhat sensitive to \( \epsilon \), the data remain in disagreement with the choice of positive \( A_0 \), which would correspond to a diagonal \( J = 1/2 \), \( \Sigma N \) potential strong enough to produce a bound state. This was first noted in Ref. 3.


10. R. Adair has suggested that part of the effect observed by Alston et al. (Ref. 4) may result from general constraints imposed on the reaction amplitudes by conservation of angular momentum and centrifugal barrier effects. [See Proc. Conf. Strong Interactions, Berkeley, Calif., 1960 (to be published)]. 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.


14. For odd \( K^\lambda \) parity, the \( \Lambda p \) 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.

Figure Legends

Fig. 1. Distribution of proton and pion kinetic energies in the reaction
\[ K^- + d \rightarrow \Lambda + \pi^- + p \] (282 events).

Fig. 2. Proton energy spectrum for the reaction \( K^- + d \rightarrow \Lambda + \pi^- + p \).
   A. Direct production.  B. \( \Sigma - \Lambda \) conversion.  C. Resonance events
   (half width \( \pm 20 \text{ Mev} \)).

Fig. 3. Pion energy spectrum for the reaction \( K^- + d \rightarrow \Lambda + \pi^- + p \).