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Υ and η_b mass shifts in nuclear matter and the ^{12}C nucleus bound states

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This is a contribution for the PANIC 2021 Proceedings based on the articles, Eur. Phys. J. A 57, 259 (2021) and [arXiv:2109.08636 [hep-ph]]. We have estimated for the first time the mass shifts of the Υ and η_b mesons in symmetric nuclear matter by an SU(5) flavor symmetric effective Lagrangian approach, as well as the in-medium mass of B^* meson by the quark-meson coupling (QMC) model. The attractive potentials for the Υ- and η_b-nuclear matter are obtained, and one can expect for these mesons to form nuclear bound states. We have indeed found such nuclear bound states with ^{12}C nucleus, where the results for the ^{12}C nucleus bound state energies are new, and we report here for the first time.

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1. Introduction

By studying the Υ- and η_b-nucleus interactions, one can advance in understanding the heavy meson and heavy quark interactions with nucleus based on quantum chromodynamics (QCD). For a possible mechanism of the bottomonium interaction with the nuclear medium (nucleus), we apply here, via the excitations of the intermediate state hadrons which contain the light quarks u and d.

We first calculate the in-medium B and B^* meson masses, then we estimate the mass shifts of the Υ and η_b mesons through the excitations of intermediate state B and B^* mesons in the Υ and η_b self-energies. The estimates will be made by an SU(5) effective Lagrangian which contains both the Υ and η_b mesons with one universal coupling constant. Thus, we need to know better the B and B^* meson properties in medium. For this purpose we use the quark-meson coupling (QMC) model invented by Guichon [1], which has been successfully applied for various studies [2, 3].

The interesting question is, whether or not the attractive Υ- and η_b-nuclear matter interactions are strong enough to form nuclear bound states. Thus, we study the Υ- and η_b-^{12}C bound states for the first time.

2. Υ and η_b mass shifts in symmetric nuclear matter

We calculated the effective masses (Lorentz scalar) of the B and B^* mesons in symmetric nuclear matter using the QMC model, where that of the B^* meson was the first time [4].

As shown in Fig. 1, the QMC model predicts a similar amount of the B and B^* mass shifts. The mass shifts predicted are, respectively, $(m^*_B - m_B) = -61$ MeV and $(m^*_{B^*} - m_{B^*}) = -61$ MeV at $\rho_0 = 0.15$ fm^{-3}, with the difference in the next digit. To calculate the Υ and η_b meson self-energies in symmetric nuclear matter via the B and B^* meson loops, we use the obtained in-medium masses shown in Fig. 1.

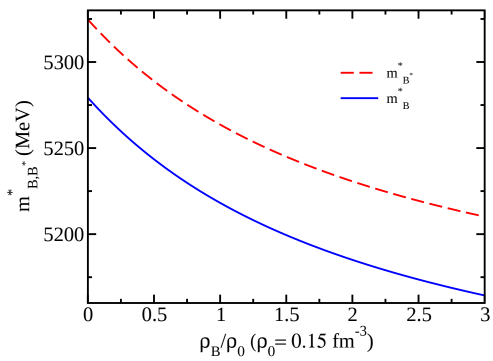

Figure 1: B and B^* meson effective masses (Lorentz scalar) in symmetric nuclear matter.

The Υ and η_b mass shifts in medium come from the modifications of the BB, BB^* and B^*B^* meson loop contributions to their self-energies, relative to those in free space, where the self-energies are calculated based on an effective flavor SU(5) symmetric Lagrangian, with the one SU(5) universal coupling constant value determined by the vector meson dominance (VMD) hypothesis (model) with the experimental data for $\Gamma(\Upsilon \to e^+e^-)$ [4]. We use phenomenological

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form factors to regularize the self-energy integrals, which are dependent on the cutoff $\Lambda_B = \Lambda_{B^*}$ values in the range 2000 MeV $\leq \Lambda_{B,B^*} \leq$ 6000 MeV.

For our predictions, we take the minimum meson loop contributions, namely, that is estimated by including only the BB meson loop for the Υ self-energy, and only the BB^* meson loop for the η_b self-energy. It is necessary to regard as our prediction only the minimum loop contributions, because the unexpectedly larger contribution from the heavier B^*B^* meson loop was observed [4]. Note that, we ignore the possible widths, or the imaginary parts in the self-energies in the present study. We plan, however, to include the effects of the widths into the calculation in the near future.

The calculated mass shifts of the Υ and η_b mesons are shown in Fig. 2. As one can see in the left panel for the Υ, the effect of the decrease in the B meson in-medium mass yields a negative mass shift of the Υ. The decrease of the B meson mass in nuclear matter enhances the BB meson loop contribution for the Υ in-medium self-energy in such a way to yield a negative mass shift, which is also dependent on the cutoff mass value Λ_B. Namely, the amount of the mass shift increases as Λ_B increases, ranging from -16 to -22 MeV at symmetric nuclear matter saturation density, ρ_0. For the η_b mass shift, which is estimated by including only the BB^* meson loop (right panel), it ranges from -75 to -82 MeV at ρ_0 for the same range of cutoff mass values as that was used for the Υ case.

As one can see, the mass shift of η_b is larger than that of the Υ. This reflects the fact that the η_b interaction Lagrangian has a larger number of interaction terms contributing to the self-energy, and results to yield more contribution than that of the Υ. The use of the SU(5) symmetric couplings also gives an impact on the calculated η_b mass shift, as well as on the ^{12}C nucleus bound states energies to be given in the next section.

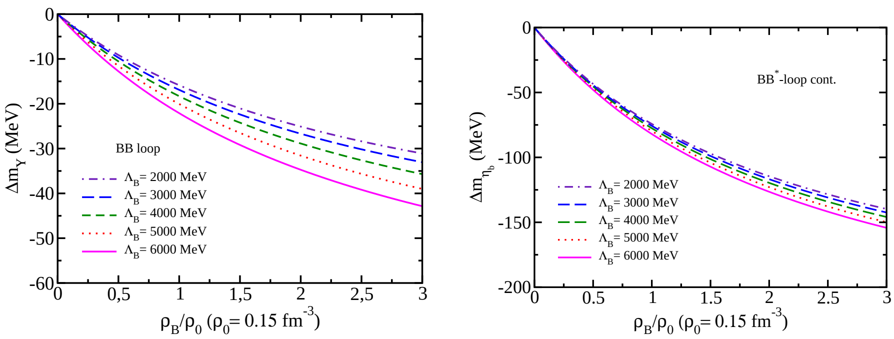

Figure 2: BB loop contribution to the Υ mass shift (left) and BB^* loop contribution to the η_b mass shift (right) for five different values of the cutoff mass $\Lambda_B(= \Lambda_{B^*})$.

3. Υ- and η_b-nucleus bound states with ^{12}C

We consider the situation that an Υ or an η_b meson is produced inside a ^{12}C nucleus with nearly zero relative momentum to ^{12}C, where the ^{12}C has baryon density distribution $\rho_B^{^{12}C}(r)$, and we follow the procedure of Refs. [5, 6]. In Ref. [7] we have presented the result for the ^{4}He case, where the density profile was parameterized and taken from [8]. However, for the ^{12}C nucleus in the present case, the density profile is calculated by the QMC model. We also use a local density approximation to obtain the Υ and η_b nuclear potentials inside the ^{12}C nucleus, which are shown in

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Fig. 3 for five values of Λ_B. The potentials are both attractive, with their depths depending on the cutoff mass values, namely, the deeper the larger Λ_B.

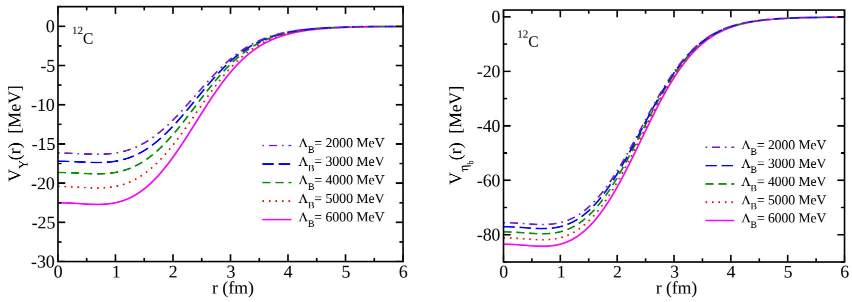

Figure 3: Υ- and η_b-nucleus potential for the ^{12}C nucleus.

The Υ- and η_b-^{12}C bound state energies are then calculated by solving the Klein-Gordon equation using the nuclear potentials shown in Fig. 3. Although Υ is a spin-1 particle, we make an approximation that the transverse and longitudinal components in the Proca equation are expected to be very similar for the Υ nearly at rest, hence it is reduced to one component, which corresponds to the Klein-Gordon equation. The bound state energies are calculated for the same values of the cutoff mass Λ_B used in the previous section, and the results are given in Table. 1. Note that, due to the large number of the η_b bound states found for ^{12}C, we have not shown the shallower bound state energies explicitly for the η_b in the table. The results indicate that both the Υ and η_b are expected to form bound states with the ^{12}C nucleus. We will consider other nuclei in the upcoming study [9]. We emphasize that, even though the values of the bound state energies vary according to the chosen values of the cutoff mass, the prediction that the Υ and η_b are expected to form bound states with the ^{12}C nucleus, is independent of the values chosen. By ignoring the widths, the experimental observation of the predicted bound states could be an issue, but the present study primarily focuses on the existence of the bound states. We plan to include the effects of the widths in the future study [9] to see the impact of them on the results.

Table 1: $^{12}_{\Upsilon}$C and $^{12}_{\eta_b}$C bound state energies. When $|E| < 10^{-1}$ MeV we consider there is no bound state, which we denote with "n". All dimensioned quantities are in MeV. The shallower bound states for the η_b are not shown explicitly.

		Bound state energies				
	$n\ell$	$\Lambda_B = 2000$	$\Lambda_B = 3000$	$\Lambda_B = 4000$	$\Lambda_B = 5000$	$\Lambda_B = 6000$
$^{12}_{\Upsilon}$C	1s	-10.6	-11.6	-12.8	-14.4	-16.3
	1p	-6.1	-6.8	-7.9	-9.3	-10.9
	1d	-1.5	-2.1	-2.9	-4.0	-5.4
	2s	-1.6	-2.1	-2.8	-3.8	-5.1
	2p	n	n	n	-0.1	-0.7
$^{12}_{\eta_b}$C	1s	-65.8	-67.2	-69.0	-71.1	-73.4
	1p	-57.0	-58.4	-60.1	-62.1	-64.3
	1d	-47.5	-48.8	-50.4	-52.3	-54.4
	...	...	...	...	...	...
	2h	n	n	n	-0.2	-1.2

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4. Summary and Conclusion

We have estimated for the first time the B^*, Υ and η_b mass shifts in symmetric nuclear matter, as well as the Υ- and η_b-^{12}C bound state energies neglecting any possible widths of the mesons, assuming each meson is produced inside the ^{12}C nucleus with nearly zero relative momentum.

The in-medium B and B^* meson masses necessary to evaluate the Υ and η_b self-energies are calculated by the quark-meson coupling model. Our predictions, taking only the BB meson loop contribution for the Υ mass shift, and only the BB^* meson loop contribution for the η_b mass shift, give the Υ mass shift that varies from -16 MeV to -22 MeV at symmetric nuclear matter saturation density (ρ_0 = 0.15 fm^{-3}) for the cutoff mass values in the range from 2000 MeV to 6000 MeV, while for the η_b it ranges from -75 to -82 MeV at ρ_0 for the same cutoff mass value range.

For the $\eta_b BB^*$ coupling constant value, we have used the SU(5) universal coupling constant and the value determined by the ΥBB coupling constant by the vector meson dominance model with the experimental data.

For the Υ or η_b meson produced inside the ^{12}C nucleus with nearly zero relative momentum to ^{12}C, their attractive interactions are strong enough to form bound states with the ^{12}C nucleus. The bound state energies have been calculated by solving the Klein-Gordon equation, with the nuclear potentials obtained using a local density approximation, and the nuclear density distribution calculated by the quark-meson coupling model.

We plan to elaborate the present study in the near future by including the effects of the widths, as well as using different regularization methods and/or form factors in the Υ and η_b self-energies.

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