$\Lambda_c^+ - \Lambda_c^-$ production asymmetries in two component models.

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ABSTRACT: Experiments on charm hadroproduction have shown a substantial difference in the production of charm and anticharm hadrons. In this work we study Λ_c^+ and Λ_c^- inclusive production in $p - N$ interactions in the framework of two component models. We show that the recombination two component model gives a qualitatively and quantitatively good description of $\Lambda_c^\pm$ production while the intrinsic charm model seems to be ruled out by recent experimental data from the SELEX Collaboration.

KEYWORDS: charm hadroproduction, recombination, intrinsic charm.

It is well known from experiments that there is a substantial difference in the production of charm and anticharm hadrons in hadron-hadron interactions. Leading (L) particles, which share one or more valence quarks with the initial hadrons, are favored in the incident hadron direction over Non-Leading (NL) particles, which share none. This effect, known as Leading Particle Effect, has been observed in inclusive production of charm mesons and baryons in $\pi^- - N$, $p - N$, $K - N$ and $\Sigma^- - N$ interactions by several experiments [1, 2, 3] .

Leading particle effects can be quantified by means of a production asymmetry, which is defined as

$$A \equiv \frac{d\sigma^L - d\sigma^{NL}}{d\sigma^L + d\sigma^{NL}} . \tag{1}$$

Asymmetries in charm-anticharm production indicate that charm hadronization cannot proceed by independent fragmentation alone. They imply also that some sort of recombination mechanism, involving valence quarks in the initial hadrons, must take place in the production.

Several models have been proposed to explain charm hadroproduction. However, no theoretical consensus has been reached yet on what is the dominant mechanism giving rise to the observed asymmetries. This is partly due to the lack of simultaneous measurements of charm-anticharm asymmetries and inclusive particle distributions in the same experiment. Actually, as models depend on a set of parameters, and these parameters can be adjusted to describe either the charm-anticharm asymmetries or the inclusive particle distributions, a meaningful comparison of models to experimental data must be done on both, asymmetries and inclusive particle distributions.

Among the proposed models are the String Fragmentation model (SF) [4], implemented in the Lund Pythia-Jetset package [5]; the recombination of charm quarks produced perturbatively with the remnants of the initial hadrons [6]; the Intrinsic Charm model (IC) [7] and the recombination two component model (R2C) [8].

Aiming to extract information on the charm hadron production mechanisms, in this work we shall compare predictions of both, the IC and R2C two component models to recent experimental data on $p + N \to \Lambda_c^\pm + X$ by the SELEX Collaboration [3].

In two component models the total cross section for charm hadron production receives contributions from two different processes, namely per-

*Coauthor: L.M. Mendoza Navas, Depto. de Física, Universidad de los Andes turbative production of a $c\bar{c}$ pair in QCD followed by independent fragmentation, and contributions coming from another, non-perturbative, mechanism. So far, two possibilities have been considered for this second contribution: IC coalescence [7] and the recombination of charm quarks, already present in the sea of the initial hadrons, with valence and sea quarks from the initial hadrons [8]. Then, in the $p+N \rightarrow \Lambda_c^{\pm}+X$ reaction,

$$\frac{d\sigma}{dx_F} = \frac{d\sigma^{Frag.}}{dx_F} + \frac{d\sigma^{IC(Rec.)}}{dx_F} \; . \qquad (2)$$

The first term in the RHS of Eq. (2) describes the production of charm hadrons by independent fragmentation, while the second one is the contribution to $\Lambda_c^{\pm}$ inclusive production coming from the IC or the recombination mechanisms.

Charm hadron production by independent fragmentation is given by

$$\begin{aligned} \frac{d\sigma^{Frag.}}{dx_F} &= \frac{1}{2}\sqrt{s} \int H^{ab}(x_a, x_b, Q^2) \\ &\times \; \frac{1}{E} \frac{D_{\Lambda_c}(z)}{z} dz dp_T^2 dy \; , \qquad (3) \end{aligned}$$

where

$$D_{\Lambda_c/c}(z) = \frac{N_{\Lambda_c}}{z\left[1 - 1/z - \epsilon_c/(1-z)\right]^2} \qquad (4)$$

is the Peterson fragmentation function [9] with N_{Λ_c} a normalization constant. $H^{ab}(x_a, x_b, Q^2)$ contains information on the initial hadron structures and the dynamics of the perturbative QCD (pQCD) charm production. At Leading Order (LO) it is given by

$$\begin{aligned} H^{ab}(x_a,\; x_b \;, Q^2) &= \Sigma_{a,b} \left[q_a(x_a, Q^2)\bar{q}_b(x_b, Q^2) \right. \\ &+ \; \left. \bar{q_a}(x_a, Q^2) q_b(x_b, Q^2) \right] \frac{d\hat{\sigma}}{d\hat{t}} \, |_{q\bar{q}} \\ &+ \; g_a(x_a, Q^2) g_b(x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}} \, |_{gg} \quad . \qquad (5) \end{aligned}$$

In Eqs. (3) (4) and (5), x_i; $i = a, b$; is the momentum fraction of the initial hadron carried by the parton i, z and p_T^2 are the momentum fraction of the initial hadron carried by the charm quark and its transverse momentum squared respectively, and y is the rapidity of the charm antiquark. The sum in Eq. (5) runs over light and strange quarks.

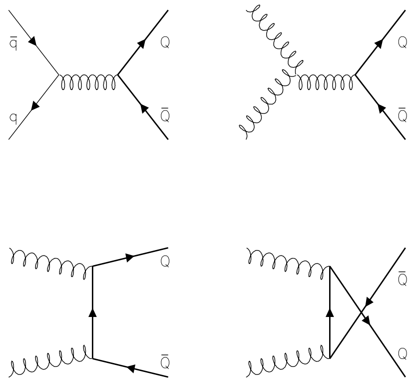

Figure 1: Parton fusion processes contributing to $c\bar{c}$ perturbative production at LO.

Up to LO in the pQCD processes (see Fig. 1), no contribution to the $\Lambda_c^+ - \Lambda_c^-$ asymmetry arises from the charm quark production. At Next to Leading Order (NLO), a small $c - \bar{c}$ asymmetry translates into a tiny $\Lambda_c^+ - \Lambda_c^-$ asymmetry [10]. However, this effect is very small and has the opposite sign to the experimentally observed asymmetry in $p + N$ interactions. Then, the second term in the RHS of Eq. (2) must give the dominant contribution to the $\Lambda_c^+ - \Lambda_c^-$ asymmetry.

In the IC model for the $p + N \rightarrow \Lambda_c^{\pm} + X$ reaction in the $x_F > 0$ region, the second term in the RHS of Eq. (2) comes from fluctuations of protons in the beam to $|uudc\bar{c}\rangle$ Fock states [7]. These Fock states break up in the collision contributing to Λ_c^+ production through the coalescence of the intrinsic charm quark with u and d quarks. To obtain a Λ_c^- purely from this process, a fluctuation of the proton to a $|uudu\bar{u}d\bar{d}c\bar{c}\rangle$ Fock state is required. As the probability of the later is smaller than for the former, Λ_c^+ production is favored in the proton direction. The Λ_c^+ differential cross section for the intrinsic charm process is [7]

$$\begin{aligned} \frac{d\sigma^{IC}}{dx_F} &= r^{IC} \int_0^1 dx_u dx_{u'} dx_d dx_c dx_{\bar{c}} \\ &\times \; \delta \; \left(x_F - x_u - x_d - x_c\right) \frac{dP^{IC}}{dx_u ... dx_{\bar{c}}} \; , \; (6) \end{aligned}$$

where

$$\frac{dP^{IC}}{dx_u ... dx_{\bar{c}}} = N_5 \alpha_s^4 \left(M_{c\bar{c}}^2\right) \times \frac{\delta\left(1 - \Sigma_{i=u}^{\bar{c}} x_i\right)}{\left(m_p^2 - \Sigma_{i=u}^{\bar{c}} \hat{m}_i^2 x_i\right)^2} \quad (7)$$

is the probability of the $|uudc\bar{c}\rangle$ fluctuation of the proton, and r^{IC} is a parameter which must be fixed from experimental data. Neglecting contributions coming from the $|uudu\bar{u}d\bar{d}c\bar{c}\rangle$ Fock states of the proton, which are very small, the Λ_c^- differential cross section is given only by the first term in the RHS of Eq. (2).

In the R2C model, the second term in the RHS of of Eq. (2) has the form [8, 11]

$$\frac{d\sigma^{Rec.}}{dx_F} = r^{Rec} \int_0^1 \frac{dx_u}{x_u} \frac{dx_d}{x_d} \frac{dx_c}{x_c} F_3\left(x_u, x_d, x_c\right) \times R_3\left(x_u, x_d, x_c, x_F\right) , \quad (8)$$

where F_3 and R_3 are the multiquark distribution and the recombination functions respectively. As for the intrinsic charm model, r^{Rec} is a parameter which must be fixed from experimental data.

For Λ_c^+ production in $p + N$ interactions in the $x_F > 0$ region, F_3 is given by

$$F_3\left(x_u, x_d, x_c\right) \sim x_u u(x_u) x_d d(x_d) x_c c(xc) \times \rho(x_u, x_d, x_c) , \quad (9)$$

while for Λ_c^- production

$$F_3\left(x_{\bar{u}}, x_{\bar{d}}, x_{\bar{c}}\right) \sim x_{\bar{u}} \bar{u}(x_{\bar{u}}) x_{\bar{d}} \bar{d}(x_{\bar{d}}) x_{\bar{c}} \bar{c}(x_{\bar{c}}) \times \rho(x_{\bar{u}}, x_{\bar{d}}, x_{\bar{c}}) . \quad (10)$$

In Eqs. (9) and (10), $xq(x)$ is the q-flavored quark distribution in the proton. Notice that the multiquark distribution of Eq. (9) receives contributions from u and d valence and sea quarks, while Eq. (10) is constructed only by using sea quark distributions. Thus, Λ_c^- production is due solely to the recombination of antiquarks popped up from the vacuum in the interaction. As quarks and antiquarks are created in pairs from the vacuum, Λ_c^+'s can also be formed by the recombination of u and d sea quarks, in addition to the u and d valence quarks, with charm quarks, thus giving rise to a $\Lambda_c^+ - \Lambda_c^-$ asymmetry.

The momentum correlation function ρ, which we assume to be the same for both Λ_c^+ and Λ_c^- production, is usualy taken as [11]

$$\rho(x_u, x_d, x_c) = (1 - x_u - x_d - x_c)^\gamma , \quad (11)$$

with the exponent γ fixed appealing to some consistency condition like [11]

$$xq\left(x_i\right) = \int_0^{1-x_i} dx_j \times \int_0^{1-x_i-x_j} dx_k \, F_3\left(x_u, x_{u'}, x_d\right) \quad i, j, k = u, u', d \quad (12)$$

for the valence quarks in the proton.

In Eqs. (9) and (10) we are assuming the existence of charm quarks inside the proton. Indeed, assuming that the global scale of the whole process is of the order of $Q^2 \sim 4m_c^2$, there should be a substantial contribution of charm quarks to the proton structure [12]. However, charm quarks in the proton may have a twofold origin, namely, a non-perturbative component which must exist over a time scale independent of Q^2, and a perturbative component due to the QCD evolution. The non-perturbative contribution is expected to be small, of the order of 1 % or less [13], and at $Q^2 \sim 4m_c^2$ the perturbative component must be dominant. On the other hand, by assuming the existence of charm inside the proton we are consistently including the flavor exitation diagrams which are not considered in the LO calculation of Eq. (2)- (5) [14] (See Fig. 2). Note that flavor exitation diagrams are usually included in the pQCD calculation at NLO, but only for the perturbatively generated charm quarks. The non-perturbative charm sea must be taken into account through the recombination process. Moreover, it is difficult to account for the recombination of the spectator c-quark (see Fig. 2) when flavor exitation diagrams are included into a NLO pQCD calculation of charm production.

The recombination function R_3 is given by [15]

$$R_3(x_u, \ x_d \ , x_c, x_F) = \alpha \frac{(x_u x_d)^{n_1} x_c^{n_2}}{x_F^{n_1+n_2-1}} \times \delta\left(x_u + x_d + x_c - x_F\right) \quad (13)$$

with $n_1 = 1$ and $n_2 = 5$ [16] and α is a normalization constant. The same recombination function is used for Λ_c^- inclusive production.

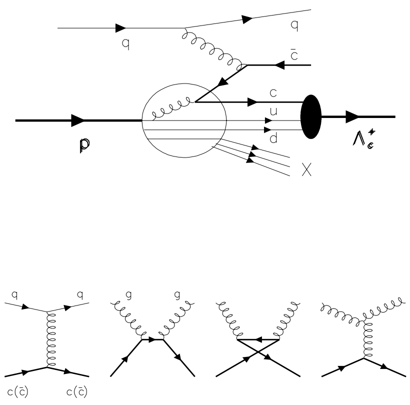

Figure 2: Upper: Λ_c^+ production by recombination of a c quark in the sea of the proton with u and d quarks. Lower: flavor exitation diagrams contributing to Λ_c^+ and Λ_c^- production by recombination.

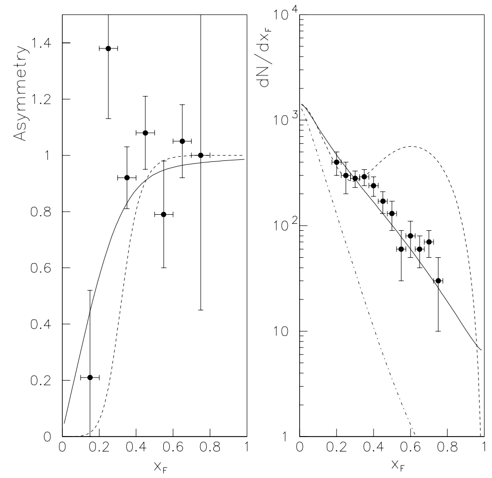

Figure 3: Left: $\Lambda_c^+ - \Lambda_c^-$ asymmetry in pN interactions. Solid line is the prediction of the R2C model with $r^{Rec} = 1.5$ and dashed line is the prediction of the IC model with $r^{IC} = 0.4$. Right: Λ_c x_F distribution in pN interactions. Solid line is the prediction of the R2C model and dashed line is the prediction of the IC. Dot-dashed line shows the Λ_c^- distribution as predicted by the R2C model. Experimental data are from Ref. [3].

In order to compare model predictions to experimental data, we have used

$$\frac{dN^{\Lambda_c^+}}{dx_F} = N\left[\frac{d\sigma}{dx_F}_{Frag} + r^{IC,Rec}\,\frac{d\sigma}{dx_F}^{\Lambda_c^+}_{Rec,IC}\right], \tag{14}$$

and similarly for the Λ_c^- differential cross section. In the equation above, N is a global normalization constant which has been adequately fixed from experimental data. The $r^{IC,Rec}$ parameter was allowed to be different for the IC and R2C models, however, it was fixed to the same value for particle and antiparticle production within each model. The $\Lambda_c^+ - \Lambda_c^-$ asymmetry as a function of x_F was calculated according to Eq. (1) using the parametrization of Eq. (14) for the particle and antiparticle x_F inclusive distributions.

To control the size of each individual contribution to the total differential cross section, the calculated distributions for the fragmentation, IC and recombination processes for Λ_c^+ production were each normalized to unity. The recombination differential cross section for Λ_c^- production was normalized by multiplying by σ^{-1}, where $\sigma = \int_0^1 \frac{d\sigma}{dx_F}^{\Lambda_c^+}_{Rec} dx$ before normalization. Thus, the contribution of the light sea to the Λ_c^+ and Λ_c^- production is the same. In this way, the coefficients r^{IC} and r^{Rec} give the relative size of the IC and Recombination component respectively, in comparison to the independent fragmentation process in the total cross section.

Prediction by the IC and R2C models are shown in Fig. 3 for both the $\Lambda_c^+ - \Lambda_c^-$ asymmetry and the inclusive particle distribution as a function of x_F. Model predictions are also compared to the $p + N \to \Lambda_c^\pm + X$ data from the SELEX Collaboration [3].

Curves were obtained using the GRV-92 [12] parton distributions in nucleons in Eqs. (5), (9) and (10). The exponent γ in the correlation function of Eq. (11) was fixed to $\gamma = -0.1$ [8] and the overall Q^2 scale was chosen as $Q^2 = 4m_c^2$ with $m_c = 1.5$ GeV. In the Peterson fragmentation function we used $\epsilon = 0.06$. In order to fix the parameter $r^{IC,Rec}$ in both the IC and R2C models, we adjusted the curves to describe first the asymmetry. Once this parameter was fixed, we compared model predictions to experimental data on the x_F particle distribution.

As can be seen in the figure, the IC model

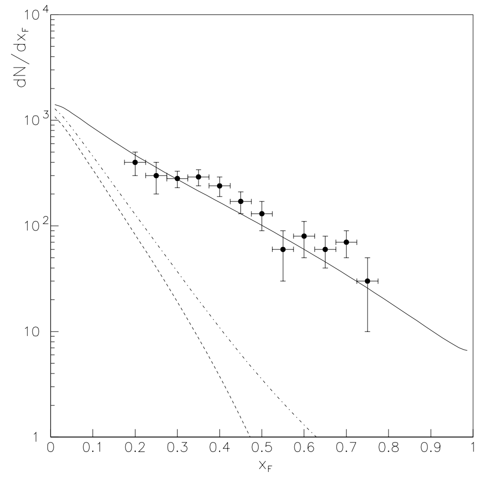

Figure 4: Λ_c^+ (solid line) and Λ_c^- (point dashed line) particle distributions predicted by the R2C model in $p-p$ interactions. Dashed line is the contribution to Λ_c^+ and Λ_c^- production coming from the independent fragmentation. Experimental data are from Ref. [3].

cannot describe simultaneously the $\Lambda_c^+ - \Lambda_c^-$ asymmetry and the Λ_c x_F distribution. On the other hand, the R2C model gives a qualitative and quantitatively good description of both, the asymmetry and the x_F particle distribution.

Furthermore, in order to fit the Λ_c x_F distribution, the recombination part of Eq. (2) must be of the order of 1.5 times bigger than the fragmentation contribution. This implies that the main mechanism in Λ_c production is recombination, even in the low x_F region (see Fig. 4). It is interesting to note also that recombination seems to be bigger than independent fragmentation also for Λ_c^- production. The IC contribution to the proton structure, which is expected to be small, can only give a marginal contribution, and only at high x_F ($x_F \to 1$) values, to the $\Lambda_c^\pm$ production in proton-proton interactions. Thus, the recombination mechanism seems to be the principal contribution to the hadronization process, even more important than independent fragmentation of charm quarks.

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