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Letter

Charmed nuclei and exotic charmed meson production at CBM@FAIR and ALICE@LHC

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ABSTRACT

We make predictions for the expected multiplicities of exotic charmed hadrons and charmed nuclei in Au + Au collisions at SIS100 and Pb + Pb collisions at LHC beam energies, using input on light hadron and charm production from the UrQMD transport model, and applying the Thermal-FIST model. We demonstrate that the CBM experiment has the capability to explore these states with production rates of 1 per second for $\chi_{c0}(1P)$ and $\chi_{c1}(1P)$, and 3 per minute for $X(3872)$ at the expected data taking rates. These rates should be seen as order-of-magnitude estimates due to the extrapolation of the charm production mechanisms into the unknown high-baryon density and subthreshold territory that FAIR explores. Due to the higher baryon density at CBM compared to the LHC, charmed nuclei, if they exist, will be equally abundant at CBM as at the LHC, even though the total charm production at CBM is much lower.

1. Introduction

Charmed hadrons are an important tool to test our understanding of the strong interaction [1–4]. Especially the study of so-called exotic states of charmed mesons can give new insights and dedicated experimental programs exist, e.g., at BESIII [5] and LHCb [6]. A downside of such programs is the rather small production probability of charmed hadrons due to their large mass, even in high energy e^+e^- or hadron-hadron collisions. Another interesting topic relating to charmed physics is the possible existence of charmed nuclei [7–9], i.e., atomic nuclei containing at least one charmed hadron. Requiring the coalescence of charmed baryons with at least one other baryon makes such states difficult to produce.

High-energy collisions of heavy nuclei, on the other hand, offer a unique opportunity for producing exotic charmed hadrons as well as charmed nuclei. Here, charm quarks are produced in the early stage of

the reaction and their number is conserved throughout the evolution of the fireball. Their distribution into various hadron species is then determined at the chemical freeze-out [10,11]. In addition, due to the large number of baryons involved in the collisions, the probability to produce light nuclei in the collision zone is large enough to allow for the formation of charmed nuclei [9,12].

In this work, we provide estimates of the production cross sections of several exotic charmed hadrons as well as charmed nuclei in Au + Au collisions at the future SIS100 and Pb + Pb collisions at the existing LHC. Using the multiplicities of light hadrons and the most common charmed hadrons as input, we can use the assumption of statistical hadron production [11] to estimate the yields of exotic charmed hadrons and charmed nuclei with the Thermal-FIST model [13]. Within the statistical hadronization model (SHM) [14], the system is described as a thermalized hadron gas, and the partition function encodes the accessible states. This framework allows to predict the production yields and

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relative abundances of charmed hadrons [11,14], including open charm mesons, charmed baryons, hidden charm states, and possible exotic configurations.

Such predictions are highly relevant for upcoming experiments at FAIR and GSI as well as at the LHC, where the observation of charm and exotic bound states would provide valuable information on QCD in extreme conditions [15].

The light and charmed hadron multiplicities are estimated for the SIS100 beam energy range using the microscopic transport model UrQMD [16–18] (for recent charm studies at FAIR energies within UrQMD see e.g. [9,19]). At LHC energies we can rely on available data from the ALICE experiment as input.

For the near- and subthreshold charm estimates at FAIR energies, a word of caution is necessary, as they rely on various theoretical assumptions due to the lack of experimental data: The physical model to calculate charm production in Au + Au reactions at near- and subthreshold energies relies on the assumption of the production of heavy resonances, which collect the available energy of the system via multi-step processes. The production and decay rates of these heavy baryonic resonances are matched to describe the available data for charm production in p + p reactions at $\sqrt{s_{NN}} = 6.7$ GeV (the only available data point for charm production at very low collision energies) [9]. In a next step one assumes that these heavy resonance states can also be excited by multi-step process in nucleus-nucleus collisions and that their branching ratios follow the usual phase space behavior. If these assumptions are satisfied, we can obtain an estimate on the initial total charm production cross section from the simulation that can then be used in the statistical model. Since detailed theoretical or experimental data on the interaction of charm quarks with hadrons are essentially non-existing, we rely on the statistical assumptions to calculate how the charm quarks are redistributed among the available hadrons. We therefore regard these calculations at FAIR energies as guidelines (i.e., order-of-magnitude estimates) to motivate a charm program at FAIR rather than a highly precise prediction of the different charm yields. It is clear that detailed predictions of charmed hadrons at FAIR need further experimental input to provide the necessary constraints for the simulations. E.g., measuring D mesons and Λ_c in p + p collisions just above their threshold would already provide sufficient input for more precise predictions below the threshold in A + A collisions.

2. Methodology

2.1. Thermal hadron yields

The statistical hadronization model has been used in the past to describe the multiplicities of hadrons produced in A + A, p + A as well as p + p collisions over a wide range of beam energies [14,20–22]. It is based on the assumption of chemical equilibrium where hadrons are produced according to thermal weights at the chemical freeze-out stage of the collision.

Due to the large mass of the charm quark, charm–anticharm pairs in nuclear collisions are predominantly created in initial hard partonic scatterings at high energies or by hadronic multi-step process at lower energies and their total number remains conserved during the subsequent evolution of the system. At beam energies relevant for FAIR and even at moderate LHC energies, the average number of charm pairs per event is significantly smaller than unity. As a consequence, charm production cannot be treated within the grand canonical ensemble but requires an exact, canonical implementation of charm conservation.

In a general canonical statistical hadronization approach, the yields of charmed hadrons, in equilibrium, would be suppressed relative to their grand-canonical expectation. This suppression originates from exact conservation of the charm quantum number within a finite correlation volume (V_c) and becomes increasingly important for small charm multiplicities (similar to the effect observed for strangeness in small systems and beam energies close to the strangeness threshold [20,23]).

The canonical formulation of the statistical hadronization model is based on the exact conservation of the relevant quantum numbers within a finite correlation volume. In this approach, the partition function is constructed by projecting the grand-canonical ensemble onto fixed values of the conserved charges. For a hadron resonance gas with conserved baryon number B , electric charge Q , strangeness S , and charm C , the canonical partition function at a given temperature T and correlation volume V_c reads [20,24,25]:

$$\mathcal{Z}(B, Q, S, C) = \int_{-\pi}^{\pi} \frac{d\phi_B}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_Q}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_S}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_C}{2\pi} \times e^{-i(B\phi_B + Q\phi_Q + S\phi_S + C\phi_C)} \times e\left[\sum_{j=1}^{\infty} z_{j,n} e^{i n (B_j \phi_B + Q_j \phi_Q + S_j \phi_S + C_j \phi_C)}\right], \quad (1)$$

with

$$z_{j,n} = (\mp 1)^{n+1} \gamma_q^{n|q_j|} \gamma_s^{n|s_j|} \gamma_c^{n|c_j|} \frac{d_j V_c}{2\pi^2} \frac{T m^2}{n^2} K_2\left(n \frac{m}{T}\right) \quad (2)$$

Canonical corrections simplify considerably when the canonical treatment is applied to charm conservation only (in this case, the baryon, strangeness, and electric charge densities are regulated by the corresponding chemical potentials). In the absence of multi-charm states, as is the case here, and applying the Maxwell-Boltzmann approximation ($n = 1$),

$$n_i^{C,cc} = n_i^{C,gce} \frac{I_1(2\sqrt{S_{+1}^C S_{-1}^C})}{I_0(2\sqrt{S_{+1}^C S_{-1}^C})} \sqrt{\frac{S_{+1}^C}{S_{-1}^C}}, \quad \text{for } C_i = \pm 1. \quad (3)$$

Here

$$S_{\pm 1}^C = V_c \sum_{i \in C_i = \pm 1} n_i^{C,gce}, \quad (4)$$

where $n_i^{C,gce}$ is the grand-canonical density

$$n_i^{C,gce} = \gamma_q^{n|q_i|} \gamma_s^{n|s_i|} \gamma_c^{n|c_i|} \frac{d_i T m^2}{2\pi^2} K_2\left(\frac{m_i}{T}\right) e^{\frac{\mu_B B_i + \mu_Q Q_i + \mu_S S_i}{T}}. \quad (5)$$

Using Thermal-FIST we verified that the canonical corrections for charges other than charm are negligible for A + A collisions studied here, and that Eq. (3) provides an accurate description of charm yields. For this reason, we treat other quantum numbers within a grand canonical partition function and fix the relevant temperature and chemical potentials using the standard chemical freeze-out systematics.

A unique feature about charm production in nuclear collisions is that, even though their multiplicity is very small, the charmed quark pairs are mainly produced in the early stage of the collision, and the total abundance of charm + anti-charm quarks is larger than what one would expect even for a grand canonical ensemble. Therefore, one assumes that charm hadrons are only in thermal, not in chemical equilibrium. A charm fugacity γ_c has to be introduced which is determined by the total charm production cross section. Canonical corrections have to be added in addition.

2.2. Model inputs: open and hidden charm yields

To make predictions for the statistical distribution of the charm quarks among the produced hadrons, the two additional inputs (in addition to temperature and the baryon-chemical potential) need to be constrained: the charm suppression/enhancement factor γ_c and the charm canonical radius R_c . Typically one uses the total charm yield, and a hidden charm meson multiplicity as input.

Practically, there are two different ways to obtain these inputs: At higher energies, like currently explored at the LHC, one conveniently uses the measured multiplicities of light and charmed hadrons as input for the thermal parameter fits. This is possible for experiments like ALICE where an extensive set of measurements exists. Unfortunately, at

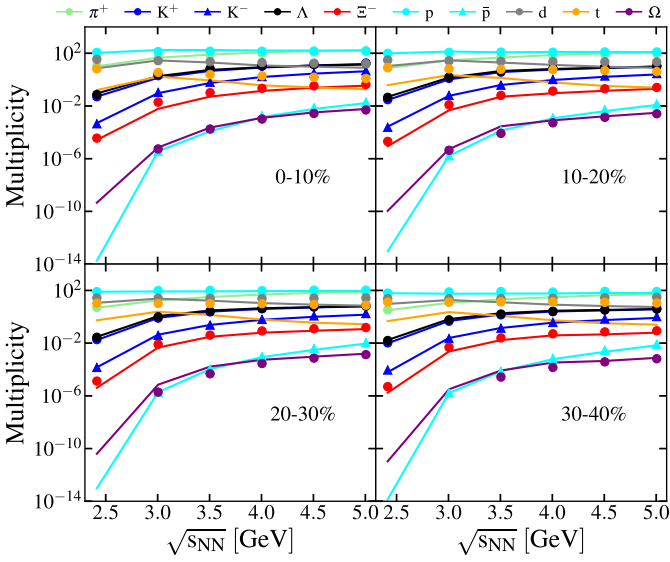


Fig. 1. Input (symbols) and fitted (lines) light hadron multiplicities from the UrQMD simulations of Au + Au collisions at different centrality selections. For the fits only hadron multiplicities without light nuclei were used.

lower energies and for reactions that have not yet been measured (like in the present case for FAIR energies), we cannot rely on existing data.

Consequently, we use the available ALICE data [26–29] for our predictions at LHC beam energies on charm production in Pb + Pb collisions at 5.02 TeV as input for the thermal fits. In the FAIR energy range, as a replacement for the yet unavailable experimental data, we use estimates based on the UrQMD model. The UrQMD transport model [16–18] has been used successfully in the past to describe hadron multiplicities in hadron and nuclear reactions over a wide range of beam energies. It is based on hadronic degrees of freedom and the excitation and fragmentation of color strings at higher energies. In the latest version, the implemented hadron spectrum includes (strange and non-strange) meson and baryon resonances up to masses of 4 GeV. The hadrons are propagated via the Hamilton equations of motion, if nuclear potentials are used. Without potentials, the hadrons follow straight line trajectories (cascade mode). Typically, the collision of two nuclei consists of three stages: I) initialization of the colliding nuclei, II) particle production, decay, and subsequent rescattering, followed by III) the freeze-out/decoupling stages, where inelastic and finally all interactions cease.

A recent study has already shown that the chemical freeze out parameters obtained from the UrQMD evolution, when including a realistic equation of state, lie close to a global chemical freeze out line that is compatible with the thermal model parameters [30,31]. It is therefore reasonable to use the temperature and chemical potentials from a fit to UrQMD as input for our predictions of expected hadron yields in the SIS100 beam energy range.

To constrain the inputs of charmed hadron production γ_c and R_c needed for the statistical analysis, we use the open charmed hadron multiplicity from Λ_c to fix γ_c and the hidden charm hadron multiplicity from J/Ψ to fix R_c . If data from FAIR become available, these estimates could be replaced by actually measured yields.

In a previous work, we have discussed how the production of these charmed hadrons at FAIR energies can be included in the UrQMD simulations. To calculate charm production near and even below threshold, it was implemented via the formation and decays of heavy resonances (in analogy to ϕ production), with parameters fitted to elementary cross sections measured by experiment in p + p interactions slightly above threshold [9]. While this approach is sufficient to predict the most common charm states, it is not detailed enough to determine the production of more exotic charmed states due to the lack of known branching ratios.

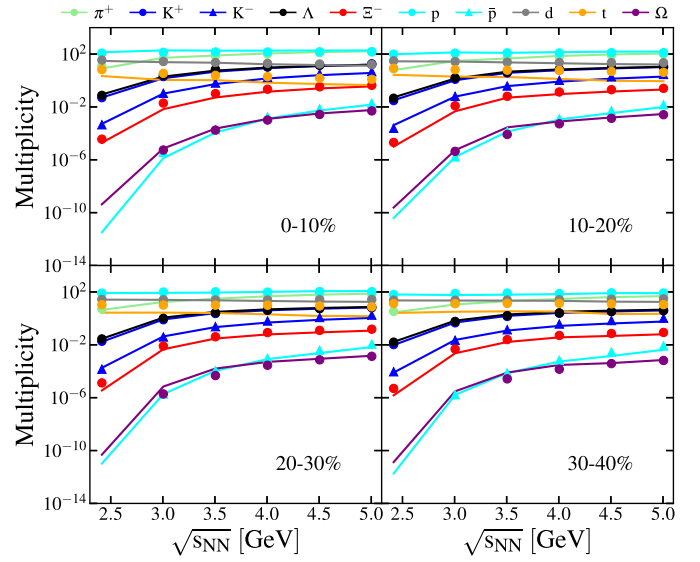


Fig. 2. Input (symbols) and fitted (lines) light hadron multiplicities from the UrQMD simulations of Au + Au collisions at different centrality selections. For the fits hadron multiplicities including deuterons were used.

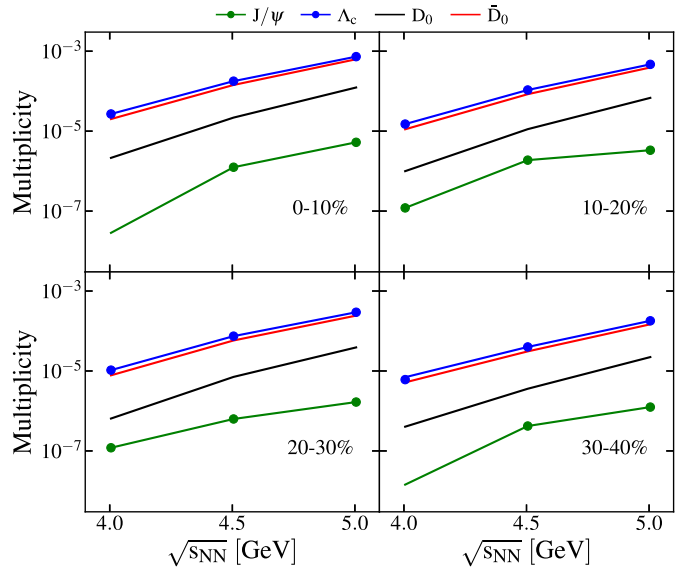


Fig. 3. Input (symbols) and predicted charm hadron multiplicities in Au + Au collisions at different centralities as function of the beam energy.

That is why we have to rely on the statistical assumption to redistribute the charm quarks.

3. Fit results - input and bulk

We start by demonstrating that the hadron yields from UrQMD can indeed be described by a statistical thermal model. To show this, we calculate the full set of final state hadrons and light clusters in UrQMD and compare these to the outcome of the thermal fits for Au + Au reactions at four different centralities. Fig. 1 shows the results of the UrQMD calculation (symbols) in comparison to the best fit using Thermal-FIST (lines), fitted to hadron yields only and neglecting clusters in the fit. The description of the UrQMD multiplicities is very good. In Fig. 2 we show the fit results (lines), now with the inclusion of the deuteron (as the most abundant cluster) and compare again to the UrQMD results (symbols). We observe that a very good fit to the data is also

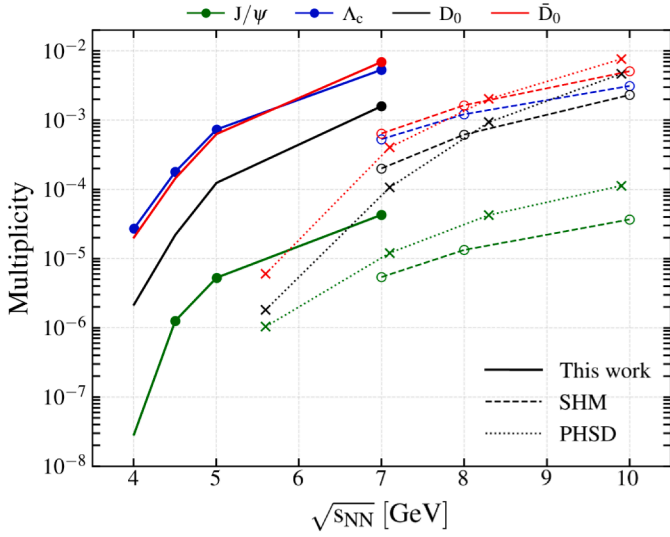


Fig. 4. Multiplicities of open charm hadrons as a function of the center-of-mass energy. Solid lines denote the results of the present Thermal-FIST calculations with filled dots representing the UrQMD data, while open symbols and dashed lines show the statistical-hadronization model (SHM) predictions of ref. [32], and dotted lines with crosses results from PHSD [33].

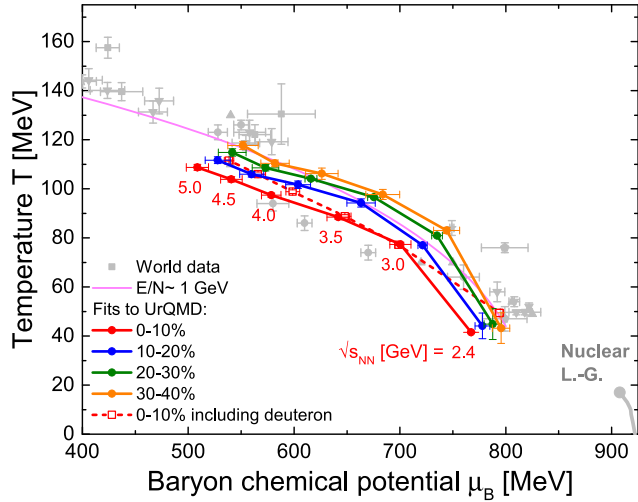


Fig. 5. Freeze out points from fits to UrQMD, in the $T - \mu_B$ phase diagram. Different centralities are shown as filled symbols with solid lines compared to world data (grey symbols) [22,34–40] and a parametrization of the freeze out line from Lysenko et al. [40]. The dashed line shows the fit for central collisions when the deuteron is included in the list of fitted particles.

possible in this case. However, differences show up in the yields of light clusters, which is expected. This difference will later define the systematic error for charmed nuclei. In the following, we will always compare the fit without nuclei and the fit including nuclei in central reactions.

As benchmark for the reproduction of the input charm yields, Fig. 3 shows a comparison of the thermal fit (lines) with the input multiplicities (Λ_c and J/Ψ) for charmed hadrons from UrQMD (symbols). As expected, the fit is very good, simply because two parameters are fixed with two inputs. The yields of D and $\bar{D}$ mesons shown are predicted and show a sizable splitting, as a consequence of a high μ_B environment.

To place the present results in the context of earlier calculations, we compare them with the predictions from the statistical hadronization

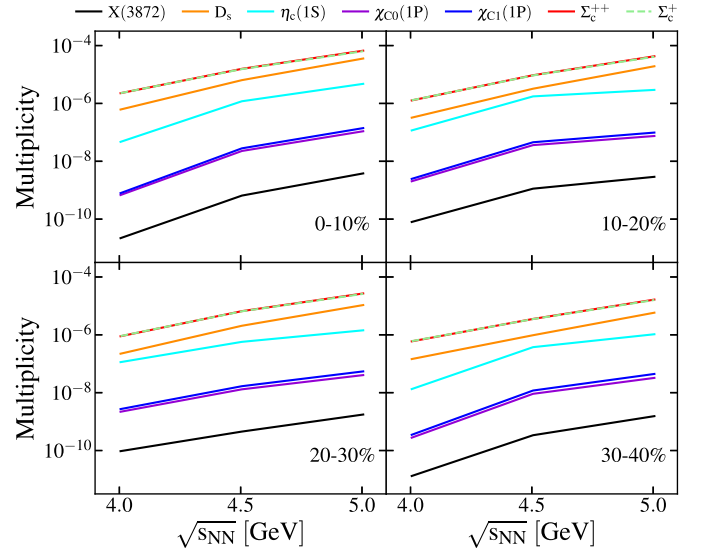


Fig. 6. Predicted (lines) exotic charmed hadron multiplicities in Au + Au collisions at different centralities as function of the beam energy.

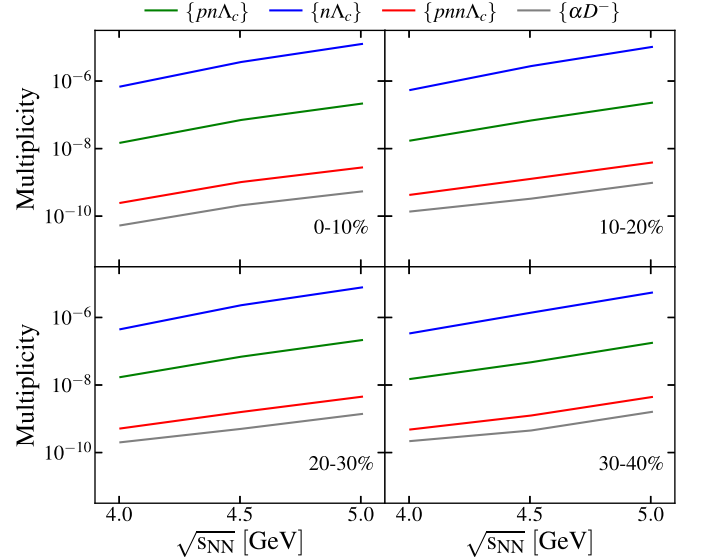


Fig. 7. Predicted (lines) charmed nuclei multiplicities in Au + Au collisions at different centralities as function of the beam energy.

approach in [32], which extend from $\sqrt{s_{NN}} = 7$ GeV to higher energies, and the HSD transport model [33]. Fig. 4 shows the multiplicities of J/ψ , Λ_c , D_0 , and $\bar{D}_0$ as a function of the center-of-mass energy for central collisions, where we have extended our UrQMD simulations to $\sqrt{s_{NN}} = 7$ GeV. Although the calculations cover different energy intervals, they exhibit a consistent energy dependence and reproduce the same ordering of charm hadron yields. Our simulations have a larger total charm cross section than the previous simulations, even though the J/Ψ production is fitted to the cross section in elementary p + p reactions at that beam energy.

The total charm production cross section $\sigma_{c\bar{c}}$ in our work is in the range between 10^{-3} and $3 \cdot 10^{-2} \mu\text{b}$ at $\sqrt{s_{NN}} = 4 - 7$ GeV, compared to $4 \cdot 10^{-2} \mu\text{b}$ at 7 GeV in [32]. The difference from the previous results is mainly due to the enhanced charm production per participant in central Au + Au collisions compared to p + p in our simulations. This enhancement is a result of the secondary reactions which become more relevant as one approaches the elementary production threshold. The two

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$\sqrt{s_{NN}} = 4 - 5$ GeV. As expected, the most abundant charmed hadrons (after the Λ_c) are the Σ_c states as they are the lightest states and couple to the high baryon density. They are followed by the D_s state and the η_c . For the highest energy, multiplicities between $10^{-6} - 10^{-4}$ are predicted per event. The next group, with multiplicities on the order of 10^{-7} , is given by the χ states followed by the X state with an estimated multiplicity around 10^{-9} per event. Thus, even studies of these exotic charm states seem feasible for the CBM experiment.

Next, we turn to the speculated charmed nuclei and investigate the yields of $\{pn\Lambda_c\}$, $\{n\Lambda_c\}$, $\{pnn\Lambda_c\}$, and $\{\alpha D^-\}$. In Fig. 7, these are shown as a function of energy and centrality. For the lightest charm nucleus ($\{n\Lambda_c\}$), we obtain multiplicities on the order of 10^{-7} per event for central events at the highest CBM energy for Au beams. As expected from the study of normal light nuclei, the addition of another nucleon comes with a penalty factor of approx 50–100 [43] in this energy regime, which is also what we observe. All explored charmed nuclei states have multiplicities above 10^{-10} per event and can therefore be explored in CBM@FAIR due to the unprecedented luminosity available.

We now compare the discovery reach of CBM to the possibilities of ALICE at the LHC. These are two extreme scenarios for charm nuclei production: At the LHC, while the initial charm yield is high (increasing charm nuclei formation), low baryon densities and high temperatures decrease the formation probability of charmed nuclei. At FAIR energies, on the other hand, the initial charm yield is very low (decreasing charm nuclei formation), but very high baryon densities and low temperatures increase the formation probability. To explore the influence of these counter-acting effects, Fig. 8 shows the expected multiplicity of the charmed light nuclei as a function of the baryon number for the three different beam energies in the SIS100 beam energy range and for Pb + Pb collisions at 5.02 TeV center-of-mass energy at the LHC. Let us clarify that the predictions for the LHC are done using measured ALICE multiplicities as input for Thermal-FIST, while in the case of FAIR, we have to rely on the model predictions as input.

The left panel of Fig. 8 shows the results without including the deuterons in the thermal fit and the right panel of Fig. 8 includes the deuterons in the fit. In general, including the deuteron in the fit leads to a small enhancement of light charmed nuclei production. However, what is even more interesting is the comparison of the predictions for SIS100 compared to the LHC. While for very light charmed nuclei ($A \leq 3$) the production is suppressed compared to the LHC by up to 3 orders of magnitude, this suppression is completely compensated by the increased baryon density for charmed nuclei with $A \geq 4$, resulting in an almost equal probability to produce heavier charmed nuclei.

In the following Table 2 we have summarized the predicted multiplicities, integrated over all phase space, for central collisions of Au + Au (at $\sqrt{s_{NN}} = 5$ GeV) and Pb + Pb (at $\sqrt{s_{NN}} = 5.02$ TeV). The table also lists the corresponding available LHC yields from statistical hadronization in ref. [11]. The predicted multiplicities are generally of the same order of magnitude as previous statistical-hadronization calculations, indicating that the present implementation yields results consistent with earlier studies at LHC energies.

5. Summary and discussion

We have presented first predictions for the production of exotic charmed hadrons and light charmed nuclei in heavy ion collisions at the upcoming CBM experiment. We further demonstrated the potential to observe charmed nuclei at the ALICE experiment which is currently taking data at CERN. The predictions were made by employing the Thermal-FIST model which assumes statistical hadronization and using either UrQMD model input (in the case of FAIR) or measured light flavor and charm multiplicities (in the case of ALICE). In both cases, the production rate of even the heavier $A = 4$ ($\{pnn\Lambda_c\}$) charmed nuclei is on the order of 10^{-9} (and for the molecular state $\{\alpha D^-\}$ on the order of 10^{-11}), while for lighter charm clusters, multiplicities above 10^{-8} ($A = 3$) are reached. Given a planned collision rate of 10^7 Hz at CBM, this yields

approx 1000 $\{pnn\Lambda_c\}$ nuclei per day. Regarding the production of light charmed nuclei, we find that the reduced production rate of the Λ_c at the SIS100 can be balanced by the higher baryon density which leads to almost identical production rates at the LHC and SIS100 for charmed nuclei with $A = 4$. We emphasize that the multiplicities quoted in this work correspond to produced yields integrated over phase space. They do not include decay branching ratios, detector acceptance, reconstruction efficiencies, or analysis-selection losses. This is particularly important for the loosely bound exotic and nuclear charm states considered here, for which experimentally reconstructible yields may be substantially below the produced multiplicities.

We have further predicted the multiplicities of the exotic charmed mesons (most of them currently under investigation at BESIII) $X(3872)$, $\chi_{c0}(1P)$, and $\chi_{c1}(1P)$, and have demonstrated that CBM also has the capability to explore these states with a production rate of 1 per second for $\chi_{c0}(1P)$ and $\chi_{c1}(1P)$ and a rate of 3 per minute in the case of $X(3872)$.

These novel predictions can guide the planned experimental programs at CBM and ALICE to make feasibility studies on the detectability of the discussed exotic nuclear states. The study of the charmed exotic and nuclear states discussed in this work has the potential to shed new light into the physics of the strong interaction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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