Pentaquark baryon production at the Relativistic Heavy Ion Collider

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Production of pentaquark $\Theta^+$ baryons in central relativistic heavy ion collisions is studied in a kinetic model. Assuming that a quark-gluon plasma is produced in the collisions, we first determine the number of $\Theta^+$ produced from the quark-gluon plasma using a parton coalescence model, and then take into consideration its production and absorption in subsequent hadronic matter via the reactions $KN \leftrightarrow \Theta$, $KN \leftrightarrow \pi\Theta$, and $\pi N \leftrightarrow K\Theta$. We find that although the final $\Theta^+$ number is affected by hadronic interactions, it remains sensitive to the initial number of $\Theta^+$ produced from the quark-gluon plasma, particularly in the case of a small $\Theta^+$ width as imposed by the $K^+N$ and $K^+d$ scattering data. Because of small baryon chemical potential in the hot dense matter produced in these collisions, the number of produced anti-$\Theta$ is only slightly smaller than that of $\Theta^+$.

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I. INTRODUCTION

In recent experiments on nuclear reactions induced by photons, kaons, and neutrinos, production of baryons consisting of five quarks $uudd\bar{s}$ has been inferred from the invariant mass spectrum of $K^+n$ or $K^0p$. The extracted mass is around 1.536 GeV with a width in the range 20-25 MeV except Ref. 7 which gives a width of 9 MeV. All these widths reflect the resolution in the experiments, so the actual width of $\Theta^+$ is expected to be smaller. The observed properties of this pentaquark baryon are consistent with those of the $\Theta^+$ baryon with spin $J = 1/2$, isospin $I = 0$, and strangeness $S = +1$ that was originally predicted by the chiral soliton model 6 and recently studied using the Skyrme model 5, 10, 11, 12, 13, 14, the constituent quark model 15, 16, 17, the chiral quark model 18, 19, the QCD sum rules 20, 21, 22, and the lattice QCD 23, 24. Studies of the $\Theta^+$ production mechanism in these reactions have also been carried out 25, 26, 27, 28. Since both kaon and nucleon numbers are not insignificant in the hadronic matter formed in relativistic heavy ion collisions, the $\Theta^+$ may also be produced in these collisions. Using a statistical model, which assumes that the $\Theta^+$ is in chemical equilibrium with other hadrons, Randrup 29 has estimated its abundance and finds that there is about one $\Theta^+$ per unit rapidity in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV available from the Relativistic Heavy Ion Collider (RHIC). As the quark-gluon plasma is expected to be formed in the initial stage of heavy ion collisions at RHIC, and it was suggested that formation of the quark-gluon plasma would enhance the production of hadrons consisting of strange quarks 20, it is of interest to know if this is also the case for $\Theta^+$ production and to determine its production from the quark-gluon plasma relative to that from the hadronic matter.

In this Letter, $\Theta^+$ production in central heavy ion collisions at RHIC is studied in a kinetic model that starts from the final stage of the quark-gluon plasma, goes through a mixed phase of quark-gluon and hadronic matter, and finally undergoes hadronic expansion. The production of $\Theta^+$ from the quark-gluon plasma is modeled by the coalescence model, which has been shown to describe quite well not only the particle yields and their ratios 31 but also their transverse momentum spectra 32, 33, 34. Production and absorption of $\Theta^+$ in the hadronic matter are taken into account via the reactions $KN \leftrightarrow \Theta$, $KN \leftrightarrow \pi\Theta$, and $\pi N \leftrightarrow K\Theta$. We find that the number of $\Theta^+$ produced from the quark-gluon plasma is appreciable and the final $\Theta^+$ number after the hadronic phase remains sensitive to the initial number of $\Theta^+$ produced from the quark-gluon plasma. Furthermore, a slightly smaller number of its antiparticle $\Theta^-$ is also expected to be produced at RHIC as a result of small baryon chemical potential in the matter produced from these collisions. We note that the quark coalescence model has also been used recently to study in heavy ion collisions at RHIC the elliptic flow of $\Theta^+$ 35, i.e., the azimuthal anisotropy of their momentum distribution in the plane perpendicular to the beam directions.

II. COLLISION DYNAMICS AT RHIC

To model the dynamics of central relativistic heavy ion collisions after the end of the quark-gluon plasma phase, we use the boost invariant picture of Bjorken augmented with accelerated transverse expansion. Specifically, the volume of produced fireball is taken to evolve with the proper time according to 37

$$V(\tau) = \pi [R_C + v_C(\tau - \tau_C) + a/(2(\tau - \tau_C)^2)]^2 \tau C,$$

where $R_C = 8$ fm and $\tau_C = 5$ fm/c are final transverse and longitudinal sizes of the quark-gluon plasma, corresponding to a volume of 1,006 fm$^3$ in central Au+Au collisions.
collisions at $\sqrt{s_{NN}} = 200$ GeV. Taking the critical temperature to be $T_C = 175$ MeV and a transverse flow velocity $v_1 = 0.4c$, the total transverse energy of quarks and gluons in the midrapidity ($|y| \leq 0.5$) is then about 1,067 GeV, if we take quarks and gluons to be massive with $m_q = 500$ MeV, $m_A = m_d = 300$ MeV and $m_s = 475$ MeV in order to take into account the nonperturbative effects of QCD near critical temperature [32] and to have chemical potentials $\mu_b = 10$ MeV and $\mu_s = 0$ to account for observed final antibaryon to baryon ratio at RHIC. The above total transverse energy includes a bag energy of about 133.8 GeV based on a bag constant of about 133 MeVfm$^3$, which is determined from the pressure difference between the quark-gluon plasma and the hadronic matter at $T_C$. Requiring that final hadronic matter freezes out at temperature $T_F = 125$ MeV and has a transverse flow velocity of $0.65c$, as extracted from measured hadron spectra in these collisions, then leads to a freeze out volume $V(T_F) \approx 11,322$ fm$^3$ if we assume that the fireball expands isentropically. The resulting total transverse energy of final hadronic matter is 788 GeV and is comparable to that of midrapidity hadrons measured in experiments [33]. It is, however, less than the initial transverse energy of midrapidity quarks and gluons. This is consistent with the reduction of midrapidity hadrons and their total transverse energy as a result of hadronic rescatterings seen in studies based on the transport model [30]. Because of the small pressure near phase transition and in hadronic matter [31], acceleration in the transverse expansion is chosen to have a small value $a = 0.02 c^2$/fm in order to obtain a lifetime of the expanding matter comparable to that from the transport model.

As the quark-gluon plasma expands, it gradually converts to hadrons leading to a mixed phase of quark-gluon plasma and hadronic matter at constant temperature $T_C$. The fraction of hadronic matter $f_H(\tau)$ can be determined by requiring that the total entropy $S_{tot}$ of the fireball remains constant during the phase transition [31], i.e.,

$$f_H(\tau)s_H(T_C) + (1 - f_H(\tau))s_{QGP}(T_C) = \frac{S_{tot}}{V(\tau)},$$

where $s_H$ and $s_{QGP}$ are the entropy densities of hadronic matter and quark-gluon plasma, respectively, which we treat as noninteracting ideal gases with finite transverse flow. The mixed phase ends at time $\tau_\Pi \approx 7.5$ fm/c when $f_H(\tau)$ reaches one, and the resulting pure hadronic matter is also assumed to expand isentropically until $\tau_T \approx 17.3$ fm/c when its temperature drops to $T_F = 125$ MeV. In panels (a) and (b) of Fig.1 we show the resulting time evolution of the volume and temperature of midrapidity particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

For normal hadrons such as pions, kaons, and nucleons, we take them to be in chemical equilibrium with baryon chemical potential $\mu_B = 30$ MeV, charge chemical potential $\mu_Q = 0$ MeV, and strangeness chemical potential $\mu_S = 10$ MeV, similar to those of the quark-gluon plasma. Since the chemical potentials vary weakly with the temperature of an isentropically expanding matter in heavy ion collisions at RHIC energies [33], we neglect their time dependence. Evaluating the densities of these hadrons using the relativistic Boltzmann distributions with inclusion of transverse flow, the time evolution of their abundance is shown in panel (c) of Fig.1. We note that the final numbers of pions, kaons, and nucleons at freeze out including contributions from decays of resonances are comparable to those measured in experiments.

III. $\Theta^+$ PRODUCTION FROM THE QGP

The number of $\Theta^+$ baryons that are produced from the quark-gluon plasma can be estimated using the coalescence model [32], i.e., given by the product of a statistical factor $g_\Theta$, which denotes the probability of combining $uudds$ quarks into a color neutral, spin 1/2, and isospin 0 hadronic state, and the overlap of the quark phase-space distribution function $f_q(x_i, p_i)$ with the Wigner distribution function $f_\Theta$ of $\Theta^+$. The latter corresponds to the probability of converting the above hadronic state into $\Theta^+$ and depends on the quark spatial wave functions in the $\Theta^+$. Explicitly, the $\Theta^+$ number is expressed as

$$N_\Theta = g_\Theta \int \prod_{i=1}^5 \frac{p_i \cdot dS_i d^3p_i}{(2\pi)^3 E_i} f_q(x_i, p_i) f_\Theta(x_1..x_5; p_1..p_5),$$

FIG. 1: (Color online) Time evolution of the volume (a), temperature (b), and abundance (c) of mid-rapidity particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
with $d\sigma$ denoting an element of a space-like hypersurface. Since the coalescence model can be viewed as formation of bound states from interacting particles with energy mismatch balanced by other particles in the system, neglecting such off-shell effects is reasonable if the binding energy is not large as in the case of $\Theta^+$ and/or if the production process is fast compared to the inverse of the binding energy. We note that the $\Theta^+$ is produced from the quark-gluon plasma during its hadronization and thus exists only in the resulting hadronic matter.

To determine the statistical factor $g_\Theta$, we note that the quark wave function of $\Theta^+$ in the color-spin-isospin space can be expressed as a linear combination of all possible orthogonal flavor, color, and spin basis states, with coefficients depending on the quark model used for $\Theta^+$, e.g., see [44]. Since these coefficients are normalized to one, the probability for the five quarks and antiquark $uudd\bar{s}$ to form a hadron with quantum numbers corresponding to a spin up $\Theta^+$ is simply given by the probability of finding these quarks in any one of these color-spin-isospin basis states, i.e., $1/3^5 \times 1/2^5 = 1/7776$. Including also the possibility of forming a spin-down $\Theta^+$ doubles the probability. As a result, the probability factor is $g_\Theta = 1/3888$.

For the phase-space distribution function of quarks, we assume that they are uniformly distributed in the transverse plane and their momentum distributions are relativistic Boltzmannian in the transverse direction but uniform in rapidity along the longitudinal direction. Imposing also the Bjorken correlation of equal spatial ($\eta$) and momentum ($y$) rapidities, then the quark momentum distribution per unit rapidity is

$$f_q(\eta, y, p_\perp) = g_q \delta(\eta - y) \exp \left( -\frac{\sqrt{p^2_\perp + m_q^2}}{T} \right), \quad (4)$$

where $g_q = 6$ is the color-spin degeneracy of a quark.

The Wigner distribution function of $\Theta^+$ depends on its internal quark wave functions. For simplicity, we take it to be Gaussian in space and momentum, i.e.,

$$f_\Theta(x; p) = \mathcal{N} \exp \left( -\sum_{i=1}^4 \frac{y_i^2}{\sigma^2_{y_i}} - \sum_{i=1}^4 \frac{k_i^2}{\sigma^2_{k_i}} \right), \quad (5)$$

where $y_i$ and $k_i$ are the relative spatial and momentum coordinates of the five quarks in $\Theta^+$, and are related to $x_i$ and $p_i$ by the normal Jacobian transformation, i.e.,

$$y_i = \left( 1 + \frac{1}{i} \right)^{-1/2} \left( \frac{\sum_{j=1}^i m_j x_j}{\sum_{j=1}^i m_j} - x_{i+1} \right) \quad (6)$$

and similarly for the momentum space coordinates. The width parameter $\sigma^2_{\Theta}$ for the $i$-th relative coordinate is defined as $\sigma^2_{\Theta} = (\mu_i \omega)^{-1}$ with

$$\mu_i = \frac{1 + \frac{1}{i}}{\sum_{j=1}^{i+1} m_j}. \quad (7)$$

Carrying out the spatial integrations in Eq. (3), the number of $\Theta^+$ produced from the coalescence of $uudd\bar{s}$ quarks is then

$$N_\Theta \approx g_\Theta N_u^2 N_d^2 N_s \left( \frac{4 m_q}{5 m_s} + \frac{1}{5} \right)^2 \left( \frac{4\pi\sigma^2}{V} \right)^4 \times \frac{\int \prod_{i=1}^5 dm_{i\perp} m_{i\perp}^2 e^{-m_{i\perp}/T} \prod_{i=1}^4 e^{-k_i^2/\sigma^2_{\Theta}}}{\prod_{i=1}^5 e^{-m_i/T} (m_i^2 T + 2m_i T^2 + 2T^3)} \quad (8)$$

In the above, $k_{i\perp}$ are the four relative momenta defined previously but determined in the center-of-mass of combined $uudd\bar{s}$ momenta, and $\bar{q}$ quarks in the quark-gluon plasma with rapidities $|y| \leq 0.5$ are denoted, respectively, by $N_u$, $N_d$, and $N_s$; and $\sigma$ is the width parameter calculated according to the mass $m_\Theta$ of the light quark. At $T = 1.9\text{ GeV}$, the number of $\Theta^+$ produced is $N_\Theta = 245$ and $N_\Theta = 149$, if we take into account the effect of gluons by converting them to quarks according to the quark flavor composition in the quark-gluon plasma as in Ref. [32]. The width parameter $\sigma$ in the $\Theta^+$ Wigner distribution function is related to the size of $\Theta^+$. Since the latter is not known empirically, we thus choose the value of $\sigma$ to fit the proton root-mean-square radius with the harmonic oscillator wave functions, i.e., $\sigma = 0.6\text{ fm}^{1/2} \approx 0.86\text{ fm}^{1/2}$, corresponding to a $\Theta^+$ root-mean-square radius

$$\langle r^2_{\Theta} \rangle^{1/2} = \sqrt{\frac{6}{5}} \sigma \left( 1 - \frac{1}{4} \frac{m_\Theta}{m_{u+d+s}} \right)^{1/2} \approx 0.9\text{ fm.} \quad (9)$$

Evaluating numerically the transverse mass integrals in Eq. (3) using the Monte Carlo method introduced in Ref. [32], we find that the number of $\Theta^+$ produced in one unit of rapidity is about 0.19. Compared to predictions from the statistical model, this number is smaller than that estimated in Ref. [29] by about a factor five and that from a more recent analysis [40] by about a factor two. The coalescence model also allows us to evaluate the number $N_{\gamma}$ of neutral hyperons $\Lambda$ and $\Sigma^0$ as well as those from decays of $\Xi^0$ and $\Xi^-$ that are produced from the quark-gluon plasma. The resulting number is about 10. Although this is about a factor of two smaller than that measured in Au+Au collisions at $\sqrt{s} = 130\text{ GeV}$ [17], including contributions from resonance decays and production in the hadronic matter is expected to bring it closer to the experimental data. In deriving Eq. (3), we have neglected the effect of transverse flow on the quark momentum distributions. Including this effect makes the spatial integrals in Eq. (3) more involved. Evaluating them by the Monte Carlo method, we find that its effect on produced $\Theta^+$ number is small. It is interesting to note that the momentum integrals, i.e., the last factor in Eq. (3), can be evaluated analytically if the quark momentum distributions are non-relativistic, leading to the expression $(1 + 2m_q T \sigma^2)^{-1}$. This gives a $\Theta^+$...
number of 0.64, which is about a factor of 3.4 larger than the relativistic case.

**IV. HADRONIC EFFECTS ON $\Theta^+$ PRODUCTION**

The abundance of $\Theta^+$ can change during subsequent evolution of the hadronic matter as a result of hadronic absorption and production. In hadronic matter, $\Theta^+$ can be produced as a resonance from interactions of $K$ and $N$. The cross section for this process is given by the Breit-Wigner formula. It can also be produced from reactions like $KN \rightarrow \pi\Theta$ and $\pi N \rightarrow K\Theta$. Cross sections for these reactions can be estimated by considering $KN \rightarrow \pi\Theta$ as a $u$-channel and $\pi N \rightarrow K\Theta$ as an $s$-channel nucleon-pole diagram. Using the coupling constant $g_{K\Theta\pi} \simeq 4.4$, determined from the width of $\Theta^+$ which we take to be $\Gamma_\Theta = 20$ MeV, we have evaluated these cross sections with empirical form factors. Details of this calculation can be found in Ref.[25]. The $\Theta^+$ can be destroyed in the hadronic matter either by decay, i.e., $\Theta \rightarrow KN$, or by the inverse reactions $\pi\Theta \rightarrow KN$ and $K\Theta \rightarrow \pi N$ with cross sections related to those of production cross sections via the detailed balance relations.

We have also evaluated the thermal average of $\Theta^+$ production and absorption cross sections. In the temperature range 125-175 MeV of interest here, their values for production cross sections are about 1 mb for $\langle \sigma_{KN\rightarrow\pi\Theta} \rangle$, 0.3 mb for $\langle \sigma_{KN\rightarrow\pi\Theta} \rangle$, and 1-3 $\mu$b for $\langle \sigma_{\pi N\rightarrow K\Theta} \rangle$, where $v$ is the relative velocity of two initial hadrons and $\langle \cdots \rangle$ denotes the average over their momentum distributions. For $\Theta^+$ absorption cross sections, they are about 6 mb for $\langle \sigma_{\pi\Theta\rightarrow KN} \rangle$ and 0.6 mb for $\langle \sigma_{K\Theta\rightarrow \pi N} \rangle$. The cross sections are thus larger for $\Theta^+$ production reactions induced by $K$ than $\pi$ and also for $\Theta^+$ absorption than production reactions as a result of large $\Theta^+$ mass.

In terms of thermal averaged cross sections and the densities of pions ($n_\pi$), kaons ($n_K$), antikaons ($n_{\bar K}$), and nucleons ($n_N$), the time evolution of $\Theta^+$ abundance $N_\Theta$ is determined by the kinetic equation [18, 19],

$$\frac{dN_\Theta}{d\tau} = R_{QGP}(\tau) + \langle \sigma_{\pi N\rightarrow K\Theta} \rangle n_\pi n_N V_{\text{H}} \nonumber$$

$$+ \langle \sigma_{KN\rightarrow\pi\Theta} \rangle n_K n_N V_{\text{H}} 
- \Gamma_\Theta N_\Theta - \langle \sigma_{K\Theta\rightarrow \pi N} \rangle n_K N_\Theta 
- \langle \sigma_{\pi\Theta\rightarrow KN} \rangle n_\pi N_\Theta. \tag{10}$$

Since hadronization of the quark-gluon plasma takes a finite time of $\tau_{\text{H}} - \tau_{\text{C}} \simeq 2.5$ fm/c, we expect $\Theta^+$ to be produced continuously from the quark-gluon plasma in the mixed phase, with a rate proportional to the volume of the quark-gluon plasma. This is included in the first term $R_{QGP}(\tau)$ of above equation.

Using the time evolution of volume, temperature, and hadron abundance shown in Fig.1 the resulting time evolution of $\Theta^+$ abundance is shown in Fig.2(a). The solid curve is obtained with 0.19 initial $\Theta^+$ from the quark-gluon plasma as given by the coalescence model discussed in the above. It is seen that the final $\Theta^+$ number is enhanced to 0.46. To see how the final $\Theta^+$ number depends on its number produced from the quark-gluon plasma, we have repeated the above calculation with different numbers of initial $\Theta^+$ baryons. As shown in Fig.2(b), the final $\Theta^+$ number is about 0.41 and 0.62, respectively, for 0 (dotted curve) and 0.94 (dashed curve) initial $\Theta^+$ baryons, roughly corresponding to a change of 30% in the value of $\sigma$ or the size of $\Theta^+$. Our results demonstrate that although the final number of $\Theta^+$ produced in relativistic heavy ion collision is affected by hadronic interactions, it is nonetheless sensitive to the initial number of $\Theta^+$ produced from the quark-gluon plasma.

This sensitivity would be even stronger if the width of $\Theta^+$ is smaller than that used here, i.e., $\Gamma_\Theta = 20$ MeV. In this case, not only the decay probability of $\Theta^+$ is reduced but also the hadronic cross sections become smaller as they are proportional to the square of the coupling constant $g_{KN\Theta}$, which is proportional to $\Gamma_\Theta$. This is shown in Figs. 2(b), (c), and (d) for the abundance of $\Theta^+$ using different $\Theta^+$ widths of 10, 5, and 1 MeV, respectively. The smaller width of 5 MeV or less is actually more consistent with available $K^+N$ and $K^+d$ data [50, 51, 52, 53, 54]. With such a small $\Theta^+$ width, the hadronic effects become insignificant, and the final $\Theta^+$ abundance is essentially determined by production from the quark-gluon plasma.

On the other hand, the dependence of final $\Theta^+$ number on its initial number from the quark-gluon plasma disappears only if hadronic cross sections are large. This happens when the latter is increased by about a factor of 3, corresponding to a $\Theta^+$ width of 60 MeV. Although such a large $\Theta^+$ width is unlikely due to the weak coupling of $\Theta^+$ to $KN$, the final $\Theta^+$ number in...
this case is about 0.35 and is comparable to that from the statistical model prediction of [46].

V. DISCUSSIONS

In the kinetic equation, Eq. (10), we have not considered reactions involving more than three particles such as $\pi \Theta \leftrightarrow \pi K N$. Taking its cross section the same as that for the reaction $\pi \Theta \leftrightarrow K N$, Eq. (10) can be generalized to include both $\Theta^+$ production and annihilation. We find that including this reaction affects the final $\Theta^+$ abundance by less than 10%. Also, medium effects on the $\Theta^+$ properties are not included. Because of the weak $\Theta^+$ coupling to $K N$ and the small hadron density after hadronization of the quark-gluon plasma, these effects are not expected to be important.

Our result that the final number of exotic pentaquark $\Theta^+$ produced in heavy ion collisions at RHIC is sensitive to its initial number produced during the hadronization of the quark-gluon plasma is, however, based on the assumption that $\Theta^+$ production from initial nucleon-nucleon collisions is not significant compared to that from the hot dense matter formed during the collisions. This is expected to be the case as string fragmentation to multiquark-anti-multiquark pairs is suppressed compared to fragmentation to diquark-anti-diquark pairs, from which normal three-quark baryons are produced in high energy proton-proton collisions. Furthermore, both the quark flavor structure and mass of $\Theta^+$, which belongs to the antidecuplet of $SU(3)$, are similar to those of the decuplet $\Omega^+$ ($s^3 s$), whose abundance in central relativistic heavy ion collisions is known to be more than an order of magnitude larger than that expected from initial nucleon-nucleon interactions [47].

Our study can be applied to production of anti-$\Theta^+$ in heavy ion collisions at RHIC. With the light antiquark to quark ratio of 0.89 and antistrange to strange quark ratio of 1 as a result of small quark baryon chemical potential $\rho_b = 10$ MeV, which gives an antiproton to proton ratio of $(0.89)^3 \approx 0.7$ at midrapidity consistent with experimental observations, the $\bar{\Theta}^-$ to $\Theta^+$ ratio is expected to be $(0.89)^2 \approx 0.63$. Relativistic heavy ion collisions at RHIC thus also allows us to find the $\bar{\Theta}^-$, which is not likely to be produced in either photo- or kaon-nucleus reactions.

VI. SUMMARY

To summarize, we have used a kinetic model to study production of pentaquark $\Theta^+$ baryon in central relativistic heavy ion collisions by including contributions both from the quark-gluon plasma via the parton coalescence model and from the hadronic matter through hadronic reactions between nucleons and pions or kaons. We find that a substantial number of $\Theta^+$ are produced from the quark-gluon plasma. Because of the expected narrow width, the $\Theta^+$ interacts weakly in the hadronic matter. As a result, the final number of $\Theta^+$ is not much affected by interactions in the hadronic matter and is thus sensitive to the initial number of $\Theta^+$ produced from the quark-gluon plasma. Study of $\Theta^+$ production in relativistic heavy ion collision thus provides the possibility of understanding the dynamics of quark-gluon hadronization.

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