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Production of a cascade hyperon in the K^--proton interaction

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We investigate the production of a cascade hyperon (Ξ) through the $K^- + p \to K^+ (K^0) + \Xi^- (\Xi^0)$ reactions, within an effective Lagrangian model where these reactions proceed via excitations of Λ and Σ resonance intermediate states in s and u channels. The coupling constants at the various vertices are taken from previous studies and SU(3) symmetry considerations. The calculated total cross sections of these reactions, which are in good agreement with the available data, are dominated by the contributions from the $\Lambda(1520)$ intermediate resonant state. However, the K^+ meson angular distributions show selectivity to other resonant states in different angular regions, and interference among these states leads to their strong backward peaking.

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Spectroscopy of hadrons is one of the key tools for studying quantum chromodynamics (QCD) in the nonperturbative regime. Lattice simulations, which provide the only *ab initio* calculations of QCD in this regime, are now able to reproduce a large part of the experimentally observed ground-state hadron spectrum (see, e.g., Refs. [1]). However, only a small subset of the excited-state hadron spectrum is currently amenable to lattice calculations. For the success of this endeavor, it is highly desirable to have a large amount of data on the excited-state spectrum, including in particular those hadrons where the widths associated with the states are not large—so that they can be easily identified [2].

A major advantage of investigating the double-strangeness ($S = -2$) Ξ states is that they are much narrower than the N^*, Δ^*, Λ^*, and Σ^* states, which reduces the overlap complications with the neighboring states. Furthermore, two of the three valence quarks in the Ξ are heavier than the third one, which cuts down the uncertainties in the extrapolations of lattice QCD calculations of the cascade masses [3]. This also makes them useful for the measurement of isospin symmetry breaking—in this case the interchangeability of an up and a down quark [4]. There are only two cascade particles of any particular mass state with just this type of quark interchange: Ξ^- and Ξ^0. On the experimental side, the detached decay vertex for many cascades allows their easier separation from various backgrounds.

In contrast to $S = -1$ hyperons, the Ξ states are under-explored. Out of more than 20 Ξ candidates expected in the SU(3) multiplet and at least 10 such candidates predicated by the quark model calculations of Ref. [5], only two ground-state cascades, Ξ and $\Xi(1530)$, are established with near certainty, as indicated by their four-star status in the latest review published by the Particle Data Group [6]. The reason is that the cross sections of $S = -2$ hyperons are relatively small, with the bulk of the cascade production data having been collected by studies of the $K^- + p \to K^+ + \Xi^-$ and $K^- + p \to K^0 + \Xi^0$ reactions in the 1960s and early 1970s using hydrogen bubble chambers [7,8]. The total-cross-section data from these measurements are tabulated in Ref. [9]. More recently, Ξ^- production has been studied at Jefferson Laboratory via the reaction $\gamma p \to K^+K^+\Xi^-$, using photon beams with energies varying from 2.75 to 3.85 GeV [10]. In this experiment, no significant signal of excited Ξ states other than $\Xi(1530)$ has been observed.

Some attempts have been made in the past to understand the mechanism of the $K^- + p \to K^+ + \Xi^-$ reaction within simplified one-meson- and two-meson-exchange models [11,12]. Both approaches were unable to describe properly the existing data even though the two-meson-exchange mechanism was somewhat better in this regard. The proper understanding of this reaction within a rigorous model is important for several reasons. A strong program is proposed at the JPARC facility in Japan and eventually at GSI-FAIR in Germany to obtain information about the spectroscopy of Ξ^-hypernuclei through the (K^-, K^+) reaction on nuclear targets using a high-intensity and high-momentum K^- beam. Establishing the existence and properties of Ξ hypernuclei is of considerable importance for a number of reasons [13], not least as a constraint on the role of the Ξ hyperon in dense matter at the core of neutron stars. The $K^- + p \to K^+ + \Xi^-$ reaction is the best tool to implant a Ξ hyperon in the nucleus through the (K^-, K^+) reaction. Coupled with recent progress in lattice QCD [14], the availability of a high-quality K^- beam is likely to revive interest in looking for a near-stable six-quark dibaryon resonance (H) with spin parity of 0^+, isospin 0, and $S = -2$ [15,16], by studying the (K^-, K^+) reaction. The amplitude for the $K^- + p \to K^+ + \Xi^-$ process must be known accurately in order to estimate the cross section for H production [17].

In this paper we investigate the $K^- + p \to K^+ + \Xi^-$ and $K^- + p \to K^0 + \Xi^0$ reactions within a single-channel effective Lagrangian model, which is similar to that developed in Ref. [18] to study the associated photoproduction of kaons off protons. These reactions are clean examples of a process in which baryon exchange plays the dominant role and the t-channel meson exchanges are absent, as no meson with $S = +2$ is known to exist. In our model, contributions are included from s- and u-channel diagrams [Figs. 1(a) and 1(b),

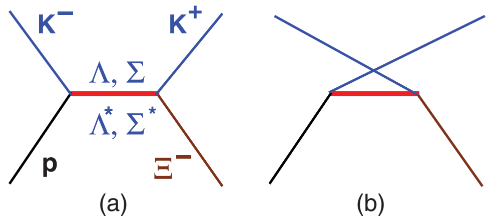

FIG. 1. (Color online) Graphical representation of our model to describe $K^- + p \rightarrow K^+ + \Xi^-$ reaction.

respectively], which have as intermediate states Λ and Σ hyperons together with eight of their three- and four-star resonances with masses up to 2.0 GeV [$\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1670)$, $\Lambda(1810)$, $\Lambda(1890)$, $\Sigma(1385)$, $\Sigma(1670)$, and $\Sigma(1750)$, which are represented by Λ^* and Σ^* in Fig. 1]. In past studies of these reactions [11,12], such a comprehensive investigation of the influence of so many intermediate resonance states has not been attempted. Moreover, the authors of Ref. [11] did not show calculations for both hyperon production channels within their respective models.

We would like to add that calculations of this reaction within a coupled-channels model along the lines of those presented in Refs. [19–21], are in principle, possible, where, e.g., $n + K^0$ intermediate states can also be included. Some contributions from the coupled-channels effects with two sequential K or K^* exchanges and intermediate π/ρ meson + Λ/Σ states are also possible. Such calculations are under development.

The form of the effective Lagrangian vertices involving spin-$\frac{1}{2}$ resonance intermediate states are taken as (see Ref. [19])

$$L_{KBR_{1/2}} = -g_{KBR_{1/2}}\left[\chi\, i\Gamma\,\varphi_K + \frac{(1-\chi)}{M}\,\Gamma\,\gamma_\mu\,(\partial^\mu\varphi_K)\right] \quad (1)$$

with $M = (m_R \pm m_B)$, where the upper sign corresponds to an even-parity and the lower sign to an odd-parity resonance, and B represents either a nucleon or a Ξ hyperon. The operator Γ is γ_5 (1) for an even- (odd-) parity resonance. The parameter χ controls the admixture of pseudoscalar and pseudovector components. The value of this parameter is taken to be 0.5 for the Λ^* and Σ^* states, but zero for Λ and Σ states, implying pure pseudovector couplings for the corresponding vertices, which is in agreement with Refs. [19,22]. For spin-$\frac{3}{2}$ resonance vertices, we have used the gauge-invariant effective Lagrangian as given in Ref. [19]. The corresponding vertex function is written as

$$L^\alpha_{KBR_{3/2}} = \frac{g_{KBR_{3/2}}}{m_K}\,[\gamma^\alpha\,(q\cdot p) - \not{p}q^\alpha][(1-\chi) + \chi\,\not{p}/M_B], \quad (2)$$

where p is the four-momentum of the resonance and q is that of the meson. The index α belongs to the spin-$\frac{3}{2}$ spinor. An interesting property of this vertex is that the product $\gamma\cdot L = 0$. As a consequence the spin-$\frac{1}{2}$ part of the corresponding propagator becomes redundant and only the spin-$\frac{3}{2}$ part gives rise to nonvanishing matrix elements [23,24].

TABLE I. Λ and Σ resonance intermediate states included in the calculation.

Intermediate state (R)	L_{IJ}	M (GeV)	Width (GeV)	g_{KRN}	$g_{KR\Xi}$
Λ		1.116	0.0	−16.750	10.132
Σ		1.189	0.0	5.580	−13.50
$\Lambda(1405)$	S_{01}	1.406	0.050	1.585	−0.956
$\Lambda(1670)$	S_{01}	1.670	0.035	0.300	−0.182
$\Lambda(1810)$	P_{01}	1.180	0.150	2.800	2.800
$\Lambda(1890)$	P_{03}	1.890	0.100	0.800	0.800
$\Lambda(1520)$	D_{03}	1.520	0.016	27.46	−16.610
$\Sigma(1750)$	S_{11}	1.750	0.090	0.500	0.500
$\Sigma(1385)$	P_{13}	1.383	0.036	−6.22	−6.220
$\Sigma(1670)$	D_{13}	1.670	0.060	2.80	2.800

We have used the following form factor at various vertices in both s and u channels:

$$F_m(s) = \frac{\lambda^4}{\lambda^4 + (s - m^2)^2}, \quad (3)$$

where m is the mass of the propagating particle and λ is the cutoff parameter, which is taken to be 1.2 GeV everywhere. Isospin manipulations have been done separately, giving rise to additional constant factors at each vertex.

In Table I, we have listed the spin parities, masses, and widths of all the intermediate resonance states included in our calculations. Also given there are the coupling constants (CCs) that have been used in our calculations at various vertices. For $K\Lambda N$ and $K\Sigma N$ vertices, the CCs adopted by us are on the upper side of those obtained within the SU(3) model [25–27] with the α_D parameter (the standard fraction involving D and F couplings) of 0.644 [28], which is very close to the SU(3) value. But given that SU(3) symmetry is broken at the level of 20% there may be uncertainty in these values of this order [29]. The relative signs of these couplings were fixed by the SU(3) predictions. For the corresponding CCs involving the Ξ hyperon, the SU(3) relations as given in Ref. [30] have been used.

Knowledge about the CCs for KRN vertices (where R represents a Λ^* or Σ^* state) is very scanty. Even more pathetic is the situation regarding the CCs of corresponding vertices involving the Ξ hyperon, where little or no information exists. In this study, the magnitudes of the CCs for the KRN vertices involving the low-lying resonances $\Lambda(1405)$, $\Lambda(1520)$, and $\Sigma(1385)$ have been adopted from those given in Ref. [31], while those of the high-energy resonances are determined from their decay widths as listed in Ref. [6]. For the signs of these couplings, we were guided by the SU(3) predictions [25], wherever possible. The CCs of the $KR\Xi$ vertices are taken to be equal to those of the corresponding KRN vertices for high-mass resonances, as suggested in Refs. [32,33], whereas the SU(3) relations have been used to determine them for the lower-mass hyperon states.

In Fig. 2, we show comparisons of our calculations with the data for the total cross sections of the $K^- + p \rightarrow K^+ + \Xi^-$ [Fig. 2(a)] and $K^- + p \rightarrow K^0 + \Xi^0$ [Fig. 2(b)] reactions for K^- beam energies (E_{K^-}) below 3.0 GeV, because the

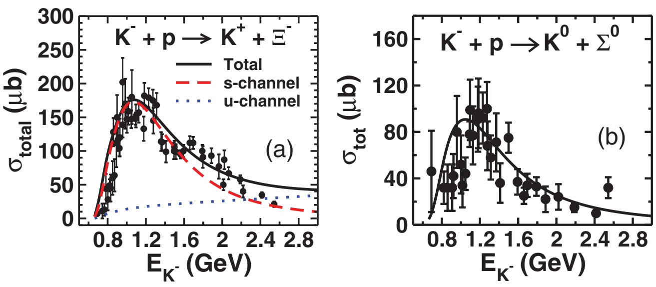

FIG. 2. (Color online) Comparison of the calculated total cross sections for the $K^- + p \to K^+ + \Xi^-$ (a) and $K^- + p \to K^0 + \Xi^0$ (b) reactions as a function of incident K^- kinetic energy with the corresponding experimental data from Ref. [9]. Also shown are the individual contributions of s- and u-channel diagrams to the total cross section for the reaction shown in (a).

resonance picture is not suitable at energies higher than this. It is clear that our model is able to reproduce the data well for both channels within the statistical errors. We shall mostly be discussing the $K^- + p \to K^+ + \Xi^-$ reaction in the rest of this paper. In this case both calculated and experimental cross sections peak at $E_{K^-} \approx 1.1$ GeV. We further note that the cross sections around the peak and the tail ($E_{K^-} \geqslant 2.1$ GeV) regions are dominated by the s- and u-channel contributions, respectively. This result is in contrast to the conclusions of past studies [11,32], where u-channel contributions dominated this reaction everywhere.

From Fig. 3, we note that the contribution from the $\Lambda(1520)$ intermediate state dominates the total cross sections over the entire regime of E_{K^-} values. We have checked that both s- and u-channel cross sections are also individually dominated by this resonance. The Λ, $\Lambda(1405)$, and $\Sigma(1385)$ states make noticeable contributions only for E_{K^-} very close to the production threshold. Other resonances contribute very weakly. Of course, our results are quite dependent on the CCs of various vertices, which are currently quite uncertain. Nevertheless, the relative cross sections shown in Fig. 3 are robust despite this. There is very little scope for increasing further the individual contributions of the Λ and Σ intermediate states, because the CCs of the corresponding vertices used by us are already larger than the upper limits for them suggested in the literature (as discussed above). Furthermore, except for the $\Sigma(1385)$ resonance, where we have again used a larger CC, the contributions of other resonances are too weak and even have the wrong E_{K^-} dependence. Therefore, the final results are unlikely to be affected too much by the known uncertainties in the corresponding CC.

It is interesting to note that in a recent study of this reaction [34], where the data were fitted by a phenomenological model, the inclusion of $\Lambda(1520)$ and $\Sigma(1385)$ resonances improved the fits considerably. Nevertheless, the quality of the agreement with the total-cross-section data obtained by these authors is considerably poorer than those shown in Figs. 2(a) and 2(b) if resonances with masses below 2 GeV only are included. Moreover, in this reference neither the contributions of individual resonances nor the coupling constants at various vertices are shown explicitly.

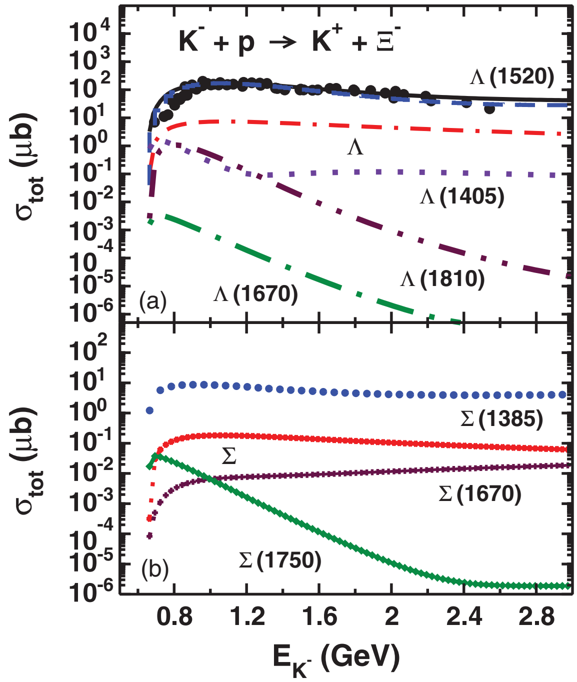

FIG. 3. (Color online) Contributions of individual Λ and Λ^* (a) and Σ and Σ^* (b) resonance intermediate states to the calculated total cross section for the same reaction as that shown in Fig. 2.

In Fig. 4, we have shown results for the angular distribution of the K^+ meson at E_{K^-} values of 1.1 GeV (where the total cross section peaks) and 2.4 GeV (where u-channel contributions dominate these cross sections). Differential cross sections provide more valuable information about the reaction mechanism because they include terms that weight the interference terms of various components of the amplitude with outgoing K^+ angles. From Figs. 4(a) and 4(b), we notice that, although the contributions of p-wave resonances and the Λ terms are rather small for the total cross sections, their interference with the dominant d-wave [$\Lambda(1520)D_{03}$] resonance influences the angular distributions strongly at both beam energies. This leads to enhanced backward peaking of the cross sections at both energies, and causes the forward bending of the angular distributions at 1.1 GeV and an increase in the forward peak value of the cross sections at 2.4 GeV. The magnitude of the interference effects is directly related to those of the individual intermediate resonance states. Therefore, the proper knowledge of the corresponding coupling constants is vital in this respect. Hence the angular distribution data are expected to put limits on the vertex constants of even those resonances that contribute only weakly to the total cross sections. The same is true also for the polarization data.

The role of interference terms of the s- and u-channel amplitudes is studied in parts 4(c) and 4(d) of this figure. We note that here too the interference terms are significant—it is somewhat of lesser importance at $E_{K^-} = 1.1$ GeV beam energy but is quite strong at 2.4 GeV. Therefore the s-channel resonance contributions cannot be ignored in the description of the angular distributions of the $K^- + p \to K^+ + \Xi^-$ reaction, even at higher beam energies.

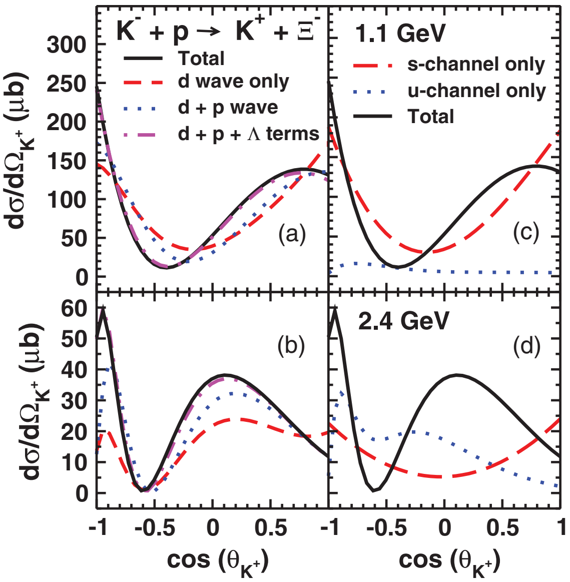

FIG. 4. (Color online) Contributions of resonance intermediate states of various partial waves [(a) and (b)], and of s- and u-channel terms [(c) and (d)] to the angular distributions of K^+ mesons at beam energies of 1.1 and 2.4 GeV, respectively.

We would like to remark that some data on the differential cross sections of the $K^- + p \to K^+ + \Xi^-$ reaction are presented in Ref. [8]. However, we found it difficult to use this data for several reasons. First, it is not clear what the data actually represent—whether they are the angular distributions of the centers of mass of the final channel or those of the Λ hyperon. Second, the data have unknown normalizations and corrections; integration over angles does not lead to the total cross sections reported by the same authors. Finally, in the absence of any table giving the data in numerical form, it is not easy to reproduce them correctly with error bars. On the other hand, because the angular distributions of the kaons are most likely to be measured at the JPARC facility, we presented our calculations for this case.

In summary, we studied the $K^- + p \to K^+ + \Xi^-$ reaction within an effective Lagrangian model that has s- and u-channel diagrams involving as intermediate states the Λ and Σ hyperons together with their eight resonance states with masses below 2.0 GeV. The magnitudes and signs of the coupling constants at various vertices have been chosen from those determined in previous studies and from the prediction of the SU(3) model.

An important result of our study is that the total cross section of this reaction is dominated by the contributions from the $\Lambda(1520)$ (with $L_{IJ} = D_{03}$) resonance intermediate state through both s- and u-channel terms. The peak region gets most contributions from the s-channel graphs, while in the tail region ($E_{K^-} > 2.0$ GeV) the u-channel terms are dominant. However, the angular distributions of the outgoing K^+ meson show sensitivity to those resonance states that otherwise contribute only weakly to the total cross section. In particular, the strong backward peaking of the K^+ differential cross sections results from the interference effects of various intermediate states in both s- and u-channel terms. This result is of vital significance as it invalidates the long-standing belief that the strong backward peaking of the angular distributions in this reaction results from the u-channel dominance. Of course, u-channel diagrams are important, particularly at higher beam energies. However, consideration of the s-channel resonances is important at these energies too. We stress that measurements of the outgoing kaon angular distributions and polarizations are of crucial importance for putting constraints on the largely unknown vertex parameters for the decay of Λ and Σ resonances to the kaon-baryon channels. This study is a precursor to a theory of the production of Ξ hypernuclei via (K^-, K^+) reactions, which is being developed.

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