Interaction of slow J/ψ and ψ' with nucleons

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The interaction of the charmonium resonances J/ψ and ψ' with nucleons at low energies is considered using the multipole expansion and low-energy theorems in QCD. A lower bound is established for the relevant gluonic operator average over the nucleon. As a result we find the discussed interaction to be significantly stronger than previously estimated in the literature. In particular we conclude that the cross section of the J/ψ - nucleon elastic scattering at the threshold is very likely to exceed 17 mb and that existence of bound states of the J/ψ in light nuclei is possible. For the ψ' resonance we estimate even larger elastic scattering cross section and also a very large cross section of the process $\psi' + N \to \psi + N$ giving rise to the decay width of tens of MeV for the ψ' resonance in heavy nuclei.

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I. INTRODUCTION

Understanding the charmonium interaction with nuclear matter is important for description of the photo- and hadroproduction of charmonium and charmed hadrons on the nuclear targets as well as for diagnostics of the hadronic final states in heavy-ion collisions and search for Quark Gluon Plasma. Such interaction has been a subject of numerous studies with a broad range of theoretical predictions.

First perturbative QCD calculations [1,2] predicted very small J/ψ dissociation cross section by hadrons, on the order of few μbarn. Such small dissociation cross section supports the prediction [3–5] that a strong J/ψ suppression is generated by the QGP formation. Indeed, a strong J/ψ suppression was observed later in relativistic heavy-ion collisions [6]. On the contrary, an alternative explanation [7–11] of the suppression requires a substantial strength of the hadronic interaction of J/ψ, corresponding to a scattering cross section on the order of few millibarn. With all the great interest to the problem of charmonium interaction with nucleons and nuclear matter and its practical importance, the discussion of this interaction is still wide open. In particular, the estimates of the strength of the interaction of J/ψ and ψ' with the nucleon range, in terms of the scattering cross section at low energy, from a fraction of millibarn [4,12] up to 10 mb or more [13–15]. Recent reviews of the subject and further references can be found in the Refs. [16–18].

In many of these applications the most interesting energy region is usually well above the threshold, where the complexity of the problem becomes more confounding due to the multitude of possible inelastic processes contributing to charmonium scattering on nuclear matter. However the strength of the interaction at energy close to the threshold is also measurable [13] and its reliable estimate can serve as a useful reference point for analyses of the behavior of the interaction at higher energies. Furthermore, the J/ψ and ψ' interactions at low energies are of explicit importance for high energy heavy-ion collisions since the relative motion between the comoving charmonium and nuclear matter is rather slow. In that case the charmonium scattering in hadronic gas is given by the strength of the J/ψ and ψ' elastic interactions and might be related to the transverse momentum component of the charmonium spectra. Moreover the forward elastic scattering amplitude can be related to J/ψ and ψ' mass shift in matter predicted by a number of models [19–22].

Here we consider the interaction of the J/ψ and ψ' resonances with nucleons and the nuclear matter at energies where the fewest inelastic processes are kinematically allowed. For the J/ψ interaction with a nucleon in this region only the elastic scattering contributes below the threshold of the lowest essential inelastic charm-exchange channel $J/\psi + N \to \Lambda_c + \bar{D}$ at $\sqrt{s} \approx 4.15$ GeV. The subthreshold process $J/\psi + N \to \eta_c + N$ should be significantly suppressed due to the heavy quark spin-flip, and is entirely neglected in this study. For the ψ' scattering, in addition to the elastic and the charm-exchange processes, there always is the essential subthreshold process $\psi' + N \to J/\psi + N$, which is included in our discussion here.

The low-energy interaction of a heavy quarkonium with soft hadrons is mediated by soft gluonic field, which should be treated nonperturbatively. In this situation a use is made of the fact that the charmonium is a relatively compact object in the scale set by Λ_{QCD}, so that its interaction with soft gluons can be expanded in multipoles [23,24]. The leading term in this expansion arises from the double $E1$ interaction with the chromo-electric component of the gluonic field, and the heavy quarkonium part of this interaction can be parametrized in terms of the quarkonium chromo-polarizability. The coupling of the soft gluonic fields to light hadrons, specifically to the nucleons, at a low momentum transfer is determined by the low-energy theorem in QCD based on the anomaly in the trace of the energy- momentum tensor. Using this approach we find a lower bound for the average value over the nucleon of the square of the chromo-electric field, and we also argue that the actual average value should be close to the lower bound. It can be mentioned that an application of a similar approach[25,26] to hadronic transitions in charmonium $\psi' \to J/\psi\pi\pi$ and bottomonium $\Upsilon' \to \Upsilon\pi\pi$ is known to be in a good agreement with the data [27].

The paper is organized as follows. In Sec. II we discuss the chromo-polarizability of the charmonium states, which arises within the multipole expansion in QCD used for description of the properties of heavy quarkonium states and transitions between them. In Sec. III we relate the discussed scattering amplitudes to the chromo-polarizability and to the matrix element of the square of the chromo-electric field over nucleon. The latter matrix element is described by the low-energy theorem following from the conformal anomaly in QCD. In Sec. IV the threshold limit of the J/ψ - nucleon scattering amplitude is considered and estimated in terms of the scattering length, the cross section, and the average potential energy of J/ψ in nuclear matter. The same characteristics are considered in Sec. V for the ψ' - nucleon interaction, with the addition of the inelastic subthreshold process $\psi' + N \to J/\psi + N$, which also contributes to decay of the ψ' in nuclear matter. Finally, Sec. VI contains our concluding remarks.

II. CHARMONIUM CHROMO-POLARIZABILITY

The leading $E1$ term in the multipole expansion for the interaction of a heavy quarkonium with soft gluon field has the form [23,24]

$$H_{E1} = -\frac{1}{2}\xi^a \vec{r} \cdot \vec{E}^a(0), \tag{1}$$

where $\xi^a = t_1^a - t_2^a$ is the difference of the color generators acting on the quark and antiquark, e.g. $t_1^a = \lambda^a/2$ with λ^a being the Gell-Mann matrices, and $\vec{r}$ is the vector for relative position of the quark and the antiquark. We use here the normalization for the gluon field where the QCD coupling g is included in the definition of the field, so that e.g. the gluon field Lagrangean reads as $L = -(F_{\mu\nu}^a)^2/(4g^2)$. The amplitude of the transition between S-wave states A and B of the heavy quarkonium in the second order in H_{E1} can then be written in terms of the effective operator

$$\langle B|H_{\rm eff}|A\rangle = -\frac{1}{2}\alpha_{AB}\vec{E}^a \cdot \vec{E}^a, \tag{2}$$

where the nonrelativistic normalization is used for the quarkonium states, and α_{AB} is the chromo-polarizability, which can be found as

$$\alpha_{AB} = \frac{1}{48}\langle B|\xi^a r_i G_A r_i \xi^a|A\rangle. \tag{3}$$

Here G_A is the Green's function for a heavy quark pair in color-octet (adjoint) state. This Green's function is not well understood presently, therefore a theoretical calculation of the chromo-polarizability is at least highly model-dependent. In the rest of the paper a slightly simplified notation is used, where the diagonal amplitudes are written with a single rather than a double subscript, i.e. α_A instead of α_{AA}.

The value of the chromo-polarizability for the transition $\psi' \to J/\psi$, namely $\alpha_{\psi' J/\psi}$, determines the amplitude of the decay $\psi' \to J/\psi\pi\pi$ [25], and can thus be found [28] from the known decay rate: $|\alpha_{\psi' J/\psi}| \approx 2\ \mathrm{GeV}^{-3}$.

The diagonal values $\alpha_{J/\psi}$ and $\alpha_{\psi'}$ are presently unknown These can be measured experimentally in the decays $J/\psi \to \ell^+\ell^-\pi^+\pi^-$ and $\psi' \to \ell^+\ell^-\pi^+\pi^-$ with soft pions [28]. It is however natural to expect that each of the diagonal amplitudes should be somewhat larger than the transition amplitude. Since the polarizability grows with the spatial size of the system, it is also natural to expect that this parameter is larger for ψ' than for the J/ψ, $|\alpha_{\psi'}| > |\alpha_{J/\psi}|$. The general restrictions on the diagonal amplitudes arise from the fact that in the Green's function in Eq. (3) there are no intermediate states with mass below ψ', so that both $\alpha_{J/\psi}$ and $\alpha_{\psi'}$ are real and positive, and their values satisfy the inequality:

$$\alpha_{\psi'}\alpha_{J/\psi} \geq |\alpha_{\psi' J/\psi}|^2. \tag{4}$$

Naturally, this inequality implies that at least one of the diagonal amplitudes is larger than the transition one, although this statement is of course weaker than the natural expectation that each of the discussed diagonal chromo-polarizabilities exceeds the known value of $|\alpha_{\psi' J/\psi}|$.

Given these estimates, we use the value $2\ \mathrm{GeV}^{-3}$ as a reference for the discussed parameters $\alpha_{J/\psi}$ and $\alpha_{\psi'}$, keeping in mind that their actual values can be somewhat larger, especially that of $\alpha_{\psi'}$.

It should be noted that our "reference" value significantly exceeds the estimate of $\alpha_{J/\psi}$ by Kaidalov and Volkovitsky [12]. In that estimate they used the approach [2] based on essentially a Coulomb-like model for charmonium wave functions, and their result can be written as $\alpha_{J/\psi} = \frac{28}{81}\pi a^3$, where a is the size parameter for charmonium (the Bohr radius in the Coulomb-like model), for which they used $a = 0.8\ \mathrm{GeV}^{-1}$. Numerically, their estimate corresponds to $\alpha_{J/\psi} \approx 0.6\ \mathrm{GeV}^{-3}$, which we believe is too low, given the arguments presented above and the known value of the transition amplitude $\alpha_{\psi' J/\psi}$.

III. THE NUCLEON MATRIX ELEMENT

The effective operator in Eq. (2) can be directly used for calculating the amplitude of the scattering of the heavy quarkonium on a nucleon $A + N \to B + N$ in terms of the matrix element of the gluon operator $\vec{E}^a \cdot \vec{E}^a$ over the nucleon:

$$\mathcal{T}_{AB} = 2\sqrt{M_A M_B}\alpha_{AB}\langle N|\frac{1}{2}\vec{E}^a\cdot\vec{E}^a|N\rangle, \qquad (5)$$

where the factor $2\sqrt{M_A M_B}$ appears due to the relativistic normalization of the scattering amplitude $\mathcal{T}$, which normalization is used in the rest of this paper in order to facilitate direct comparison with Ref. [12].

The matrix element over the nucleon can be evaluated following the approach [26] used for estimating similar matrix element over pions. Namely, one writes

$$\frac{1}{2}\vec{E}^a\cdot\vec{E}^a = \frac{1}{4}(\vec{E}^a\cdot\vec{E}^a - \vec{B}^a\cdot\vec{B}^a) + \frac{1}{4}(\vec{E}^a\cdot\vec{E}^a + \vec{B}^a\cdot\vec{B}^a) = -\frac{1}{8}(F^a_{\mu\nu})^2 + 2\pi\alpha_s\theta^{00}_G, \qquad (6)$$

where $\theta^{\mu\nu}_G$ is the energy-momentum tensor of the gluon field, and relates the term with $(F^a_{\mu\nu})^2$ to the expression for the anomalous trace of the full energy-momentum tensor in QCD in the chiral limit:

$$-\frac{b}{32\pi^2}(F^a_{\mu\nu})^2 = \theta^\mu_\mu, \qquad (7)$$

with $b = 9$ being the first coefficient in the QCD beta function with three light (massless in the chiral limit) quarks. Using these relations the matrix element over the nucleon entering Eq. (5) can be written as

$$\langle N|\frac{1}{2}\vec{E}^a\cdot\vec{E}^a|N\rangle = \frac{4\pi^2}{b}\langle N|\theta^\mu_\mu|N\rangle + 2\pi\alpha_s\langle N|\theta^{00}_G|N\rangle, \qquad (8)$$

where $\alpha_s = g^2/4\pi$ is the QCD coupling constant. The first term in the right-hand-side of Eq. (8) can be found at a small momentum transfer $q = p_1 - p_2$ using

$$\frac{4\pi^2}{b}\langle N(p_2)|\theta^\mu_\mu|N(p_1)\rangle = \frac{4\pi^2}{b}m_N\bar{N}(p_2)N(p_1). \qquad (9)$$

The only approximation made here is in neglecting the difference between the actual mass of the nucleon m_N and its value in the chiral limit. Although the correction for this difference can be taken into account, we neglect it, since this correction is likely to be less than other uncertainties in our estimates.

The last term in Eq. (8) is formally of higher order in the QCD coupling α_s, and it has been neglected in Ref. [12] in comparison with the anomalous contribution. We argue here however, that in the amplitude under discussion the contribution of this term is at least as large as that of the anomalous one. Indeed, consider the discussed matrix element at zero momentum transfer q for the nucleon being at rest. The Eq. (7) can then be written as the diagonal average of the gluonic operator

$$\langle N|\frac{1}{4}(\vec{E}^a\cdot\vec{E}^a - \vec{B}^a\cdot\vec{B}^a)|N\rangle = \frac{4\pi^2}{b}2m_N^2. \qquad (10)$$

On the other hand the diagonal average (over a nonvacuum state) of the manifestly quadratic operator $\vec{B}^a\cdot\vec{B}^a$ has to be non-negative. Thus one arrives at the inequality

$$\langle N|\frac{1}{2}\vec{E}^a\cdot\vec{E}^a|N\rangle \geq \frac{8\pi^2}{b}2m_N^2, \qquad (11)$$

which corresponds to that for a static nucleon the second term in the final expression in Eq. (8) is at least as large as the first term. It can be noticed in connection with the discussed bound that these two terms are of the same order in N_c in the large N_c counting. It is reasonable to expect that the chromo-magnetic average over the nucleon, although non-negative, is substantially smaller than the chromo-electric one, so that the actual chromo-electric amplitude is close to the lower bound required by Eq. (11).

It is also instructive to analyze the matrix element in Eq. (8) within the approach used by Novikov and Shifman [26] for an estimate of a similar amplitude for dipion production by gluonic field in the transition $\psi' \to J/\psi\pi\pi$, where it has been found that the contribution of the gluonic part of the energy-momentum tensor is indeed small in comparison with that of the anomalous term in the relevant kinematics. According to this approach the matrix element of the gluonic part of the energy-momentum tensor is parametrized in terms of the fraction ρ_G of the nucleon energy and momentum carried by gluons, and the discussed term can be written as

$$2\pi\alpha_s\langle N(p_2)|\theta^{00}_G|N(p_1)\rangle = \pi\alpha_s\rho_G(p_1^0 + p_2^0)N^\dagger(p_2)N(p_1), \qquad (12)$$

where p_1^0 (p_2^0) is the energy of the initial (final) nucleon. The appropriate normalization scale for the product $\alpha_s\rho_G$ is the characteristic size of the heavy quarkonium. Novikov and Shifman estimate for the case of the dipion transition in charmonium $\alpha_s\rho_G \approx 0.7$. By writing the expression (12) in the static limit, one finds that in the case of the nucleon amplitude discussed here, the inequality (11) in fact requires the relevant parameter $\alpha_s\rho_G$ for the nucleon to be at least as large as estimated in Ref. [26] for the pions: $\alpha_s\rho_G \geq 0.7$.

The discussed here low-energy static limit for the nucleon matrix element in the amplitude T in Eq. (5) is sufficient for considering the threshold limit of the elastic J/ψ-nucleon interaction. However in the subthreshold process $\psi' + N \to J/\psi + N$ with slow ψ' the momentum transfer is quite substantial: $-q^2 = (M^2_{\psi'} - M^2_{J/\psi})m_N/(M_{\psi'} + m_N) \approx 0.82\ \mathrm{GeV}^2$, where $M_{J/\psi}$ ($M_{\psi'}$) stands for the mass of the J/ψ (ψ') resonance. The form factor, describing the deviation of the discussed nucleon matrix element from its value at $q^2 = 0$ is presently unknown. However, for the case of the similar matrix element over pions it is known from the study of the shape of the dipion spectrum in the transition $\Upsilon' \to \Upsilon\pi\pi$ that this deviation is rather small. Namely, if the form factor $F(q^2)$ at small q^2 is parametrized as $F = 1 + q^2/M^2 +$

..., the coefficient of the q^2 term corresponds to $M > 1$GeV (a discussion of this topic can be found in the review [27]). The relatively large mass scale in this form factor agrees well with the general arguments [29] for the presence of a large mass scale in the 0^{++} flavor-singlet hadronic channel. In what follows, we use the simple parametrization of the nucleon matrix element in terms of its value at $q^2 = 0$ and one common form factor:

$$\langle N(p_2)|\frac{1}{2}\vec{E}^a \cdot \vec{E}^a|N(p_1)\rangle = \frac{4\pi^2}{b}\left[m_N\bar{N}(p_2)N(p_1) + C\frac{p_1^0 + p_2^0}{2}N^\dagger(p_2)N(p_1)\right]F(q^2), \tag{13}$$

where the constant C describes the second term in Eq. (8) relative to the first one, and is bound by the inequality (11) as $C \geq 1$. The form factor is normalized as $F(0) = 1$, which point is relevant for the low-energy J/ψ-nucleon scattering and for the real part of the elastic ψ'-nucleon scattering amplitude, while for the subthreshold process $\psi' + N \to J/\psi + N$ one inevitably has to make assumptions about the behavior of the form factor. In the subsequent numerical estimates we use the simple pole expression: $F(q^2) = (1 - q^2/M^2)^{-1}$ with $M \sim 1$ GeV. Although this assumption, when applied to the similar form factor for the pions, would be in agreement with the data on the dipion transitions in heavy quarkonia, we fully acknowledge that the behavior of the nucleon matrix element in Eq. (13) can be different, so that our estimates for the inelastic process $\psi' + N \to J/\psi + N$ suffer the largest uncertainty.

IV. THE J/ψ-NUCLEON INTERACTION AT THE THRESHOLD

The expression (5) can now be applied to evaluating the threshold amplitude of the J/ψ-nucleon scattering:

$$\mathcal{T}_{J/\psi} = \frac{16\pi^2}{9}(1 + C)\alpha_{J/\psi}M_{J/\psi}m_N^2. \tag{14}$$

The corresponding scattering length is then found as

$$a_{J/\psi} = \frac{\mathcal{T}_{J/\psi}}{8\pi(M_{J/\psi} + m_N)} \approx 0.37\ \text{fm}\left[\frac{1 + C}{2}\frac{\alpha_{J/\psi}}{2\ \text{GeV}^{-3}}\right], \tag{15}$$

where the term in brackets indicates potential uncertainties due to our present knowledge of the parameters C and $\alpha_{J/\psi}$. Accordingly, the $J/\psi N$ elastic scattering cross section is estimated as

$$\sigma_{J/\psi N} = 4\pi a_{J/\psi}^2 \approx 17\ \text{mb}\left[\frac{1 + C}{2}\frac{\alpha_{J/\psi}}{2\ \text{GeV}^{-3}}\right]^2. \tag{16}$$

We find that our estimate of the scattering length exceeds the previous one [12] by at least 7 times, and consequently the estimated cross section is also at least 50 times larger.

Within the low density theorem the result for the elastic scattering amplitude can be converted into an estimate of the J/ψ potential in nuclear matter with the density of nucleons $\rho_N = 0.16\ \text{fm}^{-3}$:

$$V_{J/\psi} = -\frac{\mathcal{T}_{J/\psi}\rho_N}{4M_{J/\psi}m_N} \approx -21\ \text{MeV}\left[\frac{1 + C}{2}\frac{\alpha_{J/\psi}}{2\ \text{GeV}^{-3}}\right], \tag{17}$$

which can be compared with the previous estimates given in Table I. Note that in our notation the J/ψ mass shift $\Delta M_{J/\psi}$ equals to the real part of the potential [20,34,35]. Table I also shows the elastic $J/\psi + N$ cross section. Moreover we do not indicate the elastic cross section evaluated [15,36] from J/ψ photoproduction off proton, since there are no available data close to the threshold [37].

The significant increase in the estimated potential also changes the conclusion about the possibility of existence of bound states of J/ψ in light nuclei. Indeed, the condition for existence of a bound state in the approximation, where a nucleus is considered as being of a uniform density ρ_N up to the sharp boundary at the radius R_A reads as

$$R_A^2 > \frac{\pi^2}{8M_{J/\psi}(-V_{J/\psi})}. \tag{18}$$

With the minimal estimate of the binding potential in Eq. (17) this condition is satisfied already at $R_A > 0.9$ fm, which points to a relevance of the problem of bound states to light nuclei. Although the criterion in Eq. (18) is not directly applicable for light nuclei, the resulting estimate gives credibility to the claims [13,38] that bound states of the J/ψ resonance in nuclei do exist starting from light nuclei.

With regards to existence of a near-threshold bound or resonant state of the J/ψ and a single nucleon, the presented here consideration is generally insufficient for arriving at a definite conclusion. It should be noted, however, that if such near-threshold singularity exists, it would

TABLE I. The mass shift $\Delta M_{J/\psi}$ and elastic $J/\psi + N$ cross section predicted by different models.

Ref.	$-\Delta M_{J/\psi}$ (MeV)	$\sigma_{J/\psi N}$ (mb)
[12]	3	0.3
[14]		1.5
[18]	$10 \div 5$	
[19]	$7 \div 4$	
[20]	4	
[29]	$11 \div 8$	
[30]		5
[31]		8
[32]	5	
this	$\gtrsim 21$	$\gtrsim 17$

TABLE II. The mass shift $\Delta M_{\psi'}$ predicted by different models.

Ref.	$-\Delta M_{\psi'}$ (MeV)
[29]	700
[32]	130
this	>21

require a substantial modification of the presented here estimates for the scattering amplitude. The estimate of the amplitude in Eq. (14) by itself, although larger than previously thought, generally does not require a unitary modification. Indeed, the estimated amplitude is still below the unitarity limit as long as the c.m. momentum satisfies the condition $p < a_{J/\psi}^{-1} \approx 530$ MeV, so that at such momenta the unitarity corrections are relatively small.

V. THE ψ' INTERACTION WITH NUCLEONS

The formulas of the previous section for the interaction of a slow J/ψ with nucleons and nuclei can be directly applied to calculation of the real part of the ψ'-nucleon scattering amplitude, and of the energy shift of the ψ' in nuclear matter, by the obvious replacement $M_{J/\psi} \to M_{\psi'}$ and $\alpha_{J/\psi} \to \alpha_{\psi'}$. In interpreting the resulting formulas in numerical terms one should keep in mind that the expected chromo-polarizability $\alpha_{\psi'}$ is very likely to substantially exceed the "reference" value 2GeV^{-3}. In particular this implies that the binding energy of the ψ' in heavy nuclei,

$$V_{\psi'} \approx -21 \text{ MeV} \times \left[\frac{1+C}{2} \frac{\alpha_{\psi'}}{2 \text{ GeV}^{-3}}\right], \tag{19}$$

should be significantly larger than the numerical value 21 MeV, which can be compared with other estimates, as shown in Table II. This shift in the energy of the ψ' can be important for the estimates of the decay $\psi' \to D\bar{D}$, which becomes possible in nuclear matter due to the shifts in the masses of the D and $\bar{D}$ mesons [39–44].

The main difference between the nuclear interactions of slow J/ψ and ψ' is that for the latter there exist subthreshold scattering processes: the charm-exchange process $\psi' + N \to \Lambda_c + \bar{D}$, the charmonium transition scattering $\psi' + N \to J/\psi + N$, and generally additional channels where in the latter process instead of a single nucleon excited states are being produced such as $N\pi$, $\Delta\pi$, etc. The processes other than $\psi' + N \to J/\psi + N$ are beyond the scope of the present paper. We can only comment here that due to the discussed relation of the relevant gluonic matrix element to the energy-momentum tensor in QCD, the processes with nondiagonal transitions, such as $N \to N\pi$, should be suppressed with respect to the diagonal one $N \to N$. It can be also noted that similar transitions from ψ' to lower charmonium states other than J/ψ should also be suppressed in comparison with $\psi' \to J/\psi$, since those other states cannot be produced in the second order in the leading $E1$ term of the multipole expansion.

The scattering amplitude for the process $\psi' + N \to J/\psi + N$ with slow ψ' is found from the Eqs. (5) and (13), where in the latter equation the momentum transfer is fixed at $-q^2 \approx 0.82$ GeV^2. Clearly, at such momentum the form factor $F(q^2)$ can be significantly different from one. The present poor knowledge of this form factor results in the largest uncertainty in estimating the scattering amplitude. In view of this uncertainty we simplify the rest of the matrix element in Eq. (13) by neglecting the kinetic energy of the final nucleon, thus writing the scattering amplitude in the form

$$\mathcal{T}_{\psi' J/\psi} \approx \frac{16\pi^2}{9}(1+C)\alpha_{\psi' J/\psi}\sqrt{M_{J/\psi}M_{\psi'}}m_N^2 F(q^2). \tag{20}$$

Using this amplitude one readily finds the scattering cross section near the $\psi' + N$ threshold at the c.m. momentum p_i of the initial particles:

$$\begin{aligned}\sigma(\psi' + N \to J/\psi + N) &= \frac{1}{p_i}\frac{|\mathcal{T}_{\psi' J/\psi}|^2 p_f}{16\pi(M_{\psi'}+m_N)^2} \\ &\approx 16 \text{ mb}\left[\frac{1\text{GeV}}{p_i}\right]\left[\frac{1+C}{2}\right]^2 \\ &\quad \times |F(q^2)|^2,\end{aligned} \tag{21}$$

where $p_f \approx 1.0$ GeV is the c.m. momentum in the final state. The inverse-velocity, $1/p_i$, behavior of the cross section is due the subthreshold kinematics of the process. Assuming, conservatively, that the form factor $|F(q^2)|$ suppresses the amplitude by not more than a factor of 2, one comes to the conclusion that the cross section of the considered process can reach tens of millibarn at rather moderately low values of the initial momentum p_i.

Furthermore, the unitarity relation implies that the amplitude of the considered inelastic process contributes to the imaginary part of the amplitude $\mathcal{T}_{\psi'}$ of the elastic $\psi' + N$ scattering near threshold:

$$\text{Im}\,\mathcal{T}_{\psi'} = |\mathcal{T}_{\psi' J/\psi}|^2 \frac{p_f}{8\pi(M_{\psi'}+m_N)}. \tag{22}$$

Using the formula in Eq. (5) for the real part of $\mathcal{T}_{\psi'}$ and the approximation in Eq. (20) for the amplitude $\mathcal{T}_{\psi' J/\psi}$ one arrives at the following estimate of the significance of this effect in terms of the ratio of the imaginary to the real part of the elastic scattering amplitude:

$$\begin{aligned}\frac{\text{Im}\mathcal{T}_{\psi'}}{\text{Re}\mathcal{T}_{\psi'}} &\approx \frac{2\pi}{9}(1+C)\frac{|\alpha_{\psi' J/\psi}|^2}{\alpha_{\psi'}}\frac{M_{J/\psi}m_N^2 p_f}{M_{\psi'}+m_N}|F(q^2)|^2 \\ &\approx 1.6\left[\frac{1+C}{2}\right]\left[\frac{2\text{ GeV}^{-3}}{\alpha_{\psi'}}\right]|F(q^2)|^2.\end{aligned} \tag{23}$$

Given the expected form factor suppression, and that, as discussed, $\alpha_{\psi'}$ should be larger than 2 GeV^{-3}, one can conclude from this estimate that the contribution of the discussed inelastic channel to the imaginary part of the elastic scattering amplitude is still somewhat smaller than the real part.

The effect of the discussed imaginary part of the amplitude, although relatively moderate in the scattering cross section, gives rise to a potentially interesting effect when considered in terms of the imaginary part of the average potential energy $V_{\psi'}$ of ψ' in nuclear medium with the nucleon density ρ_N. The imaginary part of the binding energy corresponds to the decay rate $\Gamma_{\psi'} = -2\,\mathrm{Im}V_{\psi'}$, and the contribution of the process $\psi' + N \to J/\psi + N$ to $\Gamma_{\psi'}$ can be directly estimated from Eq. (20) as

$$\Gamma_{\psi' J/\psi} = |\mathcal{T}_{\psi' J/\psi}|^2 \frac{p_f}{32\pi(M_{\psi'} + m_N) M_{\psi'} m_N} \rho_N \approx 70\ \mathrm{MeV}\left[\frac{1+C}{2}\right]^2 \left[\frac{\alpha_{\psi'}}{2\ \mathrm{GeV}^{-3}}\right]^2 |F(q^2)|^2, \quad (24)$$

and is likely reaching tens of MeV at the average nuclear density $\rho_N \approx 0.16\ \mathrm{fm}^{-3}$.

VI. CONCLUDING REMARKS

The approach used here to calculation of the interaction of the J/ψ and ψ' resonances with nucleons is based on the notion that the heavy quarkonium is a compact object and its interaction with soft gluon field can be expanded in multipoles. For the discussed processes such approximation should work best for the elastic J/ψ - nucleon interaction at energy close to the threshold. For this reason we believe that the estimates for this process suffer from the least uncertainty. The largest uncertainty in the numerical estimates for this case arises from the presently unknown chromo-polarizability of the J/ψ state of charmonium. This parameter however can be measured in the decay $J/\psi \to \ell^+\ell^-\pi^+\pi^-$, thus eliminating the largest source of uncertainty. The other unknown involved in our estimates is the coefficient C for the ratio of the nonanomalous to the anomalous part of the gluonic matrix element in Eq. (8). The inequality (11) bounds the value of this coefficient as $C \geq 1$, and it can be reasonably argued that the actual value should be close to this bound. However at present we cannot suggest a way of an independent determination of this coefficient.

The accuracy of the considered approach becomes worse with increasing energy in the J/ψ - nucleon system, since the gluonic fields mediating the interaction become less soft, thus worsening the applicability of the multipole expansion. For this reason it is troublesome at present to interpolate between our estimates in the near-threshold region and other theoretical approaches to the interaction at higher energies. For both charmonium resonances we find the scattering cross section on a nucleon at threshold to be quite large. For the $J/\psi - N$ elastic scattering the estimated cross section near threshold is 17 mb. A comparison of our estimates with the only available experimental value [45] for the J/ψ - nucleon total cross section: $\sigma_{J/\psi N} = 3.8 \pm 0.8 \pm {\sim}0.5$ mb at $\sqrt{s} \approx 5.7$ GeV suggests a noticeable rise of the cross section toward the threshold. At present we are not aware of any arguments that would exclude a considerable decrease of the cross section away from the threshold.

The issue of applicability of the multipole expansion is still more sensitive for the case of the ψ' resonance, which naturally has larger characteristic size than the J/ψ state. An application of the expansion in this case is to a certain extent justified by the very good agreement of the data on the charmonium dipion transition $\psi' \to J/\psi\pi\pi$ with the description based on the same approach. However the departure of the interaction from the considered low-energy limit at higher energies should be more rapid than for the case of J/ψ. The signature of such departure is in fact relevant already in the threshold limit for the inelastic process $\psi' + N \to J/\psi + N$ where the momentum transfer is non-negligible. In the presented here calculation the effect of the deviation from the strictly static limit is encoded in the form factor $F(q^2)$, which inevitably adds to the uncertainty of the presented estimates. According to the presented estimates the $\psi' - N$ elastic scattering cross section should be still bigger than $\sigma_{J/\psi N}$ due to a larger than for the J/ψ chromo-polarizability of the ψ' charmonium state and also due to an additional contribution of the absorptive part of the elastic scattering amplitude, arising from the inelastic process $\psi' + N \to J/\psi + N$. The cross section of the latter inelastic scattering rises toward the threshold according to the inverse-velocity behavior and is also expected to be large.

We believe that even with a rather conservative assumption about the form factor F at the actual value of the momentum transfer, one can conclude that the inelastic process gives a large contribution to the decay width of the ψ' resonance in heavy nuclei. Furthermore, it should be noted that the process $\psi' + N \to J/\psi + N$ is not the only one contributing to the decay. Another potentially large contribution can come from the charm-transfer process $\psi' + N \to \Lambda_c + \bar{D}$, which is entirely different from the type of processes considered in this paper, hence we do not present here any further discussion of this process.

The substantial modification of the J/ψ and ψ' properties in nuclear medium can be studied experimentally. It is a challenge for the future Facility for Antiproton and Ion Research (FAIR) at GSI [46–49] to provide valuable data for further progress in understanding the QCD dynamics in hadronic matter. To make specific quantitative predictions for observables one should perform explicit model calculations similar to those considered in Ref. [8–10,40]. Here we list some qualitative predictions.

The mass shift of J/ψ and ψ' can be observed through the spectrum of the dilepton pairs emerging from the decay of the produced charmonium resonances. It is clear that only the J/ψ and ψ' mesons that decay inside the region of interaction with hadronic gas have their mass shifted. If this shift is small, i.e. few MeV, there should be only little difference between the invariant mass of the lepton pairs emerging from the decays inside and outside the nuclear matter. Following our prediction the J/ψ and ψ' mass shift is large and might be observed.

Moreover the $\psi' \to J/\psi$ transition can be studied experimentally through a measurement of the A-dependence of the relative yield of the J/ψ and ψ' in nuclear collisions. Clearly in the absence of such transition the $\psi'/J/\psi$ ratio would depend only weakly on the effective number of nuclear nucleons involved in the interaction.

Finally, a strong J/ψ rescattering in the hadronic gas due to a large elastic $J/\psi - N$ cross section should result in a transverse component of the charmonium momentum, which definitely can be measured.

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