Mass shifts of charmonium states in nuclear matter

Arpita Mondal[1],* Pallabi Parui[2], and Amruta Mishra[3]
[1,2,3] Department of Physics, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi – 110016, India

1. Introduction

The mass shifts of the charmonium states are studied in the symmetric as well as in the asymmetric nuclear matter. An effective Lagrangian approach is adopted to study the medium effects. The Lagrangian is based on the chiral symmetry and the broken scale invariance of QCD.
The medium modifications of the charmonium states in high density matter, may affect the yield of open charm mesons and charmonium states, in heavy-ion collisions in compressed baryonic matter (CBM) experiments at the future facility at GSI.

2. Mass Modification of Charmonium States

The effective Lagrangian is based on the chiral symmetry and the broken scale invariance of QCD. The scale invariance breaking effect is incorporated through the scalar dilaton field, χ. The Lagrangian involves the kinetic energy terms and the interaction terms in the scalar-isoscalar (σ), vector-isoscalar(ω), pseudoscalar (π), vector-isovector (ρ) and scalar dilaton (χ), fields. The general form of the Lagrangian density is given as [1],

$$\mathcal{L} = \mathcal{L}_0 - V_G + \mathcal{L}' \tag{1}$$

Where, the terms are,

$$\begin{aligned}\mathcal{L}_0 &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\vec{\pi}.\partial^\mu\vec{\pi} + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi \\ &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\omega_\mu\omega^\mu\Big(G_{\omega\sigma}\Big(\sigma^2+\vec{\pi}^2\Big) \\ &+G_{\omega\phi}\phi^2\Big) + \overline{\psi}\Big(\gamma^\mu\Big(i\partial_\mu - g_\omega\omega_\mu\Big) - g \\ &\times\Big(\sigma + i\vec{\pi}.\vec{\tau}\gamma_5\Big)\Big)\psi\end{aligned} \tag{2}$$

Where, $F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu$ and the vacuum nucleon mass $M = g\sigma_0$. The explicit breaking of scale invariance is incorporated through a logarithmic potential term,

$$\begin{aligned}V_G &= B\chi^4\Big(ln(\frac{\chi}{\chi_0}) - \frac{1}{4}\Big) - \frac{1}{2}B\delta\chi^4 ln\frac{\sigma^2+\vec{\pi}^2}{\sigma_0^2} \\ &+\frac{1}{2}B\delta\zeta^2\chi^2\Big(\sigma^2+\vec{\pi}^2 - \frac{1}{2}\frac{\chi^2}{\zeta^2}\Big)\end{aligned} \tag{3}$$

Where, $\zeta = \frac{\chi_0}{\sigma_0}$, is taken as 1.6 [1] and $\sigma_0 = f_\pi$, $\delta = \frac{4}{33}$. The parameter B is determined through the comparison of the trace of the energy momentum tensor in QCD and the trace of the energy momentum tensor corresponding to the Lagrangian Eq.(1), leads to

$$\epsilon_{vac} = -\frac{1}{4}B\chi_0^4(1-\delta) \tag{4}$$

Where, ϵ_{vac} is the vacuum energy, taken as $\epsilon_{vac}^{\frac{1}{4}} = 269$ MeV. To include vector-isovector field b_μ (corresponding to the ρ field) to the study, the corresponding Lagrangian term must be in the form of

$$\begin{aligned}\mathcal{L}' &= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}G_\rho\phi^2 b_\mu.b^\mu \\ &-\overline{\psi}\gamma^\mu\Big(\frac{1}{2}g_\rho b_\mu.\tau\Big)\psi\end{aligned} \tag{5}$$

*Electronic address: arpita.mondal@physics.iitd.ac.in

Where, the field strength tensor is $B_{\mu\nu} = \partial_\mu b_\nu - \partial_\nu b_\mu$. Using the Lagrangian density, Eq.(1), the coupled equations of motion for χ and σ fields are solved under the mean-field approximation [1], with the effective nucleon mass $M^* = M\left(\frac{\sigma}{\sigma_0}\right)$.

The medium modifications of the masses of charmonium states, in the dense, asymmetric nuclear medium are obtained from the medium modifications of the scalar dilaton field. The mass shifts of the charmonium states, in the non-relativistic limit, are given due to the change of the gluon condensate in nuclear medium [2, 3]

$$\triangle m_\psi = \frac{4}{87} B(1-\delta) \int dk^2 \Big|\frac{\partial \psi(k)}{\partial k}\Big|^2 \frac{k}{\frac{k^2}{m_c} + \epsilon} \times \Big(\chi^4 - \chi_0^4\Big) \quad (6)$$

In Eq.(6), m_c is the mass of the charm quark, taken as 1.95 GeV, m_ψ is the vacuum mass of the corresponding charmonium state and $\epsilon = 2m_c - m_\psi$ is the binding energy. $\psi(k)$ is the wave function of the charmonium states [4],

$$\psi_{nlm}(\vec{r}) = N(\beta^2 r^2)^{\frac{l}{2}} e^{-\frac{\beta^2 r^2}{2}} L_{N-1}^{l+\frac{1}{2}}(\beta^2 r^2) \times Y_{lm}(\theta, \phi) \quad (7)$$

Where, N is the normalization constant, β [4] characterizes the strength of the harmonic potential, $L_p^k(z)$ is the associated Laguerre Polynomial, notations in small letters are the usual quantum numbers. The charmonium states, in the momentum space, are normalized as [5], $\int \frac{d^3k}{(2\pi)^3}\Big|\psi(k)\Big|^2 = 1$.

3. Results and Discussions

The mass shifts of the charmonium states are studied in the symmetric and the asymmetric nuclear medium. The masses of charmonium states are observed to decrease from the vacuum value with the increase of density from $\rho_B = 0$ to $6\rho_0$ (with $\rho_0 = 0.15\ fm^{-3}$). The magnitude of the mass shifts increase and then slightly decrease with the relative baryon density, which is due to the in-medium behavior of the χ field. The magnitude of the mass shifts are seen to decrease with the increase of asymmetry parameter, which is also because of the drop in dilaton field χ. In Fig.1 it shows the mass shift for J/ψ in symmetric and asymmetric (with $\eta = 0.5$) nuclear matter. The mass shifts of the other charmonium states, e.g., $\psi(2S)$, $\psi(1D)$ can be obtained in the similar way. It can be concluded from this work that the excited states are observed to have larger mass drop as compared to the ground state, J/ψ. Thus the production of the charmonium and the open charm mesons can be affected due to the mass shifts of charmonium states, as the mass shifts are relevant for the production of those states. The density effects can be probed into CBM experiment.

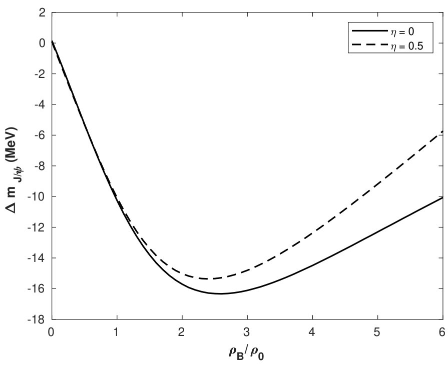

FIG. 1: The mass shift (in MeV) of the J/ψ state is plotted as a function of baryonic density ρ_B (in units of ρ_0), with asymmetry factor $\eta = 0$ and $\eta = 0.5$, where $\eta = \frac{\rho_n - \rho_p}{\rho_B}$.

References

[1] E. K. Heide and S. Rudaz and P. J. Ellis, Nucl. Phys. A **571**, 4 (1994).

[2] S. H. Lee and C. M. Ko, Phys. Rev. C **67**, 038202 (2003).

[3] A. Kumar and A. Mishra, Phys. Rev. C, **81**, 065204, (2010).

[4] B. Friman, S.H. Lee, T. Song, Phys. Lett. B **548**, 153 (2002).

[5] S. H. Lee and K. Morita, Phys. Rev. D **79** 011501 (2009).