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Hadronic interactions in heavy ion collisions

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We present results from our recent investigation on hadronic interactions in heavy ion collisions. We study the production yields of a selected set of hadrons at the chemical freeze-out and their evolutions in the hadronic matter. The scattering cross sections with light mesons are studied in the meson-exchange model using effective Lagrangians to describe the dominant hadronic interaction during the hadronic stage of heavy ion collisions. We show that the hadron abundance may vary significantly for some hadrons after they are produced at the chemical freeze-out. We also comment on how such information can be used to identify and/or discriminate quantum numbers and structure of the hadron.

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1. Introduction

Study of hadronic interactions in heavy ion collisions has attracted much attention of many researchers especially after a J/ψ meson suppression was proposed as a signature for the formation of quark-gluon plasma [1]. As one of attempts to estimate the possibilities of J/ψ absorption by light mesons during the hadronic stage, absorption cross sections of J/ψ have been evaluated using one meson exchange model with the effective Lagrangian [2]. The abundance of hadrons evaluated at the chemical freeze-out temperature changes in general due to the dissociation or the absorption by mostly light mesons in the hadronic medium. In this work we study the hadronic interaction in heavy ion collisions by focusing on one of exotic mesons, the $X(3872)$ meson, and investigate the time evolution of the $X(3872)$ meson abundance [3] based on the yield evaluated in [4, 5].

Since the first discovery of the $X(3872)$ meson by Belle Collaboration [6], the additional decay modes of $X(3872)$ mesons to $D^0\bar{D}^0\pi^0$ [7, 8], $J/\Psi\gamma$ [9], as well as the positive charge parity of the $X(3872)$ meson have been found [9]. However, the exact structure of the $X(3872)$ meson is still not clear. Suggested hypotheses for the structure of the $X(3872)$ meson include a pure charmonium state, a $\bar{D}^0D^{*0}$ hadronic molecule, a tetra-quark state, and a charmoniun-gluon hybrid state [10]. We understand that the possible quantum number J^P should be either 1^+ or 2^-.

We expect the two different spin possibilities of the $X(3872)$ meson to lead to two different experimental results in heavy ion collision experiment. The $X(3872)$ meson produced at the chemical freeze-out may be absorbed by the comoving light mesons or even produced more from interactions between charmed mesons such as D and $\bar{D}^*$. However, two different spin states interact with other hadron differently due to different interaction mechanism, and therefore evaluating the absorption cross sections of two possible spin states of the $X(3872)$ meson would be helpful not only in estimating the hadronic effects on the $X(3872)$ meson abundance in heavy ion collisions but also obtaining a idea for the quantum number of the $X(3872)$ meson. Our discussion is focused on the central heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory; using a model developed to describe the dynamics of the cental Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Hereafter, we use simplified notations for the $X(3872)$ meson; X_1 for a 1^+ state and X_2 for a 2^- state.

2. Hadronic effects on the $X(3872)$ meson

We take the interaction of the $X(3872)$ with light mesons such as pions and ρ mesons into consideration; $X\pi \to \bar{D}^*D^*$, $X\pi \to \bar{D}D$, $X\rho \to \bar{D}^*D$, $X\rho \to D^*\bar{D}$, $X\rho \to D\bar{D}$, and $X\rho \to D^*\bar{D}^*$. To evaluate the cross sections for these interactions, we consider the following Lagrangians

$$
\begin{aligned}
\mathscr{L}_{\pi DD^*} &= ig_{\pi DD^*}D^{*\mu}\vec{\tau}\cdot(\bar{D}\partial_\mu\vec{\pi}-\partial_\mu\bar{D}\vec{\pi})+\mathrm{H.c.}, \qquad \mathscr{L}_{\rho DD} = ig_{\rho DD}(D\vec{\tau}\partial_\mu\bar{D}-\partial_\mu D\vec{\tau}\bar{D})\cdot\vec{\rho}^{\mu}, \\
\mathscr{L}_{\rho D^*D^*} &= ig_{\rho D^*D^*}\,[(\partial_\mu D^{*\nu}\vec{\tau}\bar{D}^*_\nu - D^{*\nu}\vec{\tau}\partial_\mu\bar{D}^*_\nu)\cdot\vec{\rho}^{\mu}+(D^{*\nu}\vec{\tau}\cdot\partial_\mu\vec{\rho}_\nu-\partial_\mu D^{*\nu}\vec{\tau}\cdot\vec{\rho}_\nu)\bar{D}^{*\mu} \\
&\quad + D^{*\mu}(\vec{\tau}\cdot\vec{\rho}^{\nu}\partial_\mu\bar{D}^*_\nu-\vec{\tau}\cdot\partial_\mu\vec{\rho}^{\nu}\bar{D}^*_\nu)], \\
\mathscr{L}_{\psi DD} &= ig_{\psi DD}\psi^\mu(D\partial_\mu\bar{D}-\partial_\mu D\bar{D}), \\
\mathscr{L}_{\psi D^*D^*} &= ig_{\psi D^*D^*}[\psi^\mu(\partial_\mu D^{*\nu}\bar{D}^*_\nu-D^{*\nu}\partial_\mu\bar{D}^*_\nu)+(\partial_\mu\psi^\nu D^*_\nu-\psi^\nu\partial_\mu D^*_\nu)\bar{D}^{*\mu} \\
&\quad + D^{*\mu}(\psi^\nu\partial_\mu\bar{D}^*_\nu-\partial_\mu\psi^\nu\bar{D}^*_\nu)],
\end{aligned} \tag{2.1}
$$

where $\vec{\tau}$ are the Pauli matrices, and $\vec{\pi}$ and $\vec{\rho}$ represent the pion and rho meson isospin triplets, respectively, while $D^* \equiv (D^{*0}, D^{*+})$ and $D \equiv (D^0, D^+)$ denote the vector and pseudoscalar charm meson doublets, respectively. The shorthand notation ψ stands for the J/ψ meson. We also take interaction Lagrangians for the $X(3872)$ meson in different spin states, constructed to reproduce transition matrix elements for the $X(3872)$ meson decays; X$\to D^0\bar{D}^{*0}$ and X$\to J/\psi\rho$ [3, 11].

$$
\begin{aligned}
\mathscr{L}_{X_1D^*D} &= g_{X_1D*D}X_1^{\mu}\bar{D}^*_{\mu}D, \qquad\qquad \mathscr{L}_{X_1\psi\rho} = ig_{X_1\psi\rho}\varepsilon^{\mu\nu\rho\sigma}\psi_{\nu}\rho_{\rho}\partial_{\sigma}X_{1\mu}, \\
\mathscr{L}_{X_2D^*D} &= -ig_{X_2D^*D}X_2^{\mu\nu}\bar{D}^*_{\mu}\partial_{\nu}D, \\
\mathscr{L}_{X_2\psi\rho} &= -g_{X_2\psi\rho}\varepsilon^{\mu\nu\rho\sigma}X_{2\mu\alpha}(\partial_{\nu}\psi^{\alpha}\partial_{\rho}\rho_{\sigma} - \partial_{\nu}\rho^{\alpha}\partial_{\rho}\psi_{\sigma}) \\
&\quad + g'_{X_2\psi\rho}\varepsilon^{\mu\nu\rho\sigma}\partial_{\nu}X_{2\mu\alpha}(\partial^{\alpha}\psi_{\rho}\rho_{\sigma} - \psi_{\rho}\partial^{\alpha}\rho_{\sigma}).
\end{aligned}
\tag{2.2}
$$

Based on the above effective Lagrangians, we obtain amplitudes for all processes, $X\pi \to \bar{D}^*D^*$, $X\pi \to \bar{D}D$, $X\rho \to \bar{D}^*D$, $X\rho \to D^*\bar{D}$, $X\rho \to D\bar{D}$, and $X\rho \to D^*\bar{D}^*$, and finally the absorption cross section of the $X(3872)$ meson by light mesons.

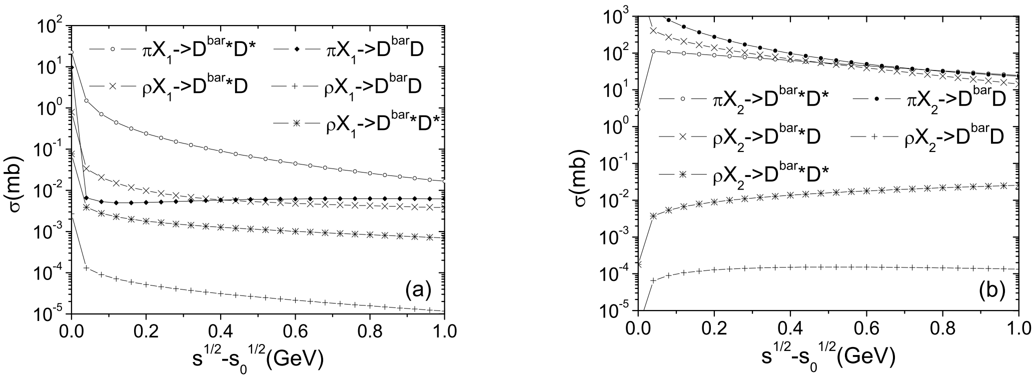

Figure 1: Cross sections for the absorption of (a) a $X_1(3872)$ meson and (b) a $X_2(3872)$ meson by π and ρ mesons via processes X$\pi \to \bar{D}^*D^*$, X$\pi \to \bar{D}D$, X$\rho \to \bar{D}^*D$, X$\rho \to D\bar{D}$, and X$\rho \to D^*\bar{D}^*$ [3].

In Fig. 1, we show the cross sections for the absorption of both a $X_1(3872)$ meson and a $X_2(3872)$ meson by pions and ρ mesons as functions of the total center-of-mass energy $s^{1/2}$ above the threshold energy $s_0^{1/2}$ of each process. We clearly see in Fig. 1 that the absorption cross sections for the processes $X\pi \to \bar{D}^*D^*$, $X\pi \to \bar{D}D$, and $X\rho \to \bar{D}^*D$ are much bigger when the spin of $X(3872)$ mesons is 2 than when it is 1. This is mostly attributed to the strong-coupling constant $g_{X_2D^*D}$ reflecting the hard decay of a $X_2(3872)$ meson to D^*D mesons. We know that the analysis of the $X(3872)$ meson decaying to $\bar{D}^0D^{*0}$ disfavors the 2^- quantum number because of the angular momentum barrier in its near-threshold decay [7, 8]. The coupling constant $g_{X_2D^*D}$ has to be large to compensate for the angular momentum suppression near threshold since it would not be so probable for D mesons to have a relative angular momentum near threshold to satisfy the angular momentum conservation when they interact with the spin-2 $X(3872)$ meson.

Using the cross sections evaluated in Eq. (1) we consider the time evolution of the $X(3872)$ meson abundance in hadronic matter. We build the evolution equation consisting of the densities and abundances for hadrons participating in all processes; π, ρ, D^*, and D mesons, and solve for $X(3872)$ meson abundance as a function of a proper time τ [3].

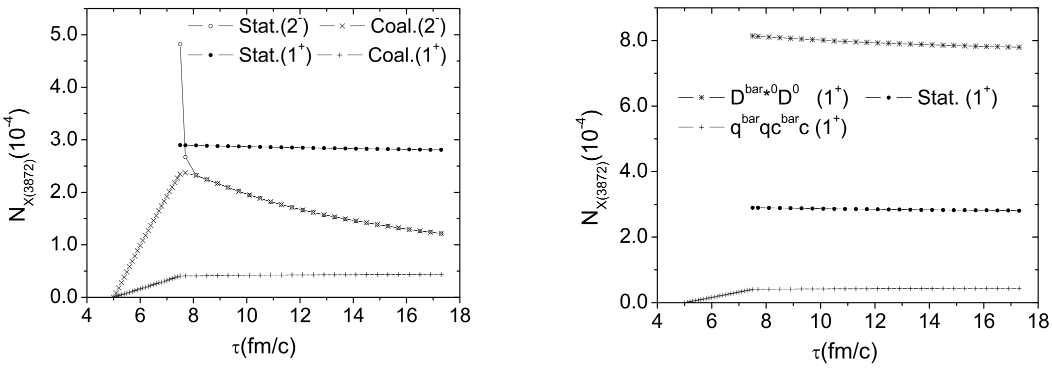

Figure 2: Time evolution of the $X(3872)$ meson abundances in central Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV; for different spin states produced from the quark-gluon plasma (Left), and for the hadronic molecular state of the spin-1 $X(3872)$ meson produced during the hadronic stage (Right). [3]

In Fig. 2, we show the time evolution of the $X(3872)$ meson abundances as a function of the proper time for different spin states in central Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The abundance of the $X(3872)$ meson in a four-quark state increases very slightly due to small scattering cross sections for the spin-1 state, and the thermal model prediction decreases also very slightly. However, the large scattering cross sections for the spin-2 state of the $X(3872)$ meson provides more chances for it to interact with light mesons in the hadronic evolution, and therefore the abundance of it decreases fast. The final ratio of the abundance for the spin-2 state over that for the spin-1 $X(3872)$ meson both in the coalescence model is expected to be $\sim$ 2.8 at the kinetic freeze-out.

We further consider the possibility of producing a hadronic molecular state of the spin-1 $X(3872)$ meson. If the state is a hadronic molecule, it will be dominantly produced at the end of the hadronic phase through hadronic coalescence. However it is also possible for hadronic molecular state to be produced in the hadronic phase through hadronic coalescence after two body hadronic interaction. With this in mind we evaluate the number of $X(3872)$ mesons in the hadronic phase by solving the rate equation for the hadronic molecular state. As shown in Fig. 2, when the hadronic molecular state of the $X_1(3872)$ meson is produced sometime during the hadronic stage, the $X(3872)$ meson abundance is expected to be in the range between 7.8×10^{-4} and 8.1×10^{-4}, finally resulting to the ratio $\sim$ 18 between the hadronic molecular state and the tetraquark state at the kinetic freeze-out.

3. Conclusion

We have discussed the hadronic interactions in heavy ion collisions by focusing on the hadronic effects on the $X(3872)$ meson abundance. Using interaction Lagrangians we have evaluated absorption cross sections for possible two $J^p = 1^+$ and 2^- states of the $X(3872)$ meson by light mesons during the hadronic stage in order to investigate the effects due to two different spin possibilities of the $X(3872)$ meson. We have found that the absorption cross sections are unrealistically bigger for a 2^- state than those for a 1^+ state as well as those for other charmed mesons, which supports the spin-1 state for a $X(3872)$ meson. We notice the experimental measurement of the $X(3872)$ quantum number by LHCb Collaboration [12], ruling out the spin-2 possibility.

We have further investigated the time evolution of the $X(3872)$ meson abundances for its two possible quantum number states. The variation of the $X(3872)$ meson abundance during the expansion of the hadronic matter is found to be strongly affected by the quantum number of the $X(3872)$ meson; the $X_1(3872)$ meson abundance slightly changes, while the $X_2(3872)$ meson abundance varies significantly. We have also discussed the production of hadronic molecular states possibly produced from open charm mesons sometime during the hadronic stage. The abundance is expected to be in the range between 7.8×10^{-4} and 8.1×10^{-4}, resulting in the final ratio ~ 18 between the hadronic molecular state and the tetraquark state.

Since the possibility of the $X(3872)$ meson production from the B meson decay is very low at RHIC energy, we can safely conclude that $X(3872)$ mesons observed at RHIC have been directly produced through either quark or hadron coalescence. The analysis based on the statistical model shows that when the number of D mesons observed is cumulated to be about 10^4, at least a few $X(3872)$ mesons are expected to be produced by hadron coalescence for the molecular state of the $X(3872)$ meson. If we need one order of magnitude larger number of D mesons to identify a $X(3872)$ meson, we can conclude that we are finding a tetraquark state of $X(3872)$ mesons produced by quark coalescence. Therefore, a factor of 18 difference in yields for the $X(3872)$ meson is enough to be used to discriminate the structure of the spin-1 $X(3872)$ meson. We therefore suggest that studying the hadronic interaction in heavy ion collisions provides a chance to infer the quantum number of the $X(3872)$ meson as well as its structure.

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