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Observation of Charmonium Mass Modification in Proton Induced Reactions

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We study the excitation function of the low-lying charmonium state: Ψ(3686) in p Au 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 charmonium contribution to the dilepton spectrum and show that for Ψ(3686) production there is a good chance to observe its in-medium modification with good resolution detectors. The energy regime will be available in JPARC.

KEYWORDS: charmonium, transport model, in-medium modification

1. Introduction

One of the most important goal of heavy ion physics is to observe hadrons in extreme conditions, e.g. at high temperature and/or high densities. Lots of experimental effort has been devoted to study hadrons in medium, however, up to now for any in-medium modifcations only indirect verifications have been found [1–4]. While the masses of hadrons consisting of light quarks changes 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 [5]. In the low density approximation the gluon condensate is expected to be reduced by $5-7\%$ at normal nuclear density [6, 7]. 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 [7, 8]. Moreover, since the D meson loops 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 [8].

The hadron $(\bar{p}, \pi, p)$ induced 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. Furthermore, the two main background contributions 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/Ψ, Ψ(3686), and Ψ(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 threshold [9]. 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 threshold, the excitation function with vacuum and with in-medium spectral functions in proton induced reactions in the considered energy region available at the JPARC facility.

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 AGeV [9]. We use a statistical model [10] to calculate the unknown cross sections, such as $\bar{p}p \to J/\psi\pi$, or $\bar{p}p \to D\bar{D}$. We apply energy independent charmonium absorption cross sections for every hadron, i.e. 4.18 mb for J/Ψ and 7.6 mb for $\Psi(3686)$ and $\Psi(3770)$ according to Ref. [11]. In hadron-nucleus 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 until 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 for the Green's functions of the particles. Applying first - order gradient expansion after a Wigner transformation [12], one arrives at a transport equation for the retarded Green's function. To solve numerically the off-shell transport equations one may exploit the test - particle ansatz for the retarded Green's function [12].

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 [12] 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:

$$\Re\Sigma_V^{ret} = 2m_V \Delta m_V \frac{n}{n_0}, \tag{1}$$

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

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

$$\Gamma_{coll} = \frac{v\sigma\rho}{\sqrt{(1-v^2)}}, \tag{3}$$

where $v = |\vec{p}|/m$ is the velocity of the particle in the local rest frame, σ is the total cross section of the particle colliding with nucleons and ρ is the local density. The parameters Δm_V are taken from [8] and are given in Table I.

Table I. Charmonium mass shift parameter values taken from [8]. In Δm_V the first term result from the second order Stark - effect, while the second term emanates from the D - meson loops.

Charmonium type (V)	Δm_V
J/Ψ	$-8 + 3$ 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 $\Re\Sigma^{ret}$. This method is energy conserving. We note that the propagation of ω and ρ mesons at the HADES energy range have been investigated in [13, 14] 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 [9].

3. Results

In ref. [9] 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. We can study the charmonium production in other hadron induced reactions as well, e.g. in proton-nucleus reactions. Since the production not very far from the threshold is dominated by first chance collisions, therefore, the physical picture is the same as in antiproton–nucleus reactions. Because of the low cross sections the event multiplicity is a very important issue, therefore, proton beam may be a good alternative to the antiproton beam, since its intensity can be much higher than the antiproton one.

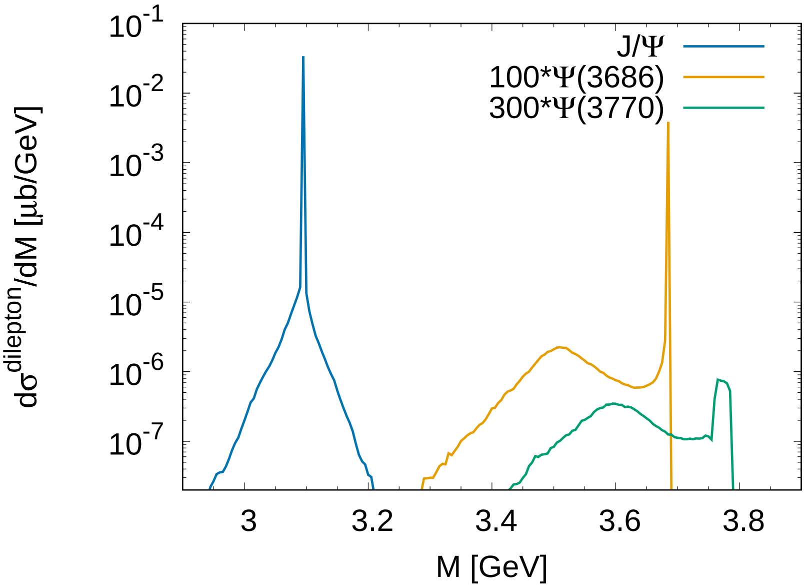

Fig. 1. Dilepton invariant mass spectrum in proton Au collisions at 12 GeV beam energy taking into account the in-medium modifications.

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.

In Fig. 1 we show the charmonium contributions to the dilepton spectrum in a p Au 12 GeV beam kinetic energy collision. We can observe the same two peak structure as in [9].

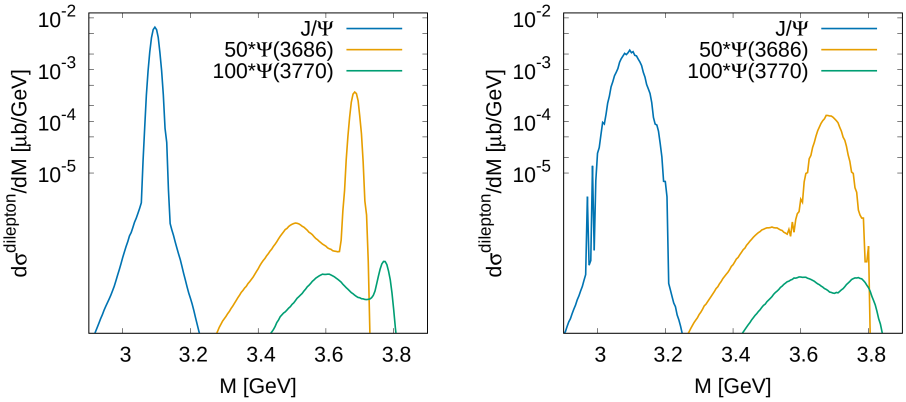

Fig. 2. The same spectra as in 1 but with 20 MeV (left panel) and with 30 MeV (right panel) detector mass resolutions.

In Fig 2 we show the same spectrum as in Fig. 1 but we introduced detector mass resolutions: 20 MeV and 30 MeV. In the Figure we can see the 20 MeV mass resolution still gives a two-peak structure, while in case of 30 MeV, the second peak melts away, the effect is practically not observable anymore. Therefore, to observe the mass shift a detector with good mass resolution ($dM \leq 20MeV$) is needed.

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: Ψ(3686) in a p Au collisions around the threshold, available e.g. at JPARC by measuring its dilepton mass spectra, however, a good mass resolution detector is required.

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