Exotic hadron production in a quark combination model

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The philosophy on production of exotic hadrons (multiquark states) in the framework of the quark combination model is investigated, taking $f_0(980)$ as an example. The production rate and p_T spectra of $f_0(980)$ considered as $(s\bar{s})$ or $(s\bar{q}\bar{s}q)$, respectively, are calculated and compared in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The unitarity of various combination models, when open for exotic hadron production, is addressed.

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I. INTRODUCTION

The basic quanta of quantum chromodynamics (QCD), quarks and gluons, are confined in their bound states, hadrons. In any high energy interaction, the produced color-singlet (CS) (anti)quark system eventually transits to various hadron states with the total probability exactly 1:

$$\sum_h |\langle h|U|q\rangle|^2 = \langle q|U^+U|q\rangle = 1. \quad (1)$$

Here we introduce the unitary time-evolution operator U to describe the hadronization process. For the quark state $|q\rangle$ and the corresponding hadron state $|h\rangle$, the matrix element $U_{hq} = \langle h|U|q\rangle$ describes the transition amplitude. U_{hq} is determined by QCD but beyond the present approach of calculation. This leaves the space for various hadronization models to mimic this transition process. As a matter of fact from experiments,

$$\sum_{h=B,\bar{B},M} |\langle h|U|q\rangle|^2 \sim 1-\varepsilon, \varepsilon \to 0^+, \quad (2)$$

here $B, \bar{B}, M$ denote baryon, antibaryon, and meson, respectively.

Naïvely from the group theory, *color* confinement seems not so restrict as Eq. (2). The CS state, i.e., the invariant, totally antisymmetric representation of the $SU_C(3)$ group, requires at least one quark and one antiquark, or three (anti)quarks (these are just the constituent/valence quark numbers for mesons and baryons, respectively), but more (anti)quarks can also construct this representation, hence possibly to form a CS "hadron." To name some possibilities, two quark-antiquark pairs, a quark-antiquark pair with three (anti)quarks, six (anti)quarks, etc., are to be called exotic hadrons in this paper.[1] Until now, no experiment can definitely show the ε in Eq. (2) is exactly 0 or a small but *non*vanishing number. If definitely $\varepsilon = 0$, there must be underlying properties of QCD which need exploring. Even if ε is not vanishing, its smallness, definitely confirmed by experiments and shown in Eq. (2), also provides interesting challenges, especially on hadronization models. The small production rate of a special kind of exotic hadron seems easy to be adopted. However, taking into account so many possibilities to construct the CS representations by *various* numbers of (anti)quarks that the total sum of them is still quite small, is very nontrivial as a property of QCD and even nontrivial for a hadronization model to reproduce.

More concretely, we investigate the quark combination models [1,2] when open for the production of multiquark states. At first sight, the quark combination model is the most feasible in such a calculation, to just allow the desirable number of (anti)quarks to combine together. But to get the total production probability of all the exotic hadrons fulfilling Eq. (2) with a universal combination rule is nontrivial. In this paper, we investigate the production of exotic hadrons via a quark combination model proposed by the Shandong Group (SDQCM) [3–8]. We demonstrate that to treat the *production process* of all the multiquark states as a hadron molecule formation could be a practical and self-consistent way, respecting Eqs. (1) and (2), the unitarity of hadronization models (see also [9], and references therein).

Of all the "on market" combination models, SDQCM is unique for its combination rule wisely designed so that mesons and baryons exhaust the probability of all the fates of the (anti)quarks in CS state. It has been realized in Monte Carlo programs and tested against data from experiments in high energy e^+e^- annihilation and pp collisions [3–8]. It has been successfully extrapolated to ultrarelativistic heavy ion collisions [10–13], reflecting the universality of the hadronization mechanism. Most recently, the application of this combination rule to the open charm and bottom hadron production at Relativistic Heavy Ion Collider (RHIC) experiments, without any more parameters for the hadronization, further demonstrates its validity and provides opportunities against more critical tests [14,15].

The main idea of the combination rule of SDQCM is to line up the (anti)quarks in a one-dimensional order in phase space, e.g., in rapidity, and then let them combine into initial hadrons one by one according to this order [3–8]. Three (anti)quarks or a quark-antiquark pair in the neighborhood form a (anti)baryon or a meson, respectively. Thus the rule sets the priority of the smallest number of (anti)quarks to form a hadron. The cases of more numbers (>3) of (anti)quarks to combine into hadrons automatically disappear. For the combination process, the inclusive cross section is proportional to the product of the quark number densities, leading to B/M enhancement

[1]There is also, the possible existence of bound states including gluons, which is not covered in this paper and the name exotic hadron here does not include glueball or hybrid except explicit statements.

in a region (which is in fact one of the motivations for the burst of combination models at RHIC). Without this special combination rule, a more-quark state could be even enhanced [9]. This will conclude a nonsense result that a CS system of (anti)quarks could prefer to combine into a giant "quark ball" with a large number of constituent quarks. So one of the key properties of combination models is whether a model can shut off the possibility that an exotic number of (anti)quarks is combined into a cluster with a large probability.

To introduce the small probability ε in Eq. (2) to SDQCM, similar as the framework to calculate the resonance production of heavy quark bound states [16], we consider the exotic hadron production as a hadron molecule production and project the free mesons and/or baryons (antibaryons) states onto their bound states. In this paper we first clarify that it does *not* mean that, in the bound state, quarks from each hadron should keep in CS, respectively, but the color interactions can transit the whole molecule into a "real" exotic hadron by some probability, which will be introduced in the following. This is especially reasonable for the circumstance of central ($0 \sim 5\%$) gold-gold collisions at RHIC, where the large number of hadrons and large bulk of thermalized area allow interactions between hadrons lasting for a long time.

In the following we first discuss the color state and "definition" of the quark number of the exotic hadrons (Sec. II). Then, taking $f_0(980)$ as a working example, we describe the calculations of the production of the exotic hadrons within the quark combination model and discuss the results (Sec. III). Section IV is the conclusion.

II. COLOR STATE AND QUARK NUMBER OF THE EXOTIC HADRONS

A. Color state in an exotic hadron

All kinds of exotic hadrons have one common property, which is that the (anti)quarks can be grouped into several clusters, with each cluster *possibly* in CS. Hence, could the exotic hadrons just be meson and/or baryon molecules? However, the ways of grouping these (anti)quarks are not unique, as it is simply known from group theory that the reduction ways for a direct product of several representations are not unique. Furthermore, these clusters need not necessarily be in CS, respectively, since the only requirement is the whole set of these clusters in CS. For example, the system $q_1\bar{q}_2q_3\bar{q}_4$ (the constituents of a "tetraquark") can be decomposed/clustered in the following ways:

$$(q_1q_3)_{\bar{3}} \otimes (\bar{q}_2\bar{q}_4)_3 \to 1, \tag{3}$$

$$(q_1\bar{q}_2)_{1or8} \otimes (q_3\bar{q}_4)_{1or8} \to 1. \tag{4}$$

$$\cdots$$

Here we just mention that such group theory analysis is applicable to the quark states as well as the quark field operators [17]. In the above example, only the second case, when these two $q\bar{q}$ pairs are in CS, respectively, does it seem possible to be considered as a hadron molecule. But dynamically, the color interactions in the system via exchanging gluons can change the color state of each separate cluster, so each kind of grouping/reduction way seems no to have special physical meaning. Such an ambiguity, which has been considered in many hadronization and decay processes as a "color recombination/rearrangement" [18–20], blocks the possibility to consider the exotic hadron in a unique and uniform way, while leading to the possibility of introducing some phenomenological duality. Namely, even if we consider the production of the exotic hadron as "hadron molecule" formation, the subsequent color interactions in the system can eventually transit this "molecule" into a "real" exotic hadron, at least by some probability.

B. How to count the quark number in an exotic hadron

Some kinds of exotic hadrons have exotic quantum number(s), e.g., one kind of pentaquark ($qqq\bar{s}q$, hereafter, q refers to the flavor up or down), has $+1$ baryon number but $+1$ strange number. If a hadron with such quantum numbers is experimentally confirmed, one seems to have to introduce five valence (anti)quarks. However, in many other cases, there exist parallel explanations because of a nonexotic quantum number of a certain hadron. The tetraquark or four-quark state discussed in this paper is an example. One of the candidates is $f_0(980)$. It is considered as an orbit-excited $l = 1$ regular meson ($s\bar{s}$) [21], but argued possibly to be a four-quark state ($s\bar{q}\bar{s}q$) by others [22]. So one naturally raises the question relating with this ambiguity, how can one count the number of quarks in a hadron? Even, what is the meaning of the "number of quarks in a hadron"? This may be one of the most ambiguities in the physical picture of the exotic hadrons, because of a lack of complete understanding of the confinement property of QCD. It is not clear what the quantum field theory definition of the "constituent quark" is. As a consequence, it is ambiguous to "count" the quark number in a hadron. Here we just state the different pictures of a proton, one is the parton model bursting from the deeply inelastic scattering and other high energy interaction processes, the other is the "static" quark model, corresponding to the properties of a proton at rest. There is no satisfaction, especially a quantitative relation between these two pictures. Even the consideration of higher Fock states or pair excitations [23] cannot remove the gap.

It is well-known that the factorization theorem confirms the parton fragmentation picture to describe the hadron production [24]. But this partonic picture is only valid in inclusive processes with hard interactions involved. For the low p_T particles, e.g, those from "fragmentation" of the hadron remnant in hadron-hadron interactions, or in a very complex circumstance such as in heavy ion collisions, this picture faces both challenges from theoretical as well as experimental aspects. It is difficult to prove the factorization theorem for these complex cases. Furthermore, the RHIC data expose some properties difficult to be understood from the fragmentation picture, such as the high p/π ratio at intermediate transverse momenta [25] and the quark number scaling of hadron elliptic flows [26], but these can be explained by coalescence or (re)combination models [27,28]. Combination models include the following picture: (1) the production of quarks, which is considered as the "dressed" quarks, i.e., constituent/valence quarks; (2) these quarks combined to certain hadrons, e.g., $q\bar{q}$ combined to meson. Within these models, the quark number in a hadron has a model-dependent but clear "definition," i.e., "the number of (anti)quarks" of a certain hadron is the number of (anti)quarks involved in combining into the hadron in the *production process*. So, as suggested by [27], one can "count" this number experimentally by measuring the v_2 in heavy-ion collisions at RHIC, since v_2 is proportional to the number of quarks combined to the certain hadron, and the following inner interactions between (anti)quarks in the hadron will not change this property of global movement. This makes the quark number an "observable," by extrapolating the combination picture to open for all kinds of exotic hadrons. Treating exotic hadron production as hadron molecule formation will not change this fact that v_2 is still proportional to the total quark number in the exotic hadron, which is a straightforward result of an associative law of addition.

III. THE PRODUCTION OF f_0(980) AT RHIC

Now we apply the above discussions into an example, f_0(980), to discuss its production in central gold-gold collisions at RHIC. This particle is considered as a tetraquark with the flavor content $s\bar{q}\bar{s}q$ [29]. The traditional consideration for it as an $l = 1$ state of $s\bar{s}$ has been included in SDQCM with all the other $l = 1$ mesons in the most recent version [15]. We also calculate that case for comparison.

As we mentioned above, the conventional SDQCM can calculate the free meson and baryon distributions, e.g., inclusive two meson distributions $\frac{E_1 E_2 d\sigma}{d^3p_1 d^3p_2}$ in central gold-gold collisions at RHIC.

Ignoring the affection of other hadrons in the system, projecting it onto the meson molecule state, one can get the inclusive bound state distribution:

$$\frac{Ed\sigma^N}{d^3p} = \sum_{N_1N_2}\int \frac{d^3p_1}{E_1}\frac{d^3p_2}{E_2}|\langle p_1, p_2, N_1, N_2|p, N\rangle|^2 \times \frac{E_1E_2 d\sigma^{N_1,N_2}}{d^3p_1 d^3p_2}. \quad (5)$$

In the above equation, the N, N_1, N_2 refer to discrete quantum numbers, corresponding to the meson molecule state and the two mesons, respectively. The conservation relations such as $\delta^4(p - p_1 - p_2)$ and $\delta_{N_1\otimes N_2,N}$ are indicated in the projection of the state vectors. In order to get these factorized formulas, some interference terms are missed. Since the free hadron distribution is calculated by the Monte Carlo programs, it cannot give the amplitude but only its square, and only this factorized form can be used in the Monte Carlo programs.

The projection of the discrete quantum numbers such as flavor, isospin, angular momentum, charge, space parity, etc., are easily calculated. In the case of angular momentum projection, spin counting is assumed. Though the system is not assumed to be nonrelativistic, only the lowest possible orbit angular momentum is considered (i.e., since in general, the parity requires an odd or even l value, in the case of even l, we only consider $l = 0$, while for odd, only $l = 1$). The detailed analysis on the projection of discrete quantum numbers is outlined in Table I.

TABLE I. The projection of discrete quantum numbers (I, C, P) of M_1, M_2 to $f_0(980)(s\bar{q}\bar{s}q)$. The cases with much smaller values of $|\langle p_1, p_2, N_1, N_2|p, N\rangle|^2$ are included in the program but ignored in the below list.

Meson pair	$\lvert\langle J_1, J_2\lvert J\rangle\rvert^2$	$\lvert\langle C_1, C_2\lvert C\rangle\rvert^2$	$\lvert\langle I_1, I_2\lvert I\rangle\rvert^2$
ϕ, ω	1/9	1	1
η, η	1	1	4/9
η, η'	1	1	5/9
η', η'	1	1	4/9
K^+, K^-	1	1	1/2
$K^0, \bar{K}^0$	1	1	1/2

The phase space wave function of the exotic hadron in terms of mesons and/or baryons is not definitely available. One of the reasons is that, as argued above, the subsequent color interactions in the "molecule" ruin a unique structure to be described by a definite wave function. To mimic the combination process, we use the same physical picture as quarks combining into regular hadrons in our model, i.e., near the rapidity correlation [3]. This says that only two mesons in the neighborhood on the rapidity axis have the chance to combine together, when starting the combination from one end to the other for this lined-up hadron system. Contrary to the case of quarks, in which the confinement property requires all quarks to be combined into certain hadrons, the hadrons need not necessarily be combined to some molecules. Rather, they may have a large probability to be free. It is natural to introduce a parameter x, smaller than 1, to parametrize the probability for two mesons neighbored to combine into a bound state. So, x not only reflects the information of some specific exotic hadrons, but also reflects the interactions among the meson and (anti)baryon system. To the "lowest order" approximation, x takes the averaged value for all kinds of exotic hadrons, since there are no exotic hadron production data at RHIC which can be seriously fitted/explained yet. However, this way of parametrization can accommodate more "higher order" corrections by introducing hadron-kind-dependent x's once enough precise data of exotic hadrons are available. This x assures the total results respecting the fact that all the quark states and all the hadron states [mesons, (anti)baryons, and exotic hadrons] respectively form two complete sets of bases for the same Hilbert space. This unitary transformation assures the unitarity of the quark combination model.

Unfortunately, the fact that the wave functions of all kinds of exotic hadrons is unknown and for similar cases for the hadron interactions means that x is almost a free parameter, only constrained by the data of mesons and baryons, as well as how many kinds of exotic hadrons are considered. It is clear that to an extreme if we have infinite kinds of exotic hadrons, x should be vanishing, expecting an infinite number of vanishing variables (production rates corresponding to each certain exotic hadron) summing up to get a finite small result (the total production rate of all exotic hadrons). For demonstration, here we only consider the existence of four-quark states such as exotic hadrons, but still with two choices: One case is that only $f_0(980)(s\bar{q}\bar{s}q)$ exists in the world; the other is not only $f_0(980)(s\bar{q}\bar{s}q)$ but also any other tetraquark state (isospin multistates) to be allowed to be produced by our model. In the latter case more mesons are "used up" to get the molecule, so the x must be smaller than the former case.

In the calculation we first tune the standard SDQCM Monte Carlo program (see, e.g., [15]) to produce the multiplicities of mesons and baryons to be the central value of the experimental data. The details of the various inputs to set up the CS (anti)quark system produced in the central gold-gold collisions at RHIC can be found in [15]. Now all the (anti)baryons and mesons accommodated in SDQCM are produced and lined up on the rapidity axial. Then we consider the combination of hadrons into the exotic, concretely $f_0(980)$, according to the order on the rapidity axial. The baryons are not used to produce the exotic hadrons, so they are definitely determined by experimental data. For two mesons in the neighborhood and to be considered as a cluster, the probability to form molecule is calculated by the factors provided in Table I times x. We tune x so that all the mesons used up should not exceed the error bar of the experimental data (within 5%).[2] From the above discussion, it is more fair to take them as up limits of the production rates. By summing up all the exotic hadrons considered, we get the up limit of ϵ in Eq. (2) as well. Some results are in Table II and Fig. 1.

Recently, argued in Ref. [29], from the production rate one can extract the information of the constituent quark number. The authors employ the combination model proposed by [27] and predict and compare the production rate of $f_0(980)$ for two cases: $s\bar{s}$ or $s\bar{q}\bar{s}q$. However, whether this idea is practical relies on whether it is "model independent." From our calculations list in Table II, one can see different results from [29]. If we take into account the case that many other kinds of exotic hadrons could also exist in nature and formed from combination of hadrons, the production rate of $f_0(980)(s\bar{q}\bar{s}q)$ should be even smaller. So, this implies that the production rates depend on the mechanism of production, and are not straightforwardly possible to relate with the constituent quark number in the framework of various quark combination models.

For the transverse momentum spectrum (Fig. 1), it is clear that the four-quark state is harder, a common property of all combination models. This is the same reason for B/M enhancement in the mid-p_T region. Such kinds of generic features are common for all kinds of combination models, no matter if the combined "bricks" are quarks or hadrons. Our calculation procedure is especially straightforward in leading to this conclusion, since the hadron combination in phase (momentum) space is similar to those of the quarks. It is quite interesting to point out that, in principle, the p_T spectrum of such kinds of exotic hadrons formed from the combination of mesons and/or (anti)baryons can be fixed in our model, *independent* of the *quark distributions*. The free hadron spectra in Eq. (5) can be fixed by experimental data, which is completely model independent. Furthermore, x can only change the absolute value but not the shape of the spectrum. So, if some exotic hadron [maybe not $f_0(980)$] is produced by a combination of regular hadrons at RHIC, we can predict the shape of its spectrum without any ambiguity.

[2]Now we take the error of ϕ's data as one of the most precise. Its production rate $\frac{dN}{dy}$ is 7.70 ± 0.30 in the midrapidity region from the central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [30]. Its error is within 5%.

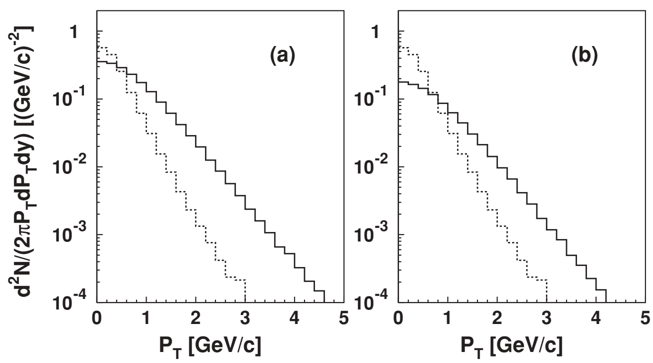

FIG. 1. Transverse momentum spectra of $f_0(980)$ at midrapidity for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. $f_0(980)(s\bar{q}\bar{s}q)$ (solid line) compared to $f_0(980)(s\bar{s})$ (dashed line). (a) and (b) respectively correspond to the cases (a) and (b) in Table II.

TABLE II. The production rate of $f_0(980)$ at midrapidity (within one rapidity unit) for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (a) corresponds the case only one exotic hadron, i.e., $f_0(980)(s\bar{q}\bar{s}q)$; (b) denotes the case where we consider all the isospin multistates.

	x	$f_0(980)(s\bar{q}\bar{s}q)$	$f_0(980)(s\bar{s})$
(a)	0.60	1.63	
(b)	0.24	0.65	0.68

IV. CONCLUSION

In this paper, we propose a way to calculate the production rates of exotic hadrons (multiquark states) within the framework of SDQCM. We point out that this special combination model employs a specific combination rule to shut off the possibility that more than three (anti)quarks can combine into some hadron. The unitarity is automatically kept but may be too restrict if there are exotic hadrons, since the to-date experiments only assure the rareness of exotic hadron production, as shown in Eq. (2). By an analysis on the complexity of the color structure of the exotic hadrons, we suggest that one can introduce the small section of exotic hadron production by treating (*only*) its production process as hadron molecule (hadron bound state) formation. Taking the possible four-quark structure of $f_0(980)$ as an example, we discuss two special cases, i.e., only one exotic hadron $f_0(980)(s\bar{q}\bar{s}q)$ exists in nature, or all the isospin multistates of $(s\bar{q}\bar{s}q)$ exist, respectively, and compare with the regular meson structure of $f_0(980)(s\bar{s})$. Such investigation demonstrates that we can keep the inherent unitarity of the SDQCM as well as improve its robustness to accommodate the exotic production. This is helpful in the exotic hadron study in experiments like RHIC.

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