# STRANGE AND NONSTRANGE HADRON RESONANCE PRODUCTION BY QUARK COALESCENCE, INVESTIGATING QUARK NUMBER SCALING*

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RHIC data on light and strange hadron resonance production induced an extended discussion on hadron production mechanisms in heavy ion collisions. Resonance yields are far from the thermal expectations and standard coalescence models have also difficulties to reproduce these yields. We have developed the Resonance Coalescence Model (RCM) which contains the features of coalescence and quark scaling, and includes the width of the hadron resonances. It opens a way to handle resonances in the high mass region for all non-strange, strange and charm hadron resonances within the same description scheme. The talk focuses on the model structure, the question of quark scaling with resonances and predictions for strange and charm resonance ratios.

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## 1. Particle production from QGP

Nowadays particle detection and reconstruction techniques give us the possibility to observe the hadron resonance production in heavy ion collisions. These measured yields differ from the thermal expectations [1].

A well known hadron production mechanism is the quark coalescence where one can get a fast rehadronization. In these models, there is an embedded quark number scaling, which has been observed experimentally in the asymmetric flow $v_2$ measurements [2]. Quark coalescence models succeed not only at the prediction of particle yields, but they can also describe the pion to proton anomalous ratio.

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Early quark coalescence models (ALCOR [3]) could predict hadron yields, but later these models have been extended to handle the particle spectra as well. The MICOR model [4] is able to predict the hadron ratios and spectra. These quantum mechanics-based statistical methods appear to be efficient and robust in predicting the final hadron yields [5]. From then on, new coalescence and recombination models have been proposed and applied successfully to SPS and RHIC data [6, 7].

These models however cannot describe the high mass resonances, therefore we have introduced a new resonance coalescence model [8], based on relativistic kinematics. We present here the particle production mechanism in this model, we discuss the light, strange and charm sectors and enlighten the remaining quark number scaling.

## 2. Resonance coalescence model

In coalescence models, the "dressed-up" quarks gain an effective mass in the QGP (like valence quark masses) and due to their color they can stick to each other. In this way one produces bound quark pairs and triplets, if these are colorless we call them prehadrons (*e.g.* premeson from $q+\overline{q}$).

In the former coalescence models, these prehadrons had a direct connection with a hadron from the stable or first exited multiplets. The series of high mass resonances cannot be produced with these methods.

Moreover, the introduction of heavier resonances generates unexpected problems: (a) In the quantum mechanics based models the prehadron mass should be the sum of the constituent valence quark effective masses, thus it excludes all the other resonances from a given family; (b) Even by breaking the above rule and putting their masses by hand, the heaviest resonance dominate the hadronization, which is in contradiction with the experimental results. In our Resonance Coalescence Model (RCM) [8], the former problems do not appear. With the proper relativistic kinematics for the valence quarks the mass of the prehadron is the invariant mass of the system, thus one gets a continuous spectrum for it

$$m_{\text{prehadron}} = M_{q\overline{q}} = \|p^\mu_{q_1} + p^\mu_{q_2}\| = \sqrt{(E_1+E_2)^2 - (\vec{p_1}+\vec{p_2})^2}\,.$$

This allows us to produce prehadrons with arbitrarily large mass, therefore all the heavy resonances will be reachable. Knowing the initial valence quark momentum distributions ($f(m,\vec{p})$), the prehadron mass spectrum ($J^Q(m)$) can be calculated, where $Q$ stands for the valence quark content (as a quantum number) of the prehadron

$$J^Q(m) = \int\limits_0^\infty \int\limits_0^\infty d^3\vec{p_1} d^3\vec{p_2} f(m_1,\vec{p_1}) f(m_2,\vec{p_2}) \delta\left(m - \|p^\mu_1 + p^\mu_2\|\right)\,.$$

In our calculation, we use the relativistic Jüttner distribution for the light and strange quarks (anti-quarks) with the same temperature parameter ($T = 180$ MeV). The obtained prehadron mass distribution (see Fig. 1) has an exponential-like tail, which gives a close-to-thermal suppression for the heavy resonances.

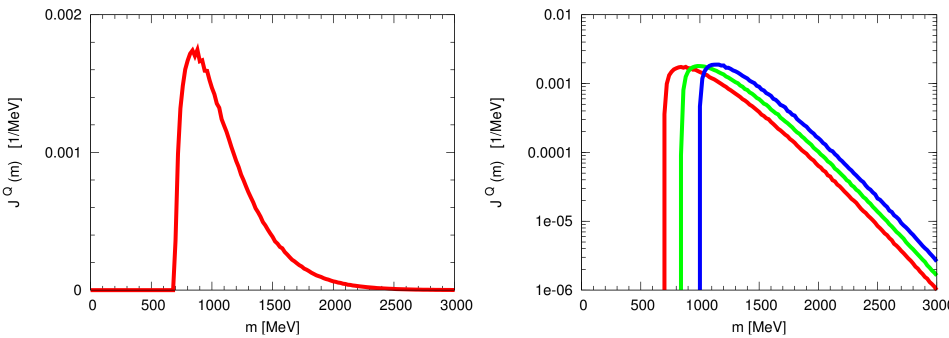


Fig. 1. Invariant mass spectrum, $J^Q(m)$, for $Q = q\bar{q}$ premesons with light quark mass $m_q = 350$ MeV on linear scale (left panel). Invariant mass spectra, $J^Q(m)$, for $Q = q\bar{q}, q\bar{s}, s\bar{s}$ quark combinations with quark masses $m_q = 350$ MeV and $m_s = 500$ MeV on logarithmic scale (right panel).

## 3. Hadron appearance probability

From the continuous prehadron mass distribution we have to make discrete hadron resonances. Considering $h_i^Q$ hadron resonance with quantum numbers $Q$, knowing its mass, width and degeneracy we can construct its spectral function $H_i^Q(m)$ by the Breit–Wigner formula or an approximation with a proper Gauss distribution.

The produced resonance should have the same quark content as its ancestor prehadron. Let us define $\mathcal{P}(h_i^Q; m)$ which is the probability that from the prehadron with mass $m$ and quark content $Q$ the hadron $h$ can be formed. This probability function can be naturally defined as the resonance spectral function's relative weight at mass $m$.

The top left panel in Fig. 2 shows the probability functions for several strange mesons. These probabilities usually peak at the mass value of the resonance, however it can have strange shape for resonances with large width and in dense resonance regions.

The production rate is given by the combination of probabilities and the proper mass spectra. The primary yield is generated similarly to the usual coalescence models.

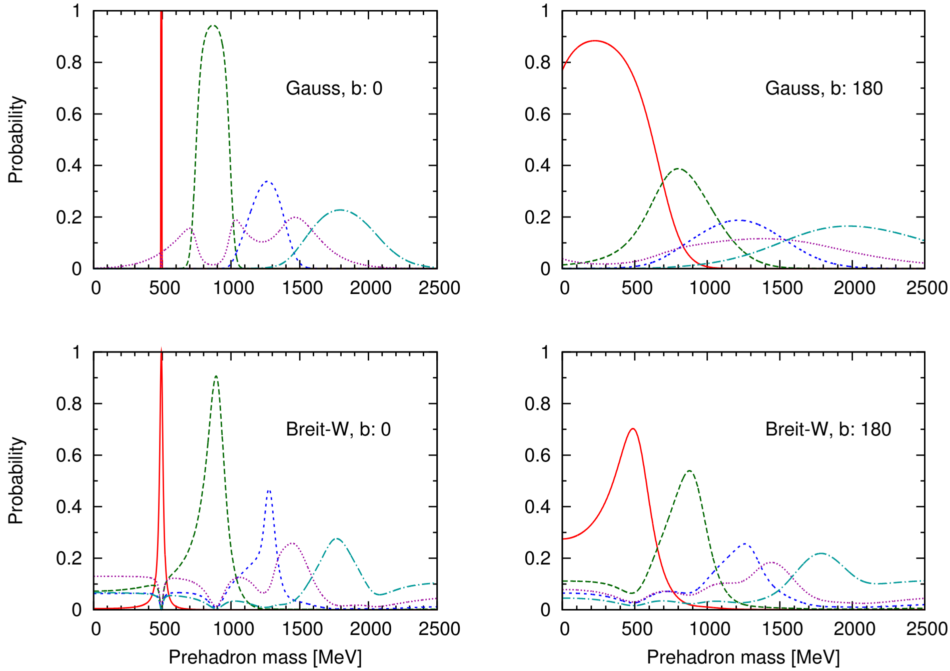


Fig. 2. Four different families of probability functions ($\mathcal{P}(h_i^Q;m)$) for several strange mesons ($K, K^*(892)$, $K_1(1270)$, $K^*(1410)$, $K_2(1770)$): in the case of Gaussian (top left) and Breit–Wigner (bottom left) type width for the production processes, the same functions (right) in the case of an extremely large gluonic broadening (+180 MeV).

The prehadrons are moving inside the hot quark-gluon plasma before they leave it and become a hadron resonance. During their journey and especially when they escape to the vacuum they can interact with the medium; this could give a broadening to their mass distribution. This can be handled in the prehadron mass level or even at the hadronization phase within the probability functions. Here we show two extreme case for the effect: with broadening 0 MeV and 180 MeV for both the Breit–Wigner and the Gaussian approximation cases (see Fig. 2).

## 4. Baryons

The baryon production goes similarly to the other coalescence models, the bound quark–quark pairs forming a diquark, which can attract a third quark and became a colorless prebaryon. From this stage it goes on as for the mesons, with the new prehadron mass distributions and the probability functions.

## 5. Charm sector

One can insert new quark flavors into the model, by giving it an effective quark mass and its momentum distribution [9]. We take the Jüttner distribution for charm quarks with the same temperature parameter as used for light quarks. For the prehadron mass distributions one needs the effective charm valence quark mass. It can differ from the charm quark mass as it differs for the light sector as well. Once these parameters are defined, the method can be applied for the charm sector by generating the prehadron mass distributions, the probability functions and calculating the yields.

The special emplacement of the charmonia masses in the mass scale makes the primary yields strongly depending on the effective charm mass. Charmonia states with mass smaller than $2m_{\mathrm{charm}}$ cannot be produced directly, only through decay chains. In the left panel of Fig. 3, we show the primary and final yields of some well measurable charmonium states, where this effect can be seen.

A change in the temperature makes only a slight difference in the interesting yields as one can see in the right panel of Fig. 3.

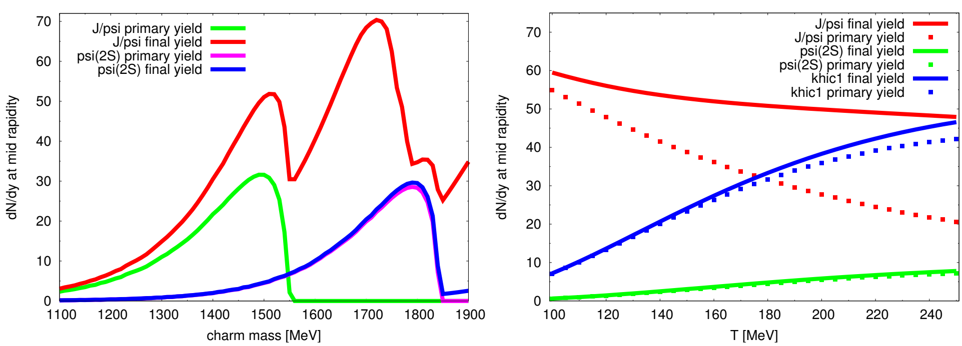


Fig. 3. Primary and total yields of charmonium resonances *versus* the effective charm mass (left) and the temperature (right). The strong dependence on charm mass is connected with the relatively small mass and narrow width of the $J/\psi$ meson.

## 6. Quark number scaling

The embedded quark number scaling is one of the strongest feature of the coalescence type models. However, one should raise the question: how could the quark number scaling be valid with the presence of resonances? The production of high mass resonances should mix the separated baryon and meson yields, thus violating our precious scaling.

In the resonance coalescence model the hadron families with different quark content can be handled in parallel. This feature originates from the definition of the appearance functions, where we use only one quark content family. All the produced resonances are marked with this quark content. If one handles the decay chains with care for the quark content, then for all the particles one could measure the quark content distribution of its ancestors.

The meson to baryon decays are negligible, however, the most common decay of a baryon is to a baryon and several mesons. This influences the $\pi$ and $K$ production the most. In the following table we show the ancestor ratios of several mesons, where one can see that the violation of the scaling is quite small.

| Particle type | Mesonic ancestors [%] | Baryonic ancestors [%] |
|---|---|---|
| $\pi$ | 84 | 16 |
| $K$ | 92 | 8 |
| $\eta$ | 92 | 8 |
| $\rho(770)$ | 94 | 6 |
| $\omega(782)$ | 99 | 1 |
| ... | | |

The separation of the hadron families can be most effectively used while fitting the parameters. In this way the quark densities in the plasma and the method of the hadronization (with the proper appearance functions) become independent.

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