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Production of $\Xi^{-}$-Hypernuclei via the $(K^-, K^+)$ Reaction in a Quark-Meson Coupling Model

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Abstract We study the production of $\Xi^{-}$-hypernuclei, $^{12}$Be and $^{28}$Mg, via the $(K^-, K^+)$ reaction within a covariant effective Lagrangian model, employing the bound $\Xi^{-}$ and proton spinors calculated by the latest quark-meson coupling model. The present treatment yields the $0^\circ$ differential cross sections for the formation of simple s-state $\Xi^{-}$ particle-hole states peak at a beam momentum around 1.0 GeV/c with a value in excess of 1 $\mu$b.

1 Introduction

The $(K^-, K^+)$ reaction is one of the most promising ways of studying the $S = -2$ systems such as $\Xi^{-}$-hypernuclei and a $\Lambda$ dibaryon. As for $\Xi$ hypernuclei, although there are some hints of their existence from emulsion events, no $\Xi$ bound state was unambiguously observed in the few experiments performed through the $(K^-, K^+)$ reaction on a $^{12}$C target. However, in the near future experiments will be performed at JPARC to search for the $\Xi^{-}$-hypernuclei via the $(K^-, K^+)$ reaction with the best energy resolution of a few MeV and with large statistics.

The elementary cross sections for $p(K^-, K^+)\Xi^{-}$ were measured in the 1960s and early 1970s using hydrogen bubble chambers. In a recent study [1], this reaction was investigated within a single-channel effective Lagrangian model where contributions were included from the s-channel (Fig. 1a) and u-channel diagrams which have as intermediate states $\Lambda$ and $\Sigma$ together with eight 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), represented by $\Lambda^*$ and $\Sigma^*$ in Fig. 1a].

Here we report on the $\Xi^{-}$-hypernuclear production via $^{12}$C$(K^-, K^+)^{12}$Be and $^{28}$Si$(K^-, K^+)^{28}$Mg reactions [2], within an effective Lagrangian model [3–6], similar to that used in Ref. [1] to study the elementary reaction, $p(K^-, K^+)\Xi^{-}$ combined with the quark-meson coupling (QMC) model [7–11]. We consider only the s-channel production diagrams (Fig. 1b) as we are interested in the region $p_{K^-} < 2$ GeV/c. The bound $\Xi^{-}$ and proton spinors are calculated in the latest version of QMC model [8]. In this version, while the quality of results for $\Lambda$ and $\Xi$ is comparable to that of the earlier QMC results [9], no bound states for the $\Sigma$ states are found in middle and heavy mass nuclei. The latter is in agreement with the experimental observations. This
is facilitated by the extra repulsion associated with the increased one-gluon-exchange hyperfine interaction between the quarks.

The use of the bound spinors obtained in the QMC model provides an opportunity to investigate the role of the quark degrees of freedom in the $\Xi^{-}$-hypernuclear production for the first time in studies of this system. Since the $\Xi^{-}$-hypernuclear production involves large momentum transfers (350–600 MeV/c) to the target nucleus, it is a good case for examining such short distance effects. In the QMC model [7–11], quarks within the non-overlapping nucleon bags, interact self-consistently with isoscalar-scalar ($\sigma$) and isoscalar-vector ($\omega$) mesons in the mean field approximation. The explicit treatment of the nucleon internal structure is a key in the model. The self-consistent response of the bound quarks to the mean $\sigma$ field leads to a new saturation mechanism for nuclear matter [7]. The QMC model has been used to study the properties of finite nuclei [10], the binding of $\omega, \eta, \eta'$ and $D$ nuclei [12–14] and also the effect of the medium on $K^\pm$ and $J/\Psi$ production [11].

### 2 Results and Discussions

In Fig. 2 (left panel), we compare our calculations with the total cross section data of $p(K^-, K^+)\Xi^-$ for $K^-$ beam momenta ($p_{K^-}$) below 3.5 GeV/c. Our model can describe well the beam momentum dependence of the elementary total cross section data within statistical errors. The measured total cross section peaks in the region of 1.35–1.4 GeV/c which is well described by our model.

To calculate the cross sections for $^{12}$C($K^-, K^+)^{12}$Be and $^{28}$Si($K^-, K^+)^{28}$Mg, we have employed pure single-particle-single-hole ($\Xi p^{-1}$) wave functions to describe the nuclear structure part [5], ignoring any configuration mixing effects. The amplitude involves the momentum space Dirac-spinors of the bound $\Xi^-$ and proton. We have used a plane wave approximation to describe the relative motion of $K^-$ ($K^+$) in the incoming (outgoing) channel. However, the distortion effects are partially accounted for by introducing reduction factors to the cross sections as described in Ref. [15].

![Fig. 2](image-url)  
**Fig. 2** Total cross section for $p(K^-, K^+)\Xi^-$ (left panel in linear scale) and the $0^\circ$ cross sections for $^{12}$C($K^-, K^+)^{12}$Be and $^{28}$Si($K^-, K^+)^{28}$Mg (right panel in logarithmic scale, the solid dashed lines are the results of the QMC [phenomenological] model). The arrows show the positions of the threshold beam momenta. See Ref. [2] for details.
The thresholds for the $^{12}$C($\bar{K}^-, K^+$)$_{\Xi^-}$Be and $^{28}$Si($\bar{K}^-, K^+$)$_{\Xi^-}$Mg reactions are about 0.761 and 0.750 GeV/c, respectively, and the momentum transfers involved at $0^\circ$, vary between 1.8–2.9 fm$^{-1}$. The initial states in both cases are doubly closed systems. The QMC model predicts only one bound state for the $^{12}$Be system with the $\Xi^-$/Xi$_{1}$ state binding energy of 3.038 MeV. For the $^{28}$Mg case, it predicts three distinct bound $\Xi^-$ states, 1s$_{1/2}$, 1p$_{3/2}$ and 1p$_{1/2}$, with the corresponding binding energies 8.982, 4.079 and 4.414 MeV, respectively.

In case of the $^{12}$C target, $\Xi^-$/Xi$_{1}$ state can populate $1^-$ and $2^-$ states of the hypernucleus corresponding to the particle-hole configuration $[\{1p_{3/2}\}^{-1}, \{1s_{1/2}\}^{-1}]$. The states populated for the $^{28}$Mg hypernucleus are, [2$^+$, 3$^+$], [1$^-$, 2$^-$, 3$^-$, 4$^-$], and [2$^-$, 3$^-$] corresponding to the configurations $[\{1d_{5/2}\}^{-1}, \{1s_{1/2}\}^{-1}]$, $[\{1d_{5/2}\}^{-1}, \{1p_{3/2}\}^{-1}]$, and $[\{1d_{5/2}\}^{-1}, \{1p_{1/2}\}^{-1}]$, respectively.

In Fig. 2 (right panel), the 0$^0$ differential cross sections are shown as a function of the beam momentum that are calculated by using the bound $\Xi^-$ and proton spinors obtained in QMC (solid lines) as well as the phenomenological model (dashed lines) for $^{12}$C($\bar{K}^-, K^+$)$_{\Xi^-}$Be and $^{28}$Si($\bar{K}^-, K^+$)$_{\Xi^-}$Mg. We have shown results for populating the hypernucleus states with maximum spin and natural parity. Although the relative motions of $\bar{K}^-$ and $K^+$ mesons respectively in the initial and final channels are described by plane waves, the distortion effects for the absorption of the incoming $\bar{K}^-$ are included by introducing factors that reduce the magnitudes of the cross sections. These factors are taken to be 2.8 and 5.0 for $^{12}$C and $^{28}$Si targets, respectively as suggested in Ref. [15]. This necessarily assumes that shapes of the angular distributions are not affected by the distortion effects. This aspect will be further investigated in a future study.

Our results in Fig. 2 (right panel) show that for the both reactions, $^{12}$C($\bar{K}^-, K^+$)$_{\Xi^-}$Be and $^{28}$Si($\bar{K}^-, K^+$)$_{\Xi^-}$Mg, the cross sections peak at $p_{\bar{K}^-}$ around 1.0 GeV/c, which is about 0.25–0.26 GeV/c above the corresponding production thresholds. This reflects the trends of the elementary $\Xi^-$ production reaction, where the peaks of the elementary total cross section as well as the zero degree differential cross section occur at about 0.35–0.40 GeV/c above the production threshold. Furthermore, the magnitudes of the cross sections near the peak position are in excess of 1 μb. It is important in this context to note that the magnitude of our cross section for the $^{12}$C target at a beam momentum of 1.6 GeV/c is similar to that obtained in Ref. [15] within an impulse approximation model. Moreover, our cross sections at 1.8 GeV/c also are very close to those of Ref. [16] for the both targets. However, we fail to corroborate the results of Ref. [16] where cross sections were shown to peak for $p_{\bar{K}^-}$ around 1.8 GeV/c. It is quite probable that the distortion effects are dependent on the beam momenta and may be relatively stronger at lower values of $p_{\bar{K}^-}$. Nevertheless, this is unlikely to lead to such a large shift in the peak position. In any case, this effect was not considered in Ref. [16] also. Thus, it seems necessary to re-examine the beam momentum dependence of the zero-degree differential cross section in order to understand this difference.

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