On the intrinsic charm and the recombination mechanisms in charm hadron production

J.C. Anjos[*], *J. Magnin*[†]

Centro Brasileiro de Pesquisas Físicas
Rua Dr. Xavier Sigaud 150, CEP 22290-180, Rio de Janeiro, Brazil

G. Herrera [‡]
Centro de Investigación y de Estudios Avanzados
Apdo. Postal 14-740, México 07000, DF, Mexico

Abstract

We study $\Lambda_c^{\pm}$ production in pN and $\pi^- N$ interactions. Recent experimental data from the SELEX and E791 Collaborations at FNAL provide important information on the production mechanism of charm hadrons. In particular, the production of the Λ_c baryon provides a good test of the intrinsic charm and the recombination mechanisms, which have been proposed to explain the so called leading particle effects.

Key-words: Heavy quarks; Charm baryons; Hadroproduction.

[*]e-mail: janjos@cbpf.br
[†]e-mail: jmagnin@cbpf.br
[‡]e-mail: gherrera@fis.cinvestav.mx

1   Introduction

Hadronization of heavy quarks produced in hadron-hadron interactions is still an open problem. The hadronization of quarks is in the realm of non-perturbative QCD and not calculable from first principles yet. This is by far the less known aspect of heavy hadron production.

The leading particle effect, which has been observed by several experiments in charm meson and baryon hadroproduction, indicates that charm hadronization cannot proceed by uncorrelated fragmentation alone. Furthermore, this effect implies the existence of some sort of recombination mechanism in the hadronization process. Several models have been proposed to explain the leading particle effect, among them, the intrinsic charm mechanism [1] and the conventional recombination two component model [2].

However, until now, no clear distinction has been made between the intrinsic charm and the conventional recombination mechanism. The reason is that there is no experimental measurements of hadron antihadron production asymmetries and differential cross sections simultaneously. As an exemption we can quote the WA82 [3] and the WA92 [4] experiments. These two experiments measured the $D^{\pm}$ and $D^{\circ}/\bar{D}^{\circ}$ asymmetries and differential cross sections as a function of x_F $(= 2p_{\parallel}/\sqrt{s})$. However, although there is some indications that the intrinsic charm model cannot describe simultaneously asymmetries and differential cross sections, these data are not conclusive as for the production mechanism.

Recently, the SELEX Collaboration presented results on the $\Lambda_c^+ - \Lambda_c^-$ production asymmetries and particle distributions as a function of x_F in the $p, \pi^-, \Sigma^- - N \rightarrow \Lambda_c^{\pm} + X$ reactions [5]. SELEX is a fixed target experiment with a beam average momentum of 600 GeV/c. As we will show in the following, these results clearly favor the recombination over the intrinsic charm hypothesis as the dominant contribution to leading particle effects (see also Ref. [6]).

Furthermore, E791 [7] results on $\Lambda_c^+ - \Lambda_c^-$ production asymmetries in 500 GeV/c $\pi^- - N$ interactions seem to imply that other contributions like associated production of charm mesons should play a role in the observed asymmetry. In addition, it is interesting to note that the $\Lambda^{\circ} - \bar{\Lambda}^{\circ}$ asymmetry measured by the E791 Collaboration [8] is similar to the $\Lambda_c^+ - \Lambda_c^-$ asymmetry, implying that the hadronization mechanisms for charm and strange quarks would be the same [9].

In what follows, we will focus our attention in the intrinsic charm [1] and recombination [2] two component models as applied to the $p - N \rightarrow \Lambda_c^{\pm} + X$ and $\pi^- - N \rightarrow \Lambda_c^{\pm} + X$ reactions.

2   The differential cross section and asymmetries

In two component models, the differential cross section is built on contributions from two different processes, namely, fragmentation of the heavy quarks (denoted *Frag*) and from the intrinsic charm (*IC*) or recombination mechanisms (*Rec*),

$$\frac{d\sigma}{dx_F} = \frac{d\sigma^{Frag}}{dx_F} + \frac{d\sigma^{IC(Rec)}}{dx_F} \ . \tag{1}$$

The first term gives the same contribution to Λ_c^+ than to Λ_c^- production, since no differences arise in charm or anticharm fragmentation. Contributions coming from the second term are, however, different for the Λ_c^+ and the Λ_c^-, thus generating a production asymmetry. The production asymmetry is defined as

$$A(x_F) = \frac{d\sigma^{\Lambda_c^+} - d\sigma^{\Lambda_c^-}}{d\sigma^{\Lambda_c^+} + d\sigma^{\Lambda_c^-}}. \tag{2}$$

In a two components model, the production asymmetry would be given by

$$A(x_F) = \frac{d\sigma^{IC(Rec)}\Big|_{\Lambda_c^+} - d\sigma^{IC(Rec)}\Big|_{\Lambda_c^-}}{2\, d\sigma^{Frag} + d\sigma^{IC(Rec)}\Big|_{\Lambda_c^+} + d\sigma^{IC(Rec)}\Big|_{\Lambda_c^-}}\ . \tag{3}$$

In what follows we will analyse each contribution to eq (1), and hence to eq. (3), separately.

2.1 Fragmentation of heavy quarks

The first component in eq. (1), which describes the production of heavy hadrons through the fragmentation of heavy quarks, is given by (see e.g. Ref. [2])

$$\frac{d\sigma^{Frag.}}{dx_F} = \frac{1}{2}\sqrt{s} \int H^{AB}(x_a, x_b, Q^2) \frac{1}{E} \frac{D_{\Lambda_c/c}(z)}{z} dz\, dp_T^2\, dy\ . \tag{4}$$

Here, $H^{AB}(x_a, x_b, Q^2)$ is given by

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

and contain contributions from the pQCD processes $q\bar{q} \to c\bar{c}$, $gg \to c\bar{c}$, etc, and from the structure of the initial hadrons A and B. $D_{\Lambda_c/c}(z)$ is the Peterson fragmentation function given by [10]

$$D_{\Lambda_c/c}(z) = \frac{N}{z\big(1 - 1/z - \epsilon/(1-z)\big)}\ , \tag{6}$$

and z, p_T^2 and y are the momentum fraction, the trasverse momentum and the rapidity of the heavy quark respectively. x_a and x_b are the momentum fractions of light quarks inside the initial hadrons A and B.

As the fragmentation function (6) is the same for c and $\bar{c}$ fragmentation, this term gives no contribution to the production asymmetry of eq. (3) at Leading Order. At Next to Leading Order, a small $c - \bar{c}$ asymmetry translates into a tiny $\Lambda_c^+ - \Lambda_c^-$ asymmetry [12]. However, this effect, which is very small, produces a negative asymmetry in disagreement with experimental observations.

In our calculations we have used the GRV-LO parton distribution functions in proton and pions [11], $Q^2 = 4\, m_c^2$, $m_c = 1.5$ GeV and $\epsilon = 0.06$ in the Peterson fragmentation function.

2.2   The intrinsic charm mechanism

In $p - N \to \Lambda_c^{\pm} + X$ reactions, the intrinsic charm contribution comes from fluctuations of the beam protons to the $|uudc\bar{c}\rangle$ Fock state, which breaks up in the collision contributing to Λ_c^+ production. The Λ_c^+ differential cross section for this process is [1]

$$
\begin{aligned}
\frac{d\sigma^{IC}}{dx_F} &= \beta \int_0^1 dx_u dx_{u'} dx_d dx_c dx_{\bar{c}} \delta \left(x_F - x_u - x_d - x_c \right) \\
&\times \frac{dP^{IC}}{dx_u dx_{u'}...dx_{\bar{c}}} \ ,
\end{aligned}
\tag{7}
$$

where

$$
\frac{dP^{IC}}{dx_u dx_{u'}...dx_{\bar{c}}} = \alpha_s^4 \left(M_{c\bar{c}}^2 \right) \frac{\delta \left(1 - \Sigma_{i=u}^{\bar{c}} x_i \right)}{\left(m_p^2 - \Sigma_{i=u}^{\bar{c}} \hat{m}_i^2 x_i \right)^2} \ ,
\tag{8}
$$

is the probability of the $|uudc\bar{c}\rangle$ fluctuation of the proton and β, which gives the probability of the fluctuation, is a parameter which must be fixed adequately to describe experimental data.

To obtain a Λ_c^- in $p - N$ interactions, a fluctuation of the proton to the $\left| uudu\bar{u}d\bar{d}c\bar{c} \right\rangle$ Fock state is required. Since the probability of a five-quarks state is larger than for a nine-quarks Fock state, Λ_c^+ production is favored over Λ_c^- in proton initiated reactions. A similar expression to those of eqs. (7) and (8) can be found for the Λ_c^- differential cross section. However, its contribution is negligible.

A similar mechanism is at work in $\pi^- - N$ interactions. However, $\Lambda_c^{\pm}$ production in π^- initiated reactions requires fluctuations of the pion to $|\bar{u}d\bar{u}u\bar{c}c\rangle$ or $\left| \bar{u}d\bar{d}dc\bar{c} \right\rangle$ Fock states. Then, after the break-up, a $\Lambda_c^+ + \Sigma_c^{--}$ or $\Lambda_c^- + \Sigma_c^0$ is formed, respectively, in the final state. Since the invariant mass of both final states should be approximately the same, the contribution to Λ_c^+ is the same than for Λ_c^- production and no asymmetry at all is obtained.

2.3   The recombination mechanism

The conventional recombination contribution to the second term of eq. (1) in $p - N$ interactions has the form [2]

$$
\frac{d\sigma^{Rec.}}{dx_F} = \beta \int_0^1 \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{dx_3}{x_3} F_3^p \left(x_1, x_2, x_3 \right) R_3 \left(x_1, x_2, x_3, x_F \right) \ ,
\tag{9}
$$

where $F_3^p \left(x_1, x_2, x_3 \right)$ is the multiquark distribution and $R_3 \left(x_1, x_2, x_3, x_F \right)$ the recombination function. As for the intrinsic charm model, β is a parameter which must be fixed from experimental data. x_i (i=1,2,3) are the momentum fractions of quarks in the initial proton which will be valence quarks in the final Λ_c^+ (Λ_c^-).

The recombination model assumes that there exist charm quarks inside the proton. The process of charm production occurs at a scale of the order of $Q^2 \sim 4m_c^2$, which is above the threshold for the perturbative production of charm inside the proton [13]. The charm inside the proton can have both, a non-perturbative and a perturbative origin due

to QCD evolution, with the first existing over a scale independent of Q^2. However, for $Q^2 \sim 4m_c^2$ the perturbative component must be dominant.

Leading particle effects in the recombination model are due to the different contributions to the multiquark distribution. Actually, for Λ_c^+ production in $p - N$ interactions

$$F_3^p (x_1, x_2, x_3) = x_1 u^p(x_1) x_2 d^p(x_2) x_3 c^p(x_3) \rho(x_1, x_2, x_3) , \qquad (10)$$

while for Λ_c^- production

$$F_3^p (x_1, x_2, x_3) = x_1 \bar{u}^p(x_1) x_2 \bar{d}^p(x_2) x_3 \bar{c}^p(x_3) \rho(x_1, x_2, x_3) . \qquad (11)$$

The multiquark distribution given in eq. (10) recibes contributions from valence and sea quarks in the proton whereas the multiquark distribution in eq. (11) has contributions coming from the sea of the proton alone. $\rho(x_1, x_2, x_3)$ in eqs. (10) and (11) correlates in momentum the single quark distributions. We used [2]

$$\rho(x_1, x_2, x_3) = (1 - x_1 - x_2 - x_3)^{-0.1} \qquad (12)$$

for both, Λ_c^+ and Λ_c^- production.

For the recombination function we simply used [2]

$$R_3 (x_1, x_2, x_3) = \alpha \frac{x_1 x_2 x_3}{x_F^2} \delta (x_1 + x_2 + x_3 - x_F) , \qquad (13)$$

with the parameter α in eq. (13) fixed by the condition [14]

$$\int_0^1 dx_1 dx_2 dx_3 \frac{R(x_1, x_2, x_3, x_)}{x_F^3} = 1 . \qquad (14)$$

In $\pi^- - N \to \Lambda_c^\pm + X$, the differential cross section and the recombination function are given by expressions formally identical to those of eqs. (9) and (13). However, the multiquark distribution function is different for Λ_c^+ and Λ_c^- production. In fact, for Λ_c^+ we have

$$F_3^{\pi^-} (x_1, x_2, x_3) = x_1 d^\pi(x_1) x_2 u^\pi(x_2) x_3 c^\pi(x_3) \rho(x_1, x_2, x_3) , \qquad (15)$$

while for Λ_c^- it is

$$F_3^{\pi^-} (x_1, x_2, x_3) = r x_1 \bar{d}^\pi(x_1) x_2 \bar{u}^\pi(x_2) x_3 \bar{c}^\pi(x_3) \rho(x_1, x_2, x_3) , \qquad (16)$$

here r is a suppression factor lower than one. For the ρ function we used the same as in eq. (12).

The origin of the suppression factor r in eq. (16) can be understood as follows: for Λ_c^- production, the multiquark distribution is built up from the $\bar{u}$, $\bar{d}$ and $\bar{c}$ quark distributions in the pion. But, $\bar{u}$ and $\bar{d}$ quarks in the pion can easily annihilate with u and d valence quarks in the nucleon, thus reducing the amount of $\bar{u}$ and $\bar{d}$ quaks in the pion available to recombine into a Λ_c^-. This suppression is not present in Λ_c^+ production since u and d quarks in the pion can only annihilate with $\bar{u}$ and $\bar{d}$ *sea* quarks in the nucleon.

2.4 Comparison to experimental data

In Figs. (1) and (2) we compare predictions of the IC and Rec models to experimental data from SELEX [5] and E791 [7] experiments on $p - N \rightarrow \Lambda_c^{\pm} + X$ and $\pi^- - N \rightarrow \Lambda_c^{\pm} + X$ respectively.

In order to fix the parameters in both models, we used

$$\frac{d\sigma}{dx_F} = N \left[\frac{d\sigma^{Frag}}{dx_F} + \beta \frac{d\sigma^{IC(Rec)}}{dx_F} \right] \ , \qquad (17)$$

where N is a global normalization factor. The individual cross sections for each contribution have been normalized to unity, except for the Λ_c^- distribution in recombination in $p - N$ interactions, which has been normalized by means of $N_{\Lambda_c^-} = 1 / \int \frac{d\sigma_{\Lambda_c^+}}{dx_F} dx_F$ to preserve the relative amount among Λ_c^+ and Λ_c^- production.

In $\pi^- - N$ interactions the Λ_c^+ and Λ_c^- recombination cross sections were normalized to unity. For the last one, the r factor was included in the definition of the parameter β in eq. (17).

In this way we can have an approximate idea of the relative size of each contribution to the total cross section.

Furthermore, in order to have the curves shown in the figures, the parameters in the IC and Rec models were fixed to values which best describe the differential cross sections. Once this was done, the asymmetry was calculated. The r parameter was fixed in order to have a good description of the asymmetry in $\pi^- - N$ interactions.

For $\Lambda_c^{\pm}$ production in $p - N$ interactions we used $\beta = 1.8$ ($\beta = 0.1$) in the Rec (IC) model , indicating that recombination is a substantial part of Λ_c production. The same value for the β parameter was used for the Rec model in $\pi^- - N$ interactions, but a slightly lower $\beta = 0.06$ was used for the IC model. A suppression factor $r = 0.6$ is required to describe the production asymmetry in the Rec model.

It must be noted that equally good descriptions for both, the differential cross section and asymmetry, can be obtained in the framework of the Rec model using values for β in the range $1 - 2$ and varying the global normalization factor N in eq. (17) accordingly. This means that parameters in the Rec model can only be fixed with accuracy once data for the differential cross section on Λ_c production in the low x_F region ($0 < x_F < 0.2$) become available.

3 Conclusions

For the first time, experimental data on Λ_c production and production asymmetries allow to distinguish among two different mechanisms of production and hadronization. It seems that the IC two components model do not describe simultaneously the differential cross sections and production asymmetries for $\Lambda_c^{\pm}$ produced in $p - N$ and $\pi^- - N$ interactions. Conversely, the Rec two component model seems to be a sensible approach to the problem, giving a good description of both, the Λ_c differential cross section and the production asymmetry.

In addition, we have shown that the *Rec* two component model is able to explain the positive asymmetry observed by the E791 [7] and SELEX [5] experiments in $\pi^- - N$ interactions. As discued in the text, the *IC* model predicts none asymmetry in this case.

Furthermore, the recombination mechanism seems to be more important than fragmentation. In fact, in $p - N \rightarrow \Lambda_c + X$ the recombination contributions is 1 to 2 times bigger than fragmentation. The same is observed in $\pi^- - N \rightarrow \Lambda_c + X$. This is a clear signal that the debris of the initial hadrons play a fundamental role in the hadronization process.

In Ref. [15], predictions in the framework of the *IC* model have been done on the $\Lambda_c^{\pm}$ production and asymmetry in $\Sigma^- - N$ interactions. Although no comparison to experimental data is made a extremely hard behaviour is seen in the curves for the differential cross section.

Acknowledgements

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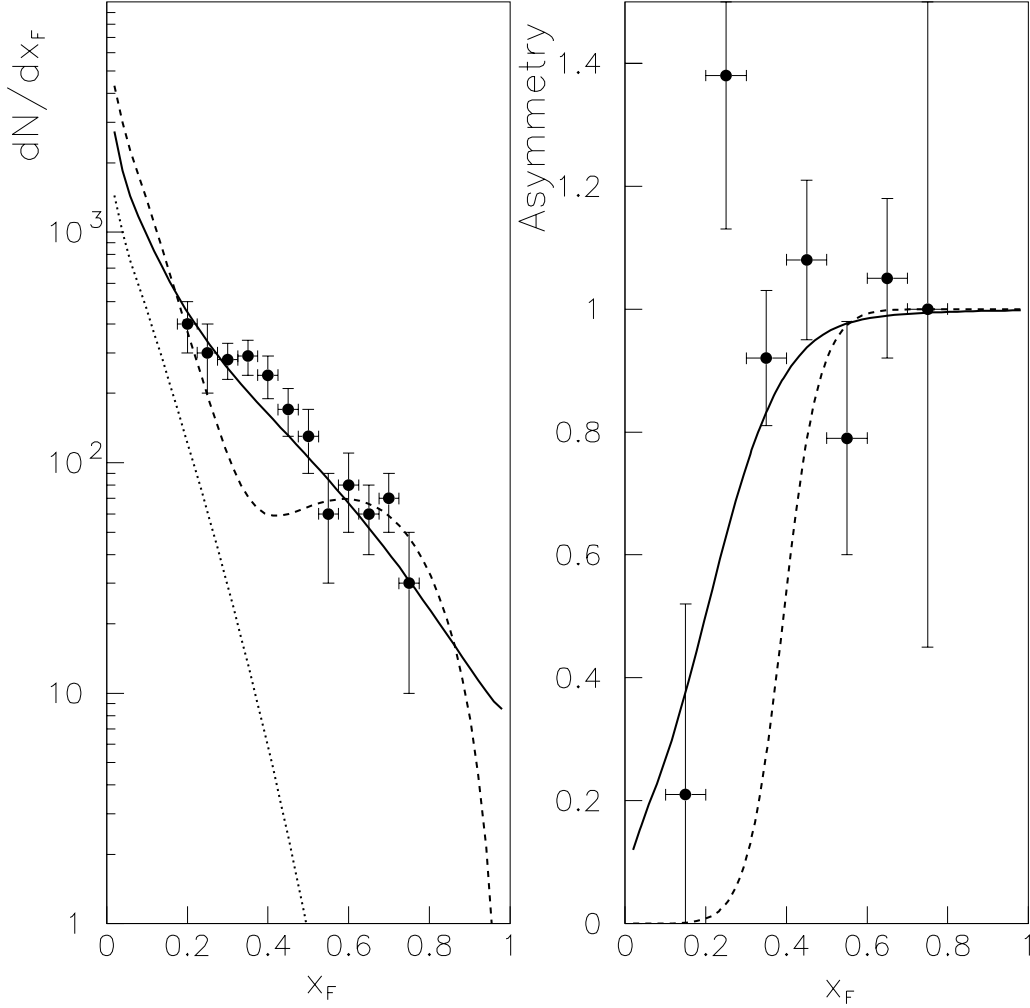[15] T. Gutierrez, R. Vogt, *Nucl.Phys.* **B539** (1999)189.

Figure 1: Differential cross section (left) and production asymmetry (right) for $\Lambda_c^{\pm}$ production in $p - N$ interactions. Experimental data were taken from Ref. [5]. The solid line shows the prediction of the Rec two component model. The IC prediction is shown by the dashed line. The dotted line shows also the contribution from Peterson fragmentation to the total cross section in the Rec model.
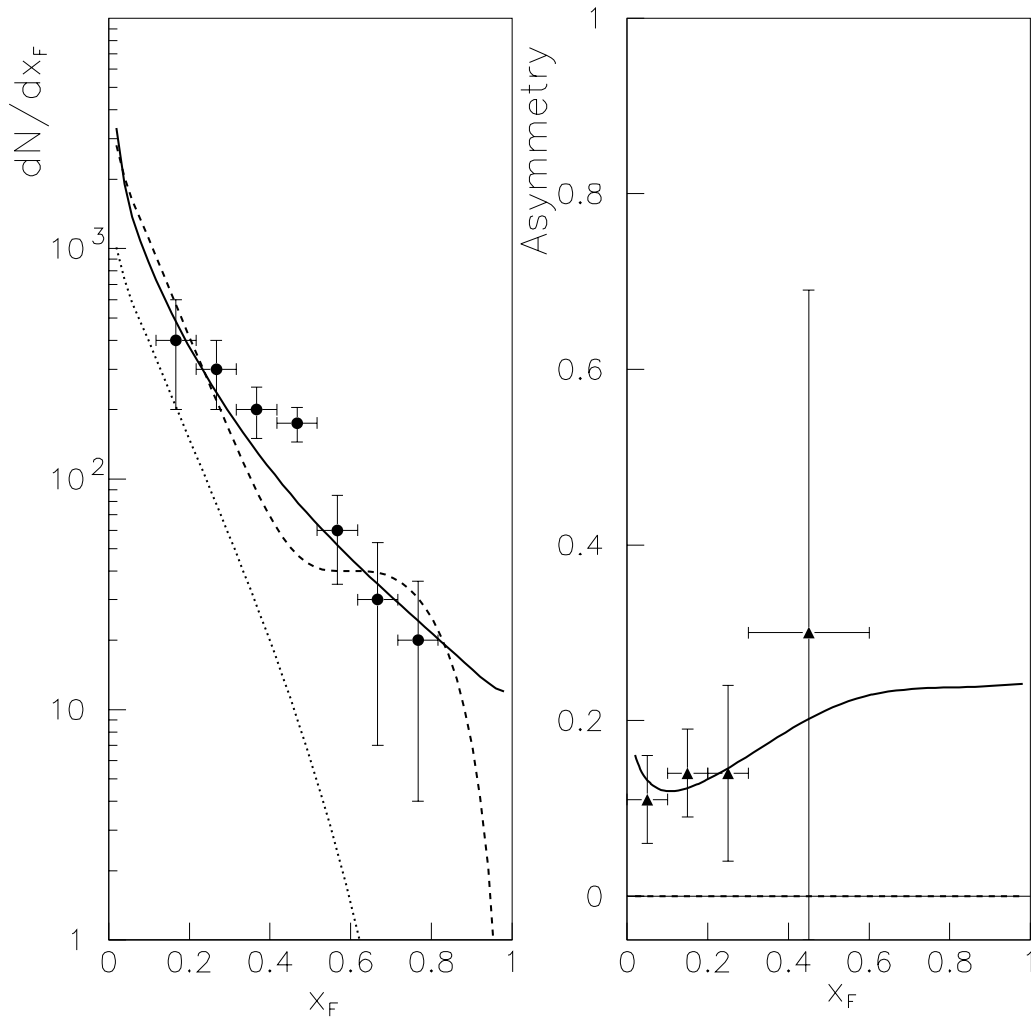
Figure 2: Differential cross section (left) and production asymmetry (right) for $\Lambda_c^{\pm}$ production in $\pi^- - N$ interactions. Experimental data on the differential cross section were taken from Ref. [5] while data on asymmetry are from Ref. [7]. The SELEX experiment has also measured the Λ_c production asymmetry in $\pi^- - N$ interactions, but with error bars larger than those of the E791 experiment. The solid line shows the prediction of the *Rec* two component model. The *IC* prediction is shown by the dashed line. The dotted line shows also the contribution from Peterson fragmentation to the total cross section in the *Rec* model.