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Study of $\bar{K}N \to Y\pi$ below $\bar{K}N$ Threshold and the Dynamical Nature of the $Y_0^*(1405)$†*

D. Cline, R. Laumann, and J. Mapp
University of Wisconsin, Madison, Wisconsin 53706
(Received 24 February 1971)

We have studied the $Y\pi$ angular distributions for the reaction $K^-d\to Y\pi N$ for the $Y\pi$ mass range 1350-1530 MeV. These data are used to study the $\bar{K}N\to Y\pi$ amplitudes below $\bar{K}N$ threshold. The analysis confirms previous SU(3) multiplet assignments for the $\Lambda(1520)$ and $\Sigma(1385)$, and indicates that the S_{01} channel is dominated by a repulsive background with the $\Lambda(1405)$ being a small effect superimposed on the background. This conclusion is at odds with the usual K-matrix analysis of the low-energy $\bar{K}N$ data but is somewhat supported by recent evidence from baryon-exchange production of the $\Lambda(1405)$.

Over the past few years considerable effort has been applied to the extrapolation of scattering amplitudes below $\bar{K}N$ threshold. Recently Dalitz has emphasized the possible uncertainties in these analyses.[1] In this Letter we suggest another way of studying the low-energy region using $\bar{K}$ scattering on virtual nucleons in the deuteron to obtain $Y\pi$ mass values below $\bar{K}N$ threshold.[2]

A different approach to the study of the below $\bar{K}N$ threshold may be useful in deciding the dynamical nature of the $\Lambda(1405)$ state. Again, as recently stressed by Dalitz,[1] there are two different viewpoints concerning the $\Lambda(1405)$:

(i) The $\Lambda(1405)$ is a virtual bound state of the $\bar{K}N$ system. The nearness of $\bar{K}N$ threshold plays an important role in the dynamical origin of this state.

(ii) The $\Lambda(1405)$ is a member of a supermultiplet whose dynamical origin perhaps derives from forces between very massive objects such as quarks. In this case the nearness of the $\bar{K}N$ threshold is not of dynamical significance.

These alternative dynamical explanations of the $\Lambda(1405)$ have also been discussed by Rajasekaran.[3] Previous analyses of low-energy $\bar{K}N$ data using the K-matrix formalism appear to favor viewpoint (i).[1,4] As shown below, the results of this work disagree with these extrapolation analyses and favor the viewpoint expressed in (ii).

In a previous note it was explicitly shown that the impulse approximation can be used to obtain the $\bar{K}N\Sigma(1385)$ coupling constant from low-energy K^-d data and that the resulting value is in good agreement with SU(3) predictions.[5] In the present Letter we assume the validity of the impulse approximation but do not perform calculations with it; instead the collisions of the $\bar{K}$ with the virtual nucleon in the deuteron are considered in the same way as is done with free-nucleon targets. A check on this assumption above $\bar{K}N$ threshold is provided by comparison of the $Y\pi$ angular distributions produced on highly virtual nucleon targets with those obtained on free-nucleon targets.

We now turn to the experimental data. The reactions studied are

$$K^-d \to \Lambda\pi^-p, \tag{1}$$

$$\to \Sigma^0\pi^-p, \tag{2}$$

$$\to \Sigma^\pm\pi^\mp n. \tag{3}$$

These events were obtained from an exposure of the Lawrence Radiation Laboratory 25-in. bubble chamber to a 400-MeV/c K^- beam at the Bevatron.[6] In all cases an appreciable number of events was found with proton or neutron momenta greater than 150 MeV/c. For single-scattering processes in the deuteron, these high-momentum proton or neutron events would correspond to a target nucleus with a mass shifted well below the physical mass. The collision of an incident K^- with these virtual nucleons can result in an effective mass of the K^--nucleon system that is below the $\bar{K}N$ physical threshold. The resulting single-scattering process can then be visualized as

$$\bar{K}\text{“}n\text{”} \to Y\pi, \tag{4}$$

where Y denotes the Λ or $\Sigma^{\pm,0}$ hyperons and "n" denotes the virtual nucleon. In this paper, as mentioned above, we assume that the high-momentum nucleon events of type 1, 2, or 3 come from single-scattering processes with the final-state nucleon acting as a spectator and we analyze the intermediate-state process (4) in the same way as for processes involving scattering on real nucleons.

The angular distribution in the $\Sigma\pi$ center-of-mass system and the polarization with respect to the $\Sigma^+\pi^-$ production plane were determined in exactly the same manner as is done for formation experiments in hydrogen. The Σ angle in the $\Sigma\pi$ center of mass was computed relative to the direction of the $\Sigma\pi$ system (the helicity system). These correspond to the usual definitions when the effective mass of the $\Sigma\pi$ system is above $\bar{K}N$ threshold. The data of Reactions (1), (2), and (3) were fitted to Legendre-polynomial expansions and the resulting coefficients of the expansion as a function of the $Y\pi$ mass were used in a phase-shift analysis described below.

A plot of the Legendre-coefficient ratios A_1/A_0 and A_2/A_0 for the $\Lambda\pi$ channel obtained from Reaction (1) compared with the corresponding coefficients obtained from hydrogen data[7] shows excellent agreement between the two sets of data for all energies above $\bar{K}N$ threshold and strongly suggests that the scattering on virtual protons and real protons gives the same results.

Structure which exists in the $\Sigma^0\pi^-$ low-mass region can be directly attributed to the excitation of the $\Sigma(1385)$ in this channel as would be expected from the known branching ratio of the $\Sigma(1385)$ into the $\Sigma\pi$ channel. Again this result is in agreement with the expected behavior of the scattering amplitude for the reaction

$$K^-\text{“}n\text{”} \to \Sigma^0\pi^- \tag{5}$$

below $\bar{K}$ threshold. The P-wave excitation in this reaction shows that there is no comparable centrifugal barrier suppression as that expected for very-low-energy $\bar{K}$ scattering on hydrogen.

The agreement of the distributions in the low-mass data with those in hydrogen suggests that the dominant processes in Reactions (1) and (2) are collisions with free nucleons and that final-state interactions between the nucleon and hyperon and the nucleon and the pion in these reactions are of secondary importance. The $N\pi$ mass distributions show no evidence for $\Delta(1238)$ production. Note that Reactions (1) and (2) involve both Λp and Σ^0p systems in the final state and that the Σ^0p interaction is expected to be the stronger of the two. Finally we have explicitly searched for evidence of important final-state interactions in the hyperon-nucleon system in the data used for the present analysis, such as evidence for the conversion process $\Sigma^+n \to \Lambda p$, etc.[8] It is concluded that the YN final-state interactions are negligible when the $Y\pi$ mass is below 1500 MeV.

Using the angular distributions and Σ^+ polarization for Reactions (2) and (3), a partial-wave analysis has been performed. The results of an analysis of the $\bar{K}N \to \Lambda\pi$ [Reaction (1)] system will be presented elsewhere.[8] The basic assumptions of this analysis are that (1) the P_{13} and D_{03} channels exhibit the background-free resonances $\Sigma(1385)$ and $\Lambda(1520)$, and (2) only the amplitudes

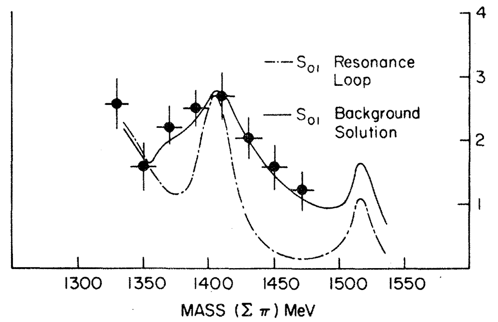

FIG. 1. The ratio of experimental cross sections for $I=0$ to $I=1$ production. Predictions of various types of S_{01} amplitude behavior are also shown.

S_{01}, P_{01}, D_{03}, S_{11}, and P_{13} are important in the $\bar{K}N\to\Sigma\pi$ system below the mass of 1500 MeV. The P_{11} amplitude is found to be extremely small in the analysis of Tripp,[9] and we neglect this amplitude in the present analysis. An adequate fit to the data was obtained with these assumptions. The basic idea of the analysis is to use the resonance amplitudes in the P_{13} and D_{03} channels as "reference" amplitudes to determine the other partial-wave amplitudes. Thus the amplitudes in the S_{01}, P_{01}, and S_{11} channels are measured relative to the resonance amplitudes in the P_{13} and D_{03} channels. *Specifically the Λ(1520) is assumed to execute a Breit-Wigner circle in the upper half-plane of the Argand diagram.* In addition, all amplitudes were required to match smoothly onto those of Tripp[9] in the high-mass region. Resonance parameters were taken from recent compilations.[10]

In Fig. 1 we plot the ratio of cross sections for $I=0$ and $I=1$ $\Sigma\pi$ production as a function of the $\Sigma\pi$ mass. This ratio is very sensitive to the behavior of the S_{01} amplitude. The dashed curve shows the expected behavior of this ratio if the S_{01} channel contains a Breit-Wigner resonance with no background.[11] The solid curves are predictions of this ratio using the partial-wave amplitudes deduced from a fit to the Legendre coefficient. The simple qualitative conclusion that can be drawn from the calculations and data presented in Fig. 1 is that the S_{01} amplitude must lie predominantly in the second quadrant and that the amplitude is not dominated by a simple Breit-Wigner resonance.[2] This expectation is borne out in the full partial-wave analysis, the results of which are presented in Figs. 2(a) and 2(b) in the form of Argand diagrams for each partial wave and each isospin state.[2]

In order for a solution to be accepted as an adequate fit, the amplitudes in the solution were required to agree with the value deduced by Tripp at 1520 MeV. These values are also shown in Fig. 2. *All acceptable solutions had S_{01} amplitudes that stayed in the second quadrant.* The dominant characteristic of this amplitude is the strong repulsive background. While it is possible to superimpose a Breit-Wigner resonance loop on the background provided the resulting amplitude does not move outside the second quadrant [see Fig. 2(b)], an adequate fit can be obtained from a scattering-length parametrization. The Σ(1385) appears as a small loop in the lower half-plane as would be expected for a decuplet assignment for this state and a singlet Λ(1520) assignment.[12] It appears that a direct result of this analysis is that the S_{01} channel is not dominated by the Λ(1405) state. *It is likely that the absence of the Λ(1405) dominance is due to the small coupling of $\bar{K}N\to\Lambda(1405)\to\Sigma\pi$.*

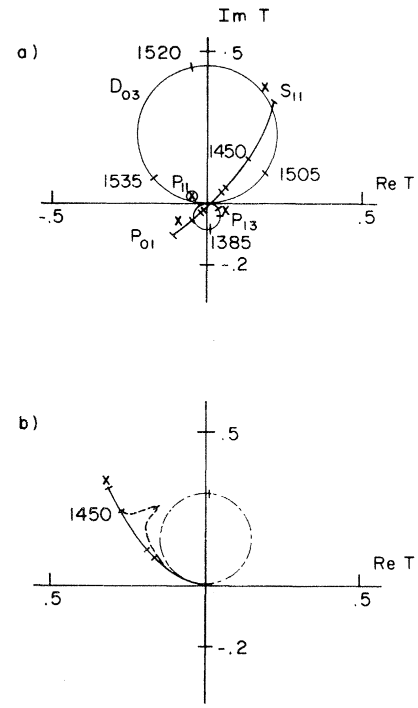

FIG. 2. (a) Argand diagram for $I=0,1$ amplitudes. Also indicated by an X is the solution of Tripp (Ref. 9). (b) Argand diagram for S_{01} amplitude. The alternative types of behavior that are shown are (1) Breit-Wigner resonance dominance of the S_{01} amplitude (dashed curve) and (2) an amplitude dominated by a negative scattering length, with a possible small contribution from the Λ(1405) state (solid curve). The analysis reported in the text strongly favors the latter solution. The position of each amplitude at 1385- and 1405-MeV center-of-mass energy is indicated.

Additional evidence in support of this conclusion comes from a recent study of baryon-exchange production of various Λ and Σ states.[13] The ratio of cross sections for a backward $\Lambda(1405)$ to $\Lambda(1520)$ production was observed to be less than

$$\frac{\Lambda(1405)\text{ production}}{\Lambda(1520)\text{ production}} < \frac{3\ \mu\text{b}}{75\ \mu\text{b}} = \frac{1}{25}. \qquad (6)$$

The ratio of coupling strengths of the $\Lambda(1405)$ and $\Lambda(1520)$ to $\bar{K}N$ deduced from the Argand diagram shown in Fig. 2 is consistent with ratio (6).

In conclusion, the data presented here suggest the possibility of *directly* studying the below-threshold $\bar{K}N \to Y\pi$ amplitude using virtual nucleons in the deuteron. A partial-wave analysis indicates that the S_{01} channel has a large repulsive background that can be described by a negative scattering length and the coupling of the $\Lambda(1405)$ to the $\bar{K}N \to \Sigma\pi$ amplitude is very small relative to $\Lambda(1520)$. This latter conclusion is in agreement with the data on baryon-exchange production of the $\Lambda(1405)$ and $\Lambda(1520)$.

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Two-Particle Distributions and the Nature of the Pomeranchuk Singularity*

D. Z. Freedman,† C. E. Jones, F. E. Low, and J. E. Young
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 18 March 1971)

We propose the measurement of reactions of the type $p_1+p_2 \to q_1+q_2+$anything at high energy in the region in which the produced particles q_1 and q_2 can be regarded as "fragments" of the incident particles p_1 and p_2, respectively. Dependence of the cross section on the angle between transverse parts of the vectors $\vec{q}_1$ and $\vec{q}_2$ would indicate that the Pomeranchuk singularity contains Regge-cut contributions.

A central problem in the theory of strong interactions is the exact nature of the Pomeranchuk singularity which governs the asymptotic behavior of high-energy collisions. Various forms of Regge cuts for the Pomeranchuk singularity have been suggested,[1] while the hypothesis of approximate dominance by a simple pole still has many supporters.[2] We present here a possible experimental probe of this question, which involves measurement of two-particle inclusive distributions of the type $p_1+p_2 \to q_1+q_2+$ anything (Fig. 1) at high energy. The measurement at a conventional accelerator would require detection of a fast, nearly forward particle in coincidence with