Multi-quark hadrons from Heavy Ion Collisions

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Identifying hadronic molecular states and/or hadrons with multi-quark 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 offer 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 non-exotic hadron with normal quark numbers, the yield of an exotic hadron is typically an order of magnitude smaller when it is a compact multi-quark state and a factor of two or more larger when it is a loosely bound hadronic molecule. We further find that due to the appreciable numbers of charm and bottom quarks produced in heavy ion collisions at RHIC and even larger numbers expected at LHC, 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 1970's, 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 cannot be properly explained within the simple quark model. These states include $D_{sJ}(2317)$ and $X(3872)$ discovered, respectively, by the BaBar collaboration [3] and the Belle collaboration [4].

An important aspect in understanding a multi-quark hadron involves the discrimination between a compact multi-quark configuration and a loosely bound molecular configuration with or without exotic quantum numbers. In a loosely bound molecular configuration, the wave function is dominantly composed of a bound state of well separated hadrons. On the other hand, in a compact multi-quark configuration, the dominant Fock component is a compact quark configuration typically of a hadron size, 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 tetra-quark 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 will 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 multi-quark hadrons in heavy ion collisions. To carry out the task, we first use the statistical model [11], which is known to describe the relative yields of normal hadrons very well, to normalize the expected yields. We then use the coalescence model, which has successfully explained the enhanced production of baryons at midrapidity in the intermediate transverse momentum region and the quark number scaling of the elliptic flow of identified hadrons [12, 13], to take into account the effects of the inner structure of hadrons, such as angular momentum and the multiplicity of quarks [9, 14].

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 with corresponding chemical potentials μ_B and μ_S, and $n_c(n_{\bar c})$ the number of (anti-)charm quarks. 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, 15] for an expanding fire-cylinder model: $V_H = 1908$ (5152) 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.

The coalescence model for particle production [16] has been extensively used to study both light nucleus production in nuclear reactions [17, 18] and hadron production from the quark-gluon plasma produced in relativistic heavy ion collisions [12, 13, 19, 20]. We use the non-relativistic approximation and consider only the central rapidity region of unit rapidity as in Refs. [8, 9]. The number of hadrons of type h produced from the coalescence of n constituents using a Gaussian wave function is then given by

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

Here, g_i is the degeneracy of the ith constituent and N_i its number, which is taken to be 245 (662) and 150 (405) for $N_u = N_d$ and N_s, respectively, 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 $\mu_i^{-1} = m_{i+1}^{-1} + (\sum_{j=1}^{i} m_j)^{-1}$. Eq. (2) shows that the addition of a s-wave or p-wave quark leads to the coalescence factor

$$\frac{1}{g_i}\frac{N_i}{V}\frac{(4\pi\sigma_i^2)^{3/2}}{(1+2\mu_i T\sigma_i^2)} \sim 0.13 \qquad (3)$$

or

$$\frac{1}{g_i}\frac{N_i}{V}\frac{2}{3}\frac{(4\pi\sigma_i^2)^{3/2} 2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)^2} \sim 0.033. \qquad (4)$$

Hadrons with more constituents are hence generally suppressed, and the p-wave coalescence is more suppressed than the s-wave coalescence [14].

In applying the coalescence model to multi-quark 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 ω = 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 contributions 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 with charm quark mass $m_c = 1500$ 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 using the coalescence of hadrons at the kinetic freezeout point (T_F = 125 MeV). If the radius for hadronic molecules is known, ω in the hadron coalescence can be fixed by $\omega = 3/(2\mu_R\langle r^2\rangle)$ for the 2-body s-wave states. If only the binding energy is given, we use the relation B.E. $\simeq \hbar^2/(2\mu a_0^2)$ 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 $f_0(980)$, $\omega_{f_0(980)} = 6 \times B.E_{f_0(980)} = 67.8$ MeV with $B.E_{f_0(980)} = M_{K^\pm} + M_{K^0,\bar K_0} - M_{f_0(980)} = 11.3$ MeV. Table I summarizes the parameters and possible decay modes for a selection of multi-quark candidates. We also include proposed states $\bar K KN$[21], $\bar K NN$[22], $\bar D N$ and $\bar D NN$ [23].

The yields of states listed in Table I are summarized in Table II. For example, possible configurations of the $f_0(980)$ could be a $s\bar s$ 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 multi-quark state is an order of magnitude smaller than that from the usual quark configuration; this is so because coalescence of additional quarks are suppressed as seen from Eqs. (3) and (4). Moreover, for the same hadronic state, the coalescence yield from the molecular configuration is similar to or larger than that from the statistical model prediction in contrast to the case in high energy pp collisions, where molecular configurations with small binding energy are hard to produce at high p_T [24]. 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 lower temperature but at a larger volume; hence the ratio of volumes σ_i^3/V appearing in Eq. (3) is similar. We note that results from the statistical model do not change significantly if only one unit of rapidity in the central rapidity region is considered as in the coalescence model.

Our results also indicate that the yields of many multi-quark hadrons are large enough to be measurable in

TABLE I: List of multi-quark states discussed in this paper. For hadron molecules, the oscillator frequency $\omega_{\rm Mol.}$ is fixed based on the binding energy of hadrons ($\omega \simeq 6 \times$ B.E., marked (B)) or the inter-hadron distances ($\omega \simeq 3/2\mu \langle r^2 \rangle$, marked (R)). For the last two states, we adopt the same $\omega_{\rm Mol.}$ as for the corresponding two-body system (marked (T)).

Pariticle	m (MeV)	g	I	$J\pi$	2q/3q/6q	4q/5q/8q	Mol.	$\omega_{\rm Mol.}$ (MeV)	decay mode
$D_s(2317)$	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)
$f_0(980)$	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)
$\Lambda(1405)$	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−	$qqqqqs$ $(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	20.5(T)-174(T)	ΛN (strong decay)
$\bar{D}NN$	3734	2	1/2	0−	-	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d$, $K^+\pi^-\pi^- + p + p$

TABLE II: Hadron yields at RHIC and LHC 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.
$D_s(2317)$	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}
$f_0(980)$	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
$\Lambda(1405)$	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}

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. Therefore, relativistic heavy ion collisions provide good opportunity to search for multi-quark hadrons. In particular, it may lead to the first observation of new multi-quark hadrons.

In Fig. 1, we show the ratio R_h of the yields 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 grey zone within the range of $0.2 < R_h < 2$ denotes the range of the ratios for normal hadrons with $2q$ and $3q$; these are denoted by open triangles inside the grey band. The ratios for the crypto-exotic hadrons with usual $2q/3q$ configurations also fall inside the grey 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 these ratios depend on the size of the hadronic molecule; loosely bound extended molecules with 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 $R_h = 1.1$. On the other hand, a coupled channel analysis [25–27] gives a larger $\langle r^2 \rangle$, leading thus to a larger $R_h = 4.9$.

As shown by diamonds in Fig. 1, the ratio of the coalescence model prediction to that of the statistical model is below the normal band ($R_h < 0.2$) when a hadron is considered to have a compact multi-quark 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 state of $f_0(980)$ and $a_0(980)$ are typical examples. This suppression also applies to $5q$

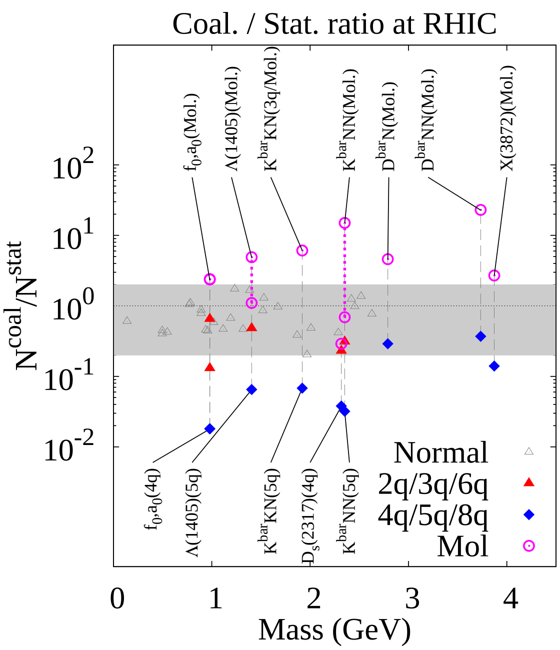

FIG. 1: (Color online) Multi-quark hadron production at RHIC in the coalescence model relative to the statistical model. The patterns also holds for LHC as freezeout conditions are similar to that of RHIC.

states in multi-quark hadrons ($\Lambda(1405)$ and $\bar{K}KN$) and the $8q$ state in $\bar{K}NN$.

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 multi-quark 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 $f_0(980)/\rho^0 \sim 0.2$ [28]. 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 to be consistent with the $K\bar{K}$ picture. Therefore, the STAR data can be taken as an evidence that the $f_0(980)$ has substantial $K\bar{K}$ components, and a pure tetraquark configuration can be ruled out for its structure. However, there are still large error bars in the STAR data. To put an end to this highly controversial issue, further experimental effort to reduce the error bar is therefore highly desirable. 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 hadron physics.

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