Production of the Doubly Charmed Baryons at the SELEX experiment – The double intrinsic charm approach

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Abstract
The high production rate and \( \langle x_F \rangle > 0.33 \) of the doubly charmed baryons measured by the SELEX experiment is not amenable to perturbative QCD analysis. In this paper we calculate the production of the doubly heavy baryons with the double intrinsic charm Fock states whose existence is rigorously predicted by QCD. The production rate and the longitudinal momentum distribution are both reproduced. We also show that the production rates of the doubly charmed baryons and double \( J/\psi \) production observed by NA3 collaboration are comparable. Recent experimental results are reviewed. The production cross section of the doubly charmed baryons at a fixed-target experiment at the LHC is presented.

1. Introduction
The SELEX measurements of the production of the doubly charmed baryons at large \( x_F \) are among the most intriguing and surprising results in modern baryonic physics \cite{1,2,3}. The SELEX experiment is a fixed-target experiment utilizing the Fermilab negative charged beam at 600 GeV/c and positive beam at 800 GeV/c to produce charm particles in a set of thin foil of Cu or in a diamond and operated in the \( x_F > 0.1 \) kinematic region. The negative beam composition was about 80% \( \Sigma^- \) and 20% \( \pi^- \). The positive beam was 90% protons.

In early 2000s the SELEX published first observation of 15.9 signal over 6.1 \pm 0.5 \footnote{The error is statistical only.} background events, at a mass of 3.52 GeV, of the doubly charmed baryons in the charged decay mode \( \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \) from 1630 \( \Lambda_c^+ \rightarrow pK^-\pi^+ \) events sample \footnote{The error is statistical only.} which was previously used for precision measurement of \( \Lambda_c^+ \) lifetime \cite{4,5}.

Using same search strategy the SELEX reported 20 signal events, at a mass of 3.76 GeV, of \( \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+ \) decay mode over 1656 \( \Lambda_c^+ \rightarrow pK^-\pi^+ \) events sample \footnote{The error is statistical only.}.

In 2005 the SELEX collaboration published an observation of 5.62 signal over 1.38 \pm 0.13 \footnote{The error is statistical only.} background events, at a mass of 3.52 GeV, of \( \Xi_{cc}^+ \rightarrow pD^+K^- \) decay mode from 1450 \( D^+ \rightarrow K^-\pi^+\pi^+ \) decays to complement the previous results \footnote{The error is statistical only.}. The SELEX measurements imply that the lifetime of \( \Xi_{cc}^+ \) is less than 33 fs at 90% confidence level \footnote{The error is statistical only.}.

The production cross section has not been provided by the SELEX collaboration. Still the production properties of \( \Xi_{cc}^+ \) and \( \Xi_{cc}^{++} \) can be compared to that of \( \Lambda_c^+ \) baryon:

\[
R_{\Lambda_c^+}(\Xi_{cc}^+) = \frac{\sigma(\Xi_{cc}^+) \cdot Br(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\Xi_{cc}^+}}{N_{\Lambda_c^+}} \cdot \frac{1}{\epsilon_+} \approx 0.09
\]

and

\[
R_{\Lambda_c^+}(\Xi_{cc}^{++}) = \frac{\sigma(\Xi_{cc}^{++}) \cdot Br(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\Xi_{cc}^{++}}}{N_{\Lambda_c^+}} \cdot \frac{1}{\epsilon_{++}} \approx 0.045,
\]

where \( N \) is number of events in the respective sample and the reconstruction efficiencies of \( \Xi_{cc}^+ \) and \( \Xi_{cc}^{++} \) are \( \epsilon_+ \approx 0.11 \) \footnote{The error is statistical only.} and \( 1/\epsilon_{++} \approx 3.7 \) \footnote{The error is statistical only.} respectively. Such a high production rate with \( \langle x_F \rangle > 0.33 \) and the relatively small mean transverse momentum \( \approx 1 \) GeV/c is not amenable to perturbative QCD analysis \footnote{The error is statistical only.}.

The production of states with two charm quarks with a high fraction of a light hadron’s momentum is unexpected if one adopts the conventional assumption that
heavy quarks can only arise from gluon splitting as in DGLAP evolution.

However, QCD predicts another source of heavy quarks in the wavefunction of a light hadron – from diagrams where the heavy quarks are multiply attached by gluons to the valence quarks [8, 7]. In this case, the frame-independent light-front wavefunction of the light hadron has maximum probability when the Fock state is minimally off-shell. This occurs when all of the constituents are at rest in the hadron rest frame and thus have the same rapidity when the hadron is boosted. Equal rapidity occurs when the light-front momentum fractions of the Fock state constituents are proportional to their transverse mass; i.e. when the heavy constituents have the largest momentum fractions. This feature underlies the Brodsky, Hoyer, Peterson, and Sakai (BHP) model for the distribution of intrinsic heavy quarks [8, 9].

Thus hadrons containing heavy quarks, such as the \( \Lambda_c \), the \( J/\psi \), and even the doubly charmed baryons such as the \( ccu \) or \( ccd \), can be produced in a hadronic collision with a high momentum fraction of the beam momentum from the coalescence of the produced heavy and valence quarks. The SELEX doubly charmed baryon results thus signify a significant probability for the existence of Fock states such as \( |hc\bar{c}c\rangle \), where \( h_1 \) is light quark content of the initial hadron.

2. The doubly charmed baryons production cross section

In the BHPS model the wavefunction of a hadron in QCD can be represented as a superposition of Fock state fluctuations, e.g. \( |h\rangle \sim |h1\rangle + |h2\rangle + |h3\rangle \ldots \), where \( h_i \), as above, is light quark content. When the projectile interacts with the target, the coherence of the Fock components is broken and the fluctuation can hadronize. The intrinsic charm Fock components are generated by virtual interactions such as \( gg \to c\bar{c} \) where gluon couple to two or more projectile valence quarks. The probability to produce such \( c\bar{c} \) fluctuations scales as \( \alpha_s^2(m_c^2)/m_c^2 \) relative to leading-twist production.

Following [3, 10] a general formula for the probability distribution of an \( n \)-particle intrinsic charm Fock state as a function of \( x_i \) and transverse momentum \( k_{T,i} \) can be written as:

\[
\frac{dP_{ic(c)}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}} \propto \frac{\delta (\sum_{i=1}^{n} k_{T,i}) \delta (1 - \sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n} m_{T,i}^2/x_i^2)},
\]

where \( m_{T,i} \) denotes \( \sqrt{m_i^2 + k_{T,i}^2} \) and \( m_h \) is mass of the initial hadron. Let us denote the probability of \( |hc\bar{c}\rangle \) and \( |h_c\bar{c}\rangle \) Fock states as \( P_c \) and \( P_{\bar{c}} \). In this paper we will also simplify the formula with replacement \( m_{T,i} \) with the effective mass \( m_0 = \sqrt{m_i^2 + (k_{T,i}^2)} \) and neglect the mass of the light quarks. This model assumes that the vertex function in the intrinsic charm wavefunction is relatively slowly varying; the particle distributions are then controlled by the light-cone energy denominator and phase space. The Fock states can be materialized by a soft collision in the target which brings the state on shell. The distribution of produced open and hidden charm states will reflect the underlying shape of the Fock state wavefunction.

2.1. The double intrinsic charm approach

We assume that all of the doubly charmed baryons are produced from \( |hc\bar{c}c\rangle \) Fock states. In the quark-hadron duality approximation the probability to produce a \( \Xi_{cc} \) is proportional to the fraction of \( cc \) production below threshold mass \( m_\Xi = m_p + \Delta m \) [11], where \( m_p \) is D-meson mass and \( \Delta m \approx 0.5-1 \) GeV. The fraction of \( cc \) pairs can be written as:

\[
f_{cc/h} \approx \int_{m_\Xi}^{\infty} \frac{d\sigma_{cc}}{d^2r_{cc}} \int_{m_\Xi}^{\infty} \frac{d\sigma_{cc}}{d^2r_{cc}},
\]

To obtain the fraction ratio of \( cc \) pairs into \( \Xi_{cc} \) baryons we have to isolate color-antitriplet states, the fraction ratio of the doubly charmed baryons is

\[
f_{\Xi_{cc}/h} \approx s_c \cdot f_{cc/h},
\]

where the \( s_c \) is the color-antitriplet factor. The \( cc \) pair has 3 \( \times 3 = 9 \) color components, 3 color-antitriplet, and 6 color-siextet. Assuming that \( cc \) are unpolarized in the color space in the double intrinsic charm Fock state, there is 1/3 probability for the color-antitriplet possibility. Finally, we get \( s_c \approx 2 \times 1/3 \). Let us remind the reader that some of \( c \)-quarks could produce open charm states so we need to interpret \( f_{\Xi_{cc}/h} \) as the upper limit.

If we take \( m_c = 1.5 \) GeV the value of \( f_{\Xi_{cc}/p} \approx 0.6 \). This model also predicts \( f_{\Xi_{cc}/p} \approx f_{\Xi_{cc}/p} \) that is comparable with the SELEX data [1].

There is a simple connection between the intrinsic charm cross section and the inelastic one [10, 12, 13]

\[
\sigma_{ic} = \frac{P_{cc}}{P_{ic}} \cdot \sigma_{ic},
\]

\[
\sigma_{ic} = P_{ic} \cdot \sigma_{ic} \approx 3 \cdot 10^{-5} \sigma_{ic},
\]

where \( \mu^2 \approx 0.2 \) GeV\(^2\) denotes the soft interaction scale parameter; \( P_{ic} \approx 0.3-2\% \) (see [14] and references
The total production cross section of the doubly charmed baryon and the perturbative approaches give too small a contribution, and can be neglected. The value is relatively small and can be neglected.

\[ \sigma_{icc} = 0.1 \cdot \sigma_{pQCD}(c\bar{c}). \]  

The normalization is fixed to be the same as Eq. 4 at \( \sqrt{s} = 20-40 \text{ GeV}. \)

Combining Eqs. \( 3, 4 \) and \( 5 \), we may expect the upper limit of the production cross section of the doubly charmed baryons to be:

\[ \sigma_{icc}(\Xi_{cc}) = f_{cc}/P_{cc} \cdot P_{icc} \cdot 0.1 \cdot \sigma_{pQCD} \approx 7 \cdot 10^4 \text{ pb}, \]

where \( \sigma_{pQCD}(c\bar{c}) \approx \sigma(gg \rightarrow c\bar{c}) \approx 5.8 \times 10^6 \text{ pb} \) is the charm production cross section at 600 GeV/c beam momentum, where most of statistics was collected, calculated with CalcHEP Monte-Carlo tool [15].

2.2. The intrinsic charm approach

The intrinsic charm production cross section of the doubly charmed baryons can be written as follows:

\[ \sigma_{icc}(\Xi_{cc}) = f_{cc}/P_{cc} \cdot P_{icc} \cdot 0.1 \cdot \sigma_{pQCD} \approx 7 \cdot 10^4 \text{ pb}, \]

where \( f_{cc}(x, \mu) \) is the gluon [16] or intrinsic charm [17] distribution functions, \( x \) is the ratio of the parton momentum to the momentum of the hadron and \( \mu \) is the energy scale of the interaction. Explicit form of \( \sigma(gg \rightarrow c\bar{c}) \) can be found in [18]. In the SELEX case, these calculations have been done in Ref. [19].

\[ \sigma_{icc}(\Xi_{cc}) \approx 102 \text{ pb}. \]

The value is relatively small and can be neglected.

2.3. The total production cross section

The charm quark fragmentation into the doubly charmed baryon and the perturbative approaches give too small a contribution and can be also neglected so the total production cross section of the doubly charmed baryons at the SELEX experiment will be:

\[ \sigma(\Xi_{cc}) \approx \sigma_{icc}(\Xi_{cc}) \approx 7 \cdot 10^4 \text{ pb}. \]

It is interesting to estimate of the doubly charmed baryon production at a fixed-target experiment at the LHC [20] with \( \sqrt{s} \approx 115 \text{ GeV} \). Following the method described above the production cross section of the doubly charmed baryons will be:

\[ \sigma_{icc}(\Xi_{cc}) \approx f_{cc}/P_{cc} \cdot P_{icc} \cdot 3 \cdot 10^{-5} \sigma_{mn} \approx 1.5 \times 10^6 \text{ pb}, \]

where the value of \( f_{cc}/P_{cc} \approx 0.56 \) and \( \sigma_{mn}(\sqrt{s} \approx 115 \text{ GeV}) \approx 28.4 \text{ mb} \) [21]. It is two orders of magnitude bigger than predicted in ref. [22] with the single intrinsic charm approach.

3. The shape of \( P_{iccc}(\Xi_{cc}) \) as a function of \( x_F \)

As we already mentioned (see Sec. 1), the large mean \( x_F \) and small mean transverse momentum is not amenable to perturbative QCD analysis. The \( x_F \) distribution of \( \Xi_{cc} \) baryons can be written as:

\[ \frac{dP_{iccc}(\Xi_{cc})}{dx_F} = \int \frac{dP_{iccc}}{dx_1 \ldots dx_n} \times \delta(x_{cc} - x_c). \]  

The mean value of \( x_F \) is

\[ \langle x_F \rangle = \int dx_F x_F \frac{dP_{iccc}(\Xi_{cc})}{dx_F}. \]

Integrating Eq. 7 over the SELEX kinematic region, \( x_F > 0.1 \), we find \( \langle x_F \rangle \approx 0.3-0.34 \) that is in agreement with the SELEX data, \( x_F \approx 0.33 \) for \( \Xi_{cc}^+ \rightarrow \Lambda_{cc}^0 K^- \pi^+ \) decay [1]. In his PhD thesis, Mattson provide the \( x_F \) distribution of the \( \Xi_{cc}^+ \) candidates into \( \Lambda_{cc}^0 K^- \pi^+ \) decay mode [2]. Integrating Eq. 7 over the region where data presents, \( x_F > 0.175 \) (see Fig. 1), we find \( \langle x_F \rangle \approx 0.36 \) that also agrees with the data. The relatively small transverse momentum also is a sign of the intrinsic charm mechanism.

![Figure 1: The solid line histogram shows number of the SELEX \( \Xi_{cc}^+ \) candidates as a function of \( x_F \) [2]. The dotted histogram represents calculation of this distribution in the double intrinsic charm model.](image)

4. Solving mystery of the SELEX result

As we noted above, the SELEX collaboration did not provide the doubly charmed baryons production cross section but we are still able to compare it to the production properties of the \( \Lambda_{cc}^0 \) baryons. Let us remind the reader the measured ratios: \( R_{\Lambda_{cc}^0}(\Xi_{cc}^-) = \sigma(\Xi_{cc}^-) \cdot Br(\Xi_{cc}^- \rightarrow \Lambda_{cc}^0 K^- \pi^+)/\sigma(\Lambda_{cc}^+) \approx 0.09 \) and \( R_{\Lambda_{cc}^0}(\Xi_{cc}^+) = \sigma(\Xi_{cc}^+) \cdot Br(\Xi_{cc}^+ \rightarrow \Lambda_{cc}^0 K^- \pi^+) / \sigma(\Lambda_{cc}^+) \approx 0.045 \). In

3
the leading order perturbative QCD the production cross section of the $\Lambda_c^+$ baryons can be approximated as:

$$\sigma(\Lambda_c^+) \approx \sigma(gg \rightarrow c\bar{c}) \cdot f(c \rightarrow \Lambda_c^+).$$

The SELEX search strategy of the doubly charmed baryons requires minimum value of $x_{\Lambda_c} > 0.15$ [1, 2, 3, 5]. Assuming that $x_{\Lambda_c} \sim x_e$ and using CalcHEP Monte-Carlo tool find $\sigma(gg \rightarrow c\bar{c})|_{x_e > 0.15} \sim 3 \cdot 10^5$ pb, fragmentation ratio $f(c \rightarrow \Lambda_c^+) = 0.071 \pm 0.003$ (exp.) $\pm 0.018$ (br.) [23] so the production cross section of the $\Lambda_c^+$ baryons at the SELEX experiment will be:

$$\sigma_{pQCD}(\Lambda_c^+)|_{x_{\Lambda_c} > 0.15} \approx \sigma(gg \rightarrow c\bar{c})|_{x_e > 0.15} \cdot f(c \rightarrow \Lambda_c^+) \approx 2.1 \cdot 10^4$$

Using the branching ratios predicted by J. Bjorken $Br(\Xi_c^+ \rightarrow \Lambda_c^+ K^- \pi^0) = 0.03$ and $Br(\Xi_c^+ \rightarrow \Lambda_c^+ K^- \pi^0) = 0.05$ [24], one can obtain the ratio of the production cross sections:

$$R_{\Lambda_c^+} = \frac{\sigma(\Xi_c^+)}{\sigma(\Lambda_c^+)|_{x_{\Lambda_c} > 0.15}} \sim 0.15. \quad (8)$$

However this result is not really accurate. Playing with parameters we can change both doubly charmed baryons and charm production cross sections in wide enough range. The most important thing about the ratio [8] is that it has the same order of magnitude as the measured ones against a few order of magnitude gap another predictions provide [11, 18, 19].

The relatively high production rate of $c\bar{c}c\bar{c}$ states to charm is not a unique feature of the SELEX experiment. The double $J/\psi$ production properties measured by the NA3 experiment [25, 26] have many similar features: the high $\sigma(\psi\psi)/\sigma(\psi) = (3 \pm 1) \times 10^{-4}$ rate, large $x_{\psi\psi}$ and small average transverse momentum, $p_{T,\psi\psi} = 0.9 \pm 0.1$ GeV/c. It is interesting to compare the SELEX result with the NA3 data on the double $J/\psi$ production. The NA3 experiment is a beam dump experiment at CERN utilizing antiprotons, protons, pions and kaons at 150, 200 and 280 GeV/c to produce charm particles with incident on hydrogen and platinum targets in the $x_F > 0$ kinematic region. The most informative data the NA3 collaboration present is the double $J/\psi$ production with $\pi^-$ beam at 280 GeV/c. It is not possible to compare the SELEX and the NA3 data directly but we are able to compare the following ratios, where $R$ denotes $\sigma(c\bar{c}c\bar{c})/\sigma(c\bar{c})$:

$$R_{SELEX} \sim R_{\Lambda_c^+} \times \frac{f(c \rightarrow \Lambda_c^+)}{f(\Xi/\rho)} = (0.8 \pm 0.2) \times 10^{-2}$$

and

$$R_{NA3} = \frac{\sigma(\psi\psi)}{\sigma(\psi)} \times \frac{f_{\psi\pi}}{f_{\psi\pi}} \approx 2 \times 10^{-2},$$

where $f_{\psi\pi} \approx 0.03$ [10] and $f_{\psi\pi} \approx 0.06$ [27]. Therefore, as we can see, the NA3 data complements the high production rate at the SELEX experiment.

5. Review of Belle and LHCb recent results

The Belle experiment [28] presented the upper limit on the $\sigma(e^+e^- \rightarrow \Xi_c^+ X)$ is $82–500$ fb for the decay mode with the $\Lambda_c^+$ at $\sqrt{s} = 10.58$ GeV using $980$ fb$^{-1}$. The most realistic calculations [11, 29] of the upper limit cross section predict $\sigma(\Xi_c^+) \approx 35 \pm 10$ fb what turns out to be at least twice as less as the given limit.

Another recent result from the LHCb experiment [30] provides the upper limits at 95% C.L. on the ratio $\sigma(\Xi_c^+)/Br(\Xi_c^+ \rightarrow \Lambda_c^+ K^- \pi^0)/\sigma(\Lambda_c^+)$ to be $1.5 \times 10^{-2}$ and $3.9 \times 10^{-4}$ for lifetimes 100 fs and 400 fs respectively, for an integrated luminosity of 0.65 fb$^{-1}$. It is compared with result from Ref. [11, 19, 18, 31] $\sim 10^{-2}$–$10^{-3}$. However, the LHCb did not reach the lifetime measured by the SELEX experiment yet. Moreover, the LHCb analysis requires that $\Lambda_c^+$ candidates have to be significantly displaced from the primary vertex so this requirement potentially cuts down most of the signal region. The contribution from the double intrinsic charm is suppressed due to LHCb experiment kinematics. Assuming that the hadron identification efficiency for pions and kaons is degraded above 100 GeV/c [32] (such that when raised to the fourth power it is negligible), and making the naive assumption that momentum is split evenly between all final-state tracks, the analysis loses sensitivity around $p(\Xi_c) = 500$ GeV/c, i.e. $x_F = 0.14$.

6. Summary

The experimental results (see Sec. 1) and theoretical predictions (see Sec. 4) on the production properties of the $\Xi_c$ in the SELEX experiment have the same order of magnitude accuracy. The predicted mean Feynman-x values (see Sec. 5) agree with the experimental data. The NA3 collaboration result on the double $J/\psi$ production strongly complements the SELEX data. We would like to specially point out the fact that unexpectedly high production rate of $\Xi_c$ baryons is due to the kinematics features of the SELEX experiment, and could not be described by the production mechanism only. We also find that the doubly intrinsic charm approach will be the leading production mechanism of the doubly charm
baryons at high Feynman-\(x\) at a future fixed-target experiment at the LHC.

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