Effect of changes in meson properties in a nuclear medium: 
$J/\Psi$ dissociation in nuclear matter, and meson-nucleus bound states

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We discuss the effect of changes in meson properties in a nuclear medium on physical observables, notably, $J/\Psi$ dissociation on pion and $\rho$ meson comovers in relativistic heavy ion collisions, and the prediction of the $\omega$, $\eta$- and $\eta'$-nuclear bound states.

1. Mean-field potentials for mesons and baryons in QMC

This report is based on the quark-meson coupling (QMC) model [1], which has been successfully applied to many problems in nuclear physics [2–6]. A detailed description of the Lagrangian density and the mean-field equations of motion are given in Ref. [2]. The Dirac equations for the quarks and antiquarks in hadron bags ($q = u, \bar{u}, d$ or $\bar{d}$, hereafter, and including up to $s, \bar{s}, c,$ and $\bar{c}$) neglecting the Coulomb force, are given by ($|x| \leq$ bag radius) [2–6]:

\[
\begin{align*}
\left[ i \gamma \cdot \partial_x - (m_q - V^q_\sigma) \right] \psi_q(x) &= 0, \\
\left[ i \gamma \cdot \partial_x - m_{s,c} \right] \psi_{s,c}(x) &= 0.
\end{align*}
\]

The mean-field potentials for a bag in nuclear matter are defined by $V^q_\sigma \equiv g^q_\sigma \sigma$, $V^q_\omega \equiv g^q_\omega \omega$, and $V^q_\rho \equiv g^q_\rho b$, with $g^q_\sigma$, $g^q_\omega$ and $g^q_\rho$ the corresponding quark-meson coupling constants.

The normalized, static solution for the ground state quarks or antiquarks with flavor $f$ in the hadron, $h$, may be written, $\psi_f(x) = N_f e^{-i\epsilon_f/R^*_h} \psi_f(x)$, where $N_f$ and $\psi_f(x)$ are the normalization factor and corresponding spin and spatial part of the wave function.

The bag radius in medium, $R^*_h$, will be determined through the stability condition for the mass of the hadron against the variation of the bag radius [2] (see Eq. (4)). The eigenenergies, $\epsilon_f$, in the wave function in units of $1/R^*_h$, are given by

\[
\begin{align*}
\begin{pmatrix} \epsilon_u \\ \epsilon_{\bar{u}} \end{pmatrix} &= \Omega^*_q \pm R^*_h \left( V^q_\omega + \frac{1}{2} V^q_\rho \right), \\
\begin{pmatrix} \epsilon_d \\ \epsilon_{\bar{d}} \end{pmatrix} &= \Omega^*_q \pm R^*_h \left( V^q_\omega - \frac{1}{2} V^q_\rho \right), \\
\epsilon_{s,c} &= \epsilon_{\bar{s},\bar{c}} = \Omega_{s,c}.
\end{align*}
\]

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masses in a nuclear medium are calculated by
\[ \Omega_2^2 = \sqrt{x_n^2 + (R^*_n m^*_n)^2}, \]
where \( m^*_n = m_n - g_\sigma^2 \sigma \) and \( \Omega_{s,c} = \sqrt{x_{s,c}^2 + (R^*_n m_{s,c})^2} \). The hadron masses in a nuclear medium are calculated by
\[
m^*_h = \frac{(n_q + n_{q})\Omega^*_q + (n_{s,c} + n_{s,c})\Omega_{s,c} - z_h} {R_h^*} + \frac{4}{3} \pi R_h^* B, \quad \frac{\partial m^*_h}{\partial R_h}\bigg|_{R_h=R^*_h} = 0, \tag{4}
\]
where \( n_q \) (\( n_{s,c} \)) are the lowest mode light quark (antiquark) and strange, charm (antistrange, anticharm) quark numbers in the hadron, \( h \), respectively, and the \( z_h \) parametrize the sum of the center-of-mass and gluon fluctuation effects, and are assumed to be independent of density. The parameters are determined in free space to reproduce the corresponding masses. We chose the values, \( m_q=5 \) MeV, \( m_s=250 \) MeV and \( m_c=1300 \) MeV for the current quark masses, and \( R_N=0.8 \) fm for the bag radius of the nucleon in free space. Other input parameters and some of the quantities calculated are given in Refs. [2, 5]. The quark-meson coupling constants, \( g_\sigma^2, g_\rho^2 \), are adjusted to fit the nuclear saturation energy and density of symmetric nuclear matter, and the bulk symmetry energy [2]. Exactly the same coupling constants, \( g_\sigma^2, g_\rho^2 \), are used for the light quarks in the mesons and hyperons as in the nucleon. However, in studies of the kaon system, we found that it was phenomenologically necessary to increase the strength of the vector coupling to the non-strange quarks in the \( K^+ \) (by a factor of \( 1.4^2 \)) in order to reproduce the empirically extracted \( K^+\)-nucleus interaction [3]. We assume this also for the \( D \) and \( \bar{D} \) mesons [3, 4]. The scalar \((U^h_s)\) and vector \((U^h_v)\) potentials felt by the hadrons, \( h \), in nuclear matter are given by:
\[
U_s = m^*_h - m_h, \quad U_v = (n_q - n_{q})V^q_\omega - I_3 V^q_\rho, \quad (V^q_\omega \to 1.4^2 V^q_\omega \text{ for } K, \bar{K}, D, \bar{D}), \tag{5}
\]
where \( I_3 \) is the third component of isospin projection of the hadron, \( h \). We show in Figs. 1 and 2 some of the calculated mean field potentials.

2. \( J/\Psi \) dissociation in nuclear matter

There is a great deal of interest in possible signals of Quark-Gluon Plasma (QGP) formation (or precursors to its formation) and \( J/\Psi \) suppression is a promising candidate. On the other hand, there may be other mechanisms which produce an increase in \( J/\Psi \) absorption in a hot, dense medium. We are particularly interested in the rather exciting suggestion that the charmed mesons, \( D, \bar{D}, D^* \) and \( \bar{D}^* \), should suffer substantial changes in their properties in a nuclear medium [3, 4] (see Fig. 1). This is expected to have a considerable impact on charm production in heavy ion collisions [6], although the mass of the \( J/\Psi \) is expected to change by a tiny amount in nuclear matter within QMC [2, 3, 6].

The suppression of \( J/\Psi \) production observed in relativistic heavy ion collisions, from \( p+A \) up to central \( S+U \) collisions, has been relatively well understood. But recent data from \( Pb+Pb \) collisions shows a considerably stronger \( J/\Psi \) suppression [3, 4]. In an attempt to explain this “anomalous” suppression, many authors have studied one of two possible mechanisms, namely hadronic processes [11–15] and QGP formation [16].

In the hadronic dissociation scenario [11] the reactions involving the \( J/\Psi, \pi+J/\Psi \to D^*+\bar{D}, \bar{D}^*+D \) and \( \rho+J/\Psi \to D+\bar{D} \), are well known. The absorption of the \( J/\Psi \) through these reactions have been found to be important in general and absolutely necessary in order to
Figure 1. Scalar and vector potentials for the $D$, $D^*$ and $\rho$ mesons in symmetric nuclear matter ($\rho_0=0.15$ fm$^{-3}$).

Figure 2. Scalar potential for the $\omega$ and $\eta$ mesons in $^{26}$Mg and $^{40}$Ca.

fit the data on $J/\Psi$ production. (See Refs. [10,12,17] and references therein.) $J/\Psi$ dissociation on comovers, combined with the absorption on nucleons, is the main mechanism proposed as an alternative to that of Matsui and Satz [16], i.e., the dissociation in a QGP.

Within the hadronic scenario the crucial point is the required dissociation strength. In particular, one needs a total cross section for the $\pi,\rho+J/\Psi$ interaction of around $1.5 \sim 3$ mb in order to explain the data in heavy ion simulations [10]. Recent calculations [13] of the reactions, $\pi+J/\Psi \to D + D^*, \bar D + D^*$ and $\rho+J/\Psi \to D + \bar D$, based on $D$ exchange, indicate a much lower cross section than this. The main uncertainty in the discussion of the $J/\Psi$ dissociation on a meson gas is associated with the estimates of the $\pi,\rho+J/\Psi$ cross sections [15]. According to the predictions for the $\pi+J/\Psi$ cross section [13] taking into account the pion kinetic energy and a thermal pion gas with average temperature of 150 MeV, one might conclude that the rate of this process is small independent of the $\pi+J/\Psi$ dissociation model used [14,17].

However, this situation changes when the in-medium potentials of the charmed mesons are taken into account, because they lower the $\pi+J/\Psi \to \bar D + D^*$ and $\rho+J/\Psi \to \bar D + D^*$ reaction thresholds [3,10,15] due to the effect of the vector and scalar potentials felt by the charmed $D$, $D^*$ and $\rho$ mesons (see Fig. 1). The cross sections calculated for the $\pi,\rho+J/\Psi$ collisions with the in-medium potentials are shown in Fig. 3. Clearly the $J/\Psi$ absorption cross sections are substantially enhanced for both the $\pi+J/\Psi$ and $\rho+J/\Psi$ reactions, not only because of the downward shift of the reaction threshold, but also because of the in-medium effect on the reaction amplitude. Moreover, now the $J/\Psi$ absorption on comovers becomes both energy and density dependent – a crucial finding given the situation in actual heavy ion collisions. These effects have never been considered before. The absorption cross section has hitherto been taken as a constant.

We found that the thermally averaged, in-medium $\pi+J/\Psi$ and $\rho+J/\Psi$ absorption
cross sections, $\langle \sigma v \rangle$, depend very strongly on the nuclear density. Even for $p_{J/\Psi}=0$, with a pion gas temperature of 120 MeV, which is close to the saturation pion density, the thermally averaged $J/\Psi$ absorption cross section on the pion at $\rho_B=3\rho_0$ is about a factor of 7 larger than that at $\rho_B=0$. As for the $\rho+J/\Psi$, the thermally averaged dissociation cross section at $\rho_B=3\rho_0$ becomes larger than 1 mb. Thus, the $J/\Psi$ absorption on $\rho$ mesons should be also appreciable, although it is expected the $\rho$ meson density is only half of the pion density in $Pb+Pb$ collisions.

In order to compare our results with the NA38/NA50 data on $J/\Psi$ suppression in $Pb+Pb$ collisions, we have adopted the heavy ion model proposed in Ref. [12] with the $E_T$ model from Ref. [13]. We introduce the absorption cross section on comovers as function of the density of comovers, while the nuclear absorption cross section is taken as 4.5 mb [13]. Our calculations are shown in Fig. 4 by the solid line, using the density dependent, thermally averaged cross section, $\langle \sigma v \rangle$, for $J/\Psi$ absorption on comovers. The dashed line in Fig. 4 shows the calculations with the phenomenological constant cross section for $J/\Psi$ absorption on comovers, $\langle \sigma v \rangle \approx 1$ mb given in Ref. [13]. Both curves clearly reproduce the data quite well, including most recent results from NA50 on the ratio of $J/\Psi$ over Drell-Yan cross sections, as a function of the transverse energy up to $E_T \approx 100$ GeV. It is important to note that if one neglected the in-medium modification of the $J/\Psi$ absorption cross section the large cross section, $\langle \sigma v \rangle \approx 1$ mb, could not be justified by microscopic theoretical calculations and thus the NA50 data [8,18] could not be described. Furthermore, our calculations with in-medium modified absorption provide a significant improvement in the understanding of the data [8] compared to the models quoted by NA50 [18].

The basic difference between our results and those quoted by NA50 [18] is that in previous heavy ion calculations [4,10,12] the cross section for $J/\Psi$ absorption on comovers...
was taken as a free parameter to be adjusted to the data \[8,18\] and was never motivated theoretically.

3. \(\omega\)-, \(\eta\)- and \(\eta'\)-nuclear bound states \[4\]

Next, we discuss the \(\omega\), \(\eta\)-, and \(\eta'\)-nuclear bound states \[4\]. We have solved the Klein-Gordon equation \[4\] using the calculated potentials (see Fig. 2):

\[
\left[ \nabla^2 + E_j^* - \tilde{m}_j^*(r) \right] \phi_j(r) = 0, \quad E_j^* \equiv E_j + m_j - i\Gamma_j/2, \quad (j = \omega, \eta, \eta'),
\]

where \(E_j^*\) is the complex valued, total energy of the meson, and we included the widths of the mesons in a nucleus assuming a specific form using \(\gamma_j\), which are treated as phenomenological parameters. According to the estimates in Refs. \[19,20\], the widths of the mesons in nuclei and at normal nuclear matter density are \(\Gamma_\eta^* \sim 30 - 70\) MeV \[19\] and \(\Gamma_\omega^* \sim 30 - 40\) MeV \[20\], respectively. Thus, we calculate the single-particle energies for the values \(\gamma_\omega = 0.2\), and \(\gamma_\eta = 0.5\), which are expected to correspond best with experiment, while for the \(\eta'\), \(\Gamma_\eta'^* = 0\) is assumed. For a comparison we give also the results for the \(\omega\) calculated using the potential obtained in Quantum Hadrodynamics (QHD) \[7\].

Table 1

Calculated \(\omega\)-, \(\eta\)- and \(\eta'\)-nuclear bound state energies (in MeV), \(E_j = Re(E_j^* - m_j) (j = \omega, \eta, \eta')\), in QMC \[4\] and those for the \(\omega\) in QHD with \(\sigma-\omega\) mixing effect \[7\]. The complex eigenenergies are given by, \(E_j^* = E_j + m_j - i\Gamma_j/2\). (* not calculated)

| \(\gamma_\eta = 0.5\) (QMC) | \(\gamma_\eta = 0.2\) (QMC) | \(\gamma_\omega = 0.2\) (QMC) | \(\gamma_\omega = 0.2\) (QHD) |
|-----------------|-----------------|-----------------|-----------------|
| \(E_\eta\) | \(\Gamma_\eta\) | \(E_{\eta'}\) | \(\Gamma_{\eta'}\) | \(E_\omega\) | \(\Gamma_\omega\) | \(E_\omega\) | \(\Gamma_\omega\) |
| \(^{6}\text{He}\) | 1s | -10.7 | 14.5 | * | -55.6 | 24.7 | -97.4 | 33.5 |
| \(^{14}\text{B}\) | 1s | -24.5 | 22.8 | * | -80.8 | 28.8 | -129 | 38.5 |
| \(^{26}\text{Mg}\) | 1s | -38.8 | 28.5 | * | -99.7 | 31.1 | -144 | 39.8 |
| | 1p | -17.8 | 23.1 | * | -78.5 | 29.4 | -121 | 37.8 |
| | 2s | — | — | * | -42.8 | 24.8 | -80.7 | 33.2 |
| \(^{16}\text{O}\) | 1s | -32.6 | 26.7 | -41.3 | | -93.4 | 30.6 | -134 | 38.7 |
| | 1p | -7.72 | 18.3 | -22.8 | | -64.7 | 27.8 | -103 | 35.5 |
| \(^{40}\text{Ca}\) | 1s | -46.0 | 31.7 | -51.8 | | -111 | 33.1 | -148 | 40.1 |
| | 1p | -26.8 | 26.8 | -38.5 | | -90.8 | 31.0 | -129 | 38.3 |
| | 2s | -4.61 | 17.7 | -21.9 | | -65.5 | 28.9 | -99.8 | 35.6 |
| \(^{90}\text{Zr}\) | 1s | -52.9 | 33.2 | -56.0 | | -117 | 33.4 | -154 | 40.6 |
| | 1p | -40.0 | 30.5 | -47.7 | | -105 | 32.3 | -143 | 39.8 |
| | 2s | -21.7 | 26.1 | -35.4 | | -86.4 | 30.7 | -123 | 38.0 |
| \(^{208}\text{Pb}\) | 1s | -56.3 | 33.2 | -57.5 | | -118 | 33.1 | -157 | 40.8 |
| | 1p | -48.3 | 31.8 | -52.6 | | -111 | 32.5 | -151 | 40.5 |
| | 2s | -35.9 | 29.6 | -44.9 | | -100 | 31.7 | -139 | 39.5 |
Our results suggest that one should expect to find bound $\omega$, $\eta$- and $\eta'$-nuclear states for all nuclei investigated and relatively wide range of the in-medium meson widths [4]. (For the predictions made by the other approaches, see Refs. [19,20].)

4. Summary

We have presented two possible signals for a change of meson properties in a nuclear medium. First, we discussed the impact on the observed $J/\Psi$ suppression in relativistic heavy ion collisions, which has received a lot of interest recently because of the Quark-Gluon Plasma. Second, we discussed the prediction of $\omega$, $\eta$- and $\eta'$-nuclear bound states. Both of these signals, for which many experiments are currently being performed or planned, certainly will provide important information about the in-medium properties of hadrons.

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