Charmonium and open charm production in nuclear collisions at SPS/FAIR energies and the possible influence of a hot hadronic medium

A. Andronic\textsuperscript{a}, P. Braun-Munzinger\textsuperscript{a,b}, K. Redlich\textsuperscript{c,b}, J. Stachel\textsuperscript{d}

\textsuperscript{a}Gesellschaft für Schwerionenforschung, GSI, D-64291 Darmstadt, Germany
\textsuperscript{b}Technical University Darmstadt, D-64289 Darmstadt, Germany
\textsuperscript{c}Institute of Theoretical Physics, University of Wrocław, PL-50204 Wrocław, Poland
\textsuperscript{d}Physikalisches Institut der Universität Heidelberg, D-69120 Heidelberg, Germany

Abstract

We provide predictions for charmonium and open charm production in nuclear collisions at SPS/FAIR energies within the framework of the statistical hadronization model. The increasing importance at lower energies of $\Lambda_c$ production is demonstrated and provides a challenge for future experiments. We also demonstrate that, because of the large charm quark mass and the different timescales for charm quark and charmed hadron production, possible modifications of charmed hadrons in the hot hadronic medium do not lead to measurable changes in cross sections for D-meson production. A possible influence of medium effects can be seen, however, in yields of charmonium. These effects are visible at all energies and results are presented for the energy range between charm threshold and RHIC energy.

1 Introduction

Charmonium production is considered, since the original proposal more than 20 years ago about its suppression in a Quark-Gluon Plasma (QGP) \cite{1}, as an important probe to determine the degree of deconfinement reached in the fireball produced in ultra-relativistic nucleus-nucleus collisions. In a recent series of publications \cite{2,3,4} we have demonstrated that, in the energy range from top SPS energy ($\sqrt{s_{NN}} \approx 17$ GeV) on, the data on $J/\psi$ and $\psi'$ production in nucleus-nucleus collisions can be well described within the statistical hadronization model proposed in \cite{5}. In particular the, at first glance surprising, rapidity dependence of the nuclear modification factor $R_{AA}^{J/\psi}$ observed by the PHENIX collaboration \cite{6} is explained as due to the statistical hadronization of $c$ and $\bar{c}$ pairs at
the phase boundary between quark gluon plasma and hot hadronic matter. We note that extrapolation to LHC energy of these results yields a rather striking centrality dependence and, depending on the magnitude of the $\bar{c}c$ cross section in central Pb-Pb collisions, possibly even an enhancement ($R^{J/\psi}_{AA} > 1$) of $J/\psi$ production due to hadronization of thermalized, deconfined and in general uncorrelated charm quarks.

In the present publication we explore, for the first time, the lower energy range from near threshold ($\sqrt{s_{NN}} \approx 6$ GeV) to top SPS energy. The lower part of this energy range can be investigated in the CBM experiment at the future FAIR facility. One of the motivations for such studies was the expectation to provide, by a measurement of D-meson production near threshold, information on their possible modification near the phase boundary. Here we demonstrate that, because of the relevant mass and time scales involved, medium effects on D-meson production are likely to be very small. Furthermore, because of the dominance of baryochemical potential (coupled with the charm neutrality condition) at low energies, it turns out to be important to measure in addition to D-meson production also the yield of charmed baryons to get a good measure of the total charm production cross section.

In section 2 we will discuss the various time scales relevant for charm, charmonium, and open charm hadron production and discuss their relevance for the applicability of the statistical hadronization model as well as for the study of possible medium effects in the charm sector. Section 3 will provide a brief review of the statistical hadronization model. Our results on open charm and charmonium production from low beam energies will be presented in section 4. In section 5 we will introduce various possible medium effects on open charm hadrons and study their influence on measurable quantities from FAIR to RHIC energies before concluding with a brief outlook in the last section.

2 On relevant time scales and medium effects

In the original scenario of $J/\psi$ suppression via Debye screening it is assumed that the charmonia are rapidly formed in initial hard collisions but are subsequently destroyed in the QGP. While it is clear that the production of a (colored) charm quark pair takes place at time $t_{cc} = 1/(2m_c) \leq 0.1$ fm, the formation time of charmonium involves color neutralization and the build-up of its wave function. The relevant time scale has been studied early on and is of order 1 fm. Similar arguments also apply for the production time of charmed hadrons and we expect comparable time scales as for charmonium.

We note that, at SPS energy where the 'melting scenario' was originally studied, this time is in the same range as the plasma formation time. At SPS and lower energies, charmonia can be formed in the pre-plasma phase and must be destroyed in the plasma if suppression by QGP is to take place.

$R^{J/\psi}_{AA}$ is defined as $R^{J/\psi}_{AA} = \frac{dN_{AuAu}^{J/\psi}/dy}{N_{coll}dN_{pp}^{J/\psi}/dy}$ and relates the charmonium yield in nucleus-nucleus collisions to that expected for a superposition of independent nucleon-nucleon collisions. In this expression, $dN_{J/\psi}/dy$ is the rapidity density of the $J/\psi$ yield integrated over transverse momentum and $N_{coll}$ is the number of binary collisions for a given centrality class.
At the collider energies of RHIC and especially LHC the plasma formation time is likely to be much shorter (comparable to $t_{\text{col}}$). Furthermore, the number of charm quark pairs can exceed 10 per unit rapidity (central collisions at LHC). Initially, the 'collider' plasma will be hotter than $T_D$, the temperature above which screening takes place, and no charmonia will be formed at all in the QGP. It is our view that the charm quarks will be effectively thermalized leading to an uncorrelated pool of $c$ and $\bar{c}$ quarks. Once the plasma temperature falls below $T_D$ charmonia can be formed in principle, as well as destroyed, but as is indicated by the studies performed in [3], their formation rate is likely to be low. This finally leads to the notion, expressed explicitly in the statistical hadronization model, that all charmonia are produced by (re-)combination of charm quarks at the phase boundary. We would like to emphasize that, in this scenario, the particular value of $T_D$ which is much discussed in the recent literature [11,12], is not very important. Models that combine the 'melting scenario' with statistical hadronization have been proposed [13]. Alternatively, charmonium formation by coalescence in the plasma [14,15,16,17] as well as within transport model approaches [18,19] has been considered.

Another issue to be considered is the collision time $t_{\text{col}} = 2R/\gamma_{\text{cm}}$, where $R$ is the radius of the (assumed equal mass) nuclei and $\gamma_{\text{cm}}$ is the Lorentz $\gamma$ factor of each of the beams in the center-of-mass system. At SPS and lower energies, $\gamma_{\text{cm}} < 10$ and $t_{\text{col}} > 1$ fm for a central Au-Au or Pb-Pb collision, so collision time, plasma formation time, and charmonium formation time are all of the same order [10]. Furthermore, the maximum plasma temperature may not exceed $T_D$. In this situation the formed charmonia may be broken up by gluons and by the high energy nucleons still passing by from the collision. In this latter case, cold nuclear suppression needs to be carefully considered, as discussed, e.g., in [20,21]. However, we note in this context that the charm quarks resulting from such break-up processes eventually have to hadronize, which might again lead to charmonium production at the phase boundary if the charm quarks are kinetically thermalized, as is assumed in the statistical hadronization model [5,3]. Consequently, our calculations, in which both charmonium formation before QGP production and cold nuclear absorption are neglected, may somewhat underestimate the charmonium production yield at SPS energies and below. In that sense the below calculated medium effects are upper limits for energies close to threshold.

At collider energies there will be yet another separation of time scales. At LHC energy, the momentum of a Pb nucleus is $p_{\text{cm}} = 2.76$ TeV per nucleon, leading to $\gamma_{\text{cm}} = 2940$, hence $t_{\text{col}} < 5 \times 10^{-3}$ fm. Even “wee” partons with momentum fraction $x_w = 2.5 \times 10^{-4}$ will pass by within a time $t_w = 1/(xp_{\text{cm}}) < 0.3$ fm, and will not destroy any charmonia since none exist at that time. We consequently expect that cold nuclear absorption will decrease from SPS to RHIC energy and should be negligible at LHC energy. First indications for this trend are visible in the PHENIX data [22].

Given the various time scales it becomes clear from the above discussion that the statistical hadronization model should become a quantitative tool to describe charmonium and open charm production at collider energies without the explicit need to take account of any charmonium or open charm hadron formation before the QGP is developed and of cold nuclear absorption effects. We note in passing that the issue of shadowing or sat-

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We choose this value since it corresponds to a wee parton energy of approximately the binding energy of the $J/\psi$ meson. Smaller $x$ values are hence not relevant for the present considerations.
uration effects is of an entirely different nature: within the framework of the statistical hadronization model we need to know the rapidity density for open charm production in nucleus-nucleus collisions. Using this quantity, which of course contains shadowing or saturation effects, as input we can then provide cross sections for the production of all open and hidden charm hadrons.

Finally we would like to discuss the effect of possible in-medium changes of charmed hadrons on their production cross section. We start the discussion by recalling that

$$\sigma_{cc} = \frac{1}{2}(\sigma_D + \sigma_{N_c} + \sigma_{\Xi_c} + \ldots) + (\sigma_{\eta_c} + \sigma_{J/\psi} + \sigma_{\chi_c} + \ldots)$$

(1)

because of charm conservation. As shown in [3], annihilation of charm quarks can be fully neglected. In the above equation, $\sigma_D$ is the total cross section for the production of any D-meson. The cross section $\sigma_{cc}$ is governed by the mass of the charm quark $m_c \approx 1.3$ GeV [23], which is much larger than any soft Quantum Chromodynamics (QCD) scale such as $\Lambda_{QCD}$. Therefore we expect no medium effects on this quantity. Such a separation of scales is not possible for strangeness production, and the situation there is not easily comparable.

The much later formed D-mesons, or other charmed hadrons, may well change their mass in the hot medium. The results of various studies on in-medium modification of charmed hadrons masses [8,23,25,26,27,28,29,30] are sometimes contradictory. Within a QCD sum rule model, Hayashigaki [27] predicts for D mesons a 50 MeV mass decrease at normal nuclear density, while for $J/\psi$ meson the shift is much smaller (5 MeV). Friman et al. [29] have concluded that the widths are little affected in dropping mass scenarios, while Tolos et al. [8] assert that only the widths could be affected by the nuclear medium but not the (pole) mass of D mesons. It is not clear whether the mass changes are different for particles and antiparticles, as advocated in [24], or identical because the vector potential may not matter if one assumes production at an early stage [28]. The "indirect" effect on $J/\psi$ production was also investigated [26,27,18,29,16]. A large mass shift of $J/\psi$ has been recently advocated [31]. We note that excellent fits of the common (non-charmed) hadrons to predictions of the thermal model have been obtained using vacuum masses [32,33,34]. An attempt to use modified masses for the RHIC energy [35] has not produced a conclusive preference for any mass or width modifications of hadrons in medium. On the other hand, some evidence for possible mass modifications was presented in the chiral model of [36].

Whatever the medium effects may be, they can, because of the charm conservation equation above, only lead to a redistribution of charm quarks. In particular, if the masses of D-mesons are lowered by the same amount at the phase boundary, this effect would practically not be visible in the D-meson cross section. Although the charm conservation equation above is strictly correct only for the total cross section we expect within the framework of the statistical hadronization model, also little influence due to medium effects on distributions in rapidity and transverse momentum. This is due to the fact that the crucial input into our model is $dN_{cc}/dy$ and there is no substantial D-meson rescattering after formation at the phase boundary. Modification of D-meson masses at the phase boundary will, however, influence the production rates for charmonia: after lowering of their masses the D-mesons will eat away the charm quarks of the charmonia but
since the D-mesons are much more abundant, their own yield will hardly change because of total charm conservation.

Much of the above argument about medium effects is essentially model-independent and applies equally well at all energies. Here we will consider various types of scenarios for medium modifications and study their effect within the statistical hadronization framework in the energy range from charm threshold to collider energies.

3 Reminder of ingredients and assumptions of the statistical hadronization model

The statistical hadronization model (SHM) \cite{5,3} assumes that the charm quarks are produced in primary hard collisions and that their total number stays constant until hadronization. Another important factor is thermal equilibration in the QGP, at least near the critical temperature, $T_c$. While data at RHIC energy \cite{37} suggest charm equilibration, at lower energies, where the initial densities and temperatures are lower, the assumption of equilibration can be questionable. In this exploratory study we have nevertheless assumed full thermalization.

We focus on the energy range $\sqrt{s_{NN}}=7-200$ GeV and perform calculations for central collisions of heavy equal mass nuclei, corresponding to $N_{\text{part}}=350$. We neglect charmonium production in the nuclear corona \cite{3}, since we focus in the following on central collisions, where such effects are small.

In the following we briefly outline the calculation steps in our model \cite{5,3}. The model has the following input parameters: i) charm production cross section in pp collisions; ii) characteristics at chemical freeze-out: temperature, $T$, baryochemical potential, $\mu_b$, and volume corresponding to one unit of rapidity $V_{\Delta y}=1$ (our calculations are for midrapidity). Since, in the end, our main results will be ratios of hadrons with charm quarks normalized to the $\bar{c}c$ yield, the detailed magnitude of the open charm cross section and whether to use integrated yield or midrapidity yields is not crucial.

The charm balance equation \cite{5}, which has to include canonical suppression factors \cite{38} whenever the number of charm pairs is not much larger than 1, is used to determine a fugacity factor $g_c$ via:

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2}g_c n_{c\bar{c}}^{\text{th}} I_1(g_c n_{c\bar{c}}^{\text{th}}) I_0(g_c n_{c\bar{c}}^{\text{th}}) + g_c^2 n_{c\bar{c}}^{\text{th}}. \tag{2}$$

Here $N_{c\bar{c}}^{\text{dir}}$ is the number of initially produced $c\bar{c}$ pairs and $I_n$ are modified Bessel functions. In the fireball of volume $V$ the total number of open ($N_{c\bar{c}}^{\text{th}} = n_{c\bar{c}}^{\text{th}}V$) and hidden ($N_{c\bar{c}}^{\text{th}} = n_{c\bar{c}}^{\text{th}}V$) charm hadrons is computed from their grand-canonical densities $n_{c\bar{c}}^{\text{th}}$ and $n_{c\bar{c}}^{\text{th}}$, respectively. This charm balance equation is the implementation within our model of the charm conservation constraint expressed in eq.1. The densities of different particle species in the grand canonical ensemble are calculated following the statistical model \cite{32,33,34}. The balance equation (2) defines the fugacity factor $g_c$ that accounts for
deviations of heavy quark multiplicity from the value that is expected in complete chemical equilibrium. The yield of charmonia of type $j$ is obtained as: $N_j = g_c^2 N_{th}^j$, while the yield of open charm hadrons is: $N_i = g_c N_{th}^{oc} I_1(g_c N_{th}^{oc})/I_0(g_c N_{th}^{oc})$.

As no information on the charm production cross section is available for energies below $\sqrt{s}=15$ GeV, we have to rely on extrapolation. The basis for this extrapolation is the energy dependence of the total charm production cross section calculated in ref. [39] for the CTEQ5M parton distribution functions in next-to-leading order (NLO), as shown in Fig. 1. We have scaled these calculations to match the more recent values calculated at $\sqrt{s}=200$ GeV in ref. [43]. We employ a threshold-based extrapolation using the following expression:

$$\sigma_{c\bar{c}} = k(1 - \sqrt{s_{thr}}/\sqrt{s})^a(\sqrt{s_{thr}}/\sqrt{s})^b$$  \hspace{1cm} (3)$$

with $k=1.85 \, \mu$b, $\sqrt{s_{thr}}=4.5$ GeV (calculated assuming a charm quark mass $m_c=1.3$ GeV), $a=4.3$, and $b=-1.44$. The parameters $a$, $b$, $k$ were tuned to reproduce the low-energy part of the (scaled) NLO curve. The extrapolated curves for charm production cross section are shown with continuous lines in Fig. 1. Also shown for comparison are calculations with PYTHIA [40]. To obtain the values at midrapidity we have extrapolated to lower energies the rapidity widths (FWHM) of the charm cross section known to be about 4 units at RHIC [43] and about 2 units at SPS [44]. With these cross section values, the rapidity density of initially produced charm quark pairs strongly rises from $1.1 \times 10^{-3}$ to 1.7 for the energy range $\sqrt{s_{NN}}=7$-200 GeV. We note that the so-obtained charm production cross section has an energy dependence similar to that measured for $J/\psi$ production, recently compiled and parametrized by the HERA-B collaboration [42]. For comparison, this is also shown in Fig. 1. The extrapolation procedure for the low-energy part of the cross section obviously implies significant uncertainties. We emphasize, however, that the

Fig. 1. Energy dependence of the charm production cross section in pp collisions. The NLO pQCD values [39] are compared to calculations using PYTHIA and to data in pA collisions, taken from ref. [40]. Our extrapolations for low energies are shown with continuous lines, for total and midrapidity ($d\sigma_{c\bar{c}}/dy$) cross section. The open square is a midrapidity measurement in pp collisions [41]. The dashed line with dots indicates a parameterization of the measured energy dependence of the $J/\psi$ production cross section [42].
most robust predictions of our model, i.e. the yields of charmed hadrons and charmonia relative to the initially produced $c\bar{c}$ pair yield are not influenced by the details of this extrapolation.

For the studied energy range, $T$ rises from 151 to 161 MeV from $\sqrt{s_{NN}}=7$ to 12 GeV and stays constant for higher energies, while $\mu_b$ decreases from 434 to 22 MeV [34]. The volume $V_{\Delta y=1}$ at midrapidity continuously rises [34] from 760 to 2400 fm$^3$. Due to the very small number of charm quarks at these low energies, the canonical suppression factor ($I_1/I_0$) is very large, but strongly decreases from about 1/30 to 1/1.2 for $\sqrt{s_{NN}}=7$ to 200 GeV. Correspondingly, the charm fugacity $g_c$ increases from 0.96 to 8.9.

4 Energy dependence of charmed hadrons yield

Our main results are presented in Fig. 2. The upper panel shows our predictions for the energy dependence of midrapidity yields for various charmed hadrons. Beyond the generally decreasing trend towards low energies for all yields one notices first a striking behavior of the production of $\Lambda_c$ baryons: their yield exhibits a weaker energy dependence than observed for other charmed hadrons. In our approach this is caused by the increase in baryochemical potential towards lower energies. A similar behavior is seen for the $\Xi_c^+$ baryon. In detail, the production yields of D-mesons depend also on their quark content.

The differing energy dependences of the yields of charmed hadrons are even more evident in the lower panel of Fig.2, where we show the predicted yields normalized to the number of initially produced $c\bar{c}$ pairs. Except very near threshold, the $J/\psi$ production yield per $c\bar{c}$ pair exhibits a slow increase with increasing energy. This increase is a consequence of the quadratic term in the $J/\psi$ yield equation discussed above. At LHC energy, the yield ratio $J/\psi/c\bar{c}$ approaches 1% [3], scaling linearly with $\sigma_{c\bar{c}}$; for details see [45]. The $\psi'$ yield shows a similar energy dependence as the $J/\psi$, except for our lowest energies, where the difference is due to the decrease of temperature (see above). We emphasize again that this model prediction, namely yields relative to $c\bar{c}$ pairs, is a robust result, as it is in the first order independent on the charm production cross section. Due to the expected similar temperature, the relative abundance of open charm hadrons at LHC is predicted [45] to be similar to that at RHIC energies.

5 Effects of in-medium modification of charmed hadrons masses

We consider two scenarios for a possible mass change $\Delta m$ of open charm hadrons containing light, $u$ or $d$, quarks: i) a common decrease of 50 MeV for all charmed mesons and their antiparticles and a decrease of 100 MeV for the $\Lambda_c$ and $\Sigma_c$ baryons (50 MeV

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$^3$ The scenarios are constructed by modification of the constituent quark masses of light ($u$ and $d$) quarks in the charmed hadrons by fixed amounts. Reducing, for example, the light quark masses by 50 MeV will lower D-meson masses by 50 MeV and the $\Lambda_c(\Xi_c)$ mass by 100 (50) MeV.
Fig. 2. Energy dependence of charmed hadron production at midrapidity. Upper panel: absolute yields, lower panel: yields relative to the number of \(c\bar{c}\) pairs. Note the scale factors of 10 and 100 for \(J/\psi\) and \(\psi'\) mesons, respectively.

decrease for \(\Xi_c\); ii) a decrease of 100 MeV for all charmed mesons and a 50 MeV increase for their antiparticles, with the same (scaled with the number of light quarks) scenario as in i) for the baryons. Scenario i) is more suited for an isospin-symmetric fireball produced in high-energy collisions and was used in [28], while scenario ii) may be realized at low energies. In both scenarios, the masses of the \(D_s\) mesons and of the charmonia are the vacuum masses. We also note that if one leaves all D-meson masses unchanged but allows their widths to increase, the resulting yields will increase by 11% (2.7%) for a width of 100 MeV (50 MeV). If the in-medium widths exhibit tails towards low masses, as has been suggested by [8], to first order the effect on thermal densities is comparable with that from a decrease in the pole mass.

The results for the two cases are presented in Fig. 3 as yields relative to the number of initially-produced \(c\bar{c}\) pairs. As a result of the redistribution of the charm quarks over the various species, the relative yields of charmed hadrons may change. For example, in scenario i) the ratios of D-mesons are all close to those computed for vacuum masses (Fig. 2), but the \(\Lambda_c/D\) ratio is increased. Obvious are for scenario ii) the changes in the
Fig. 3. Energy dependence of the yield of charmed hadrons relative to the charm quark pair yield for two scenarios of the mass change (left panel for scenario i), right panel for scenario ii), see text). For the D mesons, the full and open symbols are for particles and antiparticles, respectively. Note the factors 10 and 100 for the $J/\psi$ and $\psi'$ mesons, respectively.

relative abundances of the $D$ and $\bar{D}$ mesons, as well as for the charmed baryons and also the relative production yields of $D_s^+$ and $D_s^-$ mesons are very different. This difference is the result of the asymmetry in the mass shifts for particles and antiparticles. The change in yield of $D_s^{\pm}$ mesons occur as a consequence of the charm neutrality condition. Overall, however, charm conservation leads to rather small changes in the total yields. In contra-distinction, the effect of mass changes of charmed hadrons is very significant for charmonia, in particular the yields are more affected at low energies.

In Fig. 4 we demonstrate that the total open charm yield (sum over all charmed hadrons) exhibits essentially no change if one considers mass shifts, while the effect is large on charmonia. This is to be expected from eq. 2 as D-meson and $\Lambda_c$-baryon masses are reduced, e.g., the charm fugacity $g_c$ is changed accordingly to conserve charm. Since the D-meson and $\Lambda_c$-baryon yield varies linearly with $g_c$ we expect little change, while yields for charmonia vary strongly, since their yields are proportional to $g_c^2$. To demonstrate this we plot, in Fig. 4, the relative change of the yields with in-medium masses compared to the vacuum case. For this comparison, we have added a third case, namely considering that the mass change of charmed baryons is the same as for the mesons.

Despite showing similar trends, in our model the reduction of the $J/\psi$ yield due to reduced in-medium masses of open charm hadrons has a different origin than that investigated in previous studies [26,27,18,29,16]. Dissociation of $J/\psi$ in a gas of $\pi$ and $\rho$ mesons [26] and effects originating from opening of decay channels of $\psi'$ and $\chi_c$ states into $D\bar{D}$ [29,16] were considered in hadronic scenarios, while Zhang et al. [18] have investigated the effect of mass changes both in the partonic ($c$ quarks) and in the hadronic (D mesons) stage. In our model all hadrons with open and hidden charm are produced at chemical freeze-out.
Fig. 4. Energy dependence of the relative change in the production yield of open charm hadrons and of $J/\psi$ meson considering different scenarios for in-medium mass modifications (see text).

Under the assumption that chemical freeze-out takes place at the phase boundary [46], the medium effects could be due to the onset of chiral symmetry restoration or rescattering with the constituents of the medium. At present it cannot be ruled out that at lower energies the phase boundary does not coincide with chemical freeze-out. In this case, in-medium effects would be due to rescattering in the dense hadronic phase.

6 Conclusions

We have investigated charmonium production in the statistical hadronization model at lower energies. An interesting result is that the yield of charmed baryons ($\Lambda_c$, $\Xi_c$) relative to the total $c\bar{c}$ yield increases strongly with decreasing energy. Below $\sqrt{s_{NN}}=10$ GeV, the relative yield of $\Lambda_c$ exceeds that of any D meson except $\bar{D}_0$, implying that an investigation of open charm production at low energies needs to include careful measurements of charmed baryons, a difficult experimental task. The charmonium/open charm yield rises only slowly from energies near threshold to reach $\sim 1\%$ at LHC energy. Note that this ratio depends on the magnitude of the charm cross section, further underlining the importance to measure this quantity with precision. Our study is the first one addressing comprehensively the charm redistribution in principle and under various assumptions of in-medium masses of charmed hadrons. Because of a separation of time scales for charm quark and charmed hadron production, the overall D meson cross section is very little affected by in-medium mass changes, if charm conservation is taken into account. Measurable effects are predicted for the yields of charmonia. These effects are visible at all beam energies...
and increase slightly towards threshold.

Acknowledgments

K.R. acknowledges partial support from the Polish Ministry of Science (MEN) and the Deutsche Forschungsgemeinschaft (DFG) under Mercator Programme.

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