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Antikaon induced Ξ production from a chiral model at NLO

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Abstract. We study the meson-baryon interaction in the strangeness $S = -1$ sector using a chiral unitary approach, paying particular attention to the $\bar{K}N \to K\Xi$ reaction, especially important for constraining the next-to-leading order chiral terms, and considering also the effect of high spin hyperonic resonances. We also present results for the production of Ξ hyperons in nuclei.

1 Introduction

Chiral perturbation theory (χPT) has emerged as a powerful effective theory [1] that respects the chiral symmetry of the QCD Lagrangian and describes successfully the low energy hadron phenomenology. Unitary extensions of the theory ($U\chi PT$) have permitted to describe hadron dynamics in the vicinity of resonances, as in the case of the Λ(1405) baryon, located only 27 MeV below the $\bar{K}N$ threshold, and which, after much work [2–5], has clearly emerged as being composed by two poles coupling differently to $\bar{K}N$ and $\pi\Sigma$ states [6, 7]. The last few years have seen a renewed interest in this problem due to the availability of more precise data coming from the measurement of the energy shift and width of the 1s state in kaonic hydrogen by the SIDDHARTA collaboration [8], which has permitted to better constrain the parameters of the meson-baryon Lagrangian at next-to-leading order (NLO) [9–12].

In this work we attempt a study of the meson-baryon interaction in the $S = -1$ sector, paying a especial attention to the Ξ hyperon production reactions $K^- p \to K^+\Xi^-$, $K^0\Xi^0$, not employed in the NLO fits of earlier works, in spite of being especially sensitive to the NLO terms of the Lagrangian since the lowest-order tree level term does not contribute. A complete approach to Ξ production reactions must also implement the effect of high-spin resonances [21, 23, 24], which we also incorporate in our fit. Finally, we explore the Ξ hyperon production reaction on several nuclei.

2 Meson-baryon amplitudes from the chiral Lagrangian at NLO

The meson-baryon interaction up to NLO can be derived from the chiral Lagrangian [1] and reads $V_{ij}^{\rm NLO} = V_{ij}^{(1)} + V_{ij}^{(2)}$ with:

$$V_{ij}^{(1)} = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{M_i + E_i}{2M_i}}\sqrt{\frac{M_j + E_j}{2M_j}}\,, \quad V_{ij}^{(2)} = \frac{1}{f^2}\left(D_{ij} - 2(k_\mu k'^\mu)L_{ij}\right)\sqrt{\frac{M_i + E_i}{2M_i}}\sqrt{\frac{M_j + E_j}{2M_j}}\,, \quad (1)$$

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where the indices i, j run over the allowed coupled channels, which in the present $S = -1$ study are K^-p, $\bar{K}^0n$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\eta\Lambda$, $\eta\Sigma^0$, $K^+\Xi^-$ and $K^0\Xi^0$, C_{ij} is a matrix of numerical coefficients, f is the pion decay constant, and D_{ij} and L_{ij} are coefficient matrices that depend on the NLO parameters: b_0, b_D, b_F, d_1, d_2, d_3, d_4. The unitarized amplitude is determined from the solution of a Bethe-Salpeter equation $T_{ij} = V_{ij} + V_{il}G_lT_{lj}$, where the loop function G_l is properly regularized using dimensional regularization and depends on a subtraction constant a_l at a given energy scale which we take here to be $\mu = 630$ MeV (see [5, 9–13] for more details). Therefore, at the lowest order, the unitarized amplitudes depend on 7 parameters: the decay constant f of the Weinberg-Tomozawa term, which is taken as a free parameter to partly simulate higher-order terms, plus the loop subtraction constants which, applying isospin symmetry arguments, reduce to 6. At next-to-leading order, there are 7 additional parameters to be fitted.

In Fig. 1 we show the $K^-p \to K^+\Xi^-$ cross section obtained from our NLO fit (dashed line). The relevance of the NLO corrections in this reaction can be judged by comparing these results with those depicted by the dotted line, obtained by setting the seven NLO parameters to zero.

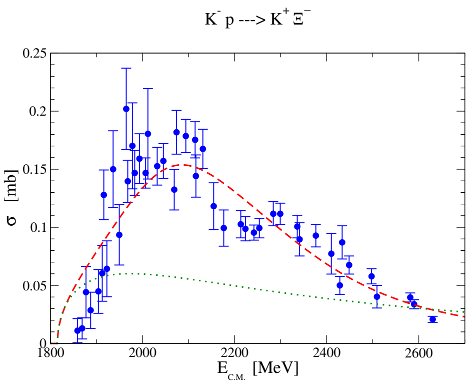

Figure 1. $K^-p \to K^+\Xi^-$ cross section as a function of the center-of-mass energy for the NLO fit (dashed line) and that obtained by setting the NLO parameters to zero (dotted line). Experimental data are taken from [14–20].

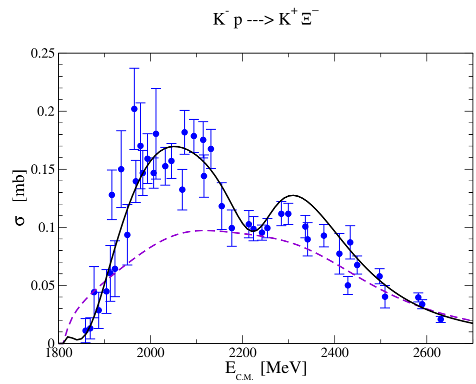

Figure 2. $K^-p \to K^+\Xi^-$ cross section as a function of the center-of-mass energy for the fit with NLO terms plus resonances (solid line) and setting the resonant parameters to zero (dashed line). Experimental data are taken from [14–20].

3 Inclusion of high spin resonances

The shape of the $\bar{K}N \to K\Xi$ cross sections reflects that terms of the type $\bar{K}N \to Y \to K\Xi$, where Y stands for some hyperon resonance, may also come into play. From the eight three- and four-star candidates listed in the PDG, the $7/2^+$ $\Sigma(2030)$ and the $5/2^-$(estimated) $\Sigma(2250)$ seem more appropriate, according to the phenomenological model of [21] and our previous fit [12, 13] . As in [22, 23], we follow the Rarita-Schwinger scheme to describe the resonance fields and build up their contribution to the amplitude, which depends on four new parameters for each resonance: its mass M_R, width Γ_R, product of couplings to the initial and final states, $g_{R\bar{K}N}g_{RK\Xi}$, and a cut-off Λ_R which suppresses high-momentum contributions. The final amplitude for initial $i = K^-p, \bar{K}^0n$ and final $j = K^+\Xi^-, K^0\Xi^0$ channels reads $T_{ij} = \sqrt{4M_pM_\Xi}T_{ij} + T^{5/2^-}_{ij} + T^{7/2^-}_{ij}$.

The cross section of the $K^-p \to K^+\Xi^-$ reaction, obtained from a fit that considers the simultaneous effect of the NLO Lagrangian and two hyperon resonances, is shown by the solid line in Fig. 2. The dashed line displays the result of setting the resonant trems to zero after the fit. We clearly see that the NLO contribution is more moderate in this case, but still produces a sizable amount of background in this energy region. The need for such background has been confirmed in [24], where it has been attributed to a u-type term contribution.

We note that our fit reproduces very satisfactorily all other elastic and inelastic cross sections in the $S = -1$ channel. The inclusion of resonances affect these other channels indirectly through their fine tuning effect on the parameters of the chiral Lagrangian at NLO. An example of the quality of the fit is shown in Table 1, where the threshold branching ratios between several channels are shown for three different fitting schemes.

Table 1. Threshold branching ratios for different fitting schemes

model	$\gamma = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)}$	$R_n = \frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutrals})}$	$R_c = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \to \text{inelastic channels})}$
WT	2.34	0.185	0.665
NLO (Ξ)	2.36	0.197	0.659
NLO+R (Ξ)	2.36	0.193	0.661
EXP	2.36 ± 0.04	0.189 ± 0.015	0.664 ± 0.011

4 Ξ production in nuclei

Finally, we perform an exploratory study on Ξ hyperon production in nuclei as a precursor reaction to form double-Λ hypernuclei. We employ a local density approach to describe the different nuclear targets. The propagation of antikaons before they reach the interaction point and that of the produced kaons as they leave the nucleus is taken within an eikonal approximation, which we consider to be a fair choice given the high momentum value of the incoming K^- ($p_{K^-} = 1.65$ GeV/c) and emitted K^+ ($0.95 < p_{K^+} < 1.30$ GeV/c). Our results for the calculated Ξ production cross section on several nuclei are shown by the square symbols joined by the solid line in Fig. 3. We obtain a good agreement with data [25], a fact that stimulates us to continue our investigations focussing on the production of bound Ξ states, much in line to what other theoretical works have attempted before [26–28].

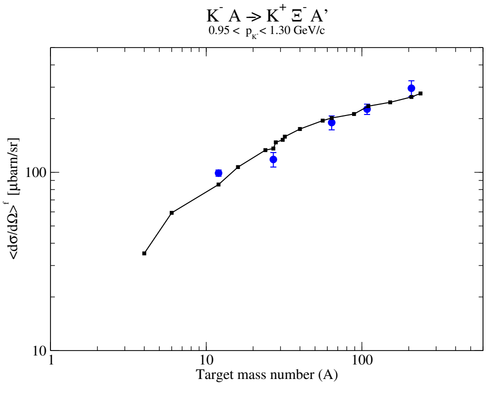

Figure 3. Cross section for Ξ hyperon production from the (K^-, K^+) reaction on various nuclear targets. Experimental data are taken from [25].

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