Heavy Flavor Enhancement as a Signal of Color Deconfinement

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We argue that the color deconfinement in heavy ion collisions may lead to enhanced production of hadrons with open heavy flavor (charm or bottom). We estimate the upper bound of this enhancement.

The production of open heavy flavor (HF) hadrons (charm and bottom) still remains a 'terra incognita' of heavy ion physics: neither open charm nor open bottom yields have been measured so far. Open charm measurements are only planned in Pb+Pb collisions at the CERN SPS. The standard theoretical picture assumes that the average number of hadron pairs with open HF (charm and bottom) still remains a 'terra incognita' of collisions, which is determined by the geometry of the nucleon-nucleon (N+N) collision $\langle HF \rangle_{NN}$:

$$\langle HF \rangle_{AB(b)} = N_{coll}^{AB(b)}(HF)_{NN} = N_{coll}^{AB(b)} \frac{\sigma_{NN\rightarrow HF+X}}{\sigma_{NN_{inel}}}$$

where $N_{coll}^{AB(b)}$ is the average number of primary nucleon collisions, which is determined by the geometry of the colliding nuclei, $\sigma_{NN\rightarrow HF+X}$ is the total cross section of the HF hadron pair production in $N+N$ collisions and $\sigma_{NN_{inel}}$ is the total inelastic cross section of $N+N$ interaction. (Note that in high energy collisions the HF production is dominated by the creation of hadrons with open HF. The HF quarkonia correspond to a tiny fraction of the total HF yield and can be safely neglected in our consideration.)

There are however some indirect indications that an essential deviation from the standard formula (1) may exist. Recent analysis of the dimuon spectrum measured in central Pb+Pb collisions at 158 A GeV by NA50 Collaboration\textsuperscript{3} reveals a significant enhancement of the dilepton production in the intermediate mass region (1.5–2.5 GeV) over the standard sources. The primary\textsuperscript{4} interpretation attributes this observation to the enhanced production of open charm\textsuperscript{3}: about 3 times above the direct extrapolation (1) from N+N data. Similar result has been recently obtained in the framework of the statistical coalescence model\textsuperscript{5,6}. This model connects the multiplicities of hadrons with open and hidden charm. It was found\textsuperscript{3,4} that an enhancement of the open charm by the factor of about 2–4 over the direct extrapolation is needed to explain the data on the $J/\psi$ multiplicity. It was suggested in Ref.\textsuperscript{3} that this enhancement may appear due to the broadening of the phase space available for the open charm because of the presence of strongly interacting medium.

In the present letter we demonstrate that a deconfined medium (quark-gluon plasma (QGP) or its precursor) can make an essential influence on the hadronization of HF (anti-)quarks. This leads to an enhancement of the HF hadron production in A+B collisions in comparison to the direct extrapolation (1) from the N+N data. We restrict ourselves to a rough estimation of the upper bound of possible HF enhancement due to the color deconfined medium.

The process of production of a HF hadron pair can be subdivided into two stages: the hard production of a HF quark-antiquark pair ($Q\bar{Q}$) and its subsequent hadronization into observed particles. Therefore, there is an essential difference between HF hadron production and, e.g., hard dilepton production (the Drell-Yan process): created $Q$ and $\bar{Q}$ can and even have to interact with the surrounding quarks and gluons to be transformed into observed HF hadrons.

To get an intuitive picture of possible medium effects let us start from the open HF production in $e^+e^-$ annihilation. The HF $Q\bar{Q}$ pair created at the first stage, hadronizes into observed particles. The hadronization has a nonperturbative nature. Its dynamics can be qualitatively understood in the framework of the string picture. When the distance between $Q$ and $\bar{Q}$ reaches the range of the confinement forces, a string connected these colored objects is formed. If the $e^+e^-$ center-of-mass (c.m.) energy $\sqrt{s}$ (equal to the invariant mass of $Q\bar{Q}$ pair $M_{Q\bar{Q}}$) lies well above the corresponding HF meson threshold $2m_M$ (equal to $2m_D$ or $2m_B$ for $\pi$ and $b\bar{b}$ quarks, respectively), $Q$ and $\bar{Q}$ break the string into two (or more) pieces, so that the final state contains a HF hadron pair (and possibly a number of light hadrons). However, when the $e^+e^-$ c.m. energy exceeds the heavy quark threshold ($\sqrt{s} > 2m_Q$) but lies below the corresponding HF meson threshold $2m_M$ ($\sqrt{s} < 2m_M$), the string cannot be broken and the open HF hadron pair

\textsuperscript{1}Here we neglect (anti-)shadowing effects which are expected to be not very large at SPS and RHIC energies.

\textsuperscript{2}Alternative explanations are also suggested\textsuperscript{3}.
cannot be formed.

Let us imagine now the $e^+e^-$ annihilation inside a deconfined medium. Due to the Debye screening, no string is formed between colored objects in this case. If the heavy $Q$ and $\bar{Q}$ are created, they can fly apart within the medium as if they were free particles. It does not matter whether their initial invariant mass $M_{Q\bar{Q}}$ exceeds the corresponding hadron threshold or not. The created $Q\bar{Q}$ pair will be able to form a HF hadron pair at the stage of QGP hadronization. This means that the $e^+e^-$ annihilation inside the QGP would produce HF hadrons even if the collision energy is not sufficient for producing these hadrons in the vacuum.

In $N+N$ or $A+B$ collisions the HF $Q\bar{Q}$ pairs are produced due to hard parton interactions. The calculations in the leading order of the perturbative quantum chromodynamics (pQCD) show that a great fraction of $Q\bar{Q}$ pairs are created with invariant masses $M_{Q\bar{Q}}$ below the corresponding meson threshold $2m_M$ even at the largest RHIC energy. If this $Q\bar{Q}$ pair creation takes place in the deconfined medium, which is expected to be formed in high energy A+B collisions, the presence of such a medium makes possible a hadronization of these pairs. This should lead to an enhancement of the HF hadron production in $A+B$ collisions in comparison to the standard result obtained within the direct extrapolation of the $N+N$ data.

There are of course essential differences between the open HF hadron production in the $e^+e^-$ annihilation and in $N+N$ or $A+B$ collisions. Even in $N+N$ collisions, when no deconfined medium is expected, the created $Q\bar{Q}$ pair can interact with the spectator partons and has therefore a chance to form HF hadron pair even if its primary invariant mass was insufficient for this process. Moreover, in contrast to the $e^+e^-$ annihilation, the most of $Q\bar{Q}$ pairs are created in the color octet state and therefore they have to interact with the spectators to form a color neutral final state. Instead of breaking the string, the $Q$ and $\bar{Q}$ can form hadron states by means of coalescence with light spectator (anti-)quarks.

As no theoretical descriptions of this complicated process exist, we restrict ourselves to a rough estimation of the upper bound of possible HF hadron enhancement due to the color deconfined medium. We assume that

- In the case of $N+N$ collisions, no subthreshold $Q\bar{Q}$ pairs contribute to the HF hadron production.
- In the case of $A+B$ collisions, provided that the deconfined medium is formed, all $Q\bar{Q}$ pairs hadronize into particles with the open HF$^3$.

The first assumption looks reasonable at low collision energies, whereas to justify the second one high energies are evidently preferable. This means that assuming validity of the both statements we overestimate the expected HF enhancement effect and, therefore, the above assumptions give its upper bound.

We make now the numerical estimates which follow from the above assumptions. The total cross section of heavy $Q\bar{Q}$ pair production by colliding nucleons is given by the formula (see e.g. Ref. $^3$)

$$\sigma_{NN\rightarrow Q\bar{Q}+X}(s) = \sigma_{12\rightarrow Q\bar{Q}+X}(\hat{s})$$

where $s$ is the squared c.m. energy of the colliding nucleons, $x_1$ ($x_2$) is the fraction of the momentum of the first (second) nucleon carried by the parton 1 (2), $f_1$ and $f_2$ are the fractional-momentum distribution functions or structure functions, $\mu_F$ is the factorization scale, $\sigma_{12\rightarrow Q\bar{Q}}(\hat{s})$ is the cross section of heavy quark-antiquark pair production by interacting partons at squared center-of-mass energy $\hat{s}$. For ultrarelativistic nucleons, $s$ is given by the formula $\hat{s} = x_1x_2 s$. The sum in the right hand side of Eq. (3) runs over all the pairs of parton types, that give nonzero contribution to the production cross section.

We restrict ourselves to the leading order of pQCD. In this case, two basic processes of heavy flavor creation have to be taken into account: the gluon fusion $gg \rightarrow Q\bar{Q}$ and the light quark-antiquark annihilation $q\bar{q} \rightarrow Q\bar{Q}$. So the sum in Eq. (3) includes $(1,2) = (g,g), (\bar{q},q), (q,\bar{q})$, where $q$ in its turn runs over all the light flavors $q = u, d, s$. The corresponding parton cross sections are given by the formulas $^4$:

$$\hat{\sigma}_{gg\rightarrow Q\bar{Q}}(\hat{s}) = \frac{\pi\alpha^2(\mu_R)}{3\hat{s}} \times \left( 7 + \frac{31m_Q^2}{\hat{s}} \right) \frac{1}{4\chi} + \left( 1 + \frac{4m_Q^2}{\hat{s}} + \frac{m_Q^2}{\hat{s}} \right) \log\frac{1 + \chi}{1 - \chi}$$

and

$$\hat{\sigma}_{q\bar{\bar{q}}\rightarrow Q\bar{Q}}(\hat{s}) = \frac{8\pi\alpha^2(\mu_R)}{27\hat{s}} \left( 1 + \frac{2m_Q^2}{\hat{s}} \right) \chi,$$

where $\chi = \sqrt{1 - 4m_Q^2/\hat{s}}$, $\mu_R$ is the renormalization scale and $m_Q$ is the mass of the heavy quark. The masses of light quarks are neglected. $^5$

$^3$ This mechanism is responsible, e.g., for the reaction $pp \rightarrow p\Lambda, \bar{\Lambda}$.

$^4$ In other words, we assume that the interaction with the spectators does not change the energy of the $Q\bar{Q}$ pair and no coalescence with the spectator (anti-)quarks takes place.

$^5$ A small fraction of them form also the hidden heavy-flavor mesons, but it can be safely neglected.
Eq. (2) can be rewritten in the form

\[ \sigma_{NN \to Q\bar{Q}+X}(s) = \int_{(2m_Q)^2}^{s} \frac{d\sigma_{NN \to Q\bar{Q}+X}}{ds} \, ds \, d\hat{s}, \]

where the differential cross section with respect to the squared invariant mass \( \hat{s} = M_{Q\bar{Q}}^2 \) of the \( Q\bar{Q} \) pair is given by the formula

\[ \frac{d\sigma_{NN \to Q\bar{Q}+X}}{d\hat{s}} = -\frac{1}{s} \sum_{(1,2)} \sigma_{12 \to Q\bar{Q}+X}(\hat{s}) \int_{\hat{s}/s-1}^{1-\hat{s}/s} dx_L \frac{f_1(x_1, \mu_F) f_2(x_2, \mu_F)}{x_1 + x_2}, \]

where

\[ x_1 = \sqrt{\left(\frac{x_L}{2}\right)^2 + \frac{\hat{s}}{s}} + \frac{x_L}{2} \]

\[ x_2 = \sqrt{\left(\frac{x_L}{2}\right)^2 + \frac{\hat{s}}{s}} - \frac{x_L}{2}. \]

The probability distributions of \( Q\bar{Q} \) pairs with respect to \( \hat{s} \)

\[ w_{Q\bar{Q}}(\hat{s}; s) = \frac{d\sigma_{NN \to Q\bar{Q}+X}/d\hat{s}}{d\sigma_{NN \to Q\bar{Q}+X}(s)} \]

are shown in Fig. [1] and Fig. [2] for charm and bottom, respectively. The computation were done using the CERN library of parton distribution functions PDFLIB [7]. The default set of structure functions MRS (G) [8] was chosen. The HF quark masses are fixed as \( m_c = 1.25 \) GeV for charm and \( m_b = 4.2 \) GeV for bottom, the c.m. energy of the colliding parton pair was used as the renormalization and factorization scales: \( \mu_F = \mu_R = \sqrt{s}. \)

We estimate now the upper bound of the HF enhancement in A+B collisions. We assume that in N+N collisions the HF \( Q\bar{Q} \) pairs cannot hadronize, unless its c.m. energy exceeds the corresponding HF hadron threshold. Therefore, to calculate the total HF hadron production cross section we cut the integral in Eq. (5) at its lower bound by the corresponding meson threshold:

\[ \sigma_{NN \to HF+X} = \int_{(2m_M)^2}^{(2m_N)^2} \frac{d\sigma_{NN \to Q\bar{Q}+X}}{ds} \, ds \]

where \( m_M \) is the mass of the lightest meson containing corresponding HF quark (D-meson for the charm and B-meson for the bottom), \( m_N \) is the nucleon mass.

In contrast, when two nucleons interact in the deconfined medium (as in high energy A+B collision), our assumption states that all \( Q\bar{Q} \) pairs survive and form HF hadrons at the stage of the QGP hadronization. Therefore, the cross section \( \sigma_{NN \to HF+X} \) in the formula (5) should be replaced by the cross section \( \sigma_{NN \to Q\bar{Q}+X} \). Hence for the upper bound of the enhancement factor we use the formula

\[ E_{\text{max}}(s) = \frac{\sigma_{NN \to Q\bar{Q}+X}(s)}{\sigma_{NN \to HF+X}}. \]

The behavior of \( E_{\text{max}}(s) \) for charm and bottom is shown in Fig. [3]. It is seen that the largest effect is expected at low energies. Therefore an experimental study of the effect should be done at the minimum energy, where the deconfinement medium is expected to be formed and the inclusive cross-section of HF production is large enough to make its measurement feasible.

The upper bound of open charm enhancement at SPS energy is by the factor of about 5 ÷ 6. This means that the enhanced production of open charm hadrons by the factor 2 ÷ 4 found in Ref. [1] and Refs. [4,5] can be explained by the influence of the deconfined medium.

We conclude that the deconfined medium, which is expected to be formed in nucleus-nucleus collisions can influence the process of hadronization of heavy quarks, this leads to the enhanced production of hadrons with open heavy flavors (charm and bottom). The rough estimation of the upper bound of the effect at SPS energies is found to be large enough to explain the indirect experimental data [1] and the phenomenological evaluations [4,5]. We consider the enhancement of the heavy flavor yield as a possible signal of the color deconfinement. The direct measurement of open charm and open bottom in nucleus-nucleus collisions could be important for the confirmation of the quark-gluon plasma formation.

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[1] M. C. Abreu et al. [NA38 Collaboration], Eur. Phys. J. C14, 443 (2000).
[2] C. Spieles et al., Nucl. Phys. A638, 507 (1998); R. Rapp and E. Shuryak, Phys. Lett. B473, 13 (2000); K. Gallmeister, B. Kämpfer and O. P. Pavlenko, Phys. Lett. B473, 20 (2000).
[3] P. Braun-Munzinger and J. Stachel, Phys. Lett. B490, 196 (2000) [nucl-th/0007059].
[4] M. I. Gorenstein, A. P. Kostyuk, H. Stocker and W. Greiner, hep-ph/0010148.
[5] M. I. Gorenstein, A. P. Kostyuk, H. Stocker and W. Greiner, hep-ph/0012015.
[6] B. L. Combridge, Nucl. Phys. B151, 429 (1979).
[7] H. Plothow-Besch, calculations,” Comput. Phys. Commun. 75, 396 (1993); H. Plothow-Besch, Int. J. Mod. Phys. A10, 2901 (1995).
[8] A. D. Martin, W. J. Stirling and R. G. Roberts, Phys. Lett. B354, 155 (1995) [hep-ph/9502336].
FIG. 1. The distribution of $c\bar{c}$ pairs created in nucleon-nucleon collisions versus their squared invariant mass $\hat{s}$. The two curves correspond to different c.m. energies of the colliding nucleons: SPS energy $\sqrt{s} = 17.4 \text{ GeV}$ and maximum RHIC energy $\sqrt{s} = 200 \text{ GeV}$. Great part of the $c\bar{c}$ pairs have the invariant mass below the $D$-meson threshold $2m_D$. 
FIG. 2. The same as in Fig. 1 but for $b\bar{b}$ pairs.
FIG. 3. The upper bound of heavy flavor enhancement versus the c.m. energy of the colliding nucleons. The vertical lines show SPS and RHIC energies.