PHYSICAL REVIEW C **85**, 064911 (2012)

J/ψ suppression in a dense baryonic medium

Partha Pratim Bhaduri, A. K. Chaudhuri, and Subhasis Chattopadhyay
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India
(Received 15 May 2012; published 15 June 2012)

We have examined the available latest super proton synchrotron (SPS) data on J/ψ suppression in Pb + Pb and In + In collisions at 158 A GeV. Our employed model, with parameters fixed by p-p and p-nucleus collisions, gives excellent description of NA50 and NA60 data on the centrality dependence of J/ψ suppression. The model is then applied to predict the centrality dependence of J/ψ production in Au + Au collisions in the facility for anti-proton and ion research (FAIR) energy domain. A much larger suppression of J/ψ is predicted. In addition the possible effects of a baryon-rich medium on J/ψ production is also investigated.

DOI: 10.1103/PhysRevC.85.064911 PACS number(s): 25.75.−q, 12.38.Mh

I. INTRODUCTION

J/ψ suppression has long been recognized as an important signature for the occurrence of color deconfinement in nuclear collisions. If quark-gluon-plasma (QGP) is produced in the collision zone, the $c\bar{c}$ binding potential gets shielded by Debye screening of colored partons, leading to the reduction in the J/ψ yield [1,2]. However, subsequent experimental investigations have revealed a considerable suppression of the charmonium production already present in proton-nucleus ($p + A$) collisions, where QGP or more generally formation of any secondary medium is not expected. In these reactions, the produced $c\bar{c}$ pair may interact with the cold nuclear medium of the target nucleus, hindering the formation of a bound state. To quantify the nuclear effects, data for different target nuclei are conventionally analyzed in the framework of the Glauber model [3], and the suppression is expressed in terms of an effective "absorption" cross section $\sigma^{\rm eff}_{J/\psi}$. When studying J/ψ suppression in nucleus-nucleus ($A + A$) collisions, a precise knowledge of nuclear effects is an essential prerequisite to disentangling the genuine hot-medium effects. With this approach, both NA50 and NA60 Collaborations at super proton synchrotron (SPS) observed significant anomalous suppression of J/ψ yield at 158 A GeV in Pb + Pb [4] and In + In [5] collisions respectively. Though the Pb + Pb data were found to be well explained by a variety of models [6–12], with or without incorporating a deconfinement scenario, none of them satisfactorily reproduced the NA60 data. The theorized origin of the additional suppression thus remained unsolved and debated. However, in both the measurements, the corresponding value of $\sigma^{\rm eff}_{J/\psi}$ was extracted from the data collected in $p + A$ collisions at 400 GeV [13]. With the new measurements of charmonium in $p + A$ collisions at 158 GeV [14], where $\sigma^{\rm eff}_{J/\psi}$ turned out to be almost twice as large as that at 400 GeV, the NA60 experiment reported the relative charmonium yield in In + In collisions to be compatible within errors with absorption in cold nuclear matter; an anomalous suppression of about 25–30% still remains visible in the most central Pb + Pb collisions.

No measurement exists on J/ψ production in heavy-ion collisions below the top SPS energy, primarily because of their low production cross sections. Researchers at the Compressed Baryonic Matter (CBM) experiment at facility for anti-proton and ion research (FAIR) [15], in GSI, Germany, plan to perform a detailed study of charmonium production in nuclear collisions, at beam energies $E_b = 10$–40 A GeV. The J/ψ mesons produced at an early stage of the collisions might help in characterizing the confining status of the highly compressed baryonic medium, predicted to be produced in these collisions. In our earlier work [16], we made an estimate of J/ψ production cross sections in proton-induced collisions at FAIR. For our study we employed and adapted the two-component QCD-based nuclear absorption model. Originally proposed by Qiu *et al.* [17], the model treats conventional normal nuclear suppression in an unconventional manner. Model parameters were tuned by analyzing the available data for inclusive J/ψ cross sections in high-energy proton-proton and proton-nucleus collisions. The aim of the present paper is to extend our studies further to calculate the centrality dependence of J/ψ production in nuclear collisions at FAIR. In addition, the possible impact of a high-baryon-density secondary medium (confined or deconfined), expected to be produced as a result of the collision, is also investigated.

II. BRIEF DESCRIPTION OF THE MODEL

In our employed model, J/ψ production in high-energy hadronic collisions is assumed to be a factorizable two-step process: (i) formation of the $c\bar{c}$ pair, which is well accounted for by perturbative QCD and (ii) formation of J/ψ meson from the $c\bar{c}$ pair, which is nonperturbative in nature. At the leading order in α_s, the partonic contributions to $c\bar{c}$ production come from two subprocesses: quark annihilation ($q\bar{q} \rightarrow c\bar{c}$) and gluon fusion ($gg \rightarrow c\bar{c}$). With the K factor accounting for effective higher order contributions, the single differential J/ψ production cross section in collisions of hadrons h_1 and h_2 at the center of mass energy $\sqrt{s}$ can be expressed as

$$\frac{d\sigma^{J/\psi}_{h_1h_2}}{dx_F} = K_{J/\psi} \int dQ^2 \left(\frac{d\sigma^{c\bar{c}}_{h_1h_2}}{dQ^2 dx_F} \right) \times F_{c\bar{c}\rightarrow J/\psi}(q^2), \qquad (1)$$

where $Q^2 = q^2 + 4m_C^2$, with m_C being the mass of the charm quark, and x_F is the Feynman scaling variable. $F_{c\bar{c}\rightarrow J/\psi}(q^2)$ is the transition probability that a $c\bar{c}$ pair with relative momentum square q^2 evolves into a physical J/ψ meson in hadronic collisions. Different parametric forms have been formulated for the transition probability following the existing models of color neutralization. Out of them, two functional forms, namely the Gaussian form $[F^{(G)}(q^2)]$ and power law form $[F^{(P)}(q^2)]$, respectively bearing the essential features of the color-singlet [18] and color-octet [19] models, have been found to describe the J/ψ production cross-section data in $p+A$ collisions reasonably well. In $p+A$ collisions, charmonium production gets affected by the prevailing cold nuclear matter of the target nucleus. At the initial stage, nuclear modifications of the parton densities inside the target nucleus affect the perturbative $c\bar{c}$ pair production cross section. In our analysis, the leading-order MSTW2008 [20] set was used for the free-proton pdf and EPS09 [21] interface for the ratio $R_i(A,x,Q^2)$, which converts the free-proton distributions for each parton i, $f_i^p(x,Q^2)$, into nuclear ones, $f_i^A(x,Q^2)$. In nucleus-nucleus collisions, parton densities are modified inside both the projectile and target nuclei. Depending on the collision geometry, either the halo or the core of the nuclei will be mainly involved, and the resulting shadowing effects will be more important in the core than in the periphery. Hence, the shadowing factors have to be calculated for various centrality intervals. Assuming shadowing is proportional to the local nuclear density [22,23], the spatial dependence is defined as

$$R_{i,\rho}(A,x,Q^2,\mathbf{s},z) = 1 + N_\rho^A[R_i(A,x,Q^2) - 1]\frac{\rho_A(\mathbf{s},z)}{\rho_0}, \tag{2}$$

where normalization N_ρ^A is fixed to ensure that $(1/A)\int d\mathbf{s}dz R_{i,\rho}(A,x,Q^2,\mathbf{s},z) = R_i(A,x,Q^2)$. At large radii, $r[=\sqrt{(s^2+z^2)}] \gg R_A$ and $R_{i,\rho} \to 1$, while at the nuclear center, the modifications are larger than the average R_i.

Once produced, the nascent $c\bar{c}$ pairs interact with nuclear medium and gain relative square momentum at the rate of ε^2 per unit path length inside the nuclear matter. As a result, some of the $c\bar{c}$ pairs can gain enough momentum to cross the threshold to become open charm mesons, leading to the reduction in J/ψ yield compared to the nucleon-nucleon collisions. For both parametrizations of transition probability, the corresponding values of ε^2, extracted from the analysis of $p+A$ collision data [16], exhibited nontrivial beam energy dependence. As the beam energy is lower, the value of ε^2 becomes larger. In the present work, we have used the previously found ε^2 values.

III. ANALYSIS OF SPS DATA

Let us now test the applicability of the model in describing the heavy-ion data on J/ψ suppression at SPS. Figure 1 shows the variation of $R_{AA}^{J/\psi}$ as a function of $N_{\rm part}$ for In + In and Pb + Pb collisions as calculated from our model in comparison with the latest available data [24]. The In + In data points can be reasonably described within errors by both Gaussian $[F^{(G)}(q^2)]$ as well as power law $[F^{(P)}(q^2)]$ forms of transition probability. In the case of Pb + Pb collisions, $F^{(G)}(q^2)$ gives less suppression than that observed in data. However, $F^{(P)}(q^2)$ can fairly describe the data for all centralities and hence does not provide any additional room for any anomalous suppression mechanism to set in. For $F^{(G)}(q^2)$, the corresponding suppression is equivalent to that obtained in the first-order approximation of the Glauber theory [16]. The corresponding value of ϵ^2 was obtained by analyzing the recent NA60 data for $p+A$ collisions at 158 A GeV. Thus, it can account for the In + In data but fails to generate enough suppression for the Pb + Pb case. On the other hand, due to the threshold effect, the power law form generates a much stronger suppression for collisions involving heavy nuclei. As all the model parameters are constrained from the $p+p$ and $p+A$ data, in our present calculations, no free parameter is required to be tuned. The observed J/ψ suppression in Pb + Pb collisions can be fully accounted for by the heavy quark rescattering in the cold nuclear medium, without considering further suppression in the hot medium created in the later expansion stages. Earlier the model has also been found successful in describing the then-available NA50 data on J/ψ suppression in Pb + Pb collisions [10]. However, in those studies shadowing corrections to nuclear

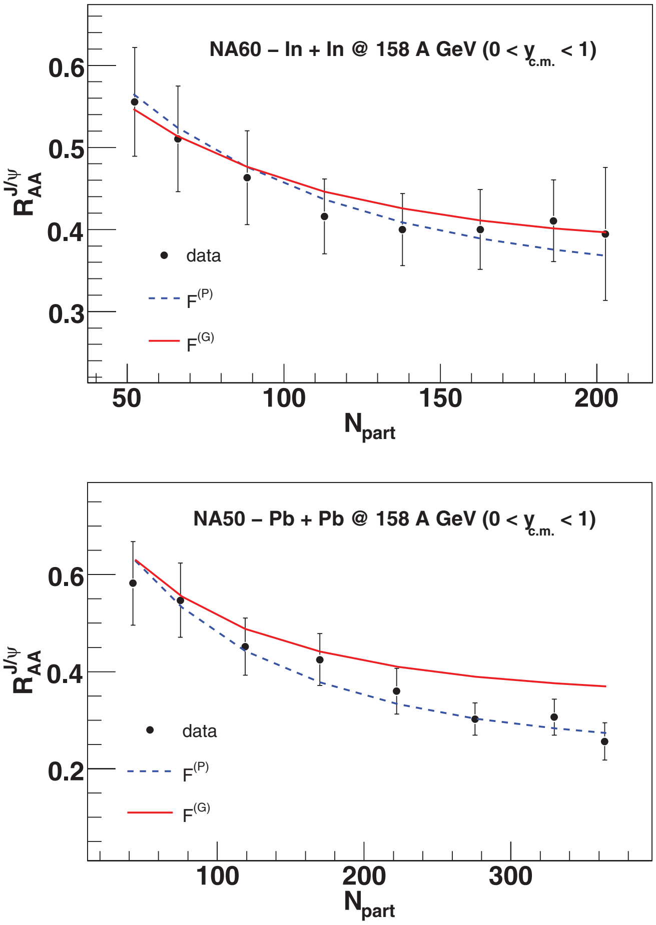

FIG. 1. (Color online) Centrality dependence of J/ψ production in In + In (top) and Pb + Pb (bottom) collisions measured at same energy ($E_b = 158$ A GeV) and kinematic domain ($0 < y_{\rm c.m.} < 1$). Data are represented in terms of nuclear modification factor R_{AA} plotted as a function of $N_{\rm part}$ estimating the collision centrality. Error bars include both statistical and systematic uncertainties. Two different parametric forms of the transition function are used for generating the theoretical curves.

parton densities were ignored and E_T fluctuations had to be explicitly incorporated, through a tunable parameter, for better reproduction of the data at large E_T.

IV. PREDICTIONS FOR FAIR ENERGIES

Our ultimate goal is to estimate the J/ψ yield in nuclear collisions at energies relevant to those available at FAIR. For this purpose, we now use our model with the power law form of transition probability $[F^{(P)}(q^2)]$ to calculate the centrality dependence of $R_{AA}^{J/\psi}$ for Au + Au reactions at a bombarding energy 25 A GeV. Previous predictions of J/ψ survival probability at this energy were made within transport model calculations [25]. Nuclear effects were incorporated through conventional Glauber suppression scenario. For simulating the anomalous suppression, two different scenarios, namely QGP threshold melting and hadronic comover absorption, were independently studied. For partonic scenario, a variant of the geometrical threshold model [6] was used with different melting energy densities for different charmonium states. For the hadronic dissociation, inelastic collisions with different mesons were considered. However, in those calculations, the magnitude of the cold nuclear matter (CNM) effects at FAIR is possibly underestimated as the value of effective absorption cross section was taken from the $p + A$ measurements at 400 GeV. Our present estimates predict a much larger nuclear suppression. Note that the degree of suppression induced by cold nuclear matter strongly depends on the passing time, $t_d = 2R_A/\gamma$, of the two colliding nuclei, where R_A is the nuclear radius and γ is the Lorentz contraction factor. At SPS energy ($E_{\rm c.m.} \simeq 17.3$ GeV) the collision time is about 1 fm/c and the magnitude of nuclear effects is large. At FAIR energies, the collision time ($t_d \simeq 3$ fm/c) is much longer and the J/ψ mesons during their evolution will mostly encounter the (primary) nuclear medium rather than any secondary medium formed eventually due to the collision. Hence, nuclear suppression will possibly play the most prominent role to govern the overall suppression pattern and we refrain from considering any probable additional suppression due to mesonic comovers. However, at FAIR energy regime, formation of highly compressed baryonic matter at low temperature is anticipated. Monte Carlo simulations [26] indicate the maximum baryon density in a central ($b = 0$) Au + Au collision at FAIR energy to reach as high as $\rho_B = 10\rho_0$. Thus, the possible imprint of such a high-density medium on J/ψ production might be worth investigating. Since J/ψ formation time ($\tau_{J/\psi} \simeq 0.5$ fm/c) is small compared to that required for the formation of any secondary medium, the highly compressed medium will most likely encounter the color-neutral physical mesons rather than their precursors. The additional suppression induced by a confined baryon dense medium can be schematically expressed as

$$S_{J/\psi}^{\rho_B}(\mathbf{b},\mathbf{s}) = exp\left(-\int_{\tau_0}^{\tau_I} d\tau \rho_B(\mathbf{b},\mathbf{s},\tau) < v\sigma_{J/\psi-N} >\right). \quad (3)$$

In the above equation, $\sigma_{J/\psi-N} = 6.8$ mb [27] is the average inelastic cross section of the nucleons with the already formed J/ψ, $v \simeq 0.6$ [2] is J/ψ velocity and $\rho_B(\mathbf{b},\mathbf{s},\tau)$ is the net baryon density at proper time τ at the J/ψ position. Following Ref. [28], the spatial dependence of the net baryon number density is set with the transverse profile of the participant density, obtained in a Glauber model. τ_0 and τ_I respectively denote the medium formation time and the interaction time up to which J/ψ will continue interacting with the medium. Both of them will depend on the path length through the nucleus and can be obtained from Ref. [2]. The evolution of baryon density with proper time τ can be followed from the equation for conservation of net baryonic current. If we neglect the transverse expansion (assuming that transverse expansion is slow and J/ψ suppression occurs much before the transverse expansion sets in), we are left with $\tau_0\rho_B(\tau_0) = \tau\rho_B(\tau)$.

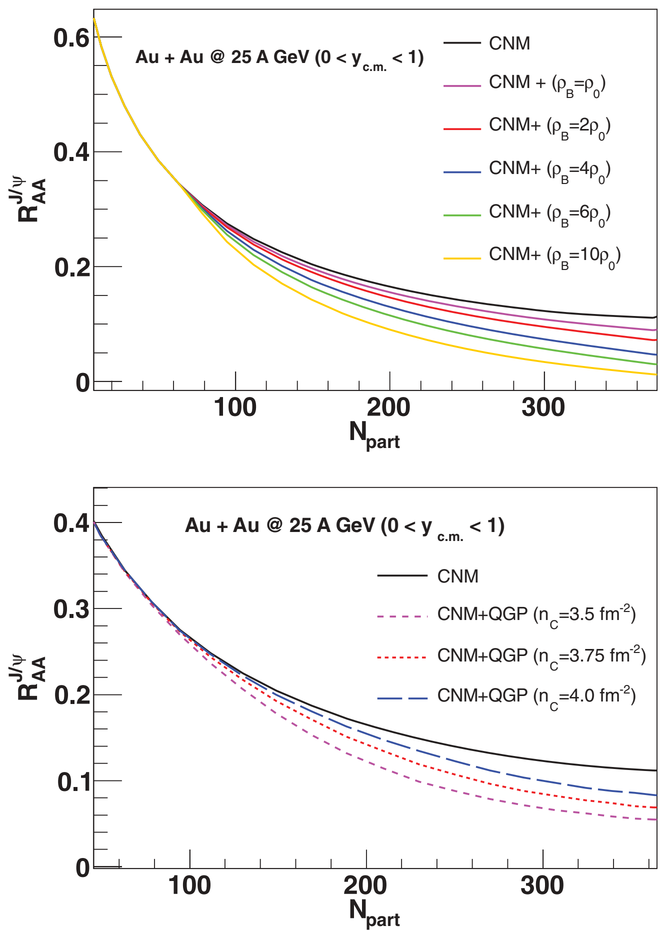

FIG. 2. (Color online) Centrality dependence of J/ψ suppression at 25 A GeV Au + Au collisions. In addition to nuclear effects, additional suppressions due to high-baryon-density (a) confined medium (top) and (b) deconfined medium (bottom) are also shown.

The suppression pattern induced by a confined compressed baryonic medium is then shown in the top panel of Fig. 2. Calculations are performed for different peak densities varying from ρ_0 to $10\rho_0$. As the density is greater, the suppression becomes more violent. If the maximum density of the produced medium is as high as $10\rho_0$, $R_{AA}^{J/\psi}$ approaches to zero and almost no J/ψ will survive. However, if such high density is achieved in the initial phase of the collision, deconfinement might set in, resulting in a phase governed by partonic degrees of freedom.

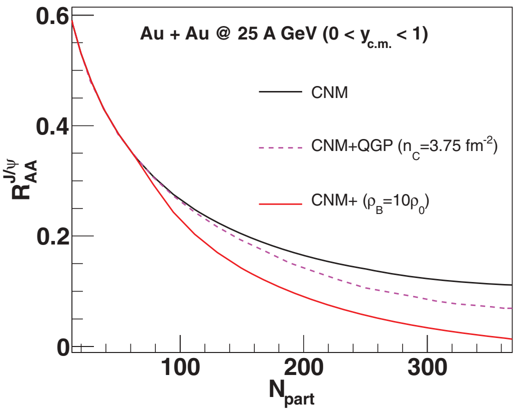

FIG. 3. (Color online) Comparison of the two different scenarios of J/ψ suppression in a compressed baryonic medium.

In a partonic phase, the J/ψ will interact differently with the medium. The interaction potential binding the c and $\bar{c}$ together will be subject to Debye screening induced by the free color charges. To mimic the suppression pattern in a deconfined plasma, we follow the geometrical threshold model [6], without considering the detailed microscopic dynamics. In this model the J/ψ suppression function, at an impact parameter b, can be written as

$$S_{J/\psi}^{\rm QGP}(b) = \int d^2\mathbf{s}\Theta[n_c - n_p(b,\mathbf{s})]. \quad (4)$$

The density $n_p(b,\mathbf{s})$ in the step function is proportional to the local energy density of the matter at position $(b,\mathbf{s})$. In the hot and dense part of the fireball where n_p is larger than a critical or threshold value n_c, all the J/ψ are absorbed in the medium and those outside this region only suffer normal suppression. The threshold density n_c in this model is a parameter, generally fixed from the data. However, it has been observed earlier that a critical density $n_c \simeq 3.6 - 3.7$ fm^{-2} can reasonably describe both the data sets from SPS [7,9] and RHIC [29]. n_c can be thought of as proportional to the threshold dissociation energy density ($\epsilon_d^{J/\psi}$) required for melting of J/ψ. If we assume a constant value of critical energy density ($\epsilon_c \simeq 1$GeV/fm^3), independent of baryon chemical potential μ_B, required for deconfinement transition, then by analogy the threshold dissociation energy density ($\epsilon_d^{J/\psi}$) and consequently the critical participant density, n_c, can be assumed to be constant. The right panel of Fig. 2 represents the behavior of $R_{AA}^{J/\psi}$ for three illustrative cases with three different critical densities. As the critical density becomes smaller, the energy density required for J/ψ melting is lower and the suppression is greater. We end this section by comparing these two different mechanisms of anomalous suppression. For this purpose we consider two illustrative cases: (a) confined baryonic medium with highest possible net baryon density ($\rho_B = 10\rho_0$) and (b) deconfined medium with approximately constant threshold energy (and hence participant) density. The results are shown in Fig. 3. Two different mechanisms produce distinguishably different amounts of suppression. In a confined high-baryon-density medium, dissociation is more severe compared to that in the QGP phase. Thus measurement of J/ψ production in nuclear collisions at FAIR might also furnish valuable information about the phase structure and the relevant degrees of freedom in such a high-baryon-density environment.

V. SUMMARY

In summary, we have estimated the J/ψ production and its possible interactions in a high-baryon-density medium anticipated in low-energy nuclear collisions at FAIR. Our model satisfactorily describes the J/ψ suppression data in heavy-ion collisions at SPS, with model parameters being fixed from $p + p$ and $p + A$ data. At FAIR, exogamous production in both the partonic and hadronic phases is expected to be small and the primordial production will dominate the overall J/ψ yield. Consequently such measurements will offer us an opportunity to exactly trace out the possible suppression pattern, which will not get masked by the subsequent regeneration. Moreover, at low energies, collision time is much longer, the lifetime of the produced medium is much shorter, and nuclear effects start playing a dominant role in deciding the observed charmonium yield. Even at SPS, the magnitude of the nuclear effects, in our employed framework, is substantially large to fully account for the observed J/ψ suppression in Pb + Pb collisions. At FAIR, effects of the cold nuclear matter will be further amplified, leading to a strong reduction of the J/ψ yield in most central collisions. The fully formed J/ψ mesons surviving the nuclear dissociation can subsequently interact with the produced high-density medium and undergo further suppression. The degree as well as the mechanism of this additional suppression depends on the net baryon density achieved in the collision and the confining status of the medium.

ACKNOWLEDGMENTS

The authors would like to thank R. Vogt, R. Arnaldi, P. Tribedy, S. Sarkar, and E. Oset for their cooperations and many stimulating discussions.

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[2] R. Vogt, Phys. Rep. **310**, 197 (1999).
[3] R. J. Glauber, *Lectures on Theoretical Physics* (Interscience, New York, 1959), Vol. I.
[4] B. Alessandro *et al.* (NA50 Collaboration), Eur. Phys. J. C **39**, 335 (2005).
[5] R. Arnaldi *et al.* (NA60 Collaboration), Phys. Rev. Lett. **99**, 132302 (2007).
[6] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).
[7] J. P. Blaizot, P. M. Dinh, and J. Y. Ollitrault, Phys. Rev. Lett. **85**, 4012 (2000).
[8] A. Capella, E. G. Ferreiro, and A. B. Kaidalov, Phys. Rev. Lett. **85**, 2080 (2000).
[9] A. K. Chaudhuri, Phys. Rev. C **64**, 054903 (2001); Phys. Lett. B **527**, 80 (2002).
[10] A. K. Chaudhuri, Phys. Rev. Lett. **88**, 232302 (2002).

[11] A. K. Chaudhuri, Phys. Rev. C **66**, 021902 (2002).
[12] L. Grandchamp, R. Rapp, and G. E. Brown, Phys. Rev. Lett. **92**, 212301 (2004).
[13] B. Alessandro *et al*. (NA50 Collaboration), Eur. J. Phys. **48**, 329 (2006).
[14] E. Scomparin *et al*. (NA60 Collaboration), Nucl. Phys. A **830**, 239C (2009).
[15] P. Senger, Nucl. Phys. A **862–863**, 139 (2011).
[16] P. P. Bhaduri, A. K. Chaudhuri, and S. Chattopadhyay, Phys. Rev. C **84**, 054914 (2011).
[17] J. Qiu, J. P. Vary, and X. Zhang, Nucl. Phys. A **698**, 571 (2002); Phys. Rev. Lett. **88**, 232301 (2002).
[18] C.-H. Chang, Nucl. Phys. B **172**, 425 (1980); E. L. Berger and D. Jones, Phys. Rev. D **23**, 1521 (1981); R. Baier and R. Rückl, Phys. Lett. B **102**, 364 (1981).
[19] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995).
[20] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. C **63**, 189 (2009); **64**, 653 (2009); **70**, 51 (2010).
[21] K. J. Eskola, H. Paukkunen, and C. A. Salgado, J. High Energy Phys. 04 (2009) 065.
[22] S. R. Klein and R. Vogt, Phys. Rev. Lett. **91**, 142301 (2003).
[23] V. Emel'yanov *et al*., Phys. Rev. C **59**, 1860 (1999).
[24] R. Arnaldi, [http://www2.physik.uni-bielefeld.de/quarkonia.html].
[25] O. Linnyk, E. L. Bratkovskaya, W. Cassing, and H. Stocker, Nucl. Phys. A **786**, 183 (2007).
[26] I. C. Arsene *et al*., Phys. Rev. C **75**, 034902 (2007).
[27] R. Molina, C. W. Xiao, and E. Oset, arXiv:1203.0979 [nucl-th].
[28] P. F. Kolb, U. Heinz P. Huovinen, K. J. Eskola, and K. Tuominen, Nucl. Phys. A **696**, 197 (2001).
[29] A. K. Chaudhuri, Phys. Rev. C **75**, 044902 (2007).