Dynamics of strangeness production in the near threshold nucleon-nucleon collisions

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Abstract: We investigate the associated strangeness production reactions $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ within an effective Lagrangian model. The initial interaction between the two nucleons is modeled by the exchange of $\pi$, $\rho$, $\omega$, and $\sigma$ mesons and the strangeness production proceeds via excitations of $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$ baryonic resonance states. The parameters of the model at the nucleon-nucleon-meson vertices are determined by fitting the elastic nucleon-nucleon scattering with an effective interaction based on the exchange of these four mesons, while those at the resonance vertices are calculated from the known decay widths of the resonances and from the vector meson dominance model. Experimental data taken recently by the COSY-11 collaboration are described well by this approach. The one-pion-exchange diagram dominates the production process at both higher and lower beam energies. The excitation of the $N^*(1650)$ resonance contributes predominantly to both the production channels at near threshold energies. Our model with final state interaction effects among the outgoing particles included within the Watson-Migdal approximation, is able to explain the observed beam energy dependence of the ratio of the total cross sections of these two reactions.

1 Introduction

In recent years, there has been a considerable amount of interest in the study of the associated strangeness production reactions in proton-proton ($pp$) collisions. This is expected to provide information on the manifestation of quantum chromodynamics (QCD) in the non-perturbative regime of energies larger than those of the low energy pion physics where the low energy theorem and partial conservation of axial current (PCAC) constraints provide a useful insight into the relevant physics.\footnote{Talk presented in the second symposium on threshold meson production in $pp$ and $pd$ interactions, Jagellonian University, Cracow, Poland, May 31-June 3, 2004.} The strangeness quantum
number introduced by this reaction leads to new degrees of freedom into this domain which are expected to probe the admixture of $\bar{s}s$ quark pairs in the nucleon wave function \[ \text{[2]} \] and also the hyperon-nucleon and hyperon-strange meson interactions \[ \text{[3, 4]} \].

The elementary nucleon-nucleon-strange meson production cross sections are the most important ingredients in the transport model studies of the $K^+$-meson production in the nucleus-nucleus collisions, which provide information on not only the initial collision dynamics but also the nuclear equation of state at high density \[ \text{[5, 6, 7, 8, 9, 10, 11, 12]} \]. Furthermore, the enhancement in the strangeness production has been proposed as a signature for the formation of the quark-gluon plasma in high energy nucleus-nucleus collisions \[ \text{[13, 14]} \].

The measurements performed in late 1960s and 1970s provided the data on the total cross sections for the associated hyperon ($Y$)-kaon production at beam momenta larger than 2.80 GeV/c (these cross sections are listed in Ref. \[ \text{[15]} \]). With the advent of the high-duty proton-synchrotron (COSY) at the Forschungszentrum, Jülich, it has become possible to perform systematic studies of the associated strangeness production at beam momenta very close to the reaction threshold (see, e.g., Ref. \[ \text{[16]} \] for a comprehensive review). At the near threshold beam energies, the final state interaction (FSI) effects among the outgoing particles are significant. Therefore, the new set of data are expected to probe also the hyperon-nucleon and hyperon-strange meson interactions.

A very interesting result of the studies performed by the COSY-11 collaboration is that the ratio ($R$) of the total cross sections for the $pp \rightarrow p\Lambda K^+$ and $pp \rightarrow p\Sigma^0 K^+$ reactions (to be referred as $\Lambda K^+$ and $\Sigma^0 K^+$ reactions, respectively) at the same excess energy (defined as $\epsilon = \sqrt{s} - m_p - m_Y - m_K$, with $m_p$, $m_Y$, and $m_K$ being the masses of proton, hyperon, and kaon respectively and $s$ the invariant mass of the collision), is about \(28^{+6}_{-9}\) for \(\epsilon < 13\) MeV \[ \text{[17]} \]. This result is very intriguing because at higher beam energies (\(\epsilon \approx 1000\) MeV) this ratio is only around 2.5.

Several calculations have been reported \[ \text{[18, 19, 20]} \] to explain this result. Assuming that the $\pi$- and $K$- exchange processes are the only mechanism leading to the strangeness production, the authors of Ref. \[ \text{[18]} \] show within a (non-relativistic) distorted wave Born approximation (DWBA) model that while the $\Lambda K^+$ reaction is dominated by the $K$-exchange only, both $K$- and $\pi$-exchange processes play an important role in the case of $\Sigma^0 K^+$ reaction. Therefore, if the amplitudes corresponding to the two exchanges in the latter case interfere destructively, the production of $\Sigma^0$ is suppressed as compared to that of $\Lambda$. It should however, be noted that in Ref. \[ \text{[19]} \], $K$-
and π- exchange amplitudes are reported to be of similar magnitudes for both ΛK+ and Σ0K+ reactions.

Nevertheless, a conclusive evidence in support of the relative signs of π- and K- exchange amplitudes being opposite to each other is still lacking. Furthermore, other mechanisms like excitation, propagation, and decay of intermediate baryonic resonances which play (see, e.g., [21, 22, 23]) an important role in the strangeness production, have not been considered by these authors. In the calculations reported in Ref. [20] also the relative sign of K− and π− exchange terms is chosen solely by the criteria of reproducing the experimental data, although in this work the theory has been applied to describe a wider range of data (which includes the polarization transfer results of the DISTO experiment [24] and the missing mass distribution obtained in the inclusive K+ production measurements performed at SATURNE [25] apart from the ratio R).

We have investigated the ΛK+ and Σ0K+ reactions at near threshold as well as higher beam energies in the framework of an effective Lagrangian approach (ELA) [21, 22, 28, 29]. In this theory, the initial interaction between two incoming nucleons is modeled by an effective Lagrangian which is based on the exchange of the π-, ρ-, ω-, and σ- mesons. The coupling constants at the nucleon-nucleon-meson vertices are determined by directly fitting the T-matrices of the nucleon-nucleon (NN) scattering in the relevant energy region. The ELA uses the pseudovector (PV) coupling for the nucleon-nucleon-pion vertex which is consistent with the chiral symmetry requirement of the quantum chromodynamics [31]. In contrast to some earlier calculations [26], both (ΛK+ and Σ0K+) reactions proceed via excitation of the N*(1650), N*(1710), and N*(1720) intermediate baryonic resonance states. The interference terms between the amplitudes of various resonances are retained. To describe the near threshold data, the FSI effects in the final channel are included within the framework of the Watson-Migdal theory [27, 20]. ELA has been used to describe rather successfully the pp → ppπ0, pp → pmπ+ [20, 28], pp → pK+Y [21, 22] as well as pp → ppe+e− [30] reactions.

2 Description of the Model

We consider the tree-level structure (Fig. 1) of the amplitudes for the associated K+Y production in proton-proton collisions, which proceeds via the excitation of the N*(1650)(1/2−), N*(1710)(1/2+), and N*(1720)(3/2+) intermediate resonances. To evaluate these amplitudes within the effective
Lagrangian approach, one needs to know the effective Lagrangians (and the coupling constants appearing therein) at (a) the nucleon-nucleon-meson, (b) the resonance-nucleon-meson, and (c) the resonance-\( K^+\)-hyperon vertices.

![Feynman diagrams](image)

Figure 1: Feynman diagrams for \( K^+ Y \) production in \( pp \) collisions. The diagram on the left shows the direct process while that on the right the exchange one.

The parameters for \( NN \) vertices are determined by fitting the \( NN \) elastic scattering \( T \) matrix with an effective \( NN \) interaction based on the \( \pi, \rho, \omega \) and \( \sigma \) meson exchanges. The effective meson-\( NN \) Lagrangians are

\[
\mathcal{L}_{NN\pi} = -\frac{g_{NN\pi}}{2m_N} \bar{\Psi}_N \gamma_5 \gamma_\mu \tau \cdot (\partial^\mu \Phi_\pi) \Psi_N. \tag{1}
\]

\[
\mathcal{L}_{NN\rho} = -g_{NN\rho} \bar{\Psi}_N \left( \gamma_\mu + \frac{k_\rho}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \tau \cdot \rho^\mu \Psi_N. \tag{2}
\]

\[
\mathcal{L}_{NN\omega} = -g_{NN\omega} \bar{\Psi}_N \left( \gamma_\mu + \frac{k_\omega}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \omega^\mu \Psi_N. \tag{3}
\]

\[
\mathcal{L}_{NN\sigma} = g_{NN\sigma} \bar{\Psi}_N \sigma \Psi_N. \tag{4}
\]

We have used the notations and conventions of Bjorken and Drell [32]. In Eq. (1) \( m_N \) denotes the nucleon mass. Note that we have used a PV coupling for the \( NN\pi \) vertex. Since we use these Lagrangians to directly model the \( T \)-matrix, we have also included a nucleon-nucleon-axial-vector-isovector vertex, with the effective Lagrangian given by

\[
\mathcal{L}_{NNA} = g_{NNA} \bar{\Psi}_N \gamma_5 \gamma_\mu \tau \Psi \cdot A^\mu, \tag{5}
\]

where \( A \) represents the axial-vector meson field. This term is introduced because in the limit of large axial meson mass \( (m_A) \) it cures the unphysical behavior in the angular distribution of \( NN \) scattering caused by the contact term in the one-pion exchange amplitude [33], if \( g_{NNA} \) is chosen to be

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g_{NNA} = \frac{1}{\sqrt{3}} m_A \left( \frac{f_\pi}{m_\pi} \right), \tag{6}
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\]
with very large \((\gg m_N) m_A\). \(f_\pi\) appearing in Eq. (6) is related to \(g_{NN\pi}\) as 
\[ f_\pi = \left( \frac{g_{NN\pi}}{2m_N} \right) m_\pi. \]

We introduce, at each interaction vertex, the form factor 
\[ F_i^{NN} = \left( \frac{\lambda_i^2 - m_i^2}{\lambda_i^2 - q_i^2} \right), \]
where \(q_i\) and \(m_i\) are the four momentum and mass of the \(i\)th exchanged meson, respectively. The form factors suppress the contributions of high momenta and the parameter \(\lambda_i\), which governs the range of suppression, can be related to the hadron size. Since \(NN\) elastic scattering cross sections decrease gradually with the beam energy (beyond certain value), we take energy dependent meson-nucleon coupling constants of the following form 
\[ g(\sqrt{s}) = g_0 \exp(-\ell \sqrt{s}), \]
in order to reproduce these data in the entire range of beam energies. The parameters, \(g_0\), \(\lambda\) and \(\ell\) were determined by fitting to the elastic proton-proton and proton-neutron scattering data at the beam energies in the range of 400 MeV to 4.0 GeV [33, 28]. It may be noted that this procedure fixes also the signs of the effective Lagrangians [Eqs. (1)-(5)]. The values of various parameters are given in Table 1 of Ref. [21]. The same parameters for these vertices were also used in calculations of the pion and the dilepton production in \(pp\) collisions. Thus we ensure that the \(NN\) elastic scattering channel remains the same in the description of various inelastic channels within this approach, as it should be.

Below 2 GeV center of mass (c.m.) energy, only three resonances, \(N^*(1650)\), \(N^*(1710)\), and \(N^*(1720)\), have significant decay branching ratios into \(KY\) channels. Therefore, we have considered only these three resonances in our calculations. The \(N^*(1700)\) resonance having very small (and uncertain) branching ratio for the decay to these channels, has been excluded. Since all the three resonances can couple to the meson-nucleon channel considered in the previous section, we require the effective Lagrangians for all the four resonance-nucleon-meson vertices corresponding to all the included resonances. Since the mass of the strange quark is much higher than that of the \(u\)- or \(d\)- quark, one does not expect the pion like strict chiral constraints for the case of other pseudoscalar mesons like \(\eta\) and \(K\) (to be called \(\zeta\) in the following). Thus, one has a choice of pseudoscalar (PS) or PV couplings for the \(NN\zeta\) and \(N_{1/2}^*N\zeta\) vertices (forms of the corresponding effective Lagrangians are given in Ref. [21]). The same holds also for the \(N_{1/2}^*YK\) vertices.
In principle, one can select a linear combination of both and fit the PS/PV ratio to the data. However, to minimize the number of parameters we choose either PS or PV coupling at a time. In the results shown below, we have used PS couplings for both \( N^*N\pi \) and \( N^*\Lambda K^+ \) vertices involving spin-1/2 resonances of even and odd parities. Calculations have also been performed with the corresponding PV couplings. The cross sections calculated with this option for the \( N^*_1/2 YK \) vertex deviate very little from those obtained with the corresponding PS couplings. However, data shows a clear preference for the PS coupling at the \( N^*_1/2 N\pi \) vertices.

The couplings constants for the vertices involving resonances are determined from the experimentally observed quantities such as branching ratios for their decays to corresponding channels. It may however, be noted that such a procedure can not be used to determine the coupling constant for the \( N^*(1650)\Sigma K \) vertices, as the on-shell decays of this resonance to \( \Sigma K \) channel are inhibited. Therefore, we have tried to determine this coupling constant by fitting the available data on the \( \pi^+p \to \Sigma^+K^+, \pi^-p \to \Sigma^0K^0 \), and \( \pi^-p \to \Sigma^-K^+ \) reactions in an effective Lagrangian coupled channels approach \[34, 35\], where all the available data for the transitions from \( \pi N \) to five meson-baryon final states, \( \pi N, \pi\pi N, \eta N, K\Lambda, \) and \( K\Sigma \) are simultaneously analyzed for center of mass energies ranging from threshold to 2 GeV. In this analysis all the baryonic resonances with spin \( \leq \frac{3}{2} \) up to excitation energies of 2 GeV are included as intermediate states. Since the resonances considered in this study have no known branching ratios for the decay into the \( N\omega \) channel, we determine the coupling constants for the \( N^*N\omega \) vertices by the strict vector meson dominance (VMD) hypothesis \[36\], which is based essentially on the assumption that the coupling of photons on hadrons takes place through a vector meson.

It should be stressed that the branching ratios determine only the square of the corresponding coupling constants; thus their signs remain uncertain in this method. Predictions from independent calculations (e.g, the quark model) can, however, be used to constrain these signs. The magnitude as well as signs of the coupling constants for the \( N^*N\pi, N^*\Lambda K, N^*N\rho, \) and \( N^*N(\pi\pi)_{s-wave} \) vertices were determined by Feuster and Mosel \[34\] and Manley and Saleski \[37\] in their analysis of the pion-nucleon data involving the final states \( \pi N, \pi\pi N, \eta N, \) and \( K\Lambda \). Predictions for some of these quantities are also given in the constituent quark model calculations of Capstick and Roberts \[38\]. Guided by the results of these studies, we have chosen the positive sign for the coupling constants for these vertices. Unfortunately, the quark model calculations for the \( N^*N\omega \) vertices are still sparse and an unambiguous prediction for the signs of the corresponding coupling con-
The resonance properties used in the calculations of the decay widths are given in Table 1, where the resulting coupling constants and the adopted values of the cut-off parameters ($\lambda^{N N^*}_i$) are also shown. It may be noted that we have fixed the latter to one value in order to minimize the number of free parameters.

Table 1: Coupling constants and cut-off parameters for the $N^* N$-meson and $N^*$-hyperon-meson vertices used in the calculations

| Resonance  | Decay channel | Branching ratio (GeV) | $g^2/4\pi$ | cut-off (GeV) |
|------------|--------------|-----------------------|------------|--------------|
| $N^*(1710)$ | $N\pi$       | 0.150                 | 0.0863     | 850.0        |
|            | $N\rho$      | 0.150                 | 1.3653     | 850.0        |
|            | $N\omega$    | 0.170                 | 0.1189     | 850.0        |
|            | $N\sigma$    | 0.150                 | 0.0361     | 850.0        |
|            | $\Lambda K$  | 0.150                 | 2.9761     |              |
|            | $\Sigma K$   |                      | 4.4044     |              |
| $N^*(1720)$ | $N\pi$       | 0.100                 | 0.0023     | 850.0        |
|            | $N\rho$      | 0.700                 | 90.637     | 850.0        |
|            | $N\omega$    | 22.810                |            | 850.0        |
|            | $N\sigma$    | 0.120                 | 0.1926     | 850.0        |
|            | $\Lambda K$  | 0.080                 | 0.0817     |              |
|            | $\Sigma K$   |                      | 0.2204     |              |
| $N^*(1650)$ | $N\pi$       | 0.700                 | 0.0521     | 850.0        |
|            | $N\rho$      | 0.080                 | 0.5447     | 850.0        |
|            | $N\omega$    | 0.2582                |            | 850.0        |
|            | $N\sigma$    | 0.025                 | 0.2882     | 850.0        |
|            | $\Lambda K$  | 0.070                 | 0.0485     |              |
|            | $\Sigma K$   |                      | 0.0165     |              |

After having established the effective Lagrangians, coupling constants and form of the propagators (which are given in Ref. [21]), it is straightforward to write down the amplitudes for various diagrams associated with the $pp \rightarrow pYK$ reactions which can be calculated numerically by following e.g. the techniques discussed in [28]. The isospin part is treated separately. This gives rise to a constant factor for each graph, which is unity for the...
reaction under study. It should be noted that the signs of various amplitudes are fixed by those of the effective Lagrangian densities, coupling constants and propagators as described above. These signs are not allowed to change anywhere in the calculations.

In the present form of our effective Lagrangian theory, the energy dependence of the cross section due to FSI is separated from that of the primary production amplitude and the total amplitude is written as,

$$A_{fi} = M_{fi}(pp \rightarrow pYK^+) \cdot T_{ff},$$  \hspace{1cm} (9)

where $M_{fi}(pp \rightarrow pYK^+)$ is the primary associated $YK$ production amplitude, while $T_{ff}$ describes the re-scattering among the final particles which goes to unity in the limit of no FSI. The latter is taken to be the coherent sum of the two-body on-mass-shell elastic scattering amplitudes $t_i$ (with $i$ going from 1 to 3), of the interacting particle pairs $j-k$ in the final channel. This type of approach has been used earlier to describe the pion [29, 40, 41], $\eta$-meson [42, 43, 44], $\Lambda K^+$ [21] and $\phi$-meson [45] production in $pp$ collisions.

An assumption inherent in Eq. (9) is that the reaction takes place over a small region of space (which is fulfilled rather well in near threshold reactions involving heavy mesons). Under this condition the amplitudes $t_i$ can be expressed in terms of the inverse of the Jost function [27, 29] which has been calculated by using a Coulomb modified effective range expansion of the phase-shift [46]. The required effective range and scattering length parameters are given in Refs. [21, 22].

3 Results and Discussions

The total cross sections for the $\Lambda K^+$ and $\Sigma^0 K^+$ reactions as a function of the excess energy are shown in Fig. 2. The calculations are the coherent sum of all resonance excitation and meson exchange processes as described earlier. In both cases a good agreement is obtained between theory and the data available from the COSY-11 collaboration. Keeping in mind the fact that all parameters of the model, except for those of $N^*Yp$ vertices and the FSI, were the same in the two calculations and that no parameter was freely varied, this agreement is quite satisfactory. It should be noted that we do not require to introduce arbitrary normalization constants to get the agreement between calculations and the data. We also show in this figure the results obtained without including the FSI effects (dashed line). It can be seen that the FSI effects are vital for a proper description of the experimental data in both the cases.
In Fig. 3, we have investigated the role of various meson exchange processes in describing the total cross sections. The dashed, long-dashed, dashed-dotted, and solid with black square curves represent the contributions of $\pi$, $\rho$, $\omega$ and $\sigma$ meson exchanges, respectively. The contribution of the heavy axial meson exchange is not shown in this figure as it is negligibly small. The coherent sum of all the meson-exchange processes is shown by the solid line. It is clear that the pion exchange graphs dominate the production process for both the reactions in the entire range of beam energies. Contributions of $\rho$ and $\omega$ meson exchanges are almost insignificant. On the other hand, the $\sigma$ meson exchange, which models the correlated $s$-wave two-pion exchange process and provides about 2/3 of this exchange in the low energy $NN$ interaction, plays a relatively more important role. This observation has also been made in case of the $NN \rightarrow NN\pi$ reaction [17, 48, 49, 28].

The individual contributions of various nucleon resonances to the total cross sections of the two reactions are shown in Fig. 4. We note that in both the cases, the cross section is dominated by the $N^*(1650)$ resonance excitation for $\epsilon < 30$ MeV. Since $N^*(1650)$ is the lowest energy baryonic resonance having branching ratios for the decay to $Y K^+$ channels, its dominance in
these reactions at beam energies very close the kaon production threshold is to be expected. In the near threshold region the relative dominance of various resonances is determined by the dynamics of the reaction where the difference of about 60 MeV in excitation energies of $N^*(1650)$ and $N^*(1710)$ resonances plays a crucial role.

However, for $\epsilon$ values between 30 - 60 MeV, while the $pp \rightarrow pK^+\Lambda$ reaction continues to be dominated by $N^*(1650)$ excitation, the $pp \rightarrow pK^+\Sigma^0$ reaction gets significant contributions also from $N^*(1710)$ and $N^*(1720)$ resonances. This difference in the role of the three resonances in the two cases can be understood in the following way. For a resonances to contribute significantly, we should have $m_Y + m_K + \epsilon \geq m_R + \Gamma_R/2$, where $m_R$ and $\Gamma_R$ are the mass and width of the resonance, respectively. Therefore, in the region of excess energies $\geq Q = (m_R + \Gamma_R/2) - (m_Y + m_K)$, the particular resonance $R$ should contribute significantly. The values of $Q$ for the $pp \rightarrow pK^+\Lambda$ reaction, are 115 MeV, 150 MeV, and 185 MeV, for the $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$ resonances, respectively. On the other hand, for the $pp \rightarrow pK^+\Sigma^0$ case, they are 36 MeV, 72 MeV and 105 MeV, respectively for these three resonances. Therefore, contributions of the $N^*(1710)$ and $N^*(1720)$ resonance excitations are negligibly small for
the $K^+\Lambda$ production in the entire energy range of the COSY-11 data (i.e., for $\epsilon \leq 60$ MeV) while they are significant for the $K^+\Sigma^0$ case for $\epsilon > 30$ MeV. It would be helpful to have data on the invariant mass spectrum at these excess energies in order to confirm these theoretical observations.

Figure 4: Contributions of $N^*(1650)$ (dashed line), $N^*(1710)$ (full line with black squares) and $N^*(1720)$ (dashed-dotted line) baryonic resonances to the total cross section for the two reactions studied in Fig. 2. Their coherent sum is shown by the solid line.

In Fig. 5, we compare our calculations with the data for the ratio $R$ as a function of $\epsilon$. We have shown here the results for excess energies up to 60 MeV, where the COSY-11 data are available. It is clear that our calculations are able to describe well the trend of the fall-off of $R$ as a function of the excess energy. It should be noted that FSI effects account for about 60%–80% of the observed ratio for $\epsilon < 30$ MeV and about 50% of it beyond this energy. Therefore, not all of the observed value of $R$ at these beam energies can be accounted for by the FSI effects, which is in agreement with the observation made in [18]. It should again be emphasized that without considering the contributions of the $N^*(1650)$ resonance for the $\Sigma^0K^+$ reactions, the calculated ratio would be at least an order of magnitude larger. Therefore, these data are indeed sensitive to the details of the reaction mechanism. At higher beam energies ($\epsilon > 300$ MeV), values of $R$ obtained with and without FSI effects are almost identical. In this region the reaction mechanism is different; here all the three resonances contribute in one way
or the other, their interference terms are significant [21], and FSI related effects are unimportant.

Figure 5: Ratio of the total cross sections for \( pp \rightarrow p\Lambda K^+ \) and \( pp \rightarrow p\Sigma^0 K^+ \) reaction as a function of the excess energy. The solid and dashed lines show the results of our calculations with and without FSI effects, respectively. The data are from [17].

4 Summary and conclusions

In summary, we have studied the \( pp \rightarrow p\Lambda K^+ \) and \( pp \rightarrow p\Sigma^0 K^+ \) reactions within an effective Lagrangian model. Most of the parameters of the model are fixed by fitting to the elastic \( NN \) T-matrix which restricts the freedom of varying them freely in order to fit the data. The reactions proceed via excitation of the \( N^*(1650) \), \( N^*(1710) \), and \( N^*(1720) \) intermediate baryonic resonant states. An important result of our study is that the \( N^*(1650) \) resonant state contributes predominantly to both these reactions at near threshold beam energies. Therefore, these reactions in this energy regime, provide an ideal means of investigating the properties of this \( S_{11} \) baryonic resonance. To the extent that the final state interaction effects in the exit
channel can be accounted for by the Watson-Migdal theory, our model is able to explain the experimentally observed large ratio of the total cross sections of the two reactions in the near threshold region.

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