Productions of hadrons, pentaquarks $\Theta^+$ and $\Theta^{*+}$, and di-baryon $(\Omega\Omega)_{0^+}$ in relativistic heavy ion collisions by a quark combination model

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The hadron production in relativistic heavy ion collisions is well described by the quark combination model. The mixed ratios for various hadrons and the transverse momentum spectra for long-life hadrons are predicted and agree with recent RHIC data. The production rates for the pentaquarks $\Theta^+$, $\Theta^{*+}$ and the di-baryon $(\Omega\Omega)_{0^+}$ are estimated, neglecting the effect from the transition amplitude for constituent quarks to form an exotic state.

PACS numbers: 13.87.Fh, 12.38.Bx, 12.40.-y

I. INTRODUCTION

Recently a lot of data for hadron multiplicities have been published from the relativistic heavy ion collision (RHIC) at Brookhaven National Laboratory [1, 2, 3, 4, 5, 6, 7, 8]. One of the purpose of this experiment is to produce a deconfined phase of quarks and gluons (QGP) under extreme conditions at high temperature and density by smashing two gold nuclei. Thus it is important to find reliable probes to judge if the QGP is really formed in the experiment, which is both theoretical and experimental challenges because one cannot directly detect the free quarks and gluons but their decay products. Hadron multiplicities and their correlations are observables encoding information on chemical properties of the medium generated from the heavy ion collisions. It is impressive that the statistical thermal models provide a good description for the available multiplicity data at almost all energies in heavy ion collisions by only a few parameters [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. While the ability to reproduce the mixed particle ratio from statistical models is not a proof that the emitting source is in thermal equilibrium [21], it is further evidence that such a state, which is one of the necessary conditions for creation of a QGP, has been created. The recombination or coalescence models [22, 23, 24, 25, 26, 27, 28, 29] are very successful in explaining the RHIC puzzles [30, 31, 32, 33, 34, 35].

The earliest quark combination model (QCM) can be dated back to 1970s [36, 37, 38], which was proposed to describe the multiparticle production or the hadronization in various reactions. Certainly the most popular hadronization models nowadays are the string model and the cluster model [39, 40, 41], but the great advantage of quark combination picture in describing the inclusive hadron production is its simplicity. The success of the quark combination model in almost all kinds of high energy collisions, e.g. electron-positron, hadron-hadron and nucleus-nucleus collisions, is partly due to the universal stochastic nature of fragmentation or hadronization. In this sense, the QCM resembles the thermal or the statistical model, but it encodes more microscopic information.

We have developed a variant of the QCM based on a simple quark combination rule [42, 43]. Using our QCM, we have described most of multiplicity data for hadrons in electron-positron and proton-proton/anti-proton collisions [44, 45, 46, 47, 48, 49, 50]. Also we solved a difficulty facing other QCMs in describing the TASSO data for baryon-antibaryon correlation: they can be successfully explained by our QCM [43, 51]. Embedded in the event generator, our QCM can also reproduce most of the global properties of hadronic events such as momentum spectra in electron-positron collisions [52, 53, 54, 55, 56]. Encouraged by the success of the statistical and recombination models in heavy ion collisions, in this paper we try to extend our QCM to reproduce the recent RHIC data for hadron multiplicities. Especially we will predict the production rates of three exotic baryons: the pentaquarks $\Theta^+$ and $\Theta^{*+}$ and di-baryon $(\Omega\Omega)_{0^+}$.

The pentaquark $\Theta^+$ is an exotic baryon made of five quarks $uud\bar{s}$, which have been discussed in the context of quark models in the early days of QCD [57, 58]. In 1997, Diakonov et. al. [59] predicted the mass and width of $\Theta^+$ at about 1540 MeV and 15 MeV respectively, using the chiral soliton model. Recent works on the property of the
II. THE QUARK COMBINATION MODEL

All kinds of hadronization models demand themselves, consciously or not, satisfy rapidity or momentum correlation for quarks in the neighborhood of phase space. The essence of this correlation is its agreement with the fundamental requirement of QCD which uniquely determines the quark combination rule (QCR) \[43\]. According to QCD, a \( \Theta^+ \) pentaquark has been carried out by BaBar collaboration \[68\] in the decay channel \( B^\pm \rightarrow p\mp K^\mp \). But the results in this experiment are preliminary yet to be confirmed. The last exotic state we are going to look at is the di-baryon \((\Omega\Omega)_{0^+}\). For more than 20 years the search for di-baryon has been another important attempt in hadronic physics \[63\]. One believes that if di-baryons do exist those with multi-strangeness must be ideal candidates to be observed because of their relatively long lifetime due to the stability with respect to strong decay. Recently the structure and properties of di-baryons with large strangeness are investigated in the chiral \( SU(3) \) model \[75, 76, 77, 78\] which quite successfully reproduces several nuclear properties. They found that some six-quark states with high strangeness have considerable binding energy provided by the chiral quark coupling. Of particular interest is \((\Omega\Omega)_{0^+}\), it is a deeply bound state (binding energy is around 100 MeV; the mean-square root of the distance between two \( \Omega \)'s is 0.84 fm). The mean lifetime of this di-baryon is as long as about twice that of \( \Omega \), because it only decays weakly. All these interesting properties together with the electric charge \( Q = -2 \) would make it easily identified in the experiments. Because of its large strangeness, \((\Omega\Omega)_{0^+}\) is not likely to be produced in proton-proton collisions. But one expects the enhanced strangeness production \((\Omega\Omega)_{0^+}\) in heavy ion collisions at RHIC energies, which can be a best place to study the production of the di-baryon \((\Omega\Omega)_{0^+}\).  

The outline of this paper is as follows. In section II and III we give a brief description of the quark combination model and basic relations among production weights of \( SU_f(3) \) multiplets. In section IV we present particle ratios and the transverse momentum spectra of the pion, proton and kaon predicted from the quark combination model. The upper limits for production rates of \( \Theta^+ \) and \((\Omega\Omega)_{0^+}\) are estimated in section V and VI. We give a summary of results and conclude in section VII.
### TABLE I: The weights of quark combination and those in terms of baryon multiplets.

| Flavor content | Combination weight | Production weight of baryon multiplets |
|----------------|--------------------|----------------------------------------|
| uuu            | 1                  | \( p_{10} \)                             |
| ddd            | 1                  | \( p_{10} \)                             |
| sss            | \( \lambda^3 \)    | \( p_{10} \lambda^3 \)                 |
| uud            | 3                  | \( p_{10} + P_s \)                       |
| uus            | 3\( \lambda \)     | \( |p_{10} + P_s| \lambda \)            |
| ddu            | 3                  | \( p_{10} + P_s \)                       |
| dds            | 3\( \lambda \)     | \( |p_{10} + P_s| \lambda \)            |
| uss            | 3\( \lambda^2 \)   | \( |p_{10} + P_s| \lambda^2 \)          |
| dss            | 3\( \lambda^2 \)   | \( |p_{10} + P_s| \lambda^2 \)          |
| uds            | 6\( \lambda \)     | \( |p_{10} + 2(p_8 + P_{1'})| \lambda \) |

The average number of primarily produced mesons \( M(N) \) and baryons \( B(N) \) are given by

\[
\langle M(N) \rangle = \sum_M \sum_B M X_{MB}(N), \tag{3}
\]

\[
\langle B(N) \rangle = \sum_M \sum_B B X_{MB}(N). \tag{4}
\]

Approximately, for \( N \geq 3 \), \( \langle M(N) \rangle \) and \( \langle B(N) \rangle \) can be well parameterized as linear functions of quark number \( N \):

\[
\langle M(N) \rangle = a N + 6 \quad \text{and} \quad \langle B(N) \rangle = (1 - a) N/3 - b/3 \quad \text{where} \quad a = 0.66 \quad \text{and} \quad b = 0.56.
\]

But for \( N < 3 \), obviously one has \( \langle M(N) \rangle = N \) and \( \langle B(N) \rangle = 0 \).

Having the number of mesons and baryons in an event, we can obtain the multiplicity of all primary hadrons from their production weights. The yield of the hadron \( h_i \) can be written as

\[
\langle h_i \rangle = \sum_j C_{M_j} \langle M_j \rangle \text{Br}(M_j \rightarrow h_i) + \sum_j C_{B_j} \langle B_j \rangle \text{Br}(B_j \rightarrow h_i) + \sum_j C_{\overline{B}_j} \langle B_j \rangle \text{Br}(\overline{B}_j \rightarrow h_i), \tag{5}
\]

where \( \langle M \rangle \) and \( \langle B \rangle \) are the average number of mesons and baryons respectively. \( C_{M_j}, C_{B_j}, \) and \( C_{\overline{B}_j} \) are the normalized weights for the primary meson \( M_j \), the primary baryon \( B_j \), and the primary anti-baryon \( \overline{B}_j \), respectively. Obviously we have the property \( C_{B_j} = C_{\overline{B}_j} \). \( \text{Br}(h_j \rightarrow h_i) \) is the weighted branching ratio for \( h_j \) to \( h_i \).

The production weights \( C_{M_j} \) and \( C_{B_j} \) for primary hadrons satisfy the \( SU_f(3) \) symmetry with a strangeness suppression factor \( \lambda_s \) for strange hadrons \( \text{[3]} \text{[8]} \text{[4]} \text{[6]} \). To determine \( C_{M_j} \) and \( C_{B_j} \), we need the ratio \( V/P \) of the vector \((J^P = 1^-)\) to the pseudoscalar \((J^P = 0^-)\) meson, and the ratio \((3/2^+) / (1/2^+)\) of the decouplet \((J^P = (3/2)^+)\) to the octet \((J^P = (1/2)^+)\) baryon. Assuming \( SU(6) \) symmetry, Anisovich et al. \( \text{[3]} \) gave \( V/P = 3 \). In this case the weights for all mesons except \( \eta \) and \( \eta' \) can be simply written as \( C_{M_j} \propto 2 J_l + 1 \lambda_s^{2} \) where \( J_l \) is the spin of \( M_l \), and \( r_i \) is the number of strange quarks and/or anti-quarks in the meson. However there is a spin suppression effect associated with baryons. In the next section, we derive the two relations between the production weights for octet, decuplet and singlet baryons from the properties of hadronization in the quark combination scheme.

### III. \( SU_f(3) \) SYMMETRY AND FLAVOR CONSERVATION IN THE QUARK COMBINATION MODEL

Hadronization is the soft process of the strong interaction and is independent of flavor, so the net flavor number remains constant during the process, which we call the property of flavor conservation. In the quark combination scheme, this means that the number of quarks of a certain flavor prior to hadronization equals to that of all primarily produced hadrons after it. The \( \lambda_s \)-broken \( SU_f(3) \) symmetry in hadron production means baryons or mesons in the same \( J^{PC} \) multiplet share an equal production rate up to a \( \lambda_s^{2} \) factor. This \( SU_f(3) \) symmetry has been supported by many experiments, particularly by the fact that the observed \( \lambda_s \) obtained from various mesons and baryons coincide with each other \( \text{[3]} \text{[8]} \). This experimental fact is unexpected in the usual diquark model for baryon production and turns out to be in favor of the quark combination scheme \( \text{[8]} \) where a baryon is formed by the stochastic combination of three constituent quarks.

From the above properties, we can obtain relations among the production weights for octet, decuplet and singlet baryons in the quark combination picture \( \text{[10]} \). As shown in Table I, all the flavor combinations are listed in the first column, with their combination weights in the second. In hadronization three quarks combine into a primary baryon.
which satisfies the $\lambda_s$-broken $SU_f(3)$ symmetry. As each flavor combination in the first column corresponds to a certain baryon belonging to several $SU_f(3)$ multiplets whose production weight is listed in the third column. The ground-state decuplet and octet baryons are denoted by 10 and 8, while the only excited baryon which we consider, the singlet $\Lambda(1520)$, is denoted by 1$'$'. Their corresponding weight are denoted by $P_{10}$, $P_8$, and $P_{1'}$ respectively. Note that the two sets of weights must be associated with a common factor, we finally derive the following relations among the production weights for octet, decuplet and singlet baryons:

\[ P_{10} = P_{1'} \]
\[ P_8 = 2P_{10} \]

They impose a global constraint on the production rates of all ground state baryons and the excited singlet baryon $\Lambda(1520)$. We can understand the so-called spin suppression from the basic relations. For those decuplet and octet baryons which are primarily produced and have the same strangeness, the ratio of their production rate is

\[ R = \frac{(3/2)^+}{(1/2)^+} = \frac{P_{10}}{P_8} = 0.5. \]

Note that the ratio $R$ measured in experiments is for the octet baryons which include decay products from the decuplet ones, we then obtain the following approximated value for $R_{\text{exp}}$ when neglecting the production of excited baryons:

\[ R_{\text{exp}} = \frac{(3/2)^+\text{(ground)}}{(1/2)^+\text{(ground)}} \sim \frac{P_{10}}{P_{10} + P_8} \sim 0.3. \]

Note that $R_{\text{exp}}$ is much less than 2 from spin counting, which is called the spin suppression effect. We can see that there is an essential difference between the spin suppression factor $R$ for the baryon and the multiplicity ratio of vector mesons to pseudo-scalar mesons $V/P$. The former is for the ratio of the $(3/2)^+$ decuplet baryon to the $(1/2)^+$ octet one. They belong to different $SU_f(3)$ multiplets. The basic relations impose a constraint upon their production weights. The latter is the ratio of vector to pseudo-scalar mesons, both of which belong to $SU_f(3)$ nonets. Flavor conservation and $SU_f(3)$ symmetry hold in each nonet and hence there is no restriction on their weights.

IV. HADRON MULTIPLEITIES AND MOMENTUM SPECTRA

In this section, we use the QCM to compute hadron multiplicities and their ratios in heavy ion collisions at RHIC energies. We will also calculate the transverse momentum spectra for pions, kaons and protons. Before we do that, we have to determine some input parameters of the QCM. The parameters which control the total multiplicity are the number of quarks and anti-quarks. In electron-positron and proton-antiproton collisions, the number of quarks is equal to that of anti-quarks, which means there are no excess baryons in contrast to anti-baryons. But for nucleus-nucleus collisions, we need two parameters, the number of quarks and that of anti-quarks, to account for the net baryon number even in central rapidity. These two parameters are determined by fitting the total charged multiplicity data, $\langle N_{\text{ch}} \rangle_{\text{data}} = 4100 \pm 210$, in central Au+Au collisions at 130 AGeV [1], which corresponds to the total number of quarks and anti-quarks $\langle N_q + N_{\bar{q}} \rangle = 7400$ in the QCM. The quark number $\langle N_q \rangle$ and the anti-quark number $\langle N_{\bar{q}} \rangle$ can be further determined by the ratio of antiproton to proton $p/p = 0.7$ [3, 4]. Then we obtain $\langle N_q \rangle = 3920$ and $\langle N_{\bar{q}} \rangle = 3500$, where we see that the net quark number is about 420. Another parameter is the strangeness suppression factor $\lambda_s$, which has also to be input from data. We find $\lambda_s = 0.5$ is consistent with data $\Phi/K^{*0} = 0.47$ [2]. At 200 AGeV, we determine in the same way the total number of quarks and anti-quarks $\langle N_q + N_{\bar{q}} \rangle = 8900$ with the net quark number 360 and $\lambda_s = 0.6$ by fitting the data [5].

Having determined the above parameters, we calculate the ratios of strange anti-baryons to their baryon counterparts, $\Xi/\Lambda$, $\Xi^+/\Xi^-, \Sigma^+\Omega^-/\Omega^-$, in mid-rapidity of central Au+Au collisions and compare our results with STAR data [3, 4]. The above antibaryon to baryon ratios are mainly controlled by the net quark number from colliding nucleons. The results are listed in Table II. The data show that the ratios increase with strangeness of the baryons. The reason for this trend is that the quark pair production is more important than the baryon transport in mid-rapidity. We see that there is a good agreement between our model predictions and the data, which means the quark combination mechanism can explain this behavior. In the QCM various ratios $B/B$ are associated with a common multiplicative factor $D$ which is given by the ratio $K^+/K^-$, for example $\bar{N}/\Lambda = D(p/p)$, $\bar{\Xi}/\Xi = D(\bar{X}/\Lambda)$ and $\bar{\Omega}/\Omega = D(\bar{\Xi}/\Xi)$. The calculated ratio $K^+/K^-$ and the $D$-factor in three compound ratios as shown above. The results are listed in Table III. We also calculate the ratios of singly-strange particles to non-strange particles and those of multi-strange particles...
TABLE II: Anti-particle to particle ratios: our predictions and STAR data at 130 AGeV [3] and 200 AGeV [4]. The second and fourth columns are STAR data at 130 and 200 AGeV respectively. The third and fifth columns are our results at 130 and 200 AGeV respectively.

|        | STAR (130) | QCM         | STAR (200) | QCM         |
|--------|------------|-------------|------------|-------------|
| π/p    | 0.71 ± 0.01 ± 0.04 | 0.71        | 0.73 ± 0.05 | 0.78        |
| Λ/Λ    | 0.71 ± 0.01 ± 0.04 | 0.79        | 0.84 ± 0.05 | 0.84        |
| Ξ/Ξ−   | 0.83 ± 0.04 ± 0.05 | 0.88        | 0.94 ± 0.08 | 0.91        |
| Ω−/Ω−  | 0.95 ± 0.15 ± 0.05 | 1.00        | 1.03 ± 0.12 | 1.00        |

TABLE III: K+/K− ratio compared with compound ratios of baryons at 130 AGeV [3].

|        | STAR          | QCM          |
|--------|---------------|--------------|
| K+/K−  | 1.092 ± 0.023 | 1.122        |
| Λ/Λ    | 0.98 ± 0.09   | 1.10         |
| Ξ/Ξ−   | 1.17 ± 0.11   | 1.11         |
| Ω−/Ω−  | 1.14 ± 0.21   | 1.15         |

to singly-strange particles. The results and the experimental data [3, 4, 5] are given in Table IV and V. All above show that the mixed ratios for various hadrons agree with RHIC data.

As a test of our QCM, we finally calculate the transverse momentum spectra for the pion, kaon and proton. Two steps are needed to get final hadron spectra. One is to obtain the spectra for initially produced hadrons which are those before their decay. We can do this through our Quark Combination Model. The next step is to let these initially produced hadron decay to final state hadrons which are observed in experiments. In our QCM, the longitudinal momentum is described by the constant distribution of rapidity, where we assume that quarks and anti-quarks are produced hadron decay to final state hadrons which are observed in experiments. In our QCM, the longitudinal momentum is described by the constant distribution of rapidity, where we assume that quarks and anti-quarks are distributed in rapidity range $y \in [-2.8, 2.8]$ at 130 GeV and $y \in [-3.0, 3.0]$ at 200 GeV with equal probability. This corresponds to the rapidity distribution of charged multiplicity at RHIC. Once the transverse momentum and rapidity for each quark are determined, its momentum is fixed. We can randomly line up all quarks in rapidity and let them combine into hadrons following our combination rule in section [11]. The momentum of a hadron is then the sum of that of its constituent quarks, while its energy is given by the mass-shell condition. The transverse momentum distribution of quark or anti-quark is extracted from the measured neutral pion spectra at 200 AGeV [57], where we assume that they are identical because the observed ratios of anti-particles to particles, i.e. $p/p, \Lambda/\Lambda, \Xi^{+}/\Xi^{-}$ and $K^{+}/K^{-}$, are almost constant with $p_T$ [3]. This is what we get for quark or antiquark $p_T$ distribution: $f(p_T) = (p_T^2 + p_T^2 + 1)^{-3.0}$. We assume that the combination occurs only among those constituent quarks which have the same azimuthal angle, similar to the strategy in Ref. [22]. Note that all these hadrons after combination are primarily produced, in order to get the spectra comparable to data one has to let them decay in their center-of-mass system. The momenta of all decayed hadrons are then boosted back into laboratory frame and recorded. Here we make use of the appropriate function of event generator JETSET. Finally we obtain the $p_T$ spectra for the pions, kaons and protons in final state which includes all contributions from decay.

TABLE IV: A group of ratios for strange hadrons compared with STAR data at 130 AGeV [3, 4, 5].

|        | DATA         | QCM          |
|--------|--------------|--------------|
| Ψ/Ψ°   | 0.49 ± 0.05 ± 0.12 | 0.47        |
| K+/π−  | 0.161 ± 0.002 ± 0.024 | 0.146       |
| K−/π−  | 0.146 ± 0.002 ± 0.022 | 0.130       |
| (Λ+ + Ω−)/h− | (2.24 ± 0.69) × 10−3 | 3.21 × 10−3 |


|                  | DATA      | QCM       |
|------------------|-----------|-----------|
| $K^-/\pi^-$      | 0.146 ± 0.024 | 0.132    |
| $\pi^-/\pi^+$   | 0.09 ± 0.01  | 0.089    |
| $\Omega^-/h^-$  | (1.20 ± 0.12) × 10^{-3} | 1.40 × 10^{-3} |
| $\pi^-/\pi^+$   | 1.025 ± 0.006 ± 0.018 | 1.068 |
| $K^-/K^+$        | 0.95 ± 0.03 ± 0.03 | 0.92    |

TABLE V: A group of ratios for strange hadrons compared with STAR data at 200 AGeV.

|                  | per rapidity (130) | per event | per rapidity (200) | per event |
|------------------|--------------------|-----------|--------------------|-----------|
| $\Theta^+$       | 1.16               | 7.97      | 1.30               | 8.93      |
| $\Theta^{*++}$   | 1.86               | 12.75     | 2.08               | 14.29     |
| $\Omega^-$       | 0.40               | 2.74      | 0.51               | 3.50      |
| $(\Omega\Omega)_0^+$ | 2.70 × 10^{-5} | 1.86 × 10^{-4} | 3.67 × 10^{-5} | 2.52 × 10^{-4} |
| $(\Omega\Omega)_v^-$ | 6.79 × 10^{-5} | 6.79 × 10^{-5} | 7.20 × 10^{-5} | 7.20 × 10^{-5} |

TABLE VI: Upper limits for multiplicities of $\Theta^+$, $\Theta^{*++}$, and $(\Omega\Omega)_0^+$ at 130 AGeV and 200 AGeV. The second and third columns are predictions at 130 AGeV, while the fourth and fifth columns are predictions at 200 AGeV. Per event values are obtained by taking the full rapidity range as $|y| < 3.43$.

shower quarks (high $p_T$). In any combination models the role of gluons has been finally taken by quark-antiquark pairs, for example, shower quarks are developed after a QCD cascade. In our QCM, the number of constituent quarks already effectively includes those quark-antiquark pairs converting from gluons. All quarks in the whole $p_T$ range are assumed to combine following the same combination rule. This assumption is widely used in other combination models: combination among shower quarks is treated in the same footing as among shower quarks and thermal quarks. The difference just lies in the sources: shower quarks are products after QCD showering while thermal quarks are from thermal distribution. Except these differences, our model is basically the same as other combination models. This can be seen that the rapidity correlation principle in our model is also implied in other models: in Hwa-Yang’s model, they assumed $y_1 = y_2 = y_h$ and $(y_1 + y_2)/2 = y_h$ where $y_1$ and $y_2$ are quark rapidities, and $y_h$ is the hadron one. While in GKL model, they used even more simple assumption $y_1 = y_2 = y_h = 0$.

Instead of giving the prediction for $p_T$ spectra, we give the spectra of the scaling variable $z = p_T/K$ where the scaling factor $K$ is defined in Ref.\cite{22}. The result for pions, kaons and protons at 130 and 200 AGeV are shown in Fig.\cite{13}. We see that the agreement between our predictions and data is quite satisfactory and we have verified the perfect scaling behavior in our model. The observed enhancement of protons and antiprotons at intermediate transverse momenta can be also naturally explained because we have got right predictions for protons.

V. MULTIPLECTITIES OF $\Theta^+$ AND $\Theta^{*++}$

In this section we will give an estimate for multiplicities of $\Theta^+$ and $\Theta^{*++}$ at 130 AGeV and 200 AGeV. Several groups have already predicted the yields of $\Theta^+$ in central Au+Au collisions by the statistical and coalescence models\cite{80, 91, 94}. In the QCM it is quite easy to estimate the production rate of $\Theta^+$ and $\Theta^{*++}$. The probabilities $P(uudds)$ and $P(uusds)$ for five quarks $uudds$ and $uusds$ respectively to come together in rapidity can be easily obtained by the QCM. The overlapping of phase space (here rapidity) has been encoded in the probability $P$. Then the probabilities to form the pentaquark $\Theta^+$ and $\Theta^{*++}$ can be estimated by the spin counting: a system composed of five quarks, each of which has spin-1/2, has totally $2^5$ spin states composed of one spin-5/2, four spin-3/2 and five spin-1/2 states. Assuming that all spin-1/2 states form $\Theta^+$, the production rate for $\Theta^+$ is then $P(\Theta^+)$ = $\frac{10}{2^5} P(uudds)$. If all spin-3/2 states go to $\Theta^{*++}$, the production rate of $\Theta^{*++}$ is then $P(\Theta^{*++})$ = $\frac{4}{2^5} P(uusds)$. Note that the current spin counting method only provides a kind of upper limits for the yields. In the real calculation one must evaluate the transition probability which involves overlapping of the wave functions of pentaquark states and their quark constituents. Here we simplify the problem by assuming the transition amplitude as unity. Also we neglect the contribution from the hadron-hadron rescattering in hadronic phase and assume the dominant source is from quark combination. Our estimates for $\Theta^+$ and $\Theta^{*++}$ are shown in Table VI. In summary of our results, at 130 AGeV there are about 1.16 $\Theta^+$ and 1.86 $\Theta^{*++}$ per rapidity produced in mid-rapidity in central Au+Au collisions, while at 200 AGeV, the yields of $\Theta^+$ and $\Theta^{*++}$ are 1.3 and 2.08 per rapidity respectively. Our predictions agree with those given by the statistical
We have calculated the ratios of strange anti-baryons to their baryon counterparts and that of Ω to negative charged particles. The results are found to be consistent with available data, see Table IV-V. Based on the result for Ω, we will predict in this section multiplicities of the di-baryon (ΩΩ)0+ in Au+Au collisions at 130 and 200 AGeV.

First we estimate the yield of Ω (Ω+ + Ω−). Assuming the ratio of Ω to h− is constant for all rapidities, we get the yield of Ω at about 5 and 6 per event from the experimental data h− ≈ 1/2Nch ≈ 2050 at 130 AGeV \[1\] and h− ≈ 1/2Nd\text{data} ≈ 2450 at 200 AGeV \[81\] respectively. In the quark combination picture, the production weight for Ω− is proportional to λs3. We find that the multiplicities increase strongly with growing λs, from 0.76 at λs = 0.3 to 6.00 at λs = 0.7. Our predictions for the Ω− yields are listed in Table VI. One sees that the yield of Ω− per event is about 2.74. Given the result for Ω−, we are now in a position to estimate the multiplicity of (ΩΩ)0+. First we get the probability P(sssssss) for six s-quarks to come together under the rule of our QCM and then we apply the spin-counting to estimate the yield of (ΩΩ)0+. There are totally 26 spin states for a six-quarks system. In terms of total spin, these are one spin-3, five spin-2, nine spin-1 and five spin-0 states. We assume that all spin-0 states go to (ΩΩ)0+. The yield of (ΩΩ)0+ is then \(\frac{5}{2}\) times that of six s quarks. The results are shown in Table VI. Same as the results for pentaquarks, the yields of (ΩΩ)0+ in Table VI are only regarded as a kind of upper limits because we have neglected the effect of the transition amplitude for 6 s-quarks to form a di-omega. One sees that the multiplicities of (ΩΩ)0+ are about \(1.86 \times 10^{-4}\) at 130 AGeV and \(2.52 \times 10^{-4}\) at 200 AGeV in an event respectively. Our predictions agree in magnitude with that of the coalescence models \[79\] and are within the scope of present RHIC experiments. Normally one can detect (ΩΩ)0+ through its decay product. Because the binding energy of (ΩΩ)0+ is relatively large which prevent it from strong decay, (ΩΩ)0+ mainly weakly decays into one Ω plus the decay products of Ω (three or more body decay) or into Ω and Ξ (two body decay). If it is produced in the experiments, one could detect it through the above decay channels. For other experimental traces of dibaryons, see, for example, Ref. \[94, 95\].

VII. SUMMARY

In this paper, we extend our quark combination model, which is very successful in describing the hadron production in electron-positron and proton-proton(anti-proton) collisions, to reproduce the multiplicity data in heavy ion collisions at RHIC energies 130 and 200 AGeV. The model can describe available data for transverse momentum spectra for pions, kaons and protons, especially the pr scaling behavior can be well reproduced within our simple model. It can explain the anormaly of the proton to pion ratio at intermediate transverse momenta. A variety of ratios for anti-baryons to baryons, single-strange hadrons to non-strange ones, and double-strange hadrons to single-strange ones can be all reproduced in our QCM. With the approximation that the transition probability for constituent quarks to form an exotic state is taken as unity if they come together in rapidity according to our combination rule, we finally estimate the yields of Θ+, Θ++ and (ΩΩ)0+ in Au+Au collisions at 130 and 200 AGeV. These yields can be regarded as a kind of upper limits. The multiplicities of Θ+ and Θ++ are estimated to be of order 1 and 2 per rapidity in mid-rapidity in a central event respectively, while the rate of (ΩΩ)0+ is of the magnitude \(10^{-5}\) per rapidity. The multiplicities of Θ+ and Θ++ are found to be almost independent of the strangeness suppression factor λs, while that of (ΩΩ)0+ increases strongly with growing λs.

Acknowledgments

The authors thank C.R. Ching, S.-Y. Li, Z.-T. Liang, T.H. Ho, Z.-G. Si, F. Wang, Y.W. Yu and Z.Y. Zhang for helpful discussions. Q.W. thanks K. Redlich for critically read the manuscript and for many insightful comments. Q.W. acknowledges support by the Virtual Institute VI-VI-041 of the Helmholtz Association of National Research Centers. The work of F.L.S. and Q.B.X. is supported in part by the National Natural Science Foundation of China under grant 10475049 and University Doctor Point Foundation of china under grant 20030422064.

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FIG. 1: The spectra in $p_T$ scaling variable $z = p_T/K$ ($K$ is the scaling factor) for $\pi^\pm$ and $\pi^0$ in the 5% and 10% most central collisions at 130 and 200 AGeV, respectively. The solid and dashed lines are our results. The data are from PHENIX.

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FIG. 2: The same spectra for $K^\pm$ in the 5% most central collisions at 130 and 200 AGeV. The solid and dashed lines are our results. The data are from PHENIX.

FIG. 3: The same spectra for $p, \bar{p}$ in the 5% most central collisions at 130 and 200 AGeV. The solid and dashed lines are our results. The data are from PHENIX.

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