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Sequential regeneration of charmonia in heavy-ion collisions

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Abstract

We investigate the production of $\psi(2S)$ in nuclear collisions at RHIC and LHC energies. We first address charmonium production in 200 GeV d–Au collisions at RHIC; the strong suppression of ψ' mesons observed in these reactions indicates mechanisms beyond initial cold nuclear matter effects. We find that a more complete treatment of hadronic dissociation reactions leads to appreciable ψ' suppression in the thermal medium of an expanding fireball background for d–Au collisions. When implementing updated hadronic reaction rates into a fireball for 2.76 TeV Pb–Pb collisions at LHC, the regeneration of ψ' mesons occurs significantly later than for J/ψ's. Despite a smaller total number of regenerated ψ', the stronger radial flow at their time of production induces a marked enhancement of their R_{AA} relative to J/ψ's in a transverse-momentum range of $p_t \simeq 3$–6 GeV. We explore the consequences and uncertainties of this "sequential regeneration" mechanism on the R_{AA} double ratio and find that it can reproduce the trends observed in recent CMS data.

Keywords: Quark–gluon plasma; Charmonia; Ultrarelativistic heavy-ion collisions

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1. Introduction

Charmonium production in ultra-relativistic heavy-ion collisions (URHICs) has been studied for over 30 years. The originally proposed J/ψ suppression signature of Quark–Gluon Plasma (QGP) formation [1] has evolved into a more complex problem where both suppression and so-called regeneration (or statistical hadronization) mechanisms need to be considered. Their interplay and relevance depend on collision energy, system size and the 3-momentum of the measured charmonia, see, e.g., Refs. [2–4] for recent reviews. The phenomenological modeling of these mechanisms, and their relation to the underlying in-medium properties, has progressed significantly in recent years. In particular, kinetic transport approaches, when calibrated with existing data from SPS and RHIC, have predicted the main features of the J/ψ production observed in the new energy regime at the LHC [5–7] (although significant uncertainties due to, e.g., the open-charm cross section persist [8]). These include the overall increase of the nuclear modification factor, R_{AA}, compared to RHIC energies and its enhancement at low transverse momentum, p_t [9].

Much less is known about the $2S$ excited state, $\psi'(3686)$. Its small "binding" energy of about 45 MeV (relative to the $D\bar{D}$ threshold) renders controlled theoretical calculations of its in-medium properties (binding energy and inelastic reaction rates) challenging. Experimentally, the ψ' over J/ψ ratio has been measured at the SPS [10], where it was found to drop by up to a factor of 3 in central 17.3 GeV Pb–Pb collisions. This is consistent with the statistical hadronization approach [11], but it can also be explained by transport approaches with large inelastic reaction rates of the ψ' in the hadronic phase [12,13]. More recently, ψ' data have become available for 0.2 TeV d–Au collisions at RHIC [14] and 5.02 TeV p–Pb collisions at LHC [15]. ψ' mesons were found to be significantly more suppressed than J/ψ mesons, which is difficult to reconcile with initial cold-nuclear-matter (CNM) effects since the passing time of the highly Lorentz-contracted incoming nuclei is much smaller than the formation time scale of the charmonia. Consequently, final-state effects have been put forward to explain these data, e.g., using the comover suppression model [16]. The latter achieves a good description of the collision energy and rapidity dependence of ψ' and J/ψ production in d–Au and p–Pb collisions including expected shadowing effects on the parton distribution functions (see also Ref. [17]).

However, rather unexpected results have emerged from recent measurements by the CMS collaboration [18] for the double-ratio of the nuclear modification factor, R_{AA}, of ψ' over J/ψ in 2.76 TeV Pb–Pb collisions at the LHC (preliminary results are also available from ALICE [19]). At slightly forward rapidities, $1.6 < |y| < 2.4$, and for transverse momenta $3 < p_t < 30$ GeV, this double ratio is around $0.9 \pm 0.45 \pm 0.3$ for semi-central collisions (similar for peripheral ones), but significantly exceeds one for central collisions, $2.3 \pm 0.5 \pm 0.35$. Especially the latter has evaded any model explanations thus far, see, e.g., the detailed studies in Ref. [20]. On the other hand, around midrapidity, and for momenta $6.5 < p_t < 30$ GeV, a double ratio of around $\sim$0.5 is found, which is much more in line with common expectations of a stronger suppression of ψ' due to its much weaker binding relative to the J/ψ.

In the present paper we put forward a potential mechanism to (partially) resolve the above "puzzle". Based on the rather large inelastic reaction rates for the ψ' in hadronic matter that we deduce from its suppression in d–Au (also in line with the aforementioned SPS data), we argue that the inverse reactions of ψ' formation in Pb–Pb collisions must also happen in the later, hadronic stages of the fireball evolution. In particular, the ψ' regeneration processes happen later than those for the J/ψ whose much larger binding energy leads to an earlier "freezeout" than for the ψ'. A consequence of such a "sequential freezeout" is that the collective expansion velocity