\( \Upsilon \) and \( \eta_b \) mass shifts in nuclear matter and the \( ^{12}\text{C} \) 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 (2021) and the accompanied article \([\text{arXiv:2109.08636 [hep-ph]}]\) (Hadron 2021 contribution). We have estimated for the first time the mass shifts of the \( \Upsilon \) and \( \eta_b \) 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 \( \Upsilon \)- and \( \eta_b \)-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 \( ^{12}\text{C} \) nucleus, where the results for the \( ^{12}\text{C} \) nucleus bound state energies are new, and we report here for the first time.
1. Introduction

By studying the Υ- and ηb-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 $\eta_b$ mesons through the excitations of intermediate state $B$ and $B^*$ mesons in the Υ and $\eta_b$ self-energies. The estimates will be made by an SU(5) effective Lagrangian which contains both the Υ and $\eta_b$ 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 $\eta_b$-nuclear matter interactions are strong enough to form nuclear bound states. Thus, we study the Υ- and $\eta_b$-$^{12}$C bound states for the first time.

2. Υ and $\eta_b$ 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 $\eta_b$ 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.](image)

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

For our predictions, we take the minimum meson loop contributions, namely, that is estimated by including only the $BB$ meson loop for the $\Upsilon$ self-energy, and only the $BB^*$ meson loop for the $\eta_b$ self-energy. This is necessary, because the unexpectedly larger contribution from the heavier $B^*B^*$ meson loop was observed\cite{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 $\Upsilon$ and $\eta_b$ mesons are shown in Fig. 2. As one can see in the left panel for the $\Upsilon$, the effect of the decrease in the $B$ meson in-medium mass yields a negative mass shift of the $\Upsilon$. The decrease of the $B$ meson mass in nuclear matter enhances the $BB$ meson loop contribution for the $\Upsilon$ in-medium self-energy in such a way to yield a negative mass shift, which is also dependent on the cutoff mass value $\Lambda_B$. Namely, the amount of the mass shift increases as $\Lambda_B$ increases, ranging from -16 to -22 MeV at symmetric nuclear matter saturation density, $\rho_0$. For the $\eta_b$ mass shift, which is estimated by including only the $BB^*$ meson loop (right panel), it ranges from -75 to -82 MeV at $\rho_0$ for the five cutoff mass values, the same as those for the $\Upsilon$.

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

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

3. $\Upsilon$- and $\eta_b$-nucleus bound states with $^{12}\text{C}$

We consider the situation that an $\Upsilon$ or an $\eta_b$ meson is produced inside a $^{12}\text{C}$ nucleus with nearly zero relative momentum to $^{12}\text{C}$, where the $^{12}\text{C}$ has baryon density distribution $\rho_{^{12}\text{C}}(r)$, and we follow the procedure of Refs. [5, 6]. In Ref. [7] we have presented the result for the $^{4}\text{He}$ case, where the density profile was parameterized and taken from [8]. However, for the $^{12}\text{C}$ nucleus in the present case, the density profile is calculated by the QMC model. We also use a local density approximation to obtain the $\Upsilon$ and $\eta_b$ nuclear potentials inside the $^{12}\text{C}$ nucleus, which are shown in
Fig. 3 for five values of \( \Lambda_B \). The potentials are both attractive, with their depths depending on the cutoff mass values, namely, the deeper the larger \( \Lambda_B \).

The \( \Upsilon \)- and \( \eta_b \)-\( ^{12}\text{C} \) bound state energies are then calculated by solving the Klein-Gordon equation using the nuclear potentials shown in Fig. 3. Although \( \Upsilon \) 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 \( \Upsilon \) 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 \( \Lambda_B \) used in the previous section, and the results are given in Table. 1. Note that, due to the large number of the \( \eta_b \) bound states found for \( ^{12}\text{C} \), we have not shown the shallower bound state energies explicitly for the \( \eta_b \) in the table. The results indicate that both the \( \Upsilon \) and \( \eta_b \) are expected to form bound states with the \( ^{12}\text{C} \) 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 \( \Upsilon \) and \( \eta_b \) are expected to form bound states with the \( ^{12}\text{C} \) 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: \( ^{12}\text{C} \) and \( \eta_b \)-\( ^{12}\text{C} \) 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 bond states for the \( \eta_b \) are not shown explicitly.

| Bound state energies | \( n\ell \) | \( \Lambda_B = 2000 \) | \( \Lambda_B = 3000 \) | \( \Lambda_B = 4000 \) | \( \Lambda_B = 5000 \) | \( \Lambda_B = 6000 \) |
|---------------------|------------|----------------|----------------|----------------|----------------|----------------|
| \( ^{12}\text{C} \)  | 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          |
| \( \Upsilon \)     | 1s         | -63.8         | -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         |
|                     | ...        | ...           | ...           | ...           | ...           | ...           |
| \( \eta_b \)       | 1s         | n             | n             | n             | -0.2          | -1.2          |
4. Summary and Conclusion

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

The in-medium $B$ and $B^*$ meson masses necessary to evaluate the $\Upsilon$ and $\eta_b$ self-energies are calculated by the quark-meson coupling model. Our predictions, taking only the $BB$ meson loop contribution for the $\Upsilon$ mass shift, and only the $BB^*$ meson loop contribution for the $\eta_b$ mass shift, give the $\Upsilon$ mass shift that varies from -16 MeV to -22 MeV at symmetric nuclear matter saturation density ($\rho_0 = 0.15 \text{ fm}^{-3}$) for the cutoff mass values in the range from 2000 MeV to 6000 MeV, while for the $\eta_b$ it ranges from -75 to -82 MeV at $\rho_0$ 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 $\Upsilon BB$ coupling constant by the vector meson dominance model with the experimental data.

For the $\Upsilon$ or $\eta_b$ meson produced inside the $^{12}\text{C}$ nucleus with nearly zero relative momentum to $^{12}\text{C}$, their attractive interactions are strong enough to form bound states with the $^{12}\text{C}$ 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 $\Upsilon$ and $\eta_b$ self-energies.

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Y and \( \eta_b \) mass shifts in nuclear matter and the nucleus bound states

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We estimate for the first time the mass shifts (scalar potentials) in symmetric nuclear matter of the \( Y \) and \( \eta_b \) mesons using an effective Lagrangian approach, as well as the in-medium mass of the \( B^* \) meson by the quark-meson coupling model. The attractive potentials of both \( Y \) and \( \eta_b \) are expected to be strong enough for these mesons to be bound to the \( ^4 \text{He} \) nucleus, and we have obtained such nuclear bound state energies.

I. INTRODUCTION

By studying the interactions of bottomonium states, such as \( Y \) and \( \eta_b \) with nuclei, we can advance in understanding the hadron properties and strongly interacting systems based on quantum chromodynamics (QCD). A possible mechanism for the bottomonium interaction with the nuclear medium is through the excitation of the intermediate state hadrons which contain light quarks.

First we calculate the in-medium \( B \) and \( B^* \) meson masses, then we estimate the mass shifts of the \( Y \) and \( \eta_b \) mesons in terms of the excitations of intermediate state hadrons with light quarks in their self-energies. The estimates will be made using an SU(5) effective Lagrangian density which contains both the \( Y \) and \( \eta_b \) mesons with one universal coupling constant. Then, the present study can also provide information on the SU(5) symmetry breaking. Thus, we need to have better knowledge on the in-medium properties (Lorenz-scalar and Lorentz-vector potentials) of the \( B \) and \( B^* \) mesons. For this purpose we use the quark-meson coupling (QMC) model invented by Guichon \([1]\), which has been successfully applied for various studies.

Another interesting question is whether or not the strengths of the bottomonium-nuclear matter interactions are strong enough to form bound states. We then use the density profiles of the \( ^4 \text{He} \) nucleus, together with the mass shifts of both \( Y \) and \( \eta_b \) to estimate the scalar \( Y \)- and \( \eta_b \)-nucleus potentials using a local density approximation.

II. \( Y \) AND \( \eta_b \) MASS SHIFTS

We have calculated the Lorentz-scalar effective masses of the \( B \) and \( B^* \) in symmetric nuclear matter \([2]\) using the QMC model, with the in-medium \( B^* \) meson mass having not been calculated nor presented in the past.

The QMC model predicts a similar amount in the decrease of the in-medium effective Lorentz-scalar masses of the \( B \) and \( B^* \) mesons in symmetric nuclear matter as shown in Fig. \([3]\). At \( \rho_0 = 0.15 \text{ fm}^{-3} \) the mass shifts of the \( B \) and \( B^* \) mesons are respectively, \((m_B^* - m_B) = -61 \text{ MeV}\) and \((m_{B^*}^* - m_{B^*}) = -61 \text{ MeV}\), the difference in their mass shift values appears in the next digit. To calculate the \( Y \) and \( \eta_b \) meson self-energies in symmetric nuclear matter by the excited \( B \) and \( B^* \) meson intermediate states in the loops, we use the calculated in-medium masses of them shown in Fig. \([4]\).

The \( Y \) and \( \eta_b \) mass shifts in medium come from the modification of the \( BB \), \( BB^* \) and \( B^*B^* \) meson loop contributions to their the self-energies relative to those in free space,

\[
V = m_{Y,\eta_b}^* - m_{Y,\eta_b},
\]

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with the free space physical Υ and η_b masses being reproduced first by,

\[ m_{\Upsilon,\eta_b}^2 = (m_{\Upsilon,\eta_b}^0)^2 + \Sigma_{\Upsilon,\eta_b}(k^2 = m_{\Upsilon,\eta_b}^2), \]  

(2) 

(the in-medium masses, \( m_{\Upsilon,\eta_b}^* \), are calculated likewise, by the total self-energies in medium using the medium-modified \( B \) and \( B^* \) meson masses with the same \( m_{\Upsilon,\eta_b}^0 \) values fixed in free space,) where \( m_{\Upsilon,\eta_b}^0 \) are the bare masses, and the self-energies \( \Sigma_{\Upsilon,\eta_b} \) are calculated based on an effective flavor SU(5) symmetry Lagrangian,

\[ \mathcal{L} = \mathcal{L}_0 + ig \text{Tr} (\partial_{\mu} P [P, V_{\mu}]) - \frac{g^2}{4} \text{Tr} \left( [P, V_{\mu}]^2 \right) 
+ ig \text{Tr} (\partial^\mu V_{\nu} [V_{\mu}, V_{\nu}]) + \frac{g^2}{8} \text{Tr} \left( [V_{\mu}, V_{\nu}]^2 \right), \]

(3) 

in which

\[ \mathcal{L}_0 = \text{Tr} \left( \partial_{\mu} P^\dagger \partial^\mu P \right) - \frac{1}{2} \text{Tr} \left( F_{\mu\nu}^\dagger F^{\mu\nu} \right), \]

(4) 

with

\[ F_{\mu\nu} = \partial_{\mu} V_{\nu} - \partial_{\nu} V_{\mu}, \]

where \( P \) and \( V \) are, respectively, the 5 \times 5 pseudoscalar and vector meson matrices in SU(5), and minimal substitutions are introduced to obtain the couplings (interactions) between the pseudoscalar mesons and vector mesons

\[ \partial_{\mu} P \rightarrow \partial_{\mu} P - \frac{ig}{2} [V_{\mu}, P], \]

(5) 

\[ F_{\mu\nu} \rightarrow \partial_{\mu} V_{\nu} - \partial_{\nu} V_{\mu} - \frac{ig}{2} [V_{\mu}, V_{\nu}]. \]

(6) 

We have used an SU(5) universal coupling constant obtained by the vector meson dominance (VMD) hypothesis (model) using the experimental data for \( \Gamma(\Upsilon \rightarrow e^+ e^-) \) [2],

\[ g_{\Upsilon BB} = g_{\eta_b B B^*} = \frac{5g}{4\sqrt{10}} = 13.2228 \approx 13.2. \]

(7) 

We use phenomenological form factors to make the regularization of the self-energy integrals, with those being dependent on a cutoff \( \Lambda_B = \Lambda_{B^*} \) with values between 2000 MeV \( \leq \Lambda_{B,B^*} \leq 6000 \) MeV

\[ \omega_{B,B^*}(q^2) = \left( \frac{\Lambda_{B,B^*}^2 + m_{\Upsilon,\eta_b}^2}{\Lambda_{B,B^*}^2 + 4\omega_{B,B^*}^2(q^2)} \right)^2, \]

(8) 

with \( \omega_{B,B^*} = (q^2 + m_{B,B^*}^2)^{1/2} \).
But we regard as our prediction for the mass shifts as taking the minimum meson loop contribution, namely, that is estimated by taking only the $BB$ meson loop contribution for the $\Upsilon$ case and the $BB^*$ for the $\eta_b$. This is necessary due to the unexpectedly large contribution from the heavier meson pairs. Therefore, we consider only the following interaction Lagrangians obtained from Eq. (3):

$$L_{TBB} = ig_{TBB} \Upsilon \left[ \bar{B} \partial_\mu B - (\partial_\mu B) \right],$$

$$L_{\eta_b, BB^*} = ig_{\eta_b, BB^*} \left\{ (\partial_\mu \eta_b) \left[ \bar{B} \partial_\mu B - \bar{B} \partial_\mu B \right] - \eta_b \left[ \bar{B} \partial_\mu (\partial_\mu B) - (\partial_\mu \bar{B}) \right] \right\}. \tag{9}$$

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 results for the mass shifts of the $\Upsilon$ and $\eta_b$ mesons are presented in Fig. 2. As one can see in the left panel for $\Upsilon$, the effect of the decrease in the $B$ meson in-medium mass yields a negative mass shift of the $\Upsilon$. The decrease of the $B$ meson mass in (symmetric) nuclear matter enhances the $BB$ meson loop contribution, thus the self-energy contribution in the medium becomes larger than that in the free space. This negative shift of the $\Upsilon$ mass is also dependent on the value of the cutoff mass $\Lambda_B$, i.e., the amount of the mass shift increases as $\Lambda_B$ value increases, ranging from -16 to -22 MeV at the symmetric nuclear matter saturation density, $\rho_0$. Now for the calculated $\eta_b$ mass shift for including only the $BB^*$ loop (right panel) at $\rho_0$ ranges from -75 to -82 MeV for five different cutoff mass values, the same as those applied for the $\Upsilon$.

As one can see, the mass shift of $\eta_b$ is different (higher) than that of $\Upsilon$. This is due to the fact that the Lagrangian for the $\eta_b$ case has a larger number of the interaction terms that contributes to the self-energy, as can be seen in Eq. (9), resulting in a larger total contribution in comparison to the $\Upsilon$ case. The use of SU(5) symmetry for the couplings also contributes to the difference in the mass shifts, with they becoming closer in a SU(5) symmetry breaking scenario. This will have an impact on the nuclear bound states in the next section.

FIG. 2: $BB$ loop contribution to the $\Upsilon$ mass shift (left) and $BB^*$ loop contribution to the $\eta_b$ mass shift (right) versus nuclear matter density for five different values of the cutoff mass $\Lambda_B (= \Lambda_{B^*})$.

### III. $\Upsilon$- AND $\eta_b$-NUCLEUS BOUND STATES

To consider the case where the $\Upsilon$ and the $\eta_b$ mesons are produced inside a $^4\text{He}$ nucleus with baryon density distribution $\rho_B^{4\text{He}}(r)$, we follow the procedure of Ref. [3]. The nuclear density distribution was obtained in Ref. [3], and we use a local density approximation to obtain the $\Upsilon$ and $\eta_b$ nuclear potentials for the $^4\text{He}$ nucleus, which are presented in Fig. 3 for various values of the parameter $\Lambda_B$. The potentials are both attractive, with their depths dependent on the value of the cutoff mass, being deeper the larger $\Lambda_B$.

The $\Upsilon$- and $\eta_b$-nucleus bound state energies for the $^4\text{He}$ nucleus are then calculated by solving the Klein-Gordon equation using the nuclear potentials above (Since $\Upsilon$ is a spin-1 particle, we make an approximation where the transverse and longitudinal components in the Proca equation are expected to be very similar for $\Upsilon$ at rest, hence it is reduced to only one component, which corresponds to the Klein-Gordon equation). The bound state energies are calculated for the same values of the cutoff parameter $\Lambda_B$ used in the previous calculations, and are listed in Table 1. The results indicate that both $\Upsilon$ and $\eta_b$ are expected to form bound states with the $^4\text{He}$ nucleus. It will be considered other nuclei for the study in an upcoming publication [3]. Note that even though the values of the bound state energies vary according the chosen value for the cutoff parameter, the overall prediction that $\Upsilon$ and $\eta_b$ shall form bound states with the $^4\text{He}$ nucleus is independent of this choice. By ignoring the widths, the observation of the predicted bound states could be an issue, but the present study is primarily concerned on predicting the existence of bound states. Furthermore, we plan to include the effects of the widths in the future, to see how much it will impact on the results.
FIG. 3: Υ- and ηb-nucleus potential for the $^4\text{He}$ nucleus.

TABLE I: $^4\text{He}$ and $^4\eta_b$ He 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.

| State | $\Lambda_B = 2000$ | $\Lambda_B = 3000$ | $\Lambda_B = 4000$ | $\Lambda_B = 5000$ | $\Lambda_B = 6000$ |
|-------|-------------------|-------------------|-------------------|-------------------|-------------------|
| $^4\text{He}$ ls | -5.6 | -6.4 | -7.5 | -9.0 | -10.8 |
| $^4\eta_b$ ls | -65.1 | -64.7 | -66.7 | -69.0 | -71.5 |
| 1p | -40.6 | -42.0 | -43.7 | -45.8 | -48.0 |
| 1d | -17.2 | -18.3 | -19.7 | -21.4 | -23.2 |
| 2s | -15.6 | -16.6 | -17.9 | -19.4 | -21.1 |
| 2p | n | n | -0.3 | -0.9 | -1.7 |

IV. CONCLUSION

We have estimated for the first time the $B^*$, Υ and ηb mass shifts in symmetric nuclear matter, as well as the Υ-nucleus and ηb-nucleus bound state energies, neglecting any possible widths of the mesons. The in-medium $B$ and $B^*$ meson masses necessary to evaluate the Υ and ηb self-energies in symmetric nuclear matter, are calculated by the quark-meson coupling model. We regard our prediction as taking the minimum meson loop contribution, namely, that is estimated by taking only the $BB$ meson loop contribution for the Υ mass shift, and only the $BB^*$ meson loop contribution for the mass shift of ηb.

Our prediction by this only $BB$-loop, gives the in-medium Υ mass shift that varies from -16 MeV to -22 MeV at the symmetric nuclear matter saturation density ($\rho_0 = 0.15$ fm$^{-3}$) for the cutoff mass values in the range from 2000 MeV to 6000 MeV, while the obtained ηb mass shift at symmetric nuclear matter saturation density ranges from -75 to -82 MeV for the same ranges of the cutoff mass values used for the Υ mass shift. For the $\eta_b B B^*$ coupling constant, we have used the SU(5) universal coupling constant determined by the Υ $B B$ coupling constant by the vector meson dominance model with the experimental data.

For the Υ and ηb mesons produced within the $^4\text{He}$ nucleus, the mass shifts obtained are strong enough to form bound states. These bound state energies have been obtained by solving the Klein-Gordon equation, with the nuclear potentials obtained using a local density approximation, and the nuclear density distribution is taken from Ref. [4]. (But for the other nuclei, the density distribution profiles will be calculated within the QMC model).

In the future we plan to perform a study to include the effects of the widths into the calculation, as well as to try alternative regularizations to be able to study including the effects of all loop contributions in our predictions.

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