Cascade production in antikaon reactions with protons and nuclei

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We study the meson-baryon interaction in S-wave in the strangeness S=-1 sector using a chiral SU(3) Lagrangian extended to next-to-leading order (NLO). Our model has 7 new parameters, coming from NLO terms in the chiral Lagrangian, which are fitted to the large set of experimental data available for different two-body channels. We pay particular attention to the $K^-p \to K\Xi$ reactions, where the effect of the NLO terms in the Lagrangian is very important. In order to improve our model in these particular channels, we take into account phenomenologically the effects of the high spin hyperonic resonances, namely $\Sigma(2030)\left(\frac{7}{2}^+\right)$ and $\Sigma(2250)\left(\frac{5}{2}^-\right)$. Finally, the developed model is applied to simulate the Ξ production in nuclei.

1 Introduction

Chiral perturbation theory (χPT) is 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 ($U\chi PT$) permit to describe hadron dynamics in the vicinity of resonances, as in the case of the $\Lambda(1405)$ baryon located only 27 MeV below the $\bar{K}N$ threshold. In the last years interest in this problem is renewed 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 [2], which has permitted to better constrain the parameters of the meson-baryon Lagrangian at next-to-leading order (NLO) [3, 4, 5, 6].

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 [7, 8, 9], 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:

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

where the indices i, j run over the allowed coupled channels, which in the present $S = -1$ study are K^-p, $\bar{K}^0 n$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\eta\Lambda$, $\eta\Sigma^0$, $K^+\Xi^-$ 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 $T_{ij} = V_{ij} + V_{il}G_l T_{lj}$, 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 $\mu = 1$ GeV (see [3, 4, 5, 6, 10] 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.

We present our results in the following, very brief, way: Fig. 1 shows the $K^-p \to K^0\Xi^0$ cross section obtained from our fits; Table 1 shows the corresponding threshold branching ratios.

Let us concentrate on the left subplot of Fig. 1. The first fit we perform is a *classical* WT fit to the cross section of different channels, excluding Ξ production channels, and to the threshold branching ratios. Obviously, the results for the $K^-p \to K^0\Xi^0$ reactions are rather bad, see *WT (no Ξ channels)* dotted line. When we force our WT model to fit also the Ξ production data - *WT* dashed line - some strength is built for the $K^-p \to K^0\Xi^0$ cross section, although the agreement is far from perfect. Now if we and into the game NLO terms of the chiral Lagrangian the progress is obvious - *NLO* line. Also we would like to comment that including NLO terms we improve the agreement in all the channels although for the $K^0\Xi^0$ and $K^+\Xi^-$ ones the changes are most drastic.

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 [8] and our previous fit [6] . As in [11, 7], 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 $i = K^-p, \bar{K}^0 n$ and final $j = K^+\Xi^-, K^0\Xi^0$ channels reads $T_{ij} = \sqrt{4M_p M_\Xi}T_{ij} + T_{ij}^{5/2^-} + T_{ij}^{7/2^-}$.

The cross sections for the $K^-p \to K^0\Xi^0$ reaction, obtained from different fits that considers the effect of these two hyperon resonances, are shown on the right subplot of Fig. 1. The dotted

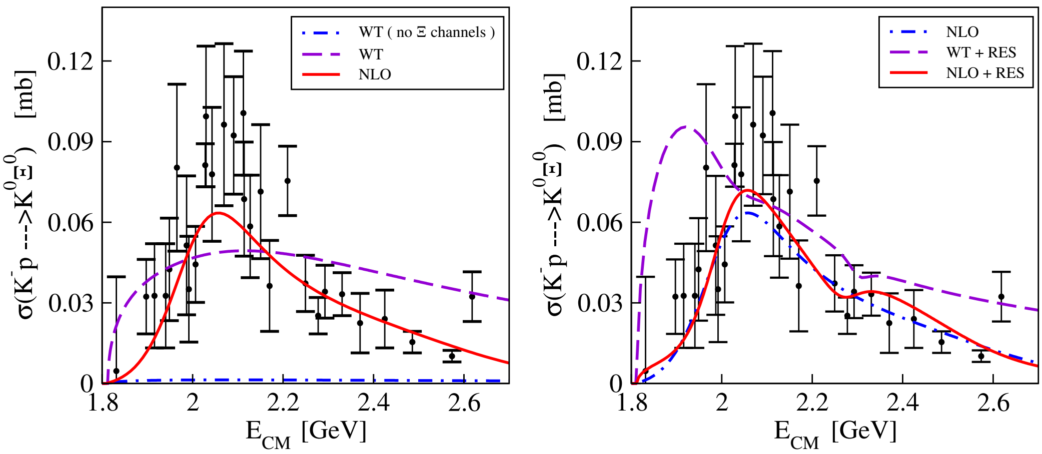

Figure 1: **Left subplot:** $K^-p \to K^0\Xi^0$ cross section as a function of the center-of-mass energy for the NLO different fits, see text for more details. **Right subplot:** $K^-p \to K^+\Xi^-$ cross section as a function of the center-of-mass energy for different fits, in particular including the contribution from high spin resonances. For both sub-figures the experimental data are taken from [12, 13, 14, 15, 16, 17, 18].

NLO line (the Ξ production data are now included in all fits) repeats the best fit without resonance contribution, i.e. it is the same as in Fig. 1A and should be used for more clear comparison. We have tried to fit the data adding the resonance terms to the WT model - *WT+Res* dashed line. Such a test clearly shows the absolute necessity of the NLO term to reproduce data on Ξ production. The full line *NLO+Res* corresponds to our best fit, where we take into account the simultaneous effect of the NLO Lagrangian and two hyperon resonances.

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 different fitting schemes.

Table 1: Threshold branching ratios for different fitting schemes:

Model	γ	R_n	R_c
WT (no Ξ)	2.34	0.185	0.665
WT	2.30	0.185	0.665
NLO	2.31	0.186	0.660
WT+Res	2.48	0.202	0.667
NLO+Res	2.50	0.188	0.664
Exp. data	2.36 ±0.04	0.189 ±0.015	0.664 ±0.011

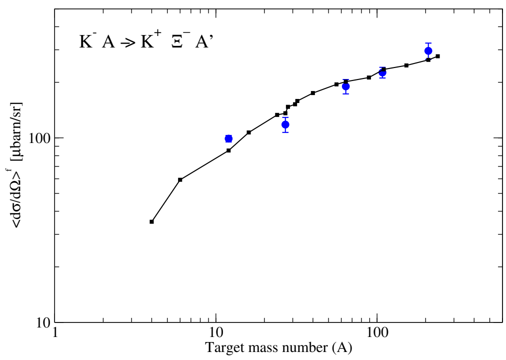

Figure 2: Cross section for Ξ hyperon production in (K^-, K^+) reaction on various nuclei [19].

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; $1.7° < \Theta_{K^+,Lab} < 13.6°$). 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. 2. We obtain a good agreement with data [19], 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 [20, 21, 22].

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