The $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ Reactions in the Chiral Unitary Approach

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We study the $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ reactions near threshold by using a chiral unitary approach. We consider the single-pion and single-kaon exchange as well as the final state interactions of nucleon-hyperon, K-hyperon and K-nucleon systems. Our results on the total cross section of the $pp \rightarrow p\Lambda K^+$ reaction is consistent with the experimental data, and the experimental observed strong suppression of $\Sigma^0$ production compared to $\Lambda$ production at the same excess energy can also be explained in our model.

1 Introduction

By using the chiral unitary approach, we study the $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ reactions near threshold considering pion and kaon exchanges [1], where the $p\Lambda$ final state interaction (FSI) is very important [2, 3]. The $\pi N \rightarrow K\Lambda$ amplitude also appears in this scheme, and the unitarization of this amplitude produces naturally the $N^*(1535)$ resonance [4], such that we can make a quantitative statement on its relevance in the $pp \rightarrow p\Lambda K^+$ reaction. We find that the $p\Lambda$ interaction close to threshold is very strong [5], and the FSI due to this source is unavoidable in an accurate calculation and we also take it into account.

We use a dynamical model similar to the one in Ref. [3] but we allow all pairs in the final state to undergo FSI, as a consequence of which we obtain a contribution from the $N^*(1535)$ using chiral unitary amplitudes. Our approach also differs from the other approaches on how the FSI is implemented, and for this we follow the steps of Ref. [6]. Furthermore, the experimental total cross section for the $pp \rightarrow p\Sigma^0 K^+$ reaction is strongly suppressed compared to that of the $pp \rightarrow p\Lambda K^+$ reaction at the same excess energy. This was explained by a destructive interference between $\pi$ and $K$ exchange in the reaction $pp \rightarrow p\Sigma^0 K^+$ [3].
2 Formalism and ingredients

At the reaction threshold, the processes involving the exchange of $\pi$ and $K$ mesons are the dominant contributions, as in Ref. [3] and other works of the Juelich group. Accordingly we show the dominant diagrams exchanging $\pi$ mesons in Fig. 1, where the definitions of the kinematics ($p_1, p_2, p_3, p_4, p_5, q$) are shown in the first diagram. Those exchanging $K$ mesons can be similarly obtained. First we write out the amplitudes for elementary production processes. For the first diagram of Fig. 1, we have

$$A^{\pi}_1 = -F_{\pi NN}(q^2) f_{\pi^0 p p}^{0}{(1)q_z} \frac{i}{q^2 - m^2_{\pi}} T_{\pi^0 p \rightarrow K^+ \Lambda},$$

where $F_{\pi NN}(q^2)$ is the form factor containing a cutoff parameter $\Lambda_{\pi}$:

$$F_{\pi NN}(q^2) = \frac{\Lambda_{\pi}^2 - m^2_{\pi}}{\Lambda_{\pi}^2 - q^2},$$

We can similarly obtain the “elementary production amplitudes” for the other diagrams, and the total production amplitude $\mathcal{M}$ can be written into two parts:

$$\mathcal{M} = \mathcal{M}_\pi + \mathcal{M}_K,$$

where $\mathcal{M}_\pi$ is for those diagrams involving $\pi$ exchange ( $\mathcal{M}_K$ for $K$ exchange):

$$\mathcal{M}_\pi = A^{\pi}_1 + \sum_{i=2}^6 A^{i}_{\pi} G^{i}_{\pi} T^{i}_{\pi},$$
where $A^i_{\pi/K}$ are the elementary production processes which can be obtained similarly to Eq. (1) and $G^i_{\pi}$ the loop functions of one meson and a baryon propagators, or two baryon propagators. Together with the final state interactions for meson-baryon cases (such as $T^3_{\pi} = T_{K^+ p \rightarrow K^+ p}$, etc.) and for baryon-baryon cases ($T^2_{\pi} = T_{\Lambda p \rightarrow \Lambda p}$, etc.), we can obtain the full total production amplitude $M$.

The meson-baryon $G$-functions and $T$-matrices have been calculated in Refs. [7], and we only need to calculate the baryon-baryon ones which are done using the experimental data [8]. We also consider the transition between $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$, which is discussed in Ref. [1] in detail.

### 3 Numerical results and Discussion

The total cross section versus the excess energy ($\epsilon$) for the $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ reactions are calculated by using a Monte Carlo multi-particle phase space integration program. The results for $\epsilon$ from 0 MeV to 14 MeV is shown in Fig. 2 for the $pp \rightarrow p\Lambda K^+$ reaction with the cutoff $\Lambda_{\pi} = 1300$ MeV, together with the experimental data [8] for comparison. The solid and dashed lines show the results from our model with and without including the $p\Lambda$ FSI, respectively.

![Figure 2](image-url)  
**Figure 2:** Total cross section vs excess energy $\epsilon$ for the $pp \rightarrow p\Lambda K^+$ reaction compared with experimental data from Refs. [8] (filled and open circles).

We can see that we can reproduce the experimental data quite well for the excess energy $\epsilon$ lower than 14 MeV. The dashed line is about two and a half times smaller than the experimental data at threshold but less than a factor of two smaller than experimental data at $\epsilon \sim 14$ MeV. This indicates that the $p\Lambda$ FSI is very important in the $pp \rightarrow p\Lambda K^+$ reaction close to threshold. This energy dependence of the FSI is what allows the determination of the $\Lambda N$ interaction in other approaches which do not try to get absolute cross sections [9].

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