



The melting and abundance of open charm hadrons



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ABSTRACT

Ratios of cumulants of conserved net charge fluctuations are sensitive to the degrees of freedom that are carriers of the corresponding quantum numbers in different phases of strong interaction matter. Using lattice QCD with 2 + 1 dynamical flavors and quenched charm quarks we calculate second and fourth order cumulants of net charm fluctuations and their correlations with other conserved charges such as net baryon number, electric charge and strangeness. Analyzing appropriate ratios of these cumulants we probe the nature of charmed degrees of freedom in the vicinity of the QCD chiral crossover region. We show that for temperatures above the chiral crossover transition temperature, charmed degrees of freedom can no longer be described by an uncorrelated gas of hadrons. This suggests that the dissociation of open charm hadrons and the emergence of deconfined charm states sets in just near the chiral crossover transition. Till the crossover region we compare these lattice QCD results with two hadron resonance gas models—including only the experimentally established charmed resonances and also including additional states predicted by quark model and lattice QCD calculations. This comparison provides evidence for so far unobserved charmed hadrons that contribute to the thermodynamics in the crossover region.

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1. Introduction

Bound states of heavy quarks, in particular the charmonium state J/ψ and its excitations as well as the heavier bottomonium states, are sensitive probes for deconfining features of the quark–gluon plasma (QGP) [1]. Different excitations of these states are expected to dissolve at different temperatures in the QGP, giving rise to a characteristic sequential melting pattern [2]. Recent lattice QCD calculations of thermal hadron correlation functions suggest that certain quarkonium states survive as bound states in the QGP well beyond the pseudo-critical temperature of the chiral crossover transition $T_c = (154 \pm 9)$ MeV [3]; the J/ψ and its pseudo-scalar partner η_c disappear at about $1.5T_c$ [4], while the heavier bottomonium ground states can survive even up to $2T_c$ [5,6].

Light quark bound states, on the other hand, dissolve already at or close to the pseudo-critical temperature, T_c , reflecting the close relation between the chiral crossover and deconfinement of light quark degrees of freedom. This leads to a sudden change in the bulk thermodynamic observables and is even more apparent in the behavior of fluctuations of conserved charges, i.e. baryon number, electric charge or strangeness [7,8]. The sudden change of ratios of different moments (cumulants) of net-charge fluctuations and their correlations in the transition region directly reflects the change of degrees of freedom that carry the relevant conserved charges. The total number of hadronic degrees of freedom, i.e. the detailed hadronic mass spectrum also influences bulk thermodynamics. For instance, the strong rise of the trace anomaly $(\epsilon - 3P)/T^4$, found in lattice QCD calculations may be indicative for contributions of yet unobserved hadron resonances [9].

Recently it has been shown that the large set of fourth order cumulants of charge fluctuations and cross-correlations among

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fluctuations of conserved charges allows for a detailed analysis of the change from hadronic to partonic degrees of freedom in different charge sectors [10]. For instance, changes of degrees of freedom in the strange meson and baryon sectors of hadronic matter can be analyzed separately by choosing appropriate combinations of charge fluctuation observables. This led to the conclusion that a description of strong interaction matter in terms of uncorrelated hadronic degrees of freedom breaks down for all strange hadrons in the chiral crossover region, i.e. at $T \lesssim 160$ MeV [10], which suggests that strangeness gets dissolved at or close to T_c . This finding has been confirmed with the analysis presented in [11].

A more intriguing question is what happens to the charmed sector of the hadronic medium at the QCD transition temperature. While it seems to be established that charmonium states, i.e. bound states with hidden charm, still exist in the QGP at temperatures well above T_c , this may not be the case for heavy–light mesons or baryons, i.e. open charm mesons (D , D_s) [12,13] or charmed baryons (Λ_c , Σ_c , Ξ_c , Ω_c). To address this question we calculate cumulants of net-charm fluctuations as well as correlations between moments of net-charm fluctuations and moments of net baryon number, electric charge or strangeness fluctuations. Motivated by the approach outlined in Ref. [10] we analyze ratios of observables that may, at low temperature, be interpreted as contributions of open charm hadrons to the partial mesonic or baryonic pressure of strong interaction matter. We show that a description of net charm fluctuations in terms of models of uncorrelated hadrons breaks down at temperatures close to the chiral crossover temperature. We furthermore show that at low temperatures the partial pressure calculated in the open charm sector is larger than expected from hadron resonance gas (HRG) model calculations based on all experimentally measured charmed resonances as listed in the particle data tables [14]. It, however, agrees well with an HRG based on charm resonances from quark model [15–18] and lattice QCD calculations [19–21]. This points at the existence and thermodynamic importance of additional, experimentally so far not established, open charm hadrons.

2. The charmed hadron resonance gas

While light quark fluctuations can be quite well described by a hadron resonance gas [22] built up from experimentally measured resonances that are listed in the particle data tables [14] it is not at all obvious that this suffices in the case of the heavy open charm resonances. The particle data tables only list a few measured open charm resonances. Many more are predicted in the relativistic quark model [15–18] and lattice QCD [20,21] calculations. In fact, the large set of excited charmed mesons and baryons found in lattice QCD calculations closely resembles the excitation spectrum predicted in quark model calculations. It is expected that many new open flavor states will be detected in upcoming experiments at Jefferson Laboratory, FAIR and the LHC [16,23–25]. If these resonances are indeed part of the charmed hadron spectrum of QCD, they become excited thermally and contribute to the thermodynamics of the charmed sector of a hadron resonance gas. They will show up as intermediate states in the hadronization process of a quark–gluon plasma formed in heavy ion collisions and influence the abundances of various particle species [26]. Heavy–light bound states also play an important role in the break-up of quarkonium bound states. In lattice QCD calculations their contribution becomes visible in the analysis of the heavy quark potential where they can help to explain the non-vanishing expectation value of the Polyakov loop at low temperatures [27,28].

In order to explore the significance of a potentially large additional set of open charm resonances in thermodynamic calculations at low temperature we have constructed HRG models based

on different sets of open charm resonances. In addition to the HRG model that is based on all experimentally observed charmed hadrons (PDG-HRG), we also construct an HRG model based on a set of charmed hadrons calculated in a quark model (QM-HRG) where we used the charmed meson [17] and charmed baryon [18] spectrum calculated by Ebert et al.¹

One may wonder whether all the resonances calculated in a quark model exist or are stable and long-lived enough to contribute to e.g. the pressure of charmed hadrons. However, as highly excited states with masses much larger than the ground state energy in a given quark flavor channel are strongly Boltzmann suppressed, they play no significant role in thermodynamics. For this reason we also need not consider multiple charmed baryons or open charm hybrid states that have been identified in lattice QCD calculations [20,21] but generally have masses more than (0.8–1) GeV above those of the ground state resonances. We explore the impact of such heavy states by introducing different cut-offs to the maximum mass up to which open charm resonances are taken into account in the HRG model. For instance, QM-HRG-3 includes all charmed hadron resonances determined in quark model calculations that have masses less than 3 GeV.

We calculate the open charm meson ($M_C(T, \vec{\mu})$) and baryon ($B_C(T, \vec{\mu})$) pressure in units of T^4 , such that the total charm contribution to the pressure is written as $P_C(T, \vec{\mu})/T^4 = M_C(T, \vec{\mu}) + B_C(T, \vec{\mu})$. As the charmed states are all heavy compared to the scale of the temperatures relevant for the discussion of the thermodynamics in the vicinity of the QCD crossover transition, a Boltzmann approximation is appropriate for all charmed hadrons,

$$\begin{aligned} M_C(T, \vec{\mu}) &= \frac{1}{2\pi^2} \sum_{i \in \text{C-mesons}} g_i \left(\frac{m_i}{T} \right)^2 K_2(m_i/T) \\ &\quad \times \cosh(Q_i \hat{\mu}_Q + S_i \hat{\mu}_S + C_i \hat{\mu}_C), \\ B_C(T, \vec{\mu}) &= \frac{1}{2\pi^2} \sum_{i \in \text{C-baryons}} g_i \left(\frac{m_i}{T} \right)^2 K_2(m_i/T) \\ &\quad \times \cosh(B_i \hat{\mu}_B + Q_i \hat{\mu}_Q + S_i \hat{\mu}_S + C_i \hat{\mu}_C). \end{aligned} \quad (1)$$

Here, $\vec{\mu} = (\mu_B, \mu_Q, \mu_S, \mu_C)$, $\hat{\mu} \equiv \mu/T$ and g_i are the degeneracy factors for the different states with electric charge Q_i , strangeness S_i and charm C_i .

Results from calculations of open charm meson and baryon pressures using different HRG models are shown in Fig. 1. The influence of additional states predicted by the quark model is clearly visible already in the QCD crossover transition region. At T_c , differences between PDG-HRG (dashed lines) and QM-HRG (solid lines) in the baryon sector are as large as 40% while they are negligible in the meson sector. This reflects that the experimentally known meson spectrum is more complete than the baryon spectrum.

In the open charm meson sector, the well established excitations cover a mass range of about 700 MeV above the ground state D , D_s -mesons. In the charmed baryon sector much less is known, for instance, experimentally well known excitations of Ξ_c range up to 350 MeV above the ground state and in the doubly strange charmed baryon sector only two Ω_c states separated by 100 MeV are well established.

As a consequence of the limited knowledge of the charmed baryon spectrum compared to the open charm meson spectrum, the ratio of partial pressures in the baryon and meson sectors differs strongly between the PDG-HRG and the QM-HRG. This is

¹ The thermodynamic considerations presented here are mainly sensitive to the number of additional hadrons included in the calculations and not to the precise values of their masses. Thus lattice QCD results on the charmed baryon spectra [21] also lead to similar conclusions.

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