

# CHARMONIUM EXCITATION FUNCTIONS IN $\bar{p}A$ COLLISIONS\*

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We study the excitation function of the low-lying charmonium state:  $\Psi(3686)$  in  $\bar{p}A$  collisions taking into account their in-medium propagation. The time evolution of the spectral functions of the charmonium state is studied with a BUU-type transport model. We calculated the excitation function of  $\Psi(3686)$  production and show that it is strongly effected by the medium. The energy regime will be available for the PANDA experiment.

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## 1. Introduction

One of the most important quantities in the phenomenology of strong interaction is the gluon condensate. We know its value in vacuum, actually its numerical value was obtained by the sum rule for  $J/\Psi$  [1]. However, in medium, we only know its first derivative with respect to the density obtained from the trace anomaly relation. Its value in matter, therefore, would be of great importance. While the masses of hadrons consisting of light quarks change mainly because of the (partial) restoration of chiral symmetry, those made of heavy quarks are sensitive mainly to the changes of the non-perturbative gluon dynamics manifested through the changes in the gluon condensates [2, 3]. In the low density approximation, the gluon condensate is expected to be reduced by 5–7% at normal nuclear density [4, 5]. Therefore, the masses of the charmonium states — which can be considered as color dipoles in color electric field — are shifted downwards because of the second order Stark effect [5–7]. Moreover, since the  $D$ -meson loops

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contribute to the charmonium self-energies and they are slightly modified in-medium, these modifications generate further minor contributions to the charmonium in-medium mass shifts [6].

In antiproton-induced reactions, a large number of charmed states are expected to be produced, creating a laboratory for studying the gluon condensate. The observation of charmonium in vacuum is an important goal of the PANDA Collaboration at the future FAIR complex. Besides that, the observation of charmonium production in matter is also a part of the PANDA program. The  $\bar{p}A$  reactions are best suited to observe charmed particles in nuclear matter, since in this case, the medium is much simpler than the one created in a heavy-ion collisions. (The other advantageous channel is the pion-induced reaction with energies of 12–15 GeV pion energy, such beam is available at JPARC, Tokai, Japan.) Furthermore, the two main background contribution to the dilepton yield in the charmonium region, namely the Drell–Yan and the “open charm decay” are expected to be small. There are only a few energetic hadron–hadron collisions that can produce heavy dileptons via the Drell–Yan process. In the open charm decay, the  $D$  mesons decay weakly. Consequently, the  $e^+$  and  $e^-$  are usually accompanied by the  $K$  and  $\bar{K}$  mesons. Therefore, not very far above the threshold, the production of electron–positron pairs via the open charm decay with large invariant mass is energetically suppressed.

The spectral functions of the  $J/\Psi$ ,  $\Psi(3686)$ , and  $\Psi(3770)$  vector mesons are expected to be modified in a strongly interacting environment. In our transport model of the BUU-type, the time evolution of single-particle distribution functions of various hadrons are evaluated within the framework of a kinetic theory. We studied in our previous work what is the effect of the in-medium modification of the charmonium spectral function on the dilepton yield well above the threshold [8]. We have learned that the most promising candidate to observe the in-medium modifications is the  $\Psi(3686)$  meson. In this paper, we study the effect of the medium on the  $\Psi(3686)$  meson around the threshold, the excitation function with vacuum and with in-medium spectral functions.

## 2. Off-shell transport of broad resonances

Our transport model, originally valid in the few GeV energy range, was recently upgraded to higher energies of up to 10 A GeV [8]. We use a statistical model [9] to calculate the unknown cross sections, such as  $\bar{p}p \rightarrow J/\psi\pi$ , or  $\bar{p}p \rightarrow D\bar{D}$ . We apply energy-independent charmonium absorption cross sections for every hadron 4.18 mb for  $J/\Psi$  and 7.6 mb for  $\Psi(3686)$  and  $\Psi(3770)$  according to Ref. [10]. In  $\bar{p}A$  collisions at relativistic energies, charmonium absorption does not play such an important role as at ultrarelativistic energies, since the hadron density is much less here. It should be noted that the decay of the charmonium states is handled perturbatively.

If we create a particle in a medium with in-medium mass, it should regain its vacuum mass during the propagation by the time it reaches the vacuum. We can describe the in-medium properties of particles with an “off-shell transport”. These equations are derived by starting from the Kadanoff–Baym equations [11] for the Green functions of the particles. Applying first-order gradient expansion after a Wigner transformation [12, 13], one arrives at a transport equation for the retarded Green function. To solve numerically the off-shell transport equations, one may exploit the test-particle Ansatz for the retarded Green function [12, 13].

The equations of motion of the test-particles have to be supplemented by a collision term which couples the equations of the different particle species. It can be shown [13] that the collision term has the same form as in the standard BUU treatment.

In our calculations, we employ a simple form of the self-energy of a vector meson  $V$

$$\text{Re}\Sigma_V^{\text{ret}} = 2m_V\Delta m_V \frac{n}{n_0}, \quad (1)$$

$$\text{Im}\Sigma_V^{\text{ret}} = -m_V(\Gamma_V^{\text{vac}} + \Gamma_{\text{coll}}). \quad (2)$$

Equation (1) describes a “mass shift”  $\Delta m = \sqrt{m_V^2 + \text{Re}\Sigma_V^{\text{ret}}} - m_V \approx \Delta m_V \frac{n}{n_0}$ . The imaginary part incorporates a vacuum width  $\Gamma_V^{\text{vac}}$  term and a collisional broadening term having the form of

$$\Gamma_{\text{coll}} = \frac{v\sigma n}{\sqrt{(1-v^2)}}, \quad (3)$$

where  $v = |\vec{p}|/m$  is the velocity of the particle in the local rest frame,  $\sigma$  is the total cross section of the particle colliding with nucleons and  $n$  is the local density. The parameters  $\Delta m_V$  are taken from [6] and are given in Table I.

TABLE I

Charmonium mass shift parameter values taken from [6]. In  $\Delta m_V$ , the first term results from the second order Stark effect, while the second term emanates from the  $D$ -meson loops.

Charmonium type ( $V$ )	$\Delta m_V$
$J/\Psi$	$-8 + 3$ MeV
$\Psi(3686)$	$-100 - 30$ MeV
$\Psi(3770)$	$-140 + 15$ MeV

The first values in Table I come from the second order Stark effect (which depends on the gluon condensate), while the second ones emanate from the  $D$ -meson loops.

If a meson is generated at normal density, its mass is distributed in accordance with the in-medium spectral function. If the meson propagates, then its mass will be modified according to  $\text{Re } \Sigma^{\text{ret}}$ . This method is energy conserving. We note that the propagation of  $\omega$  and  $\rho$  mesons at the HADES energy range have been investigated in [14, 15] with the same method, where we have shown that the “off-shell” transport is consistent in the sense that mesons reaching the vacuum regain their vacuum properties. Similar results were obtained for charmonium mesons in [8].

### 3. Results

In Ref. [8], we have studied the dynamics of charmonium production in antiproton-induced reactions not very far from the threshold, and the following plausible picture has been found: Most of the antiprotons annihilate on, or close to the surface of the heavy nucleus, creating a charmonium with a certain probability. The charmonium travels through the interior of the nucleus giving some contribution to the dilepton yield. That is, the dileptons are treated perturbatively. Traversing the thin surface again on the other side of the nucleus, it arrives to the vacuum, where most charmoniums actually decay. We found a two-peak structure, where one of the peaks comes from decays in the vacuum, the other one from the decays inside the nucleus. The distance of the two peaks corresponds to a mass shift at approximately  $0.9\rho_0$  density. The  $D$ -meson loop contributes only 25–30 MeV to the mass shift. The rest (which is expected to be the major part) is the result of the second order Stark effect, thus we can determine the gluon condensate that has resulted in such a mass shift. The considered energy regime will be available by the forthcoming PANDA experiment at FAIR. However, there might be some difficulty to get quantitative conclusions since the vacuum peak (originating from charmonium states created in the medium, but decaying outside with their vacuum mass and width) is much stronger than the one from the in-medium decays, so a good mass resolution of the detector is required. There may be another possibility to observe the mass shift, namely to measure the excitation function of the  $\Psi(3686)$  state in antiproton-induced reactions.

In Fig. 1, we show the charmonium contributions to the dilepton spectrum in a  $\bar{p}$ Au 4 GeV beam kinetic energy collision. We can observe the same two-peak structure as in [8]. In contrast to higher energies, here, the medium contribution is much larger compared to the vacuum one. The reason is that very close to threshold the charmonium is much slower than at higher energies, therefore, spend much more time inside the nucleus increasing its contribution to the dilepton yield from the medium.

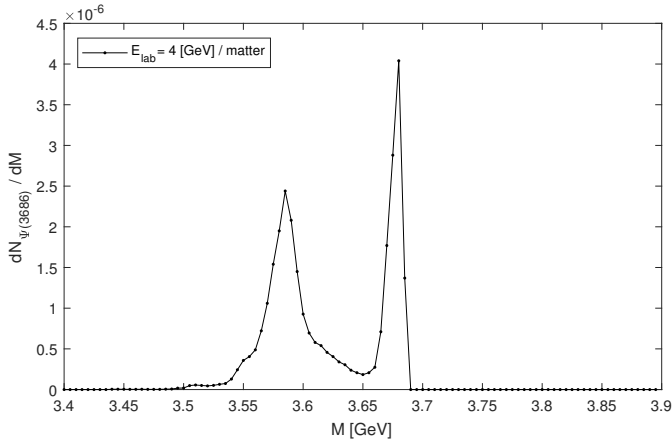


Fig. 1.  $\Psi(3686)$  contribution to the dilepton spectra taking into account the in-medium modifications.

In Fig. 2, we show the excitation function of the  $\Psi(3686)$  production in  $\bar{p}A$ u reactions using the propagation with in-medium and with the vacuum properties. If we apply the in-medium mass-shift and the collisional broadening of the  $\Psi(3686)$ , its excitation function is shifted downwards in energy drastically compared to the one calculated with propagation with its vacuum properties. Therefore, the mass shift can also be observed by comparing the excitation function of the  $\Psi(3686)$  in  $\bar{p}A$ u and in  $\bar{p}C$ , where the latter can be considered as the reference “vacuum” excitation function.

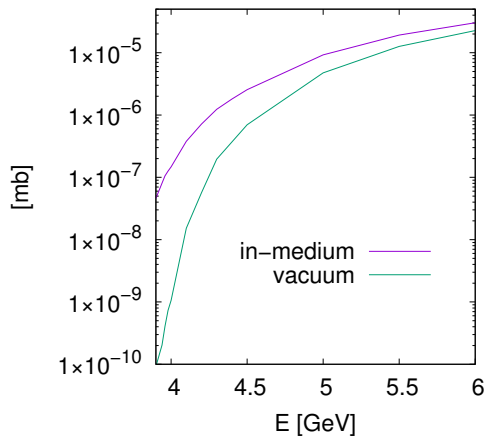


Fig. 2. Excitation function of the  $\Psi(3686)$  with in-medium and with vacuum properties.

#### 4. Summary

We calculated the charmonium contribution to the dilepton spectra. We have shown that via their dileptonic decay there is a good chance to observe the in-medium modification of the higher charmonium state:  $\Psi(3686)$  in a  $\bar{p}$ Au and  $\bar{p}$ C collisions around the threshold by measuring its excitation functions. This energy regime will be available by the PANDA experiment.

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