Exclusive and semi-inclusive strangeness and charm production in $\pi N$ and $NN$ reactions

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Abstract. Using the Quark-Gluon Strings Model (QGSM) combined with Regge phenomenology we consider the reactions $\pi^- p \rightarrow K^0\Lambda$ and $\pi^- p \rightarrow D^+\Lambda_c^+$ which are dominated by the contributions of the $K^*$ and $D^*$ Regge trajectories, respectively. The spin structure of the amplitudes is described by introducing Reggeized Born terms. It is found that the existing data for the reaction $\pi^- p \rightarrow K^0\Lambda$ are in reasonable agreement with the model predictions. To describe the absolute values of the cross sections it is necessary to introduce also suppression factors which can be related to absorption corrections. Furthermore, assuming the SU(4) symmetry to hold for Regge residues and the universality of absorption corrections we calculate the cross section of the reaction $\pi^- p \rightarrow D^+\Lambda_c^+$. Employing the latter results from $\pi^- p$ reactions we then estimate the contributions of the pion exchange mechanism to the cross sections of the reactions $NN \rightarrow NKA$ and $NN \rightarrow NDA_c$ and compare them with the contributions of the $K$ and $D$ exchanges. We find that the $NN$ reactions are dominated not by pion exchange but by $K$ and $D$ exchanges, respectively.

Moreover, assuming the SU(4) symmetry to hold approximately for the coupling constants $g_{NDA_c} = g_{NKA}$ we analyze also the production of leading $\Lambda_c$ hyperons in the reaction $NN \rightarrow \Lambda_cX$. It is shown that the non-perturbative mechanism should give an essential contribution to the $\Lambda_c$ yield for $x \geq 0.5$.

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Recently it has been argued that the open charm enhancement observed in nucleus-nucleus collisions at the SPS might be due to secondary reaction mechanisms such as $\pi N \rightarrow D\Lambda_c$ or $NN \rightarrow NDA_c$. In this work we present estimates of these elementary cross sections using the analogy with strangeness production in $\pi N$ and $NN$ collisions. We consider also semi-inclusive $\Lambda$ and $\Lambda_c$ production in the reactions $NN \rightarrow NX\Lambda$ and $NN \rightarrow NX\Lambda_c$.

It is well known that the methods of perturbative QCD can not be applied for a calculation of the cross sections mentioned above especially at invariant energies closer to threshold. For the analysis of binary reactions we instead use the nonperturbative Quark-Gluon String model and for reactions with three particles in the final state we employ the meson-exchange model taking into account the exchanges of the lowest meson states - pseudoscalar and vector.

The amplitudes for the reactions $\pi N \rightarrow KA$ and $\pi N \rightarrow D\Lambda_c$ are calculated using the Reggeized Born term approach (see e.g. Refs. 5,6) with contributions of $K^*$ and $D^*$ Regge trajectories, respectively. The parameters of the trajectories are taken from Ref. 6, whereas for the coupling constants we assume SU(4) symmetry as suggested recently by Lin and Ko. With these parameters the energy dependence of the total $\pi^- p \rightarrow K^+\Lambda$ cross section (solid line in Fig. 1) as well as the $t$-dependence of the differential $\pi^- p \rightarrow K^+\Lambda$ cross section are described rather well, except for the region close to threshold where the dominant contribution stems from the well established $s$- and $p$-wave resonances. We note that to obtain the absolute value of the cross section one has to introduce a suppression factor of $\sim 0.4$, which can be interpreted as an absorption correction. Assuming its universality we will introduce the same suppression factor for charm production, too. The resulting total cross section of the reaction $\pi^- p \rightarrow D^+\Lambda_c^+$ is shown by the dashed line in Fig. 1.

Our next step is to study $NN$ reactions where we first apply our model to strangeness production. Using the method of Yao one can express the $\pi$-exchange cross section for the reaction $pp \rightarrow pK^+\Lambda$ in terms of the $g_{NN\pi}$ coupling constant and the $\pi^0 p \rightarrow K^+\Lambda$ cross section as

\[
\sigma = \frac{g_{NN\pi}^2}{8\pi^2 p_t^2 s} \int_{W_{min}}^{W_{max}} k W^2 \sigma(\pi^0 p \rightarrow K^+\Lambda, W) \, dW \times
\]
exchange should be about leading Thus we expect that the cross section for semi-inclusive → \text{pp} \sigma \text{ratio of the cross sections can be expressed through the same coupling constant and } \Lambda \text{tion for the leading through the coupling constant } \sigma \text{scattering cross section } \sigma \text{express the cross section for the reaction } \Lambda K \pi \sigma \text{falls off with energy whereas } \Lambda K \pi \text{Fig. 2. The dashed and solid lines describe the } p \text{ function of the laboratory momentum } p_{\text{lab}}. \text{The dashed line denotes the } \pi \text{-exchange contribution while the solid line corresponds to the } K \text{-exchange with the cutoff } \Lambda_K = 1.0 \text{ GeV}

400 \mu \text{b. Furthermore, the ratio of the coupling constants } g_{K^*+pA} / g_{K^0+pA} \simeq 2 \text{ which implies that the contribution of the } K^* \text{ exchange to the cross section of the leading } A \text{ production might be } \sim 4 \text{ times larger. Thus we expect the cross section for the semi-inclusive leading } A \text{ production to be about } \sigma_{K-\text{exch}}(pp \rightarrow XA) + \sigma_{K^{*}-\text{exch}}(pp \rightarrow XA) \simeq 1.5 \pm 2 \text{mb.}

We note that Erhan et al. \cite{12} quote total cross sections for the reaction } pp \rightarrow A+X \text{ of } 4.4 \pm 0.2 \text{ and } 4.7 \pm 0.2 \text{ mb at } \sqrt{s} = 53 \text{ and } 62 \text{ GeV}, \text{respectively. This comparison shows that the mechanism considered above gives a dominant contribution to the semi-inclusive leading } A \text{ production in the reaction } pp \rightarrow XA.

Using the analogy of strangeness and charm production we can expect that the main contributions to the cross sections of the reactions } NN \rightarrow D_c(\bar{D}_c^*)A_N \text{ come from the } D_c \text{ and } D_c^* \text{ exchanges, respectively. The coupling constants – involving a charm quark – can be related to the strange ones using } SU(4) \text{ symmetry, i.e. } g_{K^0NA} = g_{D_cN_A} \text{ and } g_{K^{*0}NA} = g_{D_c^*N_A}. \text{Within the approach of Yao } \cite{14} \text{we then can express the cross section of the reaction } pp \rightarrow \bar{D}_c^0pA_c^+ \text{ through the coupling constant } g_{\bar{D}_c^0pA_c^+} \text{ and the elastic } \bar{D}_c^0p \text{ scattering cross section } \sigma_{cl}(\bar{D}_c^0p). \text{Similarly, the cross section for the leading } A \text{ production in the reaction } pp \rightarrow XA \text{ can be expressed through the same coupling constant and the total } \bar{D}_c^0p \text{ scattering cross section } \sigma_{tot}(\bar{D}_c^0p).

In our calculations we assume } \sigma_{cl}(\bar{D}_c^0p) = \sigma_{cl}(K^0p) \text{ and } \sigma_{tot}(\bar{D}_c^0p) = \sigma_{tot}(K^0p) \text{ while the form factor is taken as } \quad F_{\bar{D}_c^0}(t) = A_2^p / (A_2^p - t). \text{(2)}

In Fig. 3 we present the total cross section for the reaction } pp \rightarrow \bar{D}_c^0A_c^+p \text{ as a function of the invariant energy above threshold for } \Lambda_{D_c} = 1.5 \text{ GeV (dashed line) and } \Lambda_{D_c} = 1.0 \text{ GeV (solid line). The dash-dotted line denotes the contribution from the } \pi \text{-exchange alone. Note, that for the

\begin{equation}
\times \int_{W_{\text{min}(t)}}^{W_{\text{max}(t)}} \frac{1}{(t - m_2^2)^2} t \, dt,
\end{equation}
elementary reaction $\pi^0 p \to \bar{D}^0 A_c^+ p$ we use the amplitude calculated in the approach discussed above, while for the $\bar{D}^0 p$ cross section we adopt a value corresponding to the asymptotic $K^+ p$ cross section, i.e. $\sim 3 \text{ mb}$, which is consistent with the values used in the literature (see e.g. [13]).

We find that the main contribution to the cross section for the reaction $NN \to \bar{D}A_c N$ (a few GeV above threshold) comes from the $D_c$ exchange which is much larger than the pion exchange for cut-off parameters $A_D \geq 1 \text{ GeV}$.

To make a rough estimate of the absolute value of the $D$-exchange contribution to the leading $A_c$ production in the reaction $pp \to X A_c$ we assume that the total $\bar{D}^0 p$ cross section is as in case of $K^+ p$ scattering, i.e. $\sim 20 \text{ mb}$. Then at c.m. energies larger than $10 \text{ GeV}$ we obtain a cross section of $\sim 10 - 40 \mu \text{b}$ depending on the choice of the cutoff. As in the case of strangeness production the contribution from $D^*$ exchange might be approximately 4 times larger. Therefore, according to our estimates the cross section of the semi-inclusive leading $A_c$ production at high energy should be as large as $\sim 50 - 200 \mu \text{b}$. This estimate agrees with the experimental value of $40 - 200 \mu \text{b}$ at $\sqrt{s}=62 \text{ GeV}$ quoted in Ref. [4] which implies that the non-perturbative mechanism considered here gives an essential contribution to the leading $A_c$ production.

We finally note, that the same mechanism with $D$ and $D^*$ exchanges should provide a similar contribution to the open charm production in $p\bar{p}$ collisions.

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