1 November 2001

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 519 (2001) 207–211

www.elsevier.com/locate/npe

Heavy flavor enhancement as a signal of color deconfinement

A.P. Kostyuk [a,b], M.I. Gorenstein [a,b], W. Greiner [a]

[a] Institut für Theoretische Physik, Universität Frankfurt, Germany
[b] Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

Received 22 June 2001; received in revised form 31 August 2001; accepted 8 September 2001
Editor: P.V. Landshoff

Abstract

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 heavy flavor $\langle \mathrm{HF} \rangle_{\mathrm{AB}(b)}$ created in a nucleus–nucleus (A + B) collision at given impact parameter b is simply connected [1] with the probability to create a HF hadron pair in a nucleon–nucleon (N + N) collision $\langle \mathrm{HF} \rangle_{\mathrm{NN}}$:

$$\langle \mathrm{HF} \rangle_{\mathrm{AB}(b)} = N_{\mathrm{coll}}^{\mathrm{AB}}(b) \langle \mathrm{HF} \rangle_{\mathrm{NN}} = N_{\mathrm{coll}}^{\mathrm{AB}}(b) \frac{\sigma_{\mathrm{NN} \to \mathrm{HF+X}}}{\sigma_{\mathrm{NN}}^{\mathrm{inel}}}, \tag{1}$$

where $N_{\mathrm{coll}}^{\mathrm{AB}}(b)$ is the average number of primary nucleon collisions, which is determined by the geometry of the colliding nuclei, $\sigma_{\mathrm{NN} \to \mathrm{HF+X}}$ is the total cross section of the HF hadron pair production in N + N collisions and $\sigma_{\mathrm{NN}}^{\mathrm{inel}}$ 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 [1] reveals a significant enhancement of the dilepton production in the intermediate mass region (1.5–2.5 GeV) over the standard sources. A possible explanation of this observation is an enhanced production of open charm [1]: about 3 times above the direct extrapolation (1) from N + N data. [2] Similar result has been recently obtained in the framework of the statistical coalescence model [3–5]. This model connects the multiplicities of hadrons with open and hidden charm. It was found [4,5] 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/ψ multiplicity. It was suggested in Ref. [5] that this enhancement may appear due to the broadening of

E-mail address: kostyuk@th.physik.uni-frankfurt.de (A.P. Kostyuk).

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

[2] Alternative interpretations are also suggested [2].

0370-2693/01/© 2001 Published by Elsevier Science B.V. Open access under CC BY license.
PII: S0370-2693(01)01106-6

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 $\mathrm{A}+\mathrm{B}$ collisions in comparison to the direct extrapolation (1) from the $\mathrm{N}+\mathrm{N}$ 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 ($Q\overline{Q}$) 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 $\overline{Q}$ 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 $Q\overline{Q}$ 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 $\overline{Q}$ 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 $Q\overline{Q}$ pair $M_{Q\overline{Q}}$) lies well above the corresponding HF meson threshold $2m_M$ (equal to $2m_D$ or $2m_B$ for $c\bar{c}$ and $b\bar{b}$ quarks, respectively), Q and $\overline{Q}$ break the string into two (or more) peaces, 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 *cannot* be formed. Eventually the Q and $\overline{Q}$ have to annihilate into lighter hadrons. [3]

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 $\overline{Q}$ are created, they *can* fly apart within the medium as if they were free particles. It does not matter whether their initial invariant mass $M_{Q\overline{Q}}$ exceeds the corresponding hadron threshold [4] or not. The created $Q\overline{Q}$ 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 $\mathrm{N}+\mathrm{N}$ or $\mathrm{A}+\mathrm{B}$ collisions the HF $Q\overline{Q}$ 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 $Q\overline{Q}$ pairs are created with invariant masses $M_{Q\overline{Q}}$ below the corresponding meson threshold $2m_M$ even at the largest RHIC energy. If this $Q\overline{Q}$ pair creation takes place in the deconfined medium, which is expected to be formed in high energy $\mathrm{A}+\mathrm{B}$ 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* $\mathrm{A}+\mathrm{B}$ *collisions in comparison to the standard result* (1) *obtained within the direct extrapolation of the* $\mathrm{N}+\mathrm{N}$ *data.*

There are of course essential differences between the open HF hadron production in the e^+e^- annihilation and in $\mathrm{N}+\mathrm{N}$ or $\mathrm{A}+\mathrm{B}$ collisions. Even in $\mathrm{N}+\mathrm{N}$ collisions, when no deconfined medium is expected, the created $Q\overline{Q}$ 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 $Q\overline{Q}$ 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 $\overline{Q}$ can form hadron states by means of coalescence with light spectator (anti-)quarks. [5] Unfortunately, no theoretical description of this complicated process exists. Developing of a reliable model is impossible without detailed

[3] Some fraction of them can form quarkonium states provided that the energy is sufficient.

[4] A more elaborated mechanism of the lowering of the open heavy flavor threshold was discussed in Ref. [6] in the context of the anomalous J/ψ suppression.

[5] This mechanism is responsible, e.g., for the reaction $pp \to p\Lambda_c\overline{D}$.

input from the experimental data, which are not available at present.

Therefore, 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 $\mathrm{N}+\mathrm{N}$ collisions, *no* subthreshold $Q\overline{Q}$ pairs contribute to the open HF hadron production. [6] Most of them annihilate into lighter particles, and a small fraction forms quarkonia [7].
- In the case of $\mathrm{A}+\mathrm{B}$ collisions, provided that the deconfined medium is formed, *all* $Q\overline{Q}$ pairs hadronize into particles with the open HF [7] due to a coalescence with light quarks from the medium.

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 $Q\overline{Q}$ pair production by colliding nucleons is given by the formula (see, e.g., Ref. [8])

$$\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}(s)=\sum_{(1,2)}\int_0^1 dx_1\int_0^1 dx_2\, f_1(x_1,\mu_F)\times f_2(x_2,\mu_F)\hat{\sigma}_{12\to Q\overline{Q}+\widehat{\mathrm{X}}}(\hat{s}), \tag{2}$$

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, μ_F is the factorization scale, $\hat{\sigma}_{12\to Q\overline{Q}}(\hat{s})$ is the cross section of heavy quark–antiquark pair production by interacting partons at squared center-of-mass energy $\hat{s}$. For ultrarelativistic nucleons, $\hat{s}$ is given by the formula $\hat{s}=x_1x_2s$. The sum in the right hand side of Eq. (2) 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 $gg\to Q\overline{Q}$ and the light quark–antiquark annihilation $q\bar{q}\to Q\overline{Q}$. So the sum in Eq. (2) includes $(1,2)=(g,g),\ (\bar{q},q),\ (q,\bar{q})$, where q in its turn runs over the light flavors $q=u,d,s$. The corresponding parton cross sections are given by the formulas [8]:

$$\hat{\sigma}_{gg\to Q\overline{Q}}(\hat{s})=\frac{\pi\alpha^2(\mu_R)}{3\hat{s}}\left[-\left(7+\frac{31m_Q^2}{\hat{s}}\right)\frac{1}{4}\chi+\left(1+\frac{4m_Q^2}{\hat{s}}+\frac{m_Q^4}{\hat{s}^2}\right)\log\frac{1+\chi}{1-\chi}\right] \tag{3}$$

and

$$\hat{\sigma}_{q\bar{q}\to Q\overline{Q}}(\hat{s})=\frac{8\pi\alpha^2(\mu_R)}{27\hat{s}}\left(1+\frac{2m_Q^2}{\hat{s}}\right)\chi, \tag{4}$$

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

Eq. (2) can be rewritten in the form

$$\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}(s)=\int_{(2m_Q)^2}^{s} d\hat{s}\,\frac{d\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}}{d\hat{s}}, \tag{5}$$

where the differential cross section with respect to the squared invariant mass $\hat{s}=M^2_{Q\overline{Q}}$ of the $Q\overline{Q}$ pair is given by the formula

$$\frac{d\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}}{d\hat{s}}=\frac{1}{s}\sum_{(1,2)}\hat{\sigma}_{12\to Q\overline{Q}+\widehat{\mathrm{X}}}(\hat{s})\times\int_{\hat{s}/s-1}^{1-\hat{s}/s}dx_L\,\frac{f_1(x_1,\mu_F)f_2(x_2,\mu_F)}{x_1+x_2}, \tag{6}$$

where

$$x_1=\sqrt{\left(\frac{x_L}{2}\right)^2+\frac{\hat{s}}{s}}+\frac{x_L}{2}, \tag{7}$$

$$x_2=\sqrt{\left(\frac{x_L}{2}\right)^2+\frac{\hat{s}}{s}}-\frac{x_L}{2}. \tag{8}$$

---

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

[7] A small fraction of them form hidden heavy-flavor mesons, but this can be safely neglected.

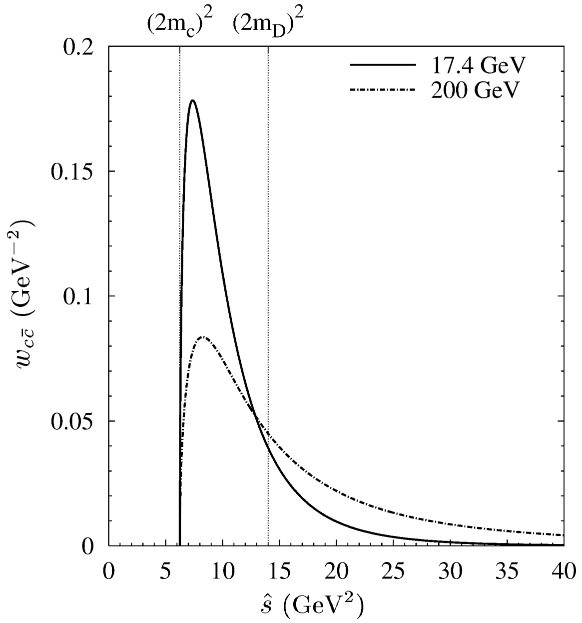

Fig. 1. The distribution of $c\bar{c}$ pairs created in nucleon–nucleon collisions versus their squared invariant mass $\hat{s}$. The two curves correspond to different c.m. energies of the colliding nucleons: SPS energy $\sqrt{s} = 17.4$ GeV and maximum RHIC energy $\sqrt{s} = 200$ GeV. Great part of the $c\bar{c}$ pairs have the invariant mass below the D-meson threshold $2m_D$.

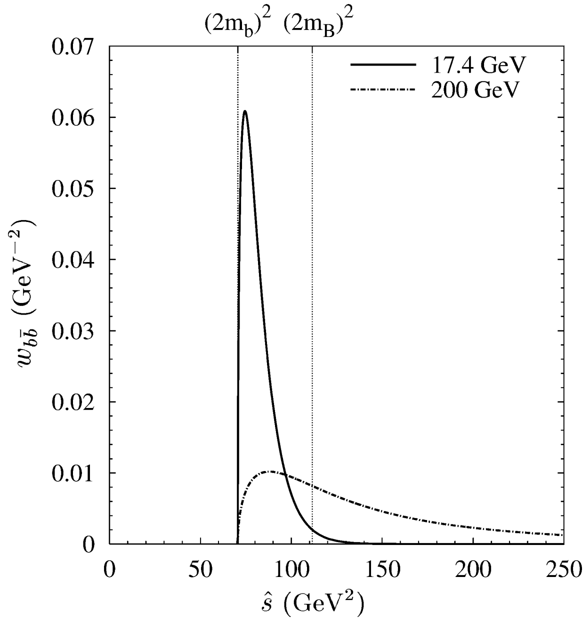

Fig. 2. The same as in Fig. 1 but for $b\bar{b}$ pairs.

The probability distributions of $Q\overline{Q}$ pairs with respect to $\hat{s}$

$$w_{Q\overline{Q}}(\hat{s}; s) = \frac{d\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}/d\hat{s}}{\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}(s)} \tag{9}$$

are shown in Figs. 1 and 2 for charm and bottom, respectively. The computation were done using the CERN library of parton distribution functions PDFLIB [9]. The default set of structure functions MRS (G) [10] 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: $\mu_F = \mu_R = \sqrt{\hat{s}}$.

We estimate now the upper bound of the HF enhancement in A + B collisions. We assume that in N + N collisions the HF $Q\overline{Q}$ 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: [8]

$$\sigma_{\mathrm{NN}\to\mathrm{HF}+\mathrm{X}} = \int\limits_{(2m_M)^2}^{(\sqrt{s}-2m_N)^2} d\hat{s}\, \frac{d\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}}{d\hat{s}}, \tag{10}$$

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 $Q\overline{Q}$ pairs survive and form HF hadrons at the stage of the QGP hadronization. Therefore, the cross section $\sigma_{\mathrm{NN}\to\mathrm{HF}+\mathrm{X}}$ in the formula (1) should be replaced by the cross section $\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}$. Hence for the upper bound of the enhancement factor we use the formula

$$E^{\max}(s) = \frac{\sigma_{\mathrm{NN}\to Q\overline{Q}+\mathrm{X}}(s)}{\sigma_{\mathrm{NN}\to\mathrm{HF}+\mathrm{X}}(s)}. \tag{11}$$

[8] One has to cut the integral also at its upper bound, to respect the baryonic number conservation. Our calculations, however, show that this cut is important only at very low collision energies: $\sqrt{s} \simeq 2m_N + 2m_M$.

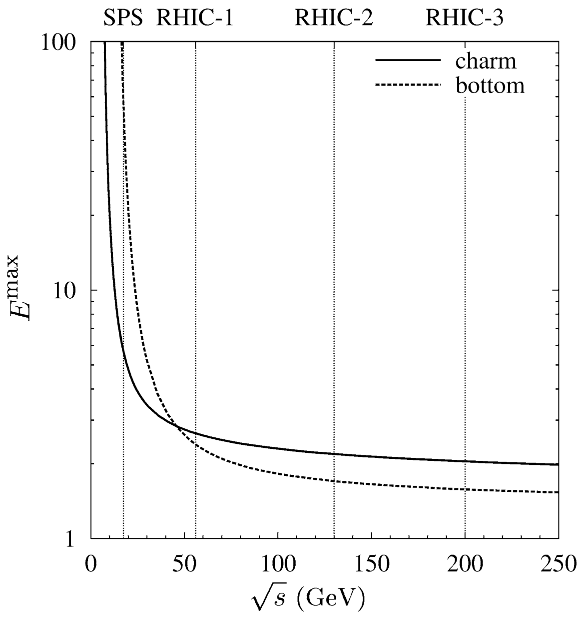

Fig. 3. The upper bound of heavy flavor enhancement versus the c.m. energy of the colliding nucleons. The vertical lines show SPS and RHIC energies.

The behavior of $E^{\max}(s)$ 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. At high energies, the proposed mechanism cannot lead to essential heavy flavor enhancement.

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 Refs. [1,4,5] 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 an 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] of charm production in Pb + Pb collisions at CERN SPS. The distinctive feature of the proposed mechanism is the *decrease* of the enhancement at larger (BNL RHIC) energies. We consider the enhancement of the heavy flavor yield as a possible signal of the color deconfinement. A direct measurement of open charm and open bottom in nucleus–nucleus collisions at SPS and RHIC and comparison to nucleon–nucleon and nucleon–nucleus data is important for a confirmation of the quark–gluon plasma formation.

Acknowledgements

The authors are thankful to K.A. Bugaev, M. Gaździcki, L. McLerran, I.N. Mishustin, G.C. Nayak, K. Redlich, E.V. Shuryak and H. Stöcker for fruitful discussions and their interest to the work. We appreciate criticism and useful comments of L. Frankfurt and L. Gerland. The financial support of DAAD, Germany is acknowledged. The research described in this publication was made possible in part by Award # UP1-2119 of the US Civilian Research and Development Foundation for the Independent States of the Former Soviet Union (CRDF).

References

[1] M.C. Abreu et al., NA38 Collaboration, Eur. Phys. J. C 14 (2000) 443.
[2] C. Spieles et al., Nucl. Phys. A 638 (1998) 507;
R. Rapp, E. Shuryak, Phys. Lett. B 473 (2000) 13;
K. Gallmeister, B. Kämpfer, O.P. Pavlenko, Phys. Lett. B 473 (2000) 20.
[3] P. Braun-Munzinger, J. Stachel, Phys. Lett. B 490 (2000) 196, nucl-th/0007059.
[4] M.I. Gorenstein, A.P. Kostyuk, H. Stöcker, W. Greiner, Phys. Lett. B 509 (2001) 277, hep-ph/0010148.
[5] M.I. Gorenstein, A.P. Kostyuk, H. Stöcker, W. Greiner, J. Phys. G 27 (2001) L47, hep-ph/0012015.
[6] G.R. Burau, D.B. Blaschke, Y.L. Kalinovsky, Phys. Lett. B 506 (2001) 297, nucl-th/0012030.
[7] R. Gavai, D. Kharzeev, H. Satz, G.A. Schuler, K. Sridhar, R. Vogt, Int. J. Mod. Phys. A 10 (1995) 3043, hep-ph/9502270;
R. Vogt, Phys. Rep. 310 (1999) 197.
[8] B.L. Combridge, Nucl. Phys. B 151 (1979) 429.
[9] H. Plothow-Besch, Comput. Phys. Commun. 75 (1993) 396;
H. Plothow-Besch, Int. J. Mod. Phys. A 10 (1995) 2901.
[10] A.D. Martin, W.J. Stirling, R.G. Roberts, Phys. Lett. B 354 (1995) 155, hep-ph/9502336.