Production of $T_{cc}^+$ in heavy ion collisions

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Abstract

We study the production of heavy multiquark states in the heavy ion collisions performed at the LHC. We assume that they are produced at the end of the quark-gluon plasma phase and then interact with light hadrons during the hadron gas phase. We use the coalescence model to compute the initial multiplicities and effective Lagrangians to describe the interactions. We find that the initial multiplicity of molecules is two orders of magnitude larger than that of tetraquarks. The interactions in the hadron gas reduce the number of molecules and increase the number of tetraquarks by a factor two in each case. At kinetic freeze-out, the difference is still very large.

Keywords: Multiquark states, QCD sum rules, Effective Lagrangians, Heavy ion collisions

1. Introduction

The number of exotic hadrons keeps continuously growing. The most recently observed exotic states were announced during this conference [1] as well as the most recent review article on the subject [3]. A more complete review can be found in [4]. With this new experimental knowledge we can expect to deepen our understanding of both the QCD and hadronic interactions. Since the observation of the first exotic hadron, the $X(3872)$, in 2003, one of the main questions in the field is: which is the internal structure [5] and spatial configuration of these multiquark states? The two most accepted configurations are loosely bound hadron molecules and compact tetraquarks. This question gained a new interest after the recent discovery of $T_{cc}^+$ [6].

We may try to answer this question using the heavy ion collisions collisions performed at LHC, as suggested in [7]. In these collisions, the number of produced charm quarks is much larger than in any other type of collision. Moreover, even if the environment is much less clean than in $e^+e^-$ or in $pp$ collisions, modern techniques allow for the reconstruction of these states. The $X(3872)$ has been recently observed by the CMS collaboration in $Pb−Pb$ collisions [8]. This opens a new chapter in heavy hadron spectroscopy.

The striking new feature of heavy ion collisions is the formation of the quark gluon plasma (QGP). It introduces a new way of formation of hadrons: coalescence during the back transition to the hadron phase. This is, of course, a non-perturbative process, which can only be calculated with the help of models, such as the one presented in [7]. This model yields an interesting prediction: molecules are much more abundantly produced than tetraquarks! This is due to the fact that, at the hadronization time, the quark system has a density which is comparable to normal hadronic matter, in which three quarks occupy the typical volume of a baryon and a quark-antiquark pair occupies the volume
of a meson. At this point, two formed mesons have a typical separation of a few fermi and can easily form a molecule. In sharp contrast, the typical separation between the quarks is much larger than the size of compact tetraquarks ($\simeq 0.2 - 0.5$ fm). The quantitative implementation of these ideas requires several assumptions concerning the quark distribution in the QGP, the interactions in the bound state and its wave function. The numerical results confirm the intuitive expectation and the conclusion is that molecules would be about hundred times more abundant than tetraquarks. This prediction was first published many years ago in (see references in [7]) but a proper treatment of the hadronic interactions of the multiquark states was only developed in the most recent years. We are going to briefly discuss the subject in the next sections.

2. Interactions in a hadron gas

After being formed during the hadronization, the particles have to live for some time ($\simeq 10$ fm) in a hot hadron gas, where they interact with light mesons. These interactions can be described by effective Lagrangians. Using this approach, we have studied the interactions of the $X(3872)$ [9], the $Z_b$ [10], the $J/\psi$ [11], the $\Upsilon$ [12] and, more recently, the $T_{cc}$ [13]. Even though the Lagrangian may be the same, molecules and tetraquarks interact in a different way. The difference comes from their different sizes and it is encoded in the form factors and coupling constants. For tetraquarks, these quantities can be calculated with QCD Sum Rules (QCDSR) [14, 15]. For molecules there are models.

In [13] we compared the interactions of a “pure” molecular state with the interactions of a “pure” tetraquark state in a hadronic medium.

The molecular model was taken from [16]. In this “quasi-free” model of the $T_{cc}^+$, the $D$ and the $D^*$ are considered to just “fly” together. Both the binding energy and the interaction between these constituent mesons are neglected. They are destroyed by any elastic scattering between a $\pi$ and one of the constituent charm mesons. The advantage of this approach is that the only Lagrangian required is the one of the $D^* \to D \pi$ vertex. Fortunately the $D^* \to D \pi$ decay is measured and the coupling constant is known. As in all effective Lagrangian approaches, we need a form factor which contains a free parameter (the cut-off $\Lambda$). This is the main source of uncertainty.

In [13] we also developed the tetraquark approach. In this case the $T_{cc}^+$ is a degree of freedom, a new field appearing in the Lagrangians. We have several interaction vertices, described by Lagrangians. All of them were already known from previous studies, where with the help of QCDSR, we had computed the form factors and coupling constants [17]. The new ingredient is the $T_{cc}^+ D D^*$ vertex. In [13] we performed the QCDSR study of the relevant three-point function and determined the form factor and the coupling constant in this vertex.

With these results we could compute the absorption cross sections of $T_{cc}^+$ by pions in both the molecular and tetraquark approach. The comparison is shown in Fig. 1. As we might expect, the molecular cross section is much larger. It is then much easier (by almost two orders of magnitude) to destroy a molecule than a tetraquark. In hadronic interactions it is also easy to create the $T_{cc}^+$ in the inverse processes, such as, for example, $D^* D \to T_{cc}^+ \pi$. However, another robust conclusion of [13] valid both for molecules and tetraquarks, is that the cross section for $T_{cc}^+$ production is ten times smaller than the cross section for $T_{cc}^+$ absorption.

![Figure 1: Cross section of the process $T_{cc}^+ \pi \to X$. The “quasi-free” molecular is represented by the black solid line (the cut-off was chosen to be $\Lambda = 1$ GeV. The other bands show the results obtained with the tetraquark model. The (wider) blue and red bands show results obtained with empirical gaussian and monopole form factors (the boundaries of the bands are defined by the cut-off choices going from 1 to 2 GeV). The central (thinner) grey band shows the results obtained with form factors derived from QCDSR.](image)

Apart from the numbers, it is interesting to observe how the QCDSR calculation reduces the uncertainties. Moreover, the uncertainties in QCDSR come from quantities, such as quark masses and condensates, which can be constrained by other experiments.

3. Hadron multiplicities and system size dependence

Having computed the cross sections, we can compute the corresponding thermal cross sections and write rate equations for the abundances $N_{T_{cc}^+}$ and $N_{X(3872)^+}$. This was done in [18] and the result is shown in Fig. 2. The
initial conditions are given by the coalescence model [7]. Comparing the two panels, we see that, not surprisingly, the multiplicities of $T_c$ and $X(3872)$ evolve with time in a quite similar way and the differences come mostly from the different initial conditions. It is also natural the fact that the multiplicities decrease for molecules and increase for tetraquarks, since the latter are much less abundant. Finally, looking at these curves we can observe that the particle abundances are approaching constant values. This would mean that they are reaching the chemical equilibrium. Interestingly, the approach to equilibrium depends on the configuration and tetraquarks seem to be already in equilibrium at the end of hadron gas phase in the considered heavy ion reaction, in contrast to the molecular configuration. This raises the possibility of discriminating between the two configurations. In the example shown in the figure, if the observed value of the abundance would be close to the value predicted by the Statistical Hadronization Model (SHM) [19], then we could conclude that the particle is a tetraquark.

![Figure 2: Time evolution of the $T_c$ (upper panel) and $X(3872)$ (lower panel) abundances as a function of the proper time in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Details can be found in [18].](image)

In order to make predictions for the measurable particle abundances we would have to combine our microscopic description of the interactions with a full simulation of the underlying event, i.e., we would need a detailed code able to generate the whole heavy ion collision. However, using various pieces of experimental information, it is possible to establish a connection between the abundance of particles given by the coalescence model and the system size, represented by the charged particle density at mid-rapidity $dN/d\eta (\eta = 0)$. This was done in [18] and the result is shown in Fig. 3. As it can be seen, as we move to smaller systems (smaller values of $N$) the difference of molecule and tetraquark yields increases. This happens because smaller systems live for shorter times and there is no time for the absorption-creation dynamics to be effective enough and reduce the difference in the yields. In this sense Fig. 3 is a consequence of Fig. 2. The pattern of separating curves for smaller values of $\tau$ translates into the same pattern for smaller values of $N$. The predictions of Fig. 3 can be compared with future data. Of course, we have to keep in mind that, as the system becomes smaller, the whole description based on QGP formation looses validity.

4. Discussion and conclusion

The picture developed above received some criticism, which we review below.

A first criticism was addressed to the coalescence model \(^2\). It assumes that if the overlap between the quark spatial distribution in the final stage of the QGP and the size of the formed hadron is large, then the abundance of this hadron will be large. If this was true, the yield of $\psi(2S)$ ($r \approx 0.8$ fm) would be larger than the yield of $J/\psi$ ($r \approx 0.4$ fm). Data show the opposite! Although this argument is correct, it would be necessary to develop a theory for the interaction of the $\psi(2S)$ with light mesons. It might well be the case that these interactions would be responsible for the suppression of this particle. Moreover the sizes are not so different as in the case of multiquark states and the initial multiplicities given by the coalescence model would certainly favor the $\psi(2S)$ over the $J/\psi$, but not by a factor 100!

A second criticism is the following. In heavy ion collisions we also observe deuterons, which are the prototype of a very weakly bound hadronic system. Also, the predictions of the SHM for particle yields have been, to a large extent, confirmed. Even for deuterons, as shown in [19]. This suggests that the hot system formed in heavy ion collisions reaches chemical equilibrium.

\(^2\)We deeply grateful to S.H. Lee and to R. Rapp, for formulating this criticism so clearly.
When this happens the production yield is controlled solely by the mass, chemical potential and temperature. The details of the initial conditions and interactions are “forgotten”. How to reconcile the microscopic transport dynamics with the success of the SHM, which knows nothing about this dynamics?

If the multiquark system is a molecule, one may assume that, if it is formed in quark-hadron transition, it is completely destroyed, absorbed by the medium. Molecule production (such as the deuteron) happens only at the last moment of the hadron gas phase by hadron coalescence. Then, if the chemical and kinetical freeze-out temperatures are close enough, the predictions of the SHM and the coalescence model may coincide. However, this has to be checked.

If the multiquark system is a tetraquark, it may be formed already inside the QGP and inherit its thermal properties [20]. Then it would traverse the hadron gas almost without interacting (in a sort of “color transparency”) and emerge at the end of the collision remembering its temperature. Again, this almost non-interacting behavior of tetraquarks has to be proven. Our results, shown in Fig. 1, suggest that the interacting behavior of tetraquarks has to be proven.

To conclude, we believe that heavy ion collisions mark the beginning of a new era for the study of exotic hadrons. From the theoretical side, it is necessary to have the best possible description of the interactions of the exotic mesons in the hadron gas.

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