Statistical hadronization of heavy flavor quarks in elementary collisions: successes and failures

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Abstract

We analyze recently compiled data on the production of open heavy flavor hadrons and quarkonia in e\textsuperscript{+}e\textsuperscript{-} as well as pp and p-nucleus collisions in terms of the statistical hadronization model. Within this approach the production of open heavy flavor hadrons is well described with parameters deduced from a thermal analysis of light flavor hadron production. In contrast, quarkonium production in such collisions cannot be described in this framework. We point out the relevance of this finding for our understanding of quarkonium production in ultra-relativistic nucleus-nucleus collisions.

1 Introduction

One of the major goals of ultrarelativistic nuclear collision studies is to obtain information on the QCD phase diagram \cite{1}. A promising approach is the investigation of hadron production. Hadron yields measured in central heavy ion collisions can be described very well (see ref. \cite{2} and references therein) within a hadro-chemical equilibrium model. In our approach \cite{2}, the only parameters are the chemical freeze-out temperature $T$ and the baryo-chemical potential $\mu_b$ (and the fireball volume $V$, in case yields rather than ratios of yields are fitted), characteristic for a given energy; for a review see \cite{3}.

Focused on production of hadrons carrying light ($u$, $d$, $s$) quarks, these investigations led to temperature values which rise rather sharply from low energies on towards $\sqrt{s_{NN}} \simeq 10$ GeV and reach afterwards a plateau near $T=165$ MeV, while the baryochemical potential decreases smoothly as a function of energy. This limiting temperature behavior reminds
of the Hagedorn temperature \[4\] and suggests a connection to the phase boundary. It was, indeed, argued \[5\] that the quark-hadron phase transition drives the equilibration dynamically, at least for SPS energies and above.

Recently, the results of ref. \[2\] strengthened the interpretation that the phase boundary is reflected in features of the hadron yields in nucleus-nucleus collisions. Whether the chemical freeze-out curve for \(T < 160\) MeV traces the QCD phase boundary at large values of chemical potential is an open question. Possibly, the chemical freeze-out in this regime is influenced by exotic new phases predicted in \[6\].

An important question is whether this statistical behavior is a unique feature of high energy nucleus-nucleus collisions or whether it is also encountered in elementary collisions, where finite size effects will obscure a possible phase transition. In early analyses (see ref. \[7\]), it is indeed argued that hadron production in \(e^+e^-\) and pp is thermal in nature. Furthermore, such analyses of hadron multiplicities (for recent results see \[8,9,10\] and refs. therein) yield also temperature values in the range of 160-170 MeV.

Consequently, alternative interpretations for the apparent statistical behavior were put forward. These include conjectures that the thermodynamical state is not reached by dynamical equilibration among constituents but rather is a generic fingerprint of hadronization \[11,12\], or is a feature of the excited QCD vacuum \[13\]. In such approaches the relation between hadronization and the QCD phase transition is not easy to make explicit. Recent results employing the gauge/string theory duality imply also a thermal behavior \[14\], but remain to be further understood.

In our recent analysis of hadron production in \(e^+e^-\) collisions \[8\] we have demonstrated that such a direct connection between thermal descriptions of hadron production in \(e^+e^-\) and relativistic nucleus-nucleus collisions is much less convincing than thought before. We first note that any thermal description of hadron production in \(e^+e^-\) collisions makes use, in addition to the thermal parameters \(T\) and \(V\), of a set of additional, non-thermal parameters such as the number of strange, charm, and bottom quark jets as well as an additional strangeness (but not charm!) suppression factor \(\gamma_s\). For details see \[8,9\]. Furthermore, we have demonstrated \[8\] that, in spite of the additional, non-thermal parameters, the quality of the fit of \(e^+e^-\) data to statistical model calculations is significantly worse than that obtained in descriptions of central nucleus-nucleus collisions. This conclusion is reached also when the fit to the data is performed using the same set of particles as in the nucleus-nucleus case. These findings call an overall thermal origin of particle production in \(e^+e^-\) collisions into question, despite the presence of statistical features.

In the present paper we explore in some detail the heavy-quark (\(c\) and \(b\)) sector, i.e. the production of the corresponding open and hidden flavor hadrons in \(e^+e^-\) as well as pp, \(p\bar{p}\) and p-nucleus collisions. The emphasis of our investigations is to establish quantitatively similarities and differences in the production of such particles in elementary collisions compared to those observed in the nucleus-nucleus case. Since the proposal \[15\] that the \(J/\psi\) meson production may be a 'smoking gun' observable for the diagnosis of the Quark-Gluon Plasma (QGP) produced in ultra-relativistic nucleus-nucleus collisions, intense research was focused on the topic, both experimentally and theoretically. A recent summary is found in \[16,17\].

Because the mass of heavy quarks exceeds the transition temperature of the QCD phase
transition by more than a factor of 5, heavy flavor hadron production cannot be described in a purely thermal approach. It was, however, realized in [18] that charmonium and charmed hadron production can be well described by assuming that all charm quarks are produced in initial, hard collisions while charmed hadron and charmonium production takes place at the phase boundary with statistical weights calculated in a thermal approach. For a recent summary of this statistical hadronization approach see [19].

In this context it became clear that even complete J/ψ melting in the QGP via Debye screening as assumed in the original proposal of [15] could lead to large J/ψ yields due to production at the phase boundary. Predictions using the corresponding statistical hadronization model (SHM)1, either in its “minimal” implementation [18,20,21,22] or with additional assumptions [23] proved quite successful when compared to data. In its application to charm quarks, the statistical model contains as input the charm production cross section, taken from pQCD calculations [24] or from experiment (see ref. [22] and ref. therein). In general, statistical production can only take place effectively if the charm quarks reach thermal (but not necessarily chemical) equilibrium. Combination of charm quarks which are initially separated by a few fm (corresponding to about 1 unit in rapidity) into charmonia effectively implies deconfinement.

To establish the uniqueness of the J/ψ probe for the diagnosis of a QGP in nucleus-nucleus collisions it becomes important to understand whether similar thermal features as observed in nucleus-nucleus collisions are also at work in heavy-flavor hadron production in elementary collisions.

Our paper is consequently organized as follows: We first briefly describe the model used to analyze particle production in elementary collisions. Section 3 deals with experimental results on heavy flavor hadron production in e+e− collisions and their analysis in terms of our statistical approach. The more complicated case of pp and p-nucleus collisions is treated in section 4, with particular emphasis on hidden charm production. In the final section we summarize our findings and provide an assessment of charmonium production as a probe for QGP and the QCD phase boundary.

2 The model

For the study of hadron production in e+e− collisions we employ the canonical statistical model described in [8,25] (see also [9]). For the present study, we perform calculations for two cases: i) a 2-jet initial state which carries the quantum numbers of the 5 flavors, with the relative abundance of the five flavors in one jet and corresponding antiflavor in the other jet taken from the measurements at the Z0 resonance quoted in [26]. These relative abundances (17.6% for u̅u and cc and 21.6% for d̅d, s̅s and bb) are thus external input values, unrelated with the thermal model. ii) a purely thermal ansatz, i.e. a 2-jet initial state characterized by vanishing quantum numbers in each jet.

For the case of hadron production in elementary hadronic collisions we employ the canonical realization of the thermal model [3,20,21,22]. For the description of the relative produc-

1 Within this statistical model heavy quarks are not chemically equilibrated, but otherwise all hadrons are thermalized. The term ‘statistical’ is used in this sense in our approach.
tion cross sections of heavy flavored hadrons, the energy dependence of the temperature parameter is the only model input, which is taken in a parametrized form from the fits of hadron abundancies in central nucleus-nucleus collisions [2]. For c.m. energies beyond 10 GeV per nucleon pair in nucleus-nucleus collisions a limiting temperature $T_{lim}=164\pm5$ MeV is reached. Recent fits of hadron yields in pp collisions [10] give very similar values, independent of anergy. The charm production cross section, which is an important model input parameter for the calculations of absolute yields [21,22], cancels out for the ratios considered in the present paper. The influence of the mass spectrum on particle production has been considered in [2]. We note that, for the ratios considered here, such an effect cancels out in first order and has been neglected.

3 Results in $e^+e^-$ collisions

In Fig. 1 we show a comparison of data [26] and model prediction for charmed and bottom hadron yields in $e^+e^-$ annihilations at $\sqrt{s}=91$ GeV. For the model we have used the parameter set: $T=170$ MeV, $V=16$ fm$^3$ and $\gamma_s=0.66$, which represents the best fit of multiplicities of hadrons with lighter quarks [8].

![Figure 1. Multiplicities of hadrons with charm and bottom quarks in $e^+e^-$ collisions compared to the thermal model calculations for two cases: i) the 5-flavor jet scheme (thick lines) and ii) no (net) flavor jet scheme (thin lines with diamonds). Note, for case ii) the factor $10^{15}$ used to scale the model calculations for bottom hadrons to fit in the plotting range. The data are from the compilation published by the Particle Data Group (PDG) [26]. The prompt $J/\psi$ measurement $J/\psi^{pr}$ is from the L3 experiment [27].](image)

We first note that the calculation employing the 5-flavor scheme is in very good agreement with the data, as demonstrated by the good $\chi^2$ per degree of freedom between the model and the data (excluding the $\Upsilon$ and prompt $J/\psi$) of 21.7/16 (34/18 when including all species). This confirms the conclusion of ref. [9]. Despite this overall agreement, the exceptions are significant: the $\Upsilon$ meson yield is underpredicted by the model by 17 orders of magnitude, while the prompt $J/\psi$ yield [27] is underpredicted by almost 2 orders of magni-
tude. Obviously, the production of quarkonia is expected to be strongly suppressed in the statistical model. The disagreement is a consequence of the separate hadronization of the $c$ and $\bar{c}$ quarks. The measured prompt $J/\psi$ production in $Z^0$ decays (into hadrons) is about $3 \times 10^{-4}$ [27]. The thermal model predicts a prompt yield for $J/\psi$ of $4.1 \times 10^{-6}$ ($1.6 \times 10^{-7}$ for $\psi'$ and $4.3 \times 10^{-7}$ for $\chi_{c1}$), identically for the two calculation schemes. The overall measured yields of charmonia are dominated by the feed down from bottom hadrons and the model agreement only reflects the agreement seen for the open bottom hadrons and their branching ratios to charmonia, properly considered in the model.

The calculation employing a purely thermal ansatz underpredicts all the measurements by many orders of magnitude, while for the light quark sector the differences between calculations with a pure thermal model and with the 5-flavor quark-antiquark scheme were found to be small [8]. The strangeness suppression factor, which for the present results only enters in the calculation of the yields of $D_s$ and $B_s$ mesons, appears to have no counterpart in the heavy quark sector. This reflects the fact that a negligible number of $c$ and $b$ quarks are formed in the fragmentation process. In this case, the thermal weights describe the distribution of the initial quarks into heavy flavor hadrons. Thermalization is not required in this process.

4 Results in elementary hadronic collisions

![Relative production cross section of charged to neutral D mesons](image_url)

Figure 2. Relative production cross section of charged to neutral D mesons. The data (symbols) in pA and $\pi A$ collisions [28] are compared to statistical model calculations [22] shown by the line (band corresponding to $\pm 5$ MeV errors in $T$). The box is the average value of all the data points with the corresponding error.

We now turn to elementary hadronic ($pp$, $p\bar{p}$, $\pi A$ and $pA$) collisions. We note an important difference in this case compared to $e^+e^-$ collisions, namely that the feeding from bottom hadrons into charmed hadrons is small at presently available energies due to the much
smaller bottom production cross section$^2$. In particular, this applies also to charmonia, although at LHC about 20% of the $J/\psi$ yield is estimated to originate from $B$ mesons decays.

In Fig. 2 we show, as a function of energy, the model comparison to data for the relative production cross section of charged to neutral D mesons. The data are from the recent compilation of ref. [28]. Considering the relatively large experimental errors, the agreement is good. This can be judged from the comparison to the average value [26] of the data points (0.405±0.030, with a \(\chi^2/d.o.f.\) of 1.12), shown as well in Fig. 2. This production ratio is largely determined by feed-down from the $D^*$ states (see discussion in [28]) and the agreement reflects the good description within the model of the relative production of the $D^*$ states.

![Figure 3: Production cross section of $\psi'$ relative to $J/\psi$.](image)

Figure 3. Production cross section of $\psi'$ relative to $J/\psi$. The data for pA collisions are from the compilation by Maltoni et al. [29]; the points for elementary collisions are from the PHENIX experiment at RHIC [30] and from the CDF experiment at Tevatron [30] (see text); the data point for Pb+Pb collisions at the SPS energy is from the NA50 experiment [32]. The average value of the pA and pp(\overline{p}) measurements with the corresponding error (see text) is represented by the shaded box. The band denotes statistical model calculations [22] for the temperature parametrization from heavy-ion fits [2] \((T_{lim}=164\,\text{MeV})\) with ±5 MeV error.

In Fig. 3 we show the model comparison to data for the relative production cross section of $\psi'$ and $J/\psi$ charmonia. The measurements in pA and pp(\overline{p}) collisions are above the model values by about a factor 4 (corresponding to 10 experimental standard deviations; the average value of the measurements is 0.137±0.009, with a \(\chi^2\) per degree of freedom of 0.88). The relative production cross sections of charmonium states, as are observed in all measurements in hadronic collisions cannot be described in the thermal approach. The temperature needed to explain the data would be 300 MeV, well above the Hagedorn limiting temperature, which is about 200 MeV. This is in sharp contrast to the (only

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2 In hadronic collisions the relative production cross sections between bottom and charm are much smaller than in $e^+e^-$ collisions. Even at the LHC energies $\sigma_b/\sigma_c \approx 1/10$, while in 91 GeV $e^+e^-$ $B(Z^0 \to b)/B(Z^0 \to c)=0.22/0.17$. 
currently existing) measurement in central nucleus-nucleus collisions, performed at the SPS by the NA50 experiment [32], which is well described. We recall that it was in part the observation of this measurement [33,18] that brought forward the idea of statistical production of charmed hadrons in nucleus-nucleus collisions [18]. We note that the pA data exhibit a constant $\psi'/J/\psi$ production ratio as a function of energy. In the model, the value is determined only by the temperature and this is reflected in the slight decrease of the ratio towards low energies. A constant value, also up to the LHC energies, is predicted beyond $\sqrt{s_{NN}} \simeq 20$ GeV. A constant value is expected in the color evaporation model [34].

The measurements reported in Fig. 3 demonstrate that the relative production cross section $\psi'/J/\psi$ is identical in pA and in pp(\bar{p}) collisions, implying no visible influence of the cold nuclear medium. Note that the ratio for the Tevatron energy was derived from the CDF measurements of $J/\psi$ [35] and $\psi'$ [31] and is for transverse momentum $p_t > 1.25$ GeV/c (we have extrapolated the $\psi'$ measurement from 2 GeV/c down to 1.25 GeV/c).

![Figure 4](image-url)

Figure 4. The energy dependence of the ratio $R_{\chi c}$ (left panel) and of the relative production cross section for $\chi_{c1}$ and $\chi_{c2}$ charmonia. The data are from a recent compilation by the HERA-B collaboration [36]. The average values of the measurements with the corresponding errors (see text) are represented by the shaded boxes.

In Fig. 4 we confront the model with the data on $\chi_{c1,2}$ production. The data are from a recent compilation by the HERA-B collaboration [36]. The ratio

$$R_{\chi c} = \frac{\sum_{J=1}^{2} \sigma(\chi_{cJ}) Br(\chi_{cJ} \rightarrow J/\psi \gamma)}{\sigma(J/\psi)},$$

representing the fraction of $J/\psi$ mesons from radiative decays of $\chi_c$ states, is clearly far above the statistical model prediction. The average value of the measurements is $0.361 \pm 0.015$, with a $\chi^2/dof=1.21$. An average value of $0.25 \pm 0.05$ was recently determined in an analysis of low energy data [37], also well above the thermal value. The relative production of the $\chi_{c1}$ and $\chi_{c2}$ charmonia, $\sigma_{\chi_{c1}}/\sigma_{\chi_{c2}}$, is consistent with the model, as can be judged from the average value of the measurements (which is $0.674 \pm 0.084$, with a $\chi^2/dof=1.39$), included in Fig. 4. We note that the data, characterized by rather large
errors, are compatible as well with the expectation based on spin statistics only, which is $\sigma_{\chi_{c1}}/\sigma_{\chi_{c2}}=0.6$.

![Diagram](image)

Figure 5. The relative production cross section of the $\Upsilon'$ and $\Upsilon''$ bottomonia relative to $\Upsilon$ in pp(\bar{p}) collisions. The data (symbols) are from the E866 [38] and CDF [39] experiments.

We investigate the production of bottomonia in Fig. 5 in terms of the relative production cross section of the $\Upsilon'$ and $\Upsilon''$ bottomonia relative to $\Upsilon$. The model is compared to the latest results for the Fermilab fixed target experiment E866 [38] and in the collider mode from the CDF experiment [39]. The data significantly exceed the thermal model calculations, by about an order of magnitude for the $\Upsilon'/\Upsilon$ ratio and by almost two orders of magnitude for $\Upsilon''/\Upsilon$. For a recent overview of the status of QCD models for hadroproduction of quarkonia see [40].

5 Conclusions

We have confronted the statistical hadronization model with the most recent data on the production of open heavy flavor hadrons and quarkonia in $e^+e^-$ and in pp and p(\pi)-nucleus collisions. Employing the parameters extracted from the analyses of light flavor hadron production the model describes well the fragmentation to open heavy flavor hadrons. In contrast, quarkonium production cannot be described in this framework. We emphasize again that, for the $e^+e^-$ collisions, we have employed a canonical treatment of the two $q$ and $\bar{q}$ jets. The relative abundance of the five flavors, taken from the measurements at the $Z^0$ resonance, are external input values unrelated with the thermal model. We note that, in contrast to the hadrons carrying strangeness, for which a strangeness suppression factor $\gamma_s < 1$ is the outcome of the fit for $e^+e^-$ as well as for pp collisions, charmed and bottom hadrons are described in $e^+e^-$ collisions without any other parameter. The strange quark, with its intermediate mass, which is comparable to $T$, seems to have an interesting intermediate status in between the very light and the very heavy quarks. In the hadronization process, the $u$ and $d$ quarks reach abundances consistent with a thermal ensemble for $T \approx 165$ MeV. On the other side, the $c$ and $b$ quark production is determined
by either pQCD (in pp) or electroweak (in $e^+e^-$) processes and the thermal model only describes hadronization phase space. In contrast, there is a significant number of newly produced $s$ and $\bar{s}$ quarks, but incomplete equilibration leads to $\gamma_s < 1$ implying that $s$ quark abundances are not thermal. Remarkably, strangeness suppression is lifted for central nucleus-nucleus collisions, implying full equilibration.

The fact that, in elementary collisions, quarkonium production cannot be described by the statistical model is in sharp contrast to the situation in nucleus-nucleus collisions, where all the measurements to date are well described by statistical hadronization. In general, statistical production can only take place effectively if the charm quarks reach thermal equilibrium and are free to travel over a large distance, implying deconfinement. The model will be most dramatically tested at the LHC energies, where data are expected within a year. If confirmed, statistical production of charmed (and possibly also bottom) hadrons, in particular of $J/\psi$, will provide a crucial determination of the QCD phase boundary. Whether the bottom quarks equilibrate in the QGP is an important open question, which will be addressed by the measurements at the LHC. Predictions exist, both within the statistical approach [21][11] as well as within a kinetic approach [42].

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