Ξ⁻ hyperon and hypernuclear production in the (K⁻, K⁺) reaction on nucleon and nuclei in a field theoretical model

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Abstract

We investigate the production of a cascade hyperon (Ξ) and bound Ξ hypernuclei in the (K⁻, K⁺) reaction on proton and nuclear targets, respectively, within a covariant effective Lagrangian model. The K⁺Ξ⁻ production vertex is described by excitation, propagation and decay of Λ and Σ resonance states in the initial collision of a K⁻ meson with a free or bound proton in the incident channel. The parameters of the resonance vertices are taken from previous studies and SU(3) symmetry considerations. The model is able to provide a good description of the available data on total and differential cross sections for the p(K⁻, K⁺)Ξ⁻ reaction. The same mechanism was used to describe the hypernuclear production reactions ¹²C(K⁻, K⁺)²⁸Ξ⁻Be and ²⁸Si(K⁻, K⁺)²⁸Ξ⁻Mg, where Ξ bound state spinors calculated within a phenomenological model have been employed. Both the elementary and hypernuclear production cross sections are dominated by the contributions from the Λ(1520) intermediate resonant state. The beam momentum dependence of the 0° differential cross sections for the formation of the Ξ hypernuclei is found to be remarkably different from what has been observed previously in the impulse approximation model calculations.

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Keywords:
Cascade hyperon and cascade hypernuclear production, Field theoretic model of (K⁻, K⁺) reaction

1. Introduction

Spectroscopy of hadrons is one of the key tools for studying quantum chromodynamics (QCD) in the non-perturbative 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. This development is important particularly for those processes which are difficult to explore in the laboratory, such as hyperon-hyperon and hyperon-nucleon interactions that may affect the late stages of the supernova evolution. The study of the double strangeness (S) hypernuclei is of great importance in this context. The binding energies and widths of the Ξ hypernuclear states are likely to determine the strengths of the ΞN and ΞN → ΛΛ interactions. This basic information is key to testing the quark exchange aspect of the strong interaction because long range pion exchange plays essentially a very minor role in the S = −2 sector. This input is also vital for understanding the multi-strange hadronic or quark matter. Since strange quarks are negatively charged they are preferred in charge neutral dense matter. Thus these studies are of crucial value for investigating the role of strangeness in the equation of state at high density, as probed in the cores of neutron stars

The (K⁻, K⁺) reaction leads to the transfer of two units of both charge and strangeness to the target nucleus. Thus this reaction is one of the most promising ways of studying the S = −2 systems such as Ξ hypernuclei and a dibaryonic resonance (H), which is a near stable six-quark state with spin parity of 0⁺ and isospin 0.²³, ³, ⁴.
The \((K^-, K^+)\) reaction implants a \(\Xi\) hyperon in the nucleus through the elementary \(p(K^-, K^+)\Xi^-\) process. The cross sections for the elementary reaction were measured in the 1960s and early 1970s using hydrogen bubble chambers - the total cross section data from these measurements are tabulated in Ref. [5]. It is essential to investigate first the \((K^-, K^+)\) reaction on a proton target leading to the production of a free \(\Xi^-\) hyperon. The input information extracted from this study will then be used in the description of the formation of \(\Xi^-\)-hypernuclei using this reaction.

In this paper, we investigate the production of free cascade hyperon and cascade hypernuclei via the \((K^-, K^+)\) reaction on proton [Fig. 1(a)] and nuclear targets [Fig. 1(b)], respectively within an effective Lagrangian model \([6, 7]\). It retains the full field theoretic structure of the interaction vertices and treats baryons as Dirac particles. The initial state interaction of the incoming \(K^-\) with a free or bound target proton leads to excitation of intermediate \(\Lambda\) and \(\Sigma\) resonant states, which propagate and subsequently decay into \(\Xi^-\) \(K^+\). In case of the reaction on nuclei, \(\Xi^-\) gets captured into one of the nuclear orbits, while the \(K^+\) meson goes out. We have considered the intermediate resonant states, \(\Lambda, \Sigma\) and eight of their resonances with masses up to 2.0 GeV \([\Lambda(1405), \Lambda(1520), \Lambda(1670), \Lambda(1810), \Lambda(1890), \Sigma(1385), \Sigma(1670), \Sigma(1750)]\), which are represented by \(\Lambda^*\) and \(\Sigma^*\) in Figs. 1(a) and 1(b).

![Graphical representation of the model used to describe \(p(K^-, K^+)\Xi^-\) (a) and \(A(K^-, K^+)\Xi^-B\) (b) reactions. \(A\) represents the target nucleus and \(\Xi^- B\) the final hypernucleus.](image)

2. Formalism

The differential cross section for the \((K^-, K^+)\) reaction is given by

\[
d\sigma = \frac{1}{(2\pi)^2} \frac{d^3p_{K^-}}{2E_{K^-}} \frac{d^3p_B}{2E_B} \frac{m_A m_B}{|p_K|} \sum_{R_i} |M_{R_i}|^2 \delta^{(4)}(p_{K^-} + p_A - (p_{K^+} + p_B)) .
\]

The summation over initial \((m_i)\) and final \((m_f)\) spin states is implied. \(\sum_{R_i}\) indicates the summation over all the resonance intermediate states. In Eq. 1, \(A\) and \(B\) represent the masses of the target and the residual nuclei, respectively. In case of the elementary reaction, they are replaced by the proton mass and the cascade mass, respectively.

In order to calculate the amplitude \(M_{R_i}\) for the elementary \(\Xi\) hyperon production reaction, one requires the effective Lagrangians at the meson-baryon-resonance vertices (which involve coupling constants and the form factors), and the propagators for various resonances. They were taken to be the same as those given Refs. [8, 9]. In addition, for the hypernuclear production reactions one needs spinors for the nucleon hole and \(\Xi^-\) particle bound states. We have used a phenomenological model to get them as discussed in the next section.

3. Results and discussions

In Figs. 2(a), we show comparisons of our calculations with the data for the total cross section of the \(p(K^-, K^+)\Xi^-\) reaction as a function of \(K^-\) beam momenta \((p_{K^-})\). It is clear that our model reproduces the data reasonably well within statistical errors. The measured total cross section peaks in the region of 1.4-1.5 GeV/c which is well described by our model. In Fig. 2(b), we show the \((p_{K^-})\) dependence of the \(0^+\) differential cross section \((d\sigma/d\Omega)_{0^+}\) for the \(p(K^-, K^+)\Xi^-\) reaction. This quantity is of interest as it enters explicitly into the expression for the cross sections of
the $A(K^-, K^+ \Xi^-)$B reactions within the impulse approximation models (see, e.g. Ref. [9]). It may be noted that we have not normalized the cross sections in Fig. 2(b) in the way it was done in the similar results shown in Fig. 5 of Ref. [9]. We see that $(d\sigma/d\Omega)_{0\pi}$ peaks in the same region of $p_K$ as the total cross section shown in Fig. 2a. The arrows in Figs. 2(a) and 2(b) show the position of the threshold beam momentum for this reaction.

Next, we discuss the hypernuclear production reactions $^{12}$C($K^-, K^+ \Xi^-)\Sigma$ Be and $^{28}$Si($K^-, K^+ \Xi^-)\Sigma$ Mg. The thresholds for these reactions are about 0.761 GeV/c and 0.750 GeV/c, respectively. We have employed pure single-particle-single-hole ($p^{-}\Xi$) configurations to describe the nuclear structure part. For the proton hole and $\Xi^-$ states, spinors were generated in a phenomenological model, where they are obtained by solving the Dirac equation with scalar and vector fields having Woods-Saxon radial forms. With a set of radius and diffuseness parameters, the depths of these fields ($V_s$ and $V_v$, respectively) are searched to reproduce the binding energy (BE) of a given state. Since the experimental values of the BEs for the $\Xi^-$ bound states are as yet unknown, we have adopted in our search procedure the predictions for BEs made in the latest version of the quark-meson coupling (QMC) model [10]. This model predicts only one bound state for the $^{12}_\Sigma$ Be hypernucleus with a binding energy of 3.038 MeV and quantum numbers $(1s_{1/2})$. On the other hand, for $^{28}_\Sigma$ Mg it predicts 3 distinct bound $\Xi^-$ states, $1s_{1/2}, 1p_{3/2}, 1p_{1/2}$, with corresponding binding energies of 8.982 MeV, 4.079 MeV, and 4.414 MeV, respectively [11]. The values of radius and diffuseness parameters were taken to be 0.983 fm and 0.606 fm, respectively for both scalar and vector fields. The derived values of $(V_s, V_v)$ were (all in MeV) (-112.11, 90.81), (-133.53, 108.16), (-188.98, 153.08) and (-205.70, 166.65) for above four states, respectively. It may be noted that these values are obtained without including the Coulomb interaction between $\Xi^-$ and $^{11}$B. $V_s + V_v$ should be comparable to the depth of the corresponding conventional Woods-Saxon potential.

In case of the $^{12}$C target, the $\Xi^-$ hyperon in a $1s_{1/2}$ state can populate $1^-$ and $2^-$ states of the hypernucleus corresponding to the particle-hole configuration $[(1p_{3/2})_{p}^{-1}, (1s_{1/2})_{\Xi^-}]$. The states populated for the $^{28}_\Sigma$ Mg hypernucleus are $[2^+, 3^+]$, $[1^-, 2^-, 3^-, 4^+]$, and $[2^-, 3^-]$ corresponding to the configurations $[(1d_{5/2})_{p}^{-1}, (1s_{1/2})_{\Xi^-}], [(1d_{3/2})_{p}^{-1}, (1p_{1/2})_{\Xi^-}]$, and $[(1d_{5/2})_{p}^{-1}, (1p_{1/2})_{\Xi^-}]$, respectively. In Fig. 3, we have shown results for populating the hypernuclear state with maximum spin of natural parity for each configuration. We have used a plane wave approximation to describe the relative motion of kaons in the incoming and outgoing channels. However, distortion effects are partially accounted for by introducing reduction factors to the cross sections as described in Refs. [12, 13]. It should be noted that the cross sections obtained with the spinors calculated within the QMC model are very close to those shown in Fig. 3 [9]. It is also of interest to note that the cross sections shown in both Figs. 2 and 3 are dominated by the contributions of the $\Lambda(1520)$ ($D_{0\Omega}$) resonance intermediate state.

It is clear from Fig. 3 that for both the hypernuclear production reactions, the cross sections peak at $p_K$ around 1.0 GeV/c which is $\approx 0.3$ GeV/c above the production thresholds of the two reactions. It is not too different from the case of the elementary $\Xi^-$ production cross sections where the peaks of the cross sections occur at about 0.35 -0.40 GeV/c above the corresponding production threshold (see Fig 2). The magnitudes of the cross sections for the $^{12}_\Sigma$ Be production are in excess of 1 $\mu$b near the peak position. It is important to note that at the beam momentum of 1.6 GeV/c, the magnitude of our cross section for this case is similar to that obtained in Ref. [13] within an
Figure 3. Differential cross section at 0° as a function of K– beam momentum for the $^{12}$C(K–, K+) $^3$Be and $^{28}$Si(K–, K+) $^{28}$Ξ Mg reactions. The spin-parity of the final hypernuclear states are indicated on each curve. The solid lines represent the cross sections obtained with the phenomenological Ξ– bound state spinors. Arrows show the threshold for the corresponding reaction.

impulse approximation model. Moreover, our cross sections at 1.8 GeV/c also are very close to those of Ref. [12] for both the targets. A more rigorous consideration of the distortion effects could alter the pattern of the beam momentum dependence, e.g. it is likely to be relatively stronger at lower values of $p_{K–}$ as compared to higher values. Furthermore, Coulomb interactions between Ξ– and the core nucleus may also have some effect for heavier targets. These effects will be investigated in a future publication.

4. Summary and conclusions

In summary, we studied the production of Ξ– hyperon and the corresponding hypernuclei in the (K–, K+) reaction on proton and nuclear targets, respectively within an effective Lagrangian model where the reaction proceeds via excitation, propagation and decay of Λ and Σ hyperon resonance states in the initial collision of K– meson with the initial free or bound proton. In the calculations of Ξ– hypernuclear production the bound state spinors were obtained within a phenomenological model. The data on the total cross section of the elementary production reaction are well described by our model. The zero degree differential cross sections for the Ξ– hypernuclear production peak around the beam momentum of 1.0 GeV/c with peak cross section of more than 1 µb. They closely follow the trends of the elementary Ξ– production cross sections. Our predictions will be useful for the future JPARC experiments.

5. Acknowledgments

The author wishes to thank O. Scholten, K. Tsushima and A.W. Thomas for several useful discussions.

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