Eur. Phys. J. A **18**, 305–307 (2003)
DOI 10.1140/epja/i2002-10222-6

The European Physical Journal A

Exclusive and semi-inclusive strangeness and charm production in πN and NN reactions

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Received: 30 September 2002 /
Published online: 22 October 2003 –

Abstract. Using the Quark-Gluon Strings Model (QGSM) combined with Regge phenomenology we consider the reactions $\pi^- p \to K^0 \Lambda$ and $\pi^- p \to D^- \Lambda_c^+$ 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 $\pi^- p \to K^0 \Lambda$ 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 $\pi^- p \to D^- \Lambda_c^+$. 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 $NN \to NK\Lambda$ and $NN \to N\bar{D}\Lambda_c$ 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 $g_{ND\Lambda_c} = g_{NK\Lambda}$ we analyze also the production of leading Λ_c-hyperons in the reaction $NN \to \Lambda_c X$. It is shown that the non-perturbative mechanism should give an essential contribution to the Λ_c yield for $x \geq 0.5$.

PACS. 13.85.Fb Inelastic scattering: two-particle final states – 13.85.Hd Inelastic scattering: many-particle final states – 14.20.Lq Charmed baryons – 14.40.Lb Charmed mesons

Recently it has been argued [1] that the open-charm enhancement observed in nucleus-nucleus collisions [2] at the SPS might be due to secondary reaction mechanisms such as $\pi N \to \bar{D}\Lambda_c$ or $NN \to N\bar{D}\Lambda_c$. In this work we present estimates of these elementary cross-sections using the anology with strangeness production in πN and NN collisions. We consider also semi-inclusive Λ and Λ_c production in the reactions $NN \to NX\Lambda$ and $NN \to NX\Lambda_c$.

It is well known that the methods of perturbative QCD cannot 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 non-perturbative Quark-Gluon String Model [3] 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 $\pi N \to K\Lambda$ and $\pi N \to D\Lambda_c$ are calculated using the Reggeized–Born-term approach (see, *e.g.*, refs. [4,5]) 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 [7]. With these parameters the energy dependence of the total $\pi^- p \to K^+ \Lambda$ cross-section (solid line in fig. 1) as well as the t-dependence of the differential $\pi^- p \to K^+ \Lambda$ 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 [8]. We note that to obtain the absolute value of the cross-section one has to introduce a suppression factor of ~ 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 $\pi^- p \to D^- \Lambda_c^+$ 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 [9] one can express the π exchange cross-section for the reaction $pp \to pK^+\Lambda$ in terms of the $g_{NN\pi}$

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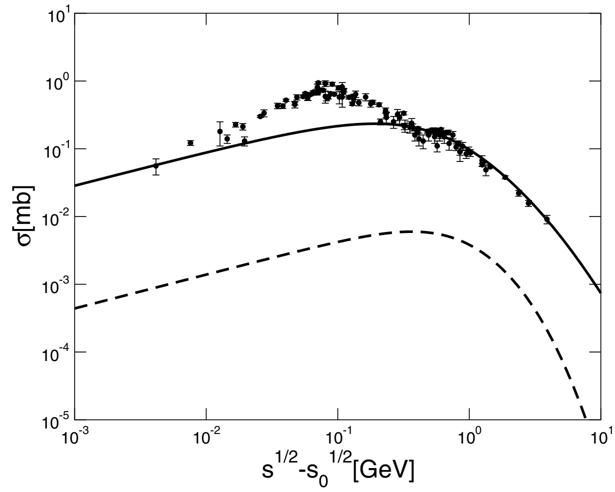

Fig. 1. Total cross-section for the reaction $\pi^- p \to K^+ \Lambda$ (solid line) and $\pi^- p \to D^- \Lambda_c^+$ (dashed line) as a function of the invariant energy above thresholds in comparison to the data from ref. [10].

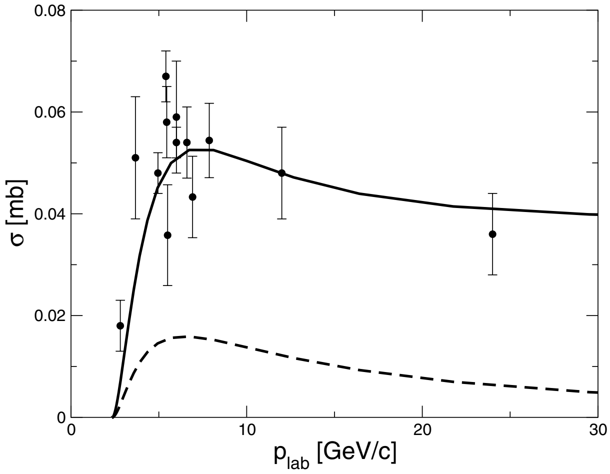

Fig. 2. The total cross-section for the reaction $pp \to K^+ \Lambda p$ as a function of proton laboratory momentum $p_{\rm lab}$. The dashed line denotes the π exchange contribution, while the solid line corresponds to the K exchange with the cutoff $\Lambda_K = 1.0$ GeV.

coupling constant and the $\pi^0 p \to K^+ \Lambda$ cross-section as

$$\sigma = \frac{g^2_{NN\pi}}{8\pi^2 p_i^2 s} \int_{W_{\rm min}}^{W_{\rm max}} k\ W^2\ \sigma(\pi^0 p \to K^+ \Lambda, W)\ {\rm d}W \times \int_{t_{\rm min}(W)}^{t^{\rm max}(W)} F_\pi^4(t) \frac{1}{(t - m_\pi^2)^2}\ t\ {\rm d}t, \qquad (1)$$

where W is the c.m. energy in the $K^+\Lambda$ subsystem and t is the 4-momentum transfer squared between the initial and final baryons. The form factor was chosen to be of the standard monopole type: $F_\pi(t) = (\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 - t)$ with $\Lambda_\pi = 1.3$ GeV. A similar expression —but with $\sigma(K^+p)$— can be written for the K exchange. For the K^+p elastic cross-section employed in this case we use the parametrization of Cugnon *et al.* [11].

The total cross-section of the reaction $pp \to K^+\Lambda p$ as a function of the laboratory momentum $p_{\rm lab}$ is shown in Fig. 2. The dashed and solid lines describe the π- and K exchange contributions, respectively, with the cutoff $\Lambda_K = 1.0$ GeV. An interesting observation is that the pion exchange contribution is substantially smaller than the K exchange and can be neglected especially at higher energies. The reason for that is a difference in the energy dependence of the elementary cross-sections: $\sigma(\pi^- p \to K\Lambda)$ falls off with energy, whereas $\sigma(K^+p)$ is almost constant since it is dominated by pomeron exchange. Moreover, the K exchange alone is able to reproduce the experimental data when choosing the cutoff $\Lambda_K = 1.0$ GeV.

We see that using the approach of Yao [9] we can express the cross-section for the reaction $pp \to K^+p\Lambda$ through the coupling constant $g_{K^+p\Lambda}$ and the elastic K^+p scattering cross-section $\sigma_{\rm el}(K^+p)$. Similarly, the cross-section for the leading-Λ production in the reaction $pp \to X\Lambda$ can be expressed through the same coupling constant and the total K^+p scattering cross-section $\sigma_{\rm tot}(K^+p)$.

As follows from fig. 2 the cross-section of the reaction $pp \to K^+p\Lambda$ is about 40–50 μb for $p_{\rm lab} \geq 5$ GeV/c. The ratio of the cross-sections $\sigma_{\rm tot}(K^+p)/\sigma_{\rm el}(K^+p) \simeq$ 7–8. Thus we expect that the cross-section for semi-inclusive leading-Λ production in the reaction $pp \to X\Lambda$ via K exchange should be about $\sigma_{K\text{-exch}}(pp \to X\Lambda) \simeq$ 300–400 μb. Furthermore, the ratio of the coupling constants $g_{K^{*+}p\Lambda}/g_{K^+p\Lambda} \simeq 2$ [5], which implies that the contribution of the K^* exchange to the cross-section of the leading-Λ production might be ~ 4 times larger. Thus, we expect the cross-section for the semi-inclusive leading-Λ production to be about

$$\sigma_{K\text{-exch}}(pp \to X\Lambda) + \sigma_{K*\text{-exch}}(pp \to X\Lambda) \simeq 1.5\text{–}2\,\text{mb}.$$

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

Using the analogy of strangeness and charm production we can expect that the main contributions to the cross-sections of the reactions $NN \to \bar{D}_c(\bar{D}_c^*)\Lambda_c N$ come from the D_c and D_c^* exchanges, respectively. The coupling constants —involving a charm quark— can be related to the strange ones using $SU(4)$ symmetry, *i.e.* $g_{KN\Lambda} = g_{D_cN\Lambda_c}$ and $g_{K^{*+}N\Lambda} = g_{D_c^*N\Lambda_c}$. Within the approach of Yao [9] we then can express the cross-section of the reaction $pp \to \bar{D}_c^0 p\Lambda_c^+$ through the coupling constant $g_{\bar{D}_c^0 p\Lambda_c^+}$ and the elastic $\bar{D}_c^0 p$ scattering cross-section $\sigma_{\rm el}(\bar{D}_c^0 p)$. Similarly, the cross-section for the leading-Λ_c production in the reaction $pp \to X\Lambda_c$ can be expressed through the same coupling constant and the total $\bar{D}_c^0 p$ scattering cross-section $\sigma_{\rm tot}(\bar{D}_c^0 p)$.

In our calculations we assume $\sigma_{\rm el}(\bar{D}_c^0 p) = \sigma_{\rm el}(K^+p)$ and $\sigma_{\rm tot}(\bar{D}_c^0 p) = \sigma_{\rm tot}(K^+p)$, while the form factor is taken as

$$F_D(t) = \Lambda_D^2/(\Lambda_D^2 - t). \qquad (2)$$

In fig. 3 we present the total cross-section for the reaction $pp \to \bar{D}_c^0 \Lambda_c^+ p$ as a function of the invariant energy

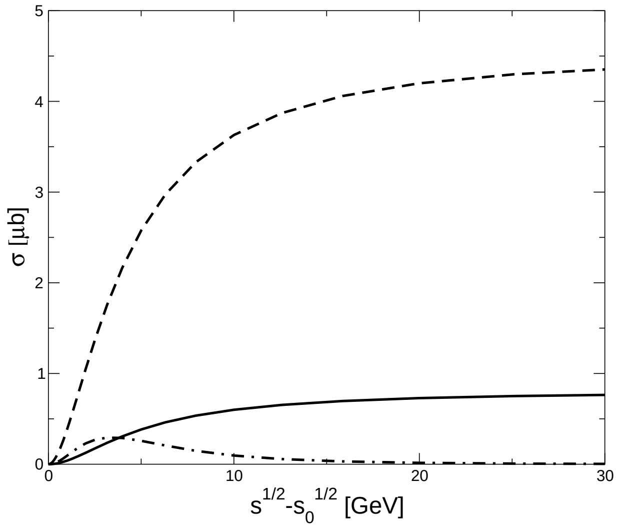

Fig. 3. The predicted total cross-section for the reaction $pp \to \bar{D}^0 \Lambda_c^+ p$ as a function of the invariant energy above threshold. The dash-dotted line denotes the contribution from the π exchange, while the solid line and the dashed line correspond to the D_c exchange with the cutoff $\Lambda_D = 1.0$ GeV and 1.5 GeV, respectively.

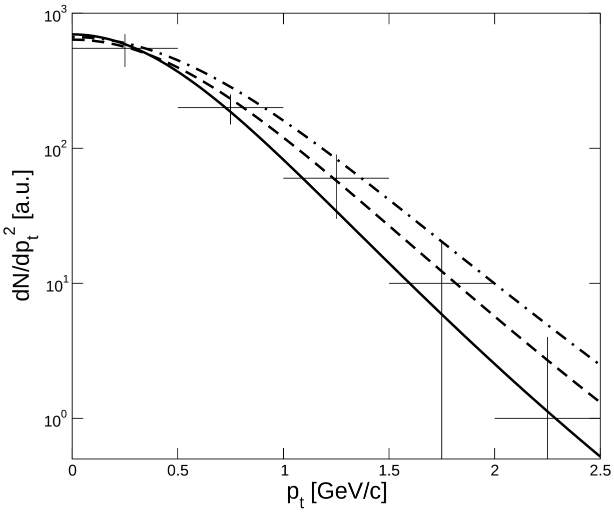

Fig. 4. The p_t dependence of the differential cross-section for the reaction $pp \to X\Lambda_c$ at $\sqrt{s} = 62$ GeV. The theoretical curves correspond to the differential cross-section $\mathrm{d}^2\sigma/\mathrm{d}p_t^2\mathrm{d}x$ calculated at $x = 0.9$ (where it peaks) for the cutoffs $\Lambda_D = 1.0$ GeV (solid line), $\Lambda_D = 1.3$ GeV (dashed line), $\Lambda_D = 1.5$ GeV (dash-dotted line). The results are normalized to the data from [14] at small transverse momentum p_t.

above threshold for $\Lambda_{D_c} = 1.5$ GeV (dashed line) and $\Lambda_{D_c} = 1.0$ GeV (solid line). The dash-dotted line denotes the contribution from the π exchange alone. Note that for the elementary reaction $\pi^0 p \to \bar{D}^0 \Lambda_c^+$ 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.* ~ 3 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 $NN \to \bar{D}\Lambda_c N$ (a few GeV above threshold) comes from the D_c exchange which is much larger than the pion exchange for cutoff parameters $\Lambda_D \geq 1$ GeV.

To find restrictions on the cutoff parameter Λ_D in (2) we use the data from ref. [14] on semi-inclusive Λ_c production in the reaction $pp \to X\Lambda_c$. We assume now that the same D exchange mechanism also gives a large contribution to the semi-inclusive Λ_c production at x close to 1. (In fact, in our calculation the cross-section is peaked at $x \sim 0.9$.) Of course, in this case one has to insert the total $\bar{D}^0 p$ cross-section in the corresponding analog of eq. (1). As shown in fig. 4 the p_t dependence of the differential cross-section constrains Λ_D to 1–1.5 GeV.

To make a rough estimate of the absolute value of the D exchange contribution to the leading-Λ_c production in the reaction $pp \to X\Lambda_c$ we assume that the total $\bar{D}^0 p$ cross-section is the same as in case of K^+p scattering, *i.e.* ~ 20 mb. Then at c.m. energies larger than 10 GeV we obtain a cross-section of $\sim$ 10–40 μb 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-Λ_c production at high energy should be as large as $\sim$ 50–200 μb. This estimate agrees with the experimental value of 40–200 μb at $\sqrt{s} = 62$ GeV quoted in ref. [14] which implies that the non-perturbative mechanism considered here gives an essential contribution to the leading-Λ_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.

This work was supported by DFG, RFFI and Forschugszentrum Jülich.

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