Signals of the double intrinsic heavy quark at the current experiments

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Abstract. In this paper we review existing data and analyze experimental opportunities for modern experiments to investigate the signals of intrinsic heavy quarks.

1. Introduction

Even though the existence of intrinsic heavy quarks was proposed more than 35 years ago, the mechanism is still under construction [1].

The existence of heavy quarks in the proton’s light-front (LF) wavefunction at a large LF momentum fraction \( x \) is in fact predicted by QCD if one analyzes the higher Fock states \( |uudc\overline{c}\rangle \) and \( |uudc\overline{cc}\overline{c}\rangle \) in the hadronic eigenstate, i.e., Fock states where the heavy quark pairs are multi-connected to the valence quarks. LF wavefunctions, the eigensolutions of the QCD LF Hamiltonian, are defined at fixed LF time \( \tau = t + z/c \) and are thus off-shell in the invariant mass. In QED for example, positronium has an analogous \( |e^+e^-\mu^+\mu^-\rangle \) Fock state due to the insertion of light-by-light scattering in the positronium self-energy amplitude.

In such an “intrinsic charm” Fock state \( |uudc\overline{c}\rangle \), the maximum kinematic configuration occurs at minimum invariant mass where all quarks are at rest in the hadron's rest frame, i.e., at equal rapidity in the moving hadron. Equal rapidity implies \( x_i \propto (m^2 + k^2) \) for each quark, so that the heavy quarks in the Fock state carry most of the hadron’s LF momentum. The operator product expansion predicts that the probability of intrinsic heavy-quark Fock states \( |uudQQ\rangle \) scales as \( 1/m^2_Q \) due to the non-Abelian couplings of QCD [2, 3].

2. Review of existing data

Using the CERN pion beam at 150 and 280 GeV/c to produce charm particles with incident on hydrogen and platinum targets, the NA3 experiment provided data on the production of the double \( J/\psi \) with very similar features: a high value for the ratio \( \sigma(\psi\psi)/\sigma(\psi) = (3 \pm 1) \times 10^{-4} \), values \( x_{\psi\psi} > 0.6 \) at 150 GeV/c and \( x_{\psi\psi} > 0.4 \) at 280 GeV/c for the Feynman-\( x \), and a transverse momentum of \( p_{T,\psi\psi} = 0.9 \pm 0.1 \) GeV/c [4, 5]. Note that perturbative QCD neither can explain the NA3 cross section nor the \( x_F \) distribution [6] (see also Fig. 1).

Utilizing the Fermilab negative and positive charged beams at 600 GeV/c to produce charmed particles in a thin foil of copper or in a diamond, the SELEX collaboration claimed...
to observe two decay channels for the $\Xi_{cc}^+(ccd)$ state at mass around 3520 MeV/$c^2$. The experiment was operated in the kinematic region $x_F > 0.1$. The negative beam composition was about 50% $\Sigma^-$ and 50% $\pi^-$ while the positive beam was composed of 50% protons. The experimental data record used both positive and negative beams. 67% of the events were induced by $\Sigma^-$, 13% by $\pi^-$, and 18% by protons. In the first observation using the sample of $\Lambda_c^+ c \rightarrow pK^- \pi^+$, a signal of 15.9 events over 6.1 ± 0.1 background events was found [10]. To complement this result, SELEX published an observation of 5.62 signal events over 1.38 ± 0.13 background events for the decay mode $\Xi_{cc}^+ \rightarrow pDK^-$ from a sample of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays [11].

It is interesting to compare the production properties of the $\Xi_{cc}^+$ at the SELEX experiment with the production properties of the double $J/\psi$ production at the NA3 experiment. Unfortunately, it is not possible to compare the results directly. However, we are still able to compare the following ratios $R = \sigma(c\bar{c}c\bar{c})/\sigma(c\bar{c})$:

$$R_{\text{SELEX}}^{\Lambda_c^+} = \frac{f(c \rightarrow \Lambda_c^+)}{f_{\Xi_{cc}}} \sim (1 - 4) \times 10^{-3}$$

and

$$R_{\text{NA3}}^{J/\psi} = \frac{\sigma(\psi\bar{\psi})}{\sigma(\psi)} \times \frac{f_{J/\psi}}{f_{\psi/\pi}} \sim 2 \times 10^{-2},$$

where $f_{\psi/\pi} \approx 0.03$ [6] and $f_{J/\psi} \approx 0.06$ [12]. $f_{\Xi_{cc}} \approx 0.25$ [13] represents the fraction of $cc$ pairs producing the sum of single charged baryons $\Xi_{cc}^+$ and double charged baryons $\Xi_{cc}^{++}$, but this fraction cannot be less than the fraction to produce $J/\psi$. Therefore, $R_{\text{SELEX}}^{\Lambda_c^+}$ should not be larger than $10^{-2}$. It is clear that the SELEX production ratio is complemented by the very trustable measurement of the double $J/\psi$ production at the NA3 experiment. It is interesting to note that the intrinsic charm mechanism predicts $\langle x_F(\Xi_{cc}) \rangle = 0.33$, as shown in Ref. [13]. This is in excellent agreement with the value $\langle x_F(\Xi_{cc}^+) \rangle \sim 0.33$ measured by the SELEX experiment.

An analysis of the masses of the mass discrepancy between the $\Xi_{cc}^+(3520 \text{ MeV})$ state measured by SELEX and the $\Xi_{cc}^{++}(3621 \text{ MeV})$ state measured by LHCb [14] also complement the SELEX data [15].
3. Double intrinsic charm at modern experiments

3.1. Double $J/\psi$ production at the COMPASS experiment

COMPASS is a fixed-target experiment using the 190 GeV/c $\pi^-$ beam at the CERN SPS. Based on the already collected and planed statistics and compared to the NA3 statics we can expect up to 100 double $J/\psi$ events [16] (see also Fig. 2).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{compass_jpsi.png}
\caption{Prediction for the double $J/\psi$ production at the COMPASS experiment}
\end{figure}

3.2. Production of the doubly charmed baryons at STAR

The STAR fixed-target program is a fixed-target experiment using the proton beam of the Relativistic Heavy Ion Collider (RHIC) with up to 250 GeV/c and the Au beam with up to 100 GeV/c colliding with a wired target. For $p_{\text{beam}} = 200$ GeV/c we may expect the production cross section of the $\Xi_{cc}$ to be $\sigma(\Xi_{cc}) \approx (0.2 - 0.3) \times 75$ nb [17].

The kinematic limits on the energy and the momentum of the doubly charmed baryon formed by the intrinsic charm from the target are given by

\begin{equation}
E_{\text{lab}} = \frac{1}{2m_{\text{tar}}}(m_{cc}^2 + m_{\text{tar}}^2), \quad p_{\text{lab}} = \frac{1}{2m_{\text{tar}}}(m_{cc}^2 - m_{\text{tar}}^2).
\end{equation}

These last expressions depend solely on the two masses $m_{cc}$ and $m_{\text{tar}}$ and no longer on the beam energy. The momentum distribution and the distribution of the rapidity difference $\Delta y = y - y_{\text{tar}}$ in the laboratory frame are shown in Fig. 3. It is obvious that experiments at the STAR detector, typical at rapidities $|y| < 1$ for track selection, have the potential to observe doubly charmed baryons.

It is interesting as well to present the momentum distribution and the distribution of the rapidity difference for the $J/\psi$ coming from the Fock state $|uudc\bar{c}\rangle$ (see Fig. 4).

4. Conclusion

Current theoretical and experimental knowledge suggests the evidence for the existence of intrinsic heavy quarks. Signals of the double intrinsic charm are widely accessible at modern experiments. The COMPASS experiment is already working on the analysis of the double $J/\psi$ production [18]. The STAR experiment is able to confirm the beautiful prediction of the intrinsic heavy quark mechanism, producing a heavy quark state nearly at rest.

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Figure 3. Prediction for the Ξ_{cc} momentum distribution (left panel) and for the distribution of the rapidity difference (right panel) in the laboratory frame.

Figure 4. Prediction for the J/ψ momentum distribution (left panel) and for the distribution of the rapidity difference (right panel) in the laboratory frame.

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