Chapter 44
Charmed Hadron Production by Recombination in Heavy Ion Collisions

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Abstract Starting from the investigation on recent experiments about charmed hadrons, e.g., nuclear modification factor ratios between charmoinum states and measurements of doubly charmed hadrons, we discuss the production of those charmed hadrons by recombination in heavy ion collisions. We adopt the coalescence model, and evaluate transverse momentum distributions of not only charmonium states but also charmed hadrons such as Ξ_{cc} baryons and $X(3872)$ mesons produced from quark-gluon plasma. We discuss the important characteristics of charmed hadron production in heavy ion collisions by showing the transverse momentum distribution ratio between various charmed hadrons.

44.1 Introduction

Heavy quark hadrons have been considered to be useful probes in understanding the properties of the quark-gluon plasma. Since heavy quarks are expected to be more produced than before as the energies available in heavy ion collisions are increased, the possibility of producing heavy quark hadrons from the quark-gluon plasma is expected to increase as well [1, 2]. Therefore it is necessary to study the production of hadrons with heavy quarks in high energy heavy ion collisions from a point of view of the coalescence model in which the hadron production is described as the process of coalescing constituents into hadrons [3, 4].

Recently, the production of various kinds of exotic hadrons with or without heavy quarks in heavy ion collision have been investigated based on the coalescence model [5–7]. Nevertheless, the production of many normal hadrons with multi-heavy quarks, e.g., Ξ^*_{cc}, Ω_{scc}, Ω^*_{scc}, and Ω_{ccc} baryons have not been studied yet in heavy ion collision experiments. We discuss here the production of those multi-charmed hadrons in heavy ion collisions, mostly by focusing on the production yield and the yield distribution as a function of transverse momenta.

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We investigate also the transverse momentum distribution of the $X(3872)$ meson. As attempts to understand the $X(3872)$ meson, e.g., the structure and spin, the $X(3872)$ meson has been studied in heavy ion collisions [8]. Here we try to understand the internal structure of the $X(3872)$ meson by evaluating the transverse momentum distribution of the $X(3872)$ in both a four-quark and a two-quark state. Since it has been found that the yield depends on the structure of hadrons [5–7], transverse momentum distributions are also expected to be dependent on the structure of hadrons as well as the wave function through the Wigner function [9]. Therefore by evaluating two different transverse momentum distribution of the $X(3872)$ meson we expect to obtain information about the dependence of the transverse momentum distribution on their constituents.

We also discuss transverse momentum distribution ratios between various multi-charmed hadrons. Studying the transverse momentum distribution ratio, especially between the $X(3872)$ and multi-charmed hadrons will shed some lights in investigating roles of heavy quarks in the heavy quark hadron production.

44.2 Production of Multi-charmed Hadrons from the Quark-Gluon Plasma

We first focus on the production yields of Ξ_{cc}, Ξ^*_{cc}, Ω_{scc}, Ω^*_{scc}, and Ω_{ccc} baryons in heavy ion collisions. Using the same method introduced in [7] we evaluate the production yields of the above multi-charmed hadrons in both the coalescence and statistical hadronization model [10]. When evaluating yields and transverse momentum distributions of Ξ_{cc} and Ω_{scc} baryons, we have not included decay contributions from Ξ^*_{cc} and Ω^*_{scc} baryons. We show results in Table 44.1.

Secondly, we calculate transverse momentum distributions of Ξ_{cc}, Ω_{scc}, Ω_{ccc} baryons, and $X(3872)$ mesons in the coalescence model. Especially, we consider two transverse momentum distributions for the $X(3872)$ meson, one in a four-quark state, and the other in a two-quark state [10]. In evaluating transverse momentum

Table 44.1 The Ξ_{cc}, Ξ^*_{cc}, Ω_{scc}, Ω^*_{scc}, and Ω_{ccc} yields at mid-rapidity in both the statistical and coalescence model expected at RHIC in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions and at LHC in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions

	RHIC		LHC	
	Stat.	Coal.	Stat.	Coal.
Ξ_{cc}	3.7×10^{-3}	4.5×10^{-4}	1.0×10^{-2}	1.6×10^{-3}
Ξ^*_{cc}	6.4×10^{-3}	9.0×10^{-4}	1.8×10^{-2}	3.3×10^{-3}
Ω_{scc}	1.3×10^{-3}	8.2×10^{-5}	3.7×10^{-3}	3.0×10^{-4}
Ω^*_{scc}	1.5×10^{-3}	1.6×10^{-4}	4.3×10^{-3}	6.0×10^{-4}
Ω_{ccc}	1.1×10^{-4}	1.1×10^{-6}	4.0×10^{-4}	5.3×10^{-6}

distributions of multi-charmed hadrons we adopt the charm quark transverse momentum distribution developed in [11], and use the oscillator frequency, ω_c, leading to consumption of all charm quarks at zero transverse momentum by quark coalescence [11, 12]. We show results in Fig. 44.1. A superscript $R(L)$ represents the transverse momentum distribution at RHIC(LHC) $\sqrt{s_{NN}} = 200\,\text{GeV}$ ($\sqrt{s_{NN}} = 2.76\,\text{TeV}$).

We also show in Fig. 44.1 some transverse momentum distribution ratios between multi-charmed hadrons. We see different shape of peaks at different transverse momentum regions in Fig. 44.1b–d. We argue that the peak appearing here in each transverse momentum distribution ratio is related to the type and number of quark constituents participating in hadron production. The peak is located at higher transverse momentum when more heavier quarks are involved; the peak at the higher transverse momentum for hadrons with heavier quarks supports the argument that the momentum of heavy quark hadrons is mostly carried by heavy quarks due to their heavier mass [11, 12].

We show in Fig. 44.2 transverse momentum distribution ratios between the $X(3872)$ in a four-quark state and the Ξ_{cc}, $c\bar{c}q\bar{q}/ccq$ and those between the $X(3872)$ in a two-quark state and the Ξ_{cc}, $c\bar{c}/ccq$ at both RHIC $\sqrt{s_{NN}} = 200\,\text{GeV}$ and LHC $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. We see clear difference between two ratios, thereby we can obtain

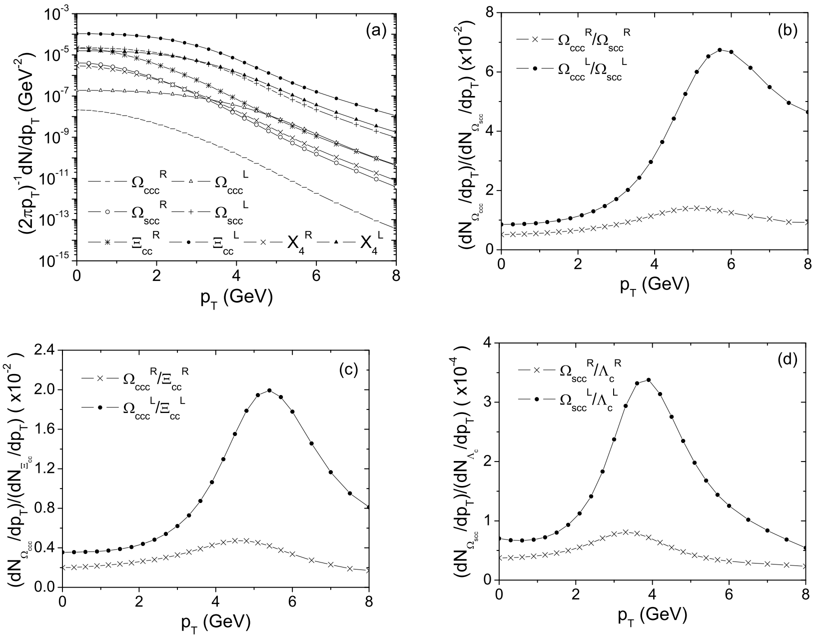

Fig. 44.1 **a** Transverse momentum distributions of Ξ_{cc}, Ω_{scc}, Ω_{ccc} baryons, and a $X(3872)$ meson in a four-quark state, X_4 and transverse momentum distribution ratios between the Ω_{ccc} and the Ω_{scc} (**b**), between the Ω_{ccc} and the Ξ_{cc} (**c**), and between the Ω_{scc} and the Λ_c (**d**) at both RHIC $\sqrt{s_{NN}} = 200\,\text{GeV}$ and LHC $\sqrt{s_{NN}} = 2.76\,\text{TeV}$

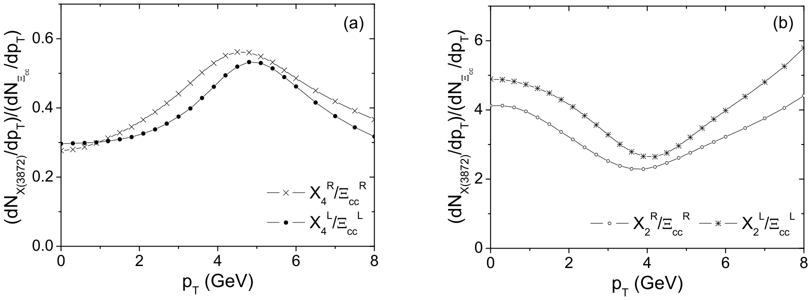

Fig. 44.2 **a** Transverse momentum distribution ratios between the $X(3872)$ in a four-quark state and the Ξ_{cc}, and **b** those between the $X(3872)$ in a two-quark state and the Ξ_{cc} at both RHIC $\sqrt{s_{NN}} = 200\,\text{GeV}$ and LHC $\sqrt{s_{NN}} = 2.76\,\text{TeV}$

the information on the quark structure of $X(3872)$ mesons by evaluating the transverse momentum distribution ratio between the $X(3872)$ meson and various multi-charmed hadrons.

44.3 Conclusion

We have investigated the yield and transverse momentum distribution of $X(3872)$ mesons as well as those of multi-charmed baryons. We find that estimated yields of multi-charmed hadrons produced in heavy ion collisions are large compared to those of the $X(3872)$, and thereby we expect to observe sufficient amount of multi-charmed hadrons in heavy ion collision. We also see that transverse momentum distributions of multi-charmed hadrons keep the information on their constituent quarks at the moment of hadron production very well, especially charm quarks carrying most of the momentum of multi-charmed hadrons due to their heavier masses. Moreover we note that the transverse momentum distribution ratio between various multi-charmed hadrons reflects the interplay between quark contents of corresponding hadrons, enabling us to infer the internal structure of the $X(3872)$ meson.

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