Identifying Multiquark Hadrons from Heavy Ion Collisions

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Identifying hadronic molecular states and/or hadrons with multiquark components either with or without exotic quantum numbers is a long-standing challenge in hadronic physics. We suggest that studying the production of these hadrons in relativistic heavy ion collisions offers a promising resolution to this problem as yields of exotic hadrons are expected to be strongly affected by their structures. Using the coalescence model for hadron production, we find that, compared to the case of a nonexotic hadron with normal quark numbers, the yield of an exotic hadron is typically an order of magnitude smaller when it is a compact multiquark state and a factor of 2 or more larger when it is a loosely bound hadronic molecule. We further find that some of the newly proposed heavy exotic states could be produced and realistically measured in these experiments.

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Finding hadrons with configurations other than the usual $q\bar{q}$ configuration for a meson and qqq for a baryon is a long-standing challenge in hadronic physics. In 1970s, the tetraquark picture [1] was suggested as an attempt to understand the inverted mass spectrum of the scalar nonet. At the same time, the exotic H dibaryon [2] was proposed on the basis of the color-spin interaction. While results from the long search for the H dibaryon in various experiments turned out to be negative, we are witnessing a renewed interest in this subject as the properties of several newly observed heavy states, including $D_{sJ}(2317)$ [3] and $X(3872)$ [4], cannot be properly explained within the simple quark model.

An important aspect in understanding a multiquark hadron involves the discrimination between a compact multiquark configuration and a loosely bound molecular configuration with or without exotic quantum numbers. While the wave function of a loosely bound molecular configuration is dominantly composed of a bound state of well separated hadrons, the main Fock component of a compact multiquark configuration typically has the size of a hadron, with little if any separable color singlet components. For a crypto-exotic state, one further has to distinguish it from a normal quark configuration. For example, $f_0(980)$ and $a_0(980)$ could be either normal quark-antiquark states [5], compact tetraquark states [1], or weakly bound $K\bar{K}$ molecules [6].

Previously, discriminating between different configurations for a hadron relied on information about the detailed properties of the hadron and its decay or reaction rate [7]. Moreover, searches for exotic hadrons have usually been pursued in reactions between elementary particles. In this Letter, we show that measurements from heavy ion collisions at ultrarelativistic energies can provide new insights into the problem and give answers to some of the fundamental questions raised above [8–10]. In particular, we focus on the yields of multiquark hadrons in heavy ion collisions. To carry out this task, we first use the statistical model [11], which assumes that the produced matter in relativistic heavy ion collisions is in thermodynamical equilibrium and is known to describe the relative yields of normal hadrons very well, to normalize the expected yields. We then use the coalescence model [12], which is based on the sudden approximation by calculating the overlap of the density matrix of the constituents in an emission source with the Wigner function of the produced particle, to take into account the effects of the inner structure of hadrons, such as angular momentum [13] and the multiplicity of quarks [9]. The coalescence model has been extensively used to study both light nucleus production in nuclear reactions [14] and hadron production from the quark-gluon plasma produced in relativistic heavy ion collisions [15–18]. In particular, it has successfully explained the observed enhancement of baryon production in the intermediate transverse momentum region [19,20] and the quark number scaling of the elliptic flow of identified hadrons [21,22] as well as the yield of recently discovered antihypertritons in heavy ion collisions at RHIC [23].

In the statistical model, the number of produced hadrons of a given type h is given by [11]

$$N_h^{\rm stat} = V_H \frac{g_h}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\gamma_h^{-1} e^{E_h/T_H} \pm 1} \qquad (1)$$

with g_h being the degeneracy of the hadron and V_H (T_H) the volume (temperature) of the source when statistical production occurs. The fugacity is $\gamma_h = \gamma_c^{n_c+n_{\bar c}} e^{(\mu_B B + \mu_s S)/T_H}$, where B and S are the baryon and strangeness numbers of the hadron, respectively, with corresponding chemical potentials μ_B and μ_S, and n_c ($n_{\bar c}$) the number of (anti)charm quarks in the hadron. For central Au + Au (Pb + Pb) collisions at $\sqrt{s_{NN}} = 200$ GeV (5.5 TeV) at RHIC (LHC), values for these parameters have been determined in Refs. [8,24] for particles in one unit of central rapidity in an expanding fire-cylinder model: $V_H = 1908\ (5152)\ \mathrm{fm}^3$, $T_H = 175$ MeV, $\mu_s = 10\ (0)$ MeV, and $\mu_B = 20\ (0)$ MeV. We fix $\gamma_c = 6.40$ (15.8) by requiring the expected total charm quark number $N_c = 3$ (20) extracted from initial hard scattering at RHIC (LHC) to be equal to the sum of the yields of D, D^*, D_s, and Λ_c estimated in the statistical model. We note that all statistically produced hadrons from this fire cylinder are essentially in the central unit rapidity.

In the coalescence model, the number of hadrons of type h produced from the coalescence of n constituents, based on harmonic oscillator wave functions for the hadron internal structure, is given by

$$N_h^{\rm coal} \simeq g_h \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \left[\frac{4\mu_i T\sigma_i^2}{3(1+2\mu_i T\sigma_i^2)}\right]^{l_i}, \qquad (2)$$

if we use the nonrelativistic approximation, neglect the transverse flow of produced matter, and consider only the central unit rapidity as in Refs. [8,9]. In Eq. (2), g_j is the degeneracy of the jth constituent, N_j is its number taken to be $N_u = N_d = 245$ (662) and $N_s = 150$ (405), and $V = 1000\ (2700)\ \mathrm{fm}^3$ for RHIC (LHC) [8]; l_i is 0 (1) for a $s(p)$-wave constituent; and $\sigma_i = 1/\sqrt{\mu_i \omega}$ with ω being the oscillator frequency and μ_i the reduced mass defined by $\mu_i^{-1} = m_{i+1}^{-1} + (\sum_{j=1}^{i} m_j)^{-1}$ with $m_{u,d}$ (m_s) = 300 (500) MeV. By using the ω determined below, Eq. (2) shows that the addition of an s-wave (p-wave) u/d quark leads to the coalescence factor of about 0.360 (0.093) or less at both RHIC and LHC. Therefore, hadrons with more constituents are generally suppressed, and the p-wave coalescence is hindered with respect to the s-wave coalescence [13].

In applying the coalescence model to multiquark-hadron production, we fix the oscillator frequencies by requiring the coalescence model to reproduce the reference *normal* hadron yields in the statistical model. This leads to $\omega = 550$ MeV for hadrons composed of light quarks. For hadrons composed of light and strange (charm) quarks, we fix ω_s (ω_c) to reproduce the yields of $\Lambda(1115)$ [$\Lambda_c(2286)$] in the statistical model. For the $\Lambda_c(2286)$ yield, we include the feed-down contribution according to $N^{\rm stat,total}_{\Lambda_c(2286)} = N^{\rm stat}_{\Lambda_c(2286)} + N^{\rm stat}_{\Sigma_c(2455)} + N^{\rm stat}_{\Sigma_c(2520)} + 0.67 \times N^{\rm stat}_{\Lambda_c(2625)}$. Fitting this yield to that calculated in the coalescence model, we obtain $\omega_c = 385$ MeV for $m_c = 1500$ MeV. Similarly, we get $\omega_s = 519$ MeV from the $\Lambda(1115)$ yield after including the feed-down from the octet and decuplet states.

The yields for weakly bound hadronic molecules are estimated by using the coalescence of hadrons at the kinetic freeze-out point [$T_F = 125$ MeV, $V_F = 11\,322\ (30\,569)\ \mathrm{fm}^3$ for RHIC (LHC)]. If the radius of a hadronic molecule is known, the oscillator frequency ω can be fixed by $\omega = 3/(2\mu_1\langle r^2\rangle)$ for the two-body s-wave state. If only the binding energy is given, we use the relation B.E. $\simeq \hbar^2/(2\mu_1 a_0^2)$ and $\langle r^2\rangle \simeq a_0^2/2$, with a_0 being the s-wave scattering length, between the binding energy and the rms radius to obtain $\omega = 6 \times$ B.E. For example, for $f_0(980)$, $\omega_{f_0(980)} = 67.8$ MeV by using $\mathrm{B.E.}_{f_0(980)} = M_{K^\pm} + M_{K^0,\bar K^0} - M_{f_0(980)} = 11.3$ MeV. Table I summarizes the parameters and possible decay modes for a selection of multiquark candidates as well as proposed states $\bar K KN$ [25], $\bar K NN$ [26], $\bar D N$, and $\bar D NN$ [27].

The yields of states listed in Table I are summarized in Table II. For example, possible configurations of the $f_0(980)$ could be an $s\bar s$ or a $u\bar u$ and $d\bar d$ state in addition to crypto-exotic configurations discussed before. For most of the states considered here, the coalescence yield from the compact multiquark state is an order of magnitude smaller than that from the usual quark configuration as the coalescence of additional quarks is suppressed. Also, for the same hadronic state, the coalescence yield from the molecular configuration is similar to or larger than that from the statistical model prediction. The similarity in the yields from the statistical model and the coalescence model prediction for a molecular configuration, despite the difference in the production temperatures T_C and T_F, can be attributed to the larger size of the molecular configuration forming at a lower temperature but at a larger volume; hence, the ratio of volumes σ_i^3/V is similar. The predicted appreciable yields of hadronic molecules in relativistic heavy ion collisions are in sharp contrast to those in high energy pp collisions, where molecular configurations with small binding energy are hard to produce, particularly at high p_T [28]. Our results do not change much if different

TABLE I. List of multiquark states. For hadron molecules, the oscillator frequency $\omega_{\rm Mol.}$ is fixed by using the binding energy (B) or the interhadron distance (R). The $\omega_{\rm Mol.}$ for the last two states is taken from the corresponding two-body system (T).

Particle	m (MeV)	g	I	$J\pi$	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\rm Mol.}$ (MeV)	Decay mode
$f_0(980)$	980	1	0	0+	$q\bar{q}$ ($L = 1$)	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (strong decay)
$a_0(980)$	980	3	1	0+	$q\bar{q}$ ($L = 1$)	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (strong decay)
$D_s(2317)$	2317	1	0	0+	$c\bar{s}$ ($L = 1$)	$q\bar{q}c\bar{s}$	DK	273(B)	$D_s\pi$ (strong decay)
$X(3872)$	3872	3	0	1+	···	$q\bar{q}c\bar{c}$	$\bar{D}\bar{D}^*$	3.6(B)	$J/\psi\pi\pi$ (strong decay)
$\Lambda(1405)$	1405	2	0	1/2−	qqs ($L = 1$)	$qqqs\bar{q}$	$\bar{K}N$	20.5(R) − 174(B)	$\pi\Sigma$ (strong decay)
$\bar{K}KN$	1920	4	1/2	1/2+	···	$qqqs\bar{s}$ ($L = 1$)	$\bar{K}KN$	42(R)	$K\pi\Sigma$, $\pi\eta N$ (strong decay)
$\bar{D}N$	2790	2	0	1/2−	···	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{K}NN$	2352	2	1/2	0−	$qqqqqs$ ($L = 1$)	$qqqqqqs\bar{q}$	$\bar{K}NN$	20.5(T) − 174(T)	ΛN (strong decay)
$\bar{D}NN$	3734	2	1/2	0−	···	$qqqqqqq\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d$, $K^+\pi^-\pi^- + p + p$

forms of hadron wave functions are used and the temperature and chemical potentials are varied in a reasonable range. Moreover, the correlated uncertainties in the number of charm quark and its fugacity largely cancel out in the studied ratios.

Our results also indicate that the yields of many multiquark hadrons are large enough to be measurable in experiments. In particular, the heavy exotic hadrons containing charm or strange quarks can be produced at RHIC with appreciable abundance and even more so at LHC. Moreover, since the newly proposed states with charm quark are below the strong decay threshold, the background of their weak hadronic decays could be substantially reduced through vertex reconstruction. Since the expected number of D^0 observed through the vertex detector is of the order of 10^5 per month at LHC, even the $\bar{D}NN$ states are definitely measurable. Therefore, relativistic heavy ion collisions provide a good opportunity to search for multiquark hadrons, and this may very well lead to the first observation of new multiquark hadrons.

In Fig. 1, we show the ratio R_h of the yields at RHIC calculated in the coalescence model $N_h^{\rm coal}$ to those of the statistical model $N_h^{\rm stat}$ for the hadrons given in Table I. The gray band ($0.2 < R_h < 2$) shows the range of the ratios for normal hadrons with $2q$ and $3q$, which are denoted by triangles inside the gray band. The ratios for the crypto-exotic hadrons with usual $2q/3q$ configurations also fall inside the gray band. The circles indicate the ratios obtained by assuming hadronic molecular configurations and are found to lie mostly above the normal band ($R_h > 2$). Moreover, we find that loosely bound extended molecules with a larger size would be formed more abundantly. One typical example is $\Lambda(1405)$. Using the previous relation between the binding energy and the oscillator frequency ω, we find a small size for $\Lambda(1405)$ ($\omega = 174$ MeV) and a ratio $R_h = 1.1$. A coupled channel analysis [29–31] gives, however, a larger $\langle r^2\rangle$, leading thus to a larger $R_h = 4.9$. The patterns shown in Fig. 1 also hold for LHC as the freeze-out conditions are similar to those at RHIC.

As shown by diamonds in Fig. 1, the ratio R_h is below the normal band ($R_h < 0.2$) when a hadron has a compact multiquark configuration. In particular, for light quark configurations, these ratios are an order of magnitude smaller than those of normal hadrons or molecular configurations. This is consistent with the naive expectation that the probability to combine n quarks into a compact region is suppressed as n increases. The tetraquark states of $f_0(980)$ and $a_0(980)$ are typical examples. This suppression also applies to $5q$ states in multiquark hadrons [$\Lambda(1405)$ and $\bar{K}KN$] and the $8q$ state in $\bar{K}NN$. On the other hand, the yield of hadrons at higher transverse momenta is expected to be enhanced if they have multiquark configurations since quark coalescence enhances the

TABLE II. Yields in one unit of central rapidity with oscillator frequencies $\omega = 550$ MeV, $\omega_s = 519$ MeV, and $\omega_c = 385$ MeV.

	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
$f_0(980)$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	11	0.31	40	17	31	0.83	1.1×10^2	46
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
$X(3872)$	···	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	···	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$\Lambda(1405)$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
$\bar{K}KN$	···	0.019	1.7	0.28	···	5.2×10^{-2}	4.2	0.67
$\bar{D}N$	···	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	···	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{K}NN$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026–0.54	3.7×10^{-2}
$\bar{D}NN$	···	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	···	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}

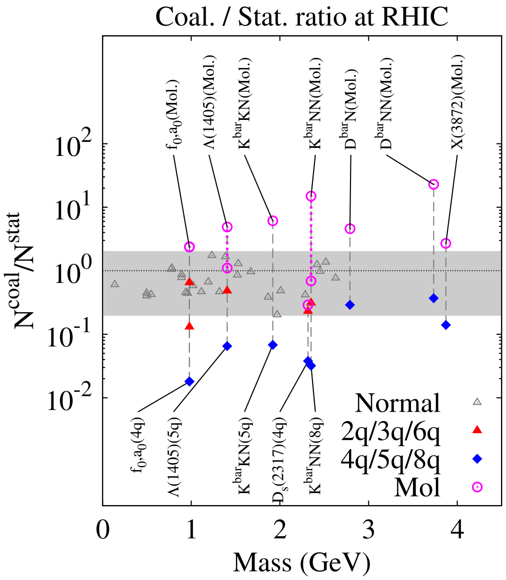

FIG. 1 (color online). Ratio of hadron yields at RHIC in the coalescence model to those in the statistical model.

baryon/meson ratio at intermediate transverse momenta [15–17] as observed in experiments [19,20].

We conclude from the above discussions that the yield of a hadron in relativistic heavy ion collisions reflects its structure and thus can be used as a new method to discriminate the different pictures for the structures of multiquark hadrons. As a specific example, we consider $f_0(980)$. So far, STAR has a preliminary measurement of $f_0(980)/\pi$ and ρ^0/π from which we find $f_0(980)/\rho^0 \sim 0.2$ [32]. Using the statistical model prediction for the yield of $\rho^0 = 42$ leads to $f_0(980) \sim 8$. Comparing this number to the numbers predicted for $f_0(980)$ in Table II, we find the data consistent with the $K\bar{K}$ picture. Therefore, despite the quoted experimental error of around 50%, the STAR data can be taken as evidence that the $f_0(980)$ has a substantial $K\bar{K}$ component, and a pure tetraquark configuration can be ruled out for its structure. Such a conclusion could not be reached from analyzing the data for $f_0(980) \to 2\gamma$ [7,33]. Because of the large error bars in the STAR data, further experimental effort is highly desirable for putting an end to this controversial issue. Similarly, efforts to measure the yields of other hadrons and newly proposed exotic states listed in Table I will provide new insights to a long-standing challenge in hadronic physics.

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