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Hadron production from heavy ion collisions

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Abstract. A brief review of some topics in hadron production from heavy ion collisions is given. They include charged pion ratio as a probe of nuclear symmetry energy, in-medium effects on pion production, enhanced Λ_c/D^0 ratio, Λ local polarization, and $X(3872)$ production.

1 Introduction

Hadron production from heavy ion collisions has been a topic of continuous interest since earlier experiments at Bevalac on pion [1, 2] and kaon [3] production. Following the demonstration in Ref. [4] that kaon production in heavy ion collisions at energy below its production threshold of 1.56 GeV in a nucleon-nucleon collision is sensitive to the stiffness of nuclear equation of state at high density, the comparison of transport model results with the experimental data from Au + Au collisions at SIS has led to the conclusion that the nuclear equation of state is soft with a compressibility of $K \sim 200$ MeV at the nuclear matter saturation density [5], similar to that extracted from the flow observables in heavy ion collisions [6]. Hadron production from heavy ion collisions has since been extensively studied at SIS, AGS, SPS, RHIC and the LHC. The present talk gives a brief review on some topics from these studies, which include charged pion ratio as a probe of nuclear symmetry energy, in-medium effects on pion production, enhanced Λ_c/D^0 ratio, Λ hyperon local polarization, and X(3872) production.

2 Charged pion ratio and the nuclear symmetry energy

As for subthreshold kaon production, studies based on isospin-dependent transport models have shown that the π^-/π^- ratio in heavy ion collisions with neutron-rich nuclei at near-threshold energies is sensitive to the density dependence of the nuclear symmetry energy [7], which is the energy needed per nucleon to convert a symmetric nuclear matter to a pure neutron matter, with the soft one giving a larger value than the stiff one. Dedicated experiments have recently been carried out by the SπRIT Collaboration to study pion production from ^{108}Sn+^{112}Sn, ^{112}Sn+^{124}Sn, and ^{132}Sn+^{124}Sn collisions at $E/A = 270$ MeV [8], and the measured π^-/π^- ratios have been compared with the predictions from seven transport codes using both a stiff and a soft symmetry energy of $\sim 46-56$ MeV and $\sim 120-150$ MeV, respectively, for the

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density slope parameter L at the nuclear matter saturation density. Although the difference between the predicted single π^-/π^- ratio from ^{132}Sn+^{124}Sn and ^{108}Sn+^{112}Sn collisions for soft and stiff symmetry energies in some codes is smaller than the errors in experimental measurements, it is larger in other codes. The differences among predictions from the different transport codes are thus too large to allow for the extraction of reliable constraints on the nuclear symmetry energy from the data. This finding may explain previous contradictory conclusions on symmetry energy constraints obtained from the pion data in Au+Au system by the FOPI Collaboration [9]. These new results call for a better understanding of the differences among transport codes, which has been pursued for many years by the transport model evaluation project (TMEP) Collaboration [10], and new observables that may be more sensitive to the density dependence of the symmetry energy. However, a subsequent study of the SπRIT π^-/π^- ratio data [11] based on the dcQMD model [12], which includes the implementation of total energy conservation for the colliding system besides at the two-body level due to the momentum and isospin asymmetry dependence of nuclear interactions, which is neglected in most transport codes, has deduced the value $42 < L < 117$ MeV from ratios of measured high transverse momentum charged pions. This value is slightly lower but consistent with that deduced from the measured neutron skin thickness $R_n - R_p = 0.283 \pm 0.071$ fm of ^{208}Pb by the PREX-2 Collaboration [13] but contradicts the expected smaller L from the smaller $R_n - R_P = 0.121 \pm 0.026(\text{exp}) \pm 0.024(\text{model})$ fm of ^{48}Ca [14] measured by the CEREX Collaboration. It is also inconsistent with the value $L = 58 \pm 19$ MeV based on constraints from neutron star masses, radii, and tidal deformability as well as the predictions from chiral effective theory [15, 16].

3 In-medium effects on pion production

In high energy heavy ion collisions without the formation of a quark-gluon plasma, pions are mainly produced from the reactions $NN \leftrightarrow N\Delta$ and $\Delta \leftrightarrow N\pi$ involving the Δ resonance. This is the case in the SπRIT experiments on Sn+Sn collisions at $E/A = 270$ MeV and also in the HADES experiments at SIS on Au+Au collisions at $E/A = 1.23$ GeV or the center-of-mass energy of $\sqrt{S_{NN}} = 2.4$ GeV [17]. Using information for these reactions extracted in free space, results from five popular transport models not only fail to describe the data by giving too large pion yields but also disagree among themselves. Since the cross section for the reaction $NN \leftrightarrow N\Delta$ is known to become smaller in nuclear medium [18–20], a recent study has included this effect in the RVUU model by introducing the density-dependent cross section $\sigma^{\text{med}}_{NN\to N\Delta} = \sigma^{\text{free}}_{NN\to N\Delta} e^{-\alpha(\rho/\rho_0)^{1.5}}$ [21]. With $\alpha = 0.39$ for Δ^{++} and Δ^+ production and $\alpha = 0.7$ for Δ^0 and Δ^-, a good description of the measured collision centrality dependence of π^+ and π^- multiplicities, rapidity distributions, and transverse momentum spectra is obtained. Remaining small differences between the theoretical results and the experimental data, particularly for the pion transverse momentum spectra, may indicate the need of the pion mean-field potentials, which are at present absent in RVUU.

4 Enhanced Λ_c/D^0 ratio at RHIC and the LHC

Because of the attractive color-spin interaction between quarks, color nonsinglet diquark $[qq]$ states may be present in QGP [22, 23]. In vacuum, the color-spin interaction between two quarks gives the $[ud]$ diquark mass as $m_{[\text{ud}]} = m_\text{u} + m_\text{d} - C\vec{s}_\text{u} \cdot \vec{s}_\text{d}/m_\text{u}m_\text{d}$.

With the coonstituent quark mass $m_\mathrm{u} = m_\mathrm{d} = 0.3$ GeV, the spin operator $\vec{s}_i$ $(i = \mathrm{u}, \mathrm{d})$, and a constant $C/m_\mathrm{u}^2 = 0.193$ GeV fitted to the $N - \Delta$ mass splitting [24], a maximum binding energy of 0.145 GeV or mass $m_{[\mathrm{ud}]} = 0.455$ GeV is obtained for the diquark. Expecting decreasing coupling in QGP, the diquark mass could be increased to $m_{[\mathrm{ud}]} = 0.6$ GeV but still be present, which would then lead to enhanced production of Λ_c and Λ_b in relativistic heavy ion collisions at RHIC and the LHC through the coalescence of c and b quarks with bound diquarks near the phase transition [25, 26]. Experiments have recently been carried out by the STAR Collaboration for Au+Au collisions at 200 GeV [27] and the ALICE Collaboration for Pb+Pb collisions at 5.02 TeV [28] to measure the transverse momentum dependence of the Λ_c/D^0 yield ratio. These results can be successfully described by various theoretical studies based on the quark coalescence model without diquarks present in the produced QGP but with additional assumptions, such as a unit coalescence probability for charm quarks of zero momentum [29], the collective flow effect in the coalescence process [30, 31], and the contribution of missing resonances to Λ_c production [32] as in the study of deeply subthreshold Ξ^- and ϕ meson [33] production in heavy ion collisions at SIS. Because of these very different assumptions, to decisively exclude the presence of diquarks in QGP require further studies.

5 Λ local polarization

The Λ hyperon global polarization in the direction perpendicular to the reaction plane of non-central Au+Au collisions measured by the STAR Collaboration [34] can be successfully described by both hydrodynamic [35] and coarse-grained transport [36] models with the assumption that Λ hyperons are in thermal equilibrium with the vorticity field generated during collisions. These models [37, 38] failed, however, to describe the measured Λ local polarization along the beam direction [39] by giving a wrong sign for its azimuthal angle dependence in the transverse plane of the collisions. On the other hand, the nonequilibrium chiral kinetic approach [40], which takes into account the effect of the vorticity field on the equations of motion and scatterings of quarks and antiquarks, can describe not only the Λ global polarization [41], when Λ hyperons are formed from the coalescence of polarized strange quarks with u and d quarks, but can also give the correct sign in the azimuthal dependence of the Λ local polarization [42] due to the redistribution of axial charges in the transverse plane. The latter result was confirmed by a covariant angular-momentum-conserved chiral transport model study [43]. This dynamic effect in the chiral kinetic approach can be included in the hydrodynamic approach by adding the effect from the thermal shear field [44–46]. The study based on the 3+1 MUSIC hydrodynamic model then indicates that strange quarks show a similar local spin polarization as that of measured Λ [47]. In another study based on the 3+1 viscous eHLLe and EVHO-QGP hydrodynamic models, the experimental data is found to be consistent with the isothermal local equilibrium of Λ spin polarization in thermal vorticity and shear fields at temperature of 150 MeV [48]. Both Λ global and local spin polarizations decrease, however, with temperature as the hadronic matter cools [49]. The fact that the experimental data is consistent with Λ spin polarizations at the hadronization temperature indicates that they freeze out or decouple early from the hadronic matter. This would be the case if the $\Lambda - \pi$ scattering is through the spin 3/2, parity positive $\Sigma^*(1358)$ resonance since the ratio of Λ spin non-flip to flip probabilities in this scattering is 3.5.

6 Exotic X(2872) production

Besides allowing the study of the properties of QGP, heavy ion collisions at relativistic energies also provides a new method for studying the structure of exotic hadrons [50–52], which is a topic of the most active areas of research in hadron physics. Based on the coalescence model for hadron production, it was shown in Refs. [50–52] that compared to the case of a nonexotic hadron with normal quark numbers, the yield of an exotic hadron is typically an order of magnitude smaller when it is a compact multiquark state and a factor of 2 or more larger when it is a loosely bound hadronic molecule. More detailed studies based on the kinetic approach have been carried out to study the hadronic effects on the production of the exotic hadron $X(3872)$, which was first observed by the Belle Collaboration [53] at KEK from the exclusive decay process $B^\pm \to K^\pm\pi^+\pi^- J/\Psi$ as a narrow charmonium-like state that has a mass of 3872 MeV near the $M_{D^0} + M_{D^{*0}}$ mass threshold and decays into $\pi^+\pi^- J/\Psi$. With its quantum numbers $J^{PC} = 1^{++}$ determined recently by the LHCb Collaboration at the LHC [54], $X(3872)$ can thus be either a compact $c\bar{c}d\bar{d}$ tetraquark state or a $D^0\bar{D}^{*0}$ ($\bar{D}^0 D^{*0}$) molecule. In Ref. [55], $X(2872)$ production from Au+Au collisions at 200 GeV was studied in the kinetic approach with the initial $X(3872)$ abundance given by the coalescence model for the tetraquark or the hadronic molecule scenario, including the reactions $X\rho \leftrightarrow D^0\bar{D}^{*0}$ and $X\rho \leftrightarrow \bar{D}^0 D^{*0}$ is found not to affect much its initial abundance in both scenarios, with the conclusion of an order-of-magnitude larger yield for the tetraquark than the hadronic molecule scenario as in Refs. [50–52]. A factor of four reduction of $X(3872)$ yield in the tetraquark scenario is, however, reported in Ref. [56] after including an anomalous vertex in the reactions $X\rho \leftrightarrow D^0\bar{D}^{*0}$ and $X\rho \leftrightarrow \bar{D}^0 D^{*0}$ as it enhances their cross sections by more than two order-of-magnitude to about 1 mb. In a more recent study [57], the initial $X(3872)$ abundance in Pb+Pb collisions at 5 TeV for the tetraquark scenario is taken from the statistical hadronization model, and it remains essentially unchanged during the hadronic evolution by using cross sections of about 50 mb for the reactions $X\rho \leftrightarrow D^0\bar{D}^{*0}$ and $X\rho \leftrightarrow \bar{D}^0 D^{*0}$ estimated from the $X(3872)$ radius of 1.3 fm. For the hadronic molecule scenario in this study, $X(3872)$ is assumed to be produced from the above reactions with its final abundance depending on the temperature below which $X(3872)$ is bounded, with its final yield always less than that in the tetraquark scenario, resulting in a conclusion that is opposite to that of Ref. [55]. In another study [58] based on a schematic coalescence of the quarks or charmed mesons from the AMPT model [59], it is again found that the yield of $X(3872)$ is larger for the hadronic molecule than for the tetraquark scenario. However, instead of a factor of ten in the yield ratio for the two scenarios, a factor of 200 is reported due to the unrealistic application of the coalescence model only in the coordinate space.

Experimentally, $X(3872)$ has recently been unambiguously identified from the $J/\Psi\pi^+\pi^-$ invariant mass spectrum in Pb+Pb collisions at 5.02 TeV by the CMS Collaboration [60]. The yield ratio $X(3872)/\Psi(2S)$ measured at $15 < p_T < 50$ GeV$/c$ is about one. Because of the large momentum, the observed $X(3872)$ is likely formed from hard quarks or charmed mesons from initial hard scatterings in heavy ion collisions instead of the thermal ones in the produced QGP considered in above theoretical studies. According to Ref. [61], the ratio $X(3872)/\Psi(2S)$ at $p_T = 10$ GeV from initial hard scatterings is about 0.1 as in pp collisions, which is about an order-of-magnitude smaller than that measured in CMS experiments. Understanding such a large enhancement of high momentum $X(3872)$ production in relativistic heavy ion collisions is an interesting question and may also provide a means to understand the structure of $X(3872)$. Of course, it is important to also measure low momentum $X(3872)$ in these collisions and compare the experimental data with the theoretical predictions.

7 Summary

Since the first experiments at Bevalac on pion and kaon production from heavy ion collisions, a lot of progress has been made in the study of hadron production in heavy ion collisions from energies near the pion production threshold in a nucleon-nucleon collision to ultrarelativistic energies at the LHC. These studies have led to a better understanding of the equation of state of both symmetric and asymmetric nuclear matter at high density as well as the in-medium effects on hadron production. Although the enhanced Λ_c/D^0 at intermediate momentum measured at RHIC and the LHC can be described without diquarks in the QGP, different assumptions have been introduced in the coalescence description of Λ_c production. Besides the vorticity field generated in non-central collisions, which is responsible for the Λ global polarization, the shear field is needed to better understand the measured Λ local polarization. The study of the production of exotic hadrons, whether they are multiquark or hadronic molecules, in heavy ion collisions provides a new means to understand their structures. However, there remain many puzzles such as the role of diquarks in heavy baryon production and the large $X(3872)/\Psi(2S)$ ratio at high momentum. Many more progresses and puzzles, which are not discussed here, have made the study of hadron production from heavy ion collisions an exciting topics in high energy nuclear physics, which is expected to continue in the future.

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