

Υ and η_b mass shifts in nuclear matter and the nucleus bound states

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Motivations

- By studying the interactions of bottomonium states, such as Υ and η_b with nuclei, we can advance in understanding the **hadron properties and strongly interacting systems**
- Exploring the sources of the binding of bottomonia to atomic nuclei can provide important information on the **nature of mesic nuclei**
- Estimates made using SU(5) effective Lagrangian densities for Υ and η_b can provide information on the **SU(5) symmetry breaking**

Introduction

- The in-medium potential for the $\Upsilon (\eta_b)$ meson comes from the modifications of the B , B^* and B^*B^* meson loop contributions to the $\Upsilon (\eta_b)$ **self-energy** relative to those in free space
- Estimates for the self-energies are made using an **effective Lagrangian approach at the hadronic level**
- **Bound state energies** are found for various nuclei by solving the Klein-Gordon equation
- B and B^* meson masses and the density distributions in nuclei are calculated within the **quark-meson coupling model**

The quark meson coupling model

- The QMC model is a quark-based, **relativistic mean field model** of nuclear matter and nuclei
- The relativistically moving confined light quarks in the nucleon bags (MIT bag) self-consistently interact directly with the **scalar-isoscalar σ** , **vector-isoscalar ω** , and **vector-isovector ρ** mean fields (Hartree approximation) generated by the light quarks in the other nucleons
- The nuclear binding comes from the **self-consistent couplings** of the confined light quarks

QMC Model

$$x = (t, \vec{r}) \quad (|\vec{r}| \leq \text{bag radius}), \quad V_\sigma^q \equiv g_\sigma^q \sigma, \quad V_\omega^q \equiv g_\omega^q \omega, \quad V_\rho^q \equiv g_\rho^q b$$

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q + \frac{1}{2} V_\rho^q \right) \right] \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} = 0$$

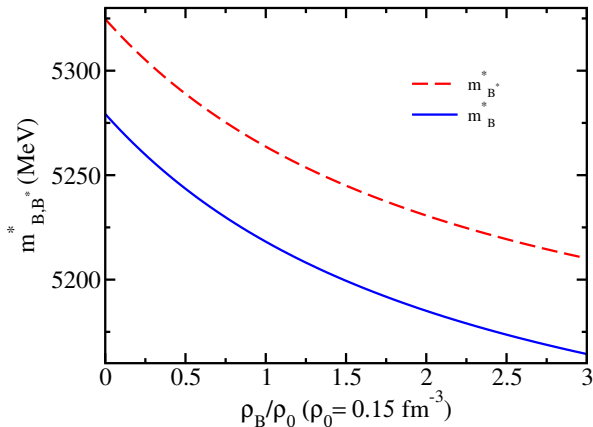
$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q - \frac{1}{2} V_\rho^q \right) \right] \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} = 0$$

$$[i\gamma \cdot \partial_x - m_b] \psi_b(x) \text{ (or } \psi_{\bar{b}}(x)) = 0$$

$$m_h^* = \sum_{j=q,\bar{q},b,\bar{b}} \frac{n_j \Omega_j^* - z_h}{R_h^*} + \frac{4}{3} \pi R_h^{*3} B_\rho, \quad \left. \frac{dm_h^*}{dR_h} \right|_{R_h=R_h^*} = 0$$

$$\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_h^* m_q^*)^2]^{1/2}, \text{ with } m_q^* = m_q - g_\sigma^q \sigma$$

$$\Omega_b^* = \Omega_{\bar{b}}^* = [x_b^2 + (R_h^* m_b)^2]^{1/2} \quad (h = B, B^*)$$

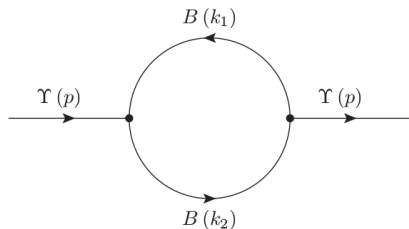


- Quark masses: $m_q = 5 \text{ MeV}$, $m_b = 4200 \text{ MeV}$

One loop contribution study for Υ

- $SU(5)$ effective Lagrangian density
- $SU(5)$ universal coupling constant determined by the **vector meson dominance model**

BB loop cont. to $\Sigma_{\Upsilon}(k^2) \longrightarrow$



- Phenomenological **form factors** to regularize the self-energy loop integrals
- **Cutoff mass values** chosen so that the form factors reflect the finite size effect of the mesons

Effective lagrangian

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

$$F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

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

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

Z. w. Lin and C. M. Ko, Phys. Lett. B 503, 104 (2001)

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} P_1 & \pi^+ & K^+ & \bar{D}^0 & B^+ \\ \pi^- & P_2 & K^0 & D^- & B^0 \\ K^- & \bar{K}^0 & P_3 & D_s^- & B_s^0 \\ D^0 & D^+ & D_s^+ & P_4 & B_c^+ \\ B^- & \bar{B}^0 & \bar{B}_s^0 & B_c^- & P_5 \end{pmatrix}$$

$$P_1 = \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} + \frac{\eta_b}{\sqrt{20}}$$

$$P_2 = \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} + \frac{\eta_b}{\sqrt{20}}$$

$$P_3 = \frac{-2\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} + \frac{\eta_b}{\sqrt{20}}$$

$$P_4 = \frac{-3\eta_c}{\sqrt{12}} + \frac{\eta_b}{\sqrt{20}}$$

$$P_5 = \frac{-2\eta_b}{\sqrt{5}}$$

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} V_1 & \rho^+ & K^{*+} & \bar{D}^{*0} & B^{*+} \\ \rho^- & V_2 & K^{*0} & D^{*-} & B^{*0} \\ K^{*-} & \bar{K}^{*0} & V_3 & D_s^{*-} & B_s^{*0} \\ D^{*0} & D^{*+} & D_s^{*+} & V_4 & B_c^{*+} \\ B^{*-} & \bar{B}^{*0} & \bar{B}_s^{*0} & B_c^{*-} & V_5 \end{pmatrix}$$

$$V_1 = \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\Psi}{\sqrt{12}} + \frac{\Upsilon}{\sqrt{20}}$$

$$V_2 = \frac{-\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\Psi}{\sqrt{12}} + \frac{\Upsilon}{\sqrt{20}}$$

$$V_3 = \frac{-2\omega}{\sqrt{6}} + \frac{J/\Psi}{\sqrt{12}} + \frac{\Upsilon}{\sqrt{20}}$$

$$V_4 = \frac{-3J/\Psi}{\sqrt{12}} + \frac{\Upsilon}{\sqrt{20}}$$

$$V_5 = \frac{-2\Upsilon}{\sqrt{5}}$$

$$\begin{aligned} \mathcal{L}_{\Upsilon BB} &= ig_{\Upsilon BB} \Upsilon^\mu (\bar{B} \partial_\mu B - (\partial_\mu \bar{B}) B), \\ \mathcal{L}_{\Upsilon BB^*} &= \frac{g_{\Upsilon BB^*}}{m_\Upsilon} \varepsilon_{\alpha\beta\mu\nu} (\partial^\alpha \Upsilon^\beta) \left[(\partial^\mu \bar{B}^{*\nu}) B + \bar{B} (\partial^\mu B^{*\nu}) \right], \\ \mathcal{L}_{\Upsilon B^* B^*} &= ig_{\Upsilon B^* B^*} \left[\Upsilon^\mu \left((\partial_\mu \bar{B}^{*\nu}) B_\nu^* - \bar{B}^{*\nu} \partial_\mu B_\nu^* \right) \right. \\ &\quad + \left((\partial_\mu \Upsilon^\nu) \bar{B}_\nu^* - \Upsilon^\nu \partial_\mu \bar{B}_\nu^* \right) B^{*\mu} \\ &\quad \left. + \bar{B}^{*\mu} (\Upsilon^\nu \partial_\mu B_\nu^* - (\partial_\mu \Upsilon^\nu) B_\nu^*) \right], \end{aligned}$$

$$B = \begin{pmatrix} B^+ \\ B^0 \end{pmatrix}, \quad \bar{B} = \begin{pmatrix} B^- & \bar{B}^0 \end{pmatrix}, \quad B^* = \begin{pmatrix} B^{*+} \\ B^{*0} \end{pmatrix}, \quad \bar{B}^* = \begin{pmatrix} B^{*-} & \bar{B}^{*0} \end{pmatrix}.$$

$$g_{\Upsilon BB} = g_{\Upsilon BB^*} = g_{\Upsilon B^* B^*} = \frac{5g}{4\sqrt{10}} = 13.228 \rightarrow \text{by the VMD Model}$$

Υ mass shift

$$V = \Delta m_\Upsilon = m_\Upsilon^* - m_\Upsilon \quad m_\Upsilon^2 = (m_\Upsilon^0)^2 + \Sigma (k^2 = m_\Upsilon^2)$$

$$\Sigma_I (m_\Upsilon^2) = \Sigma_I \left(-\frac{g_{\Upsilon I}^2}{3\pi^2} \right) \int_0^\infty dq \mathbf{q}^2 F_I(\mathbf{q}^2) K_I(\mathbf{q}^2)$$

$$I = BB, BB^*, B^*B^*$$

$$F_{BB}(\mathbf{q}^2) = u_B^2(\mathbf{q}^2), \quad F_{BB^*}(\mathbf{q}^2) = u_B(\mathbf{q}^2) u_{B^*}(\mathbf{q}^2),$$

$$F_{B^*B^*}(\mathbf{q}^2) = u_{B^*}^2(\mathbf{q}^2)$$

$$u_{B,B^*}(\mathbf{q}^2) = \left(\frac{\Lambda_{B,B^*}^2 + m_\Upsilon^2}{\Lambda_{B,B^*}^2 + 4\omega_{B,B^*}^2(\mathbf{q}^2)} \right)^2$$

$$\Lambda_B = \Lambda_{B^*} \quad 2000 \text{ MeV} \leq \Lambda_B \leq 6000 \text{ MeV}$$

Loop contributions

$$K_{BB}(\mathbf{q}^2) = \frac{1}{\omega_B} \left(\frac{\mathbf{q}^2}{\omega_B^2 - m_\Upsilon^2/4} \right)$$

$$K_{BB^*}(\mathbf{q}^2) = \frac{\mathbf{q}^2 \bar{\omega}_B}{\omega_B \omega_{B^*}} \frac{1}{\bar{\omega}_B^2 - m_\Upsilon^2/4}$$

$$K_{B^*B^*}(\mathbf{q}^2) = \frac{1}{4m_\Upsilon \omega_{B^*}} \left[\frac{A(q^0 = \omega_{B^*})}{\omega_{B^*} - m_\Upsilon/2} - \frac{A(q^0 = \omega_{B^*} + m_\Upsilon)}{\omega_{B^*} + m_\Upsilon/2} \right]$$

$$\omega_B = (\mathbf{q}^2 + m_B^2)^{1/2}, \omega_{B^*} = (\mathbf{q}^2 + m_{B^*}^2)^{1/2}, \bar{\omega}_B = (\omega_B + \omega_{B^*})$$

$$A(q) = \sum_{i=1}^4 A_i(q)$$

$$A_1(q) = -4q^2 \left[4 - \frac{q^2 + (q-k)^2}{m_{B^*}^2} + \frac{[q \cdot (q-k)]^2}{m_{B^*}^4} \right]$$

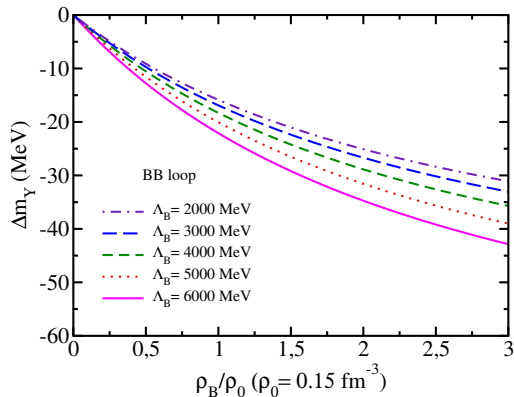
$$A_2(q) = 8 \left[q^2 - \frac{[q \cdot (q-k)]^2}{m_{B^*}^2} \right] \left[2 + \frac{(q^0)^2}{m_{B^*}^2} \right]$$

$$A_3(q) = 8(2q^0 - m_\Upsilon) \left[q^0 - (2q^0 - m_\Upsilon) \frac{q^2 + q \cdot (q-k)}{m_{B^*}^2} + q^0 \frac{[q \cdot (q-k)]^2}{m_{B^*}^4} \right]$$

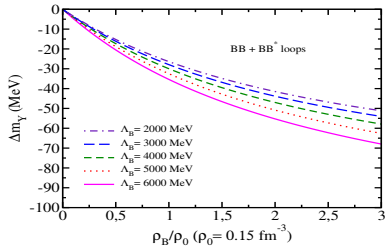
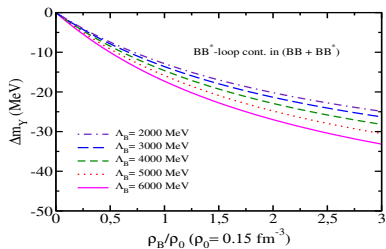
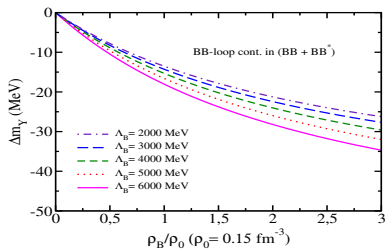
$$A_4(q) = -8 \left[q^0 - (q^0 - m_\Upsilon) \frac{q \cdot (q-k)}{m_{B^*}^2} \right] \left[(q^0 - m_\Upsilon) - q^0 \frac{q \cdot (q-k)}{m_{B^*}^2} \right]$$

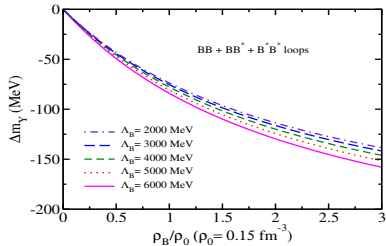
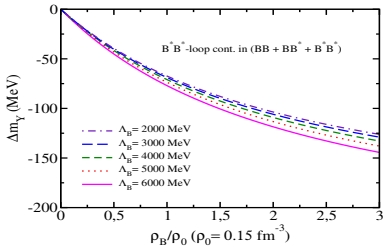
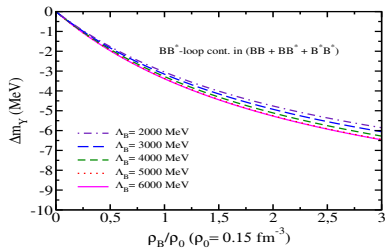
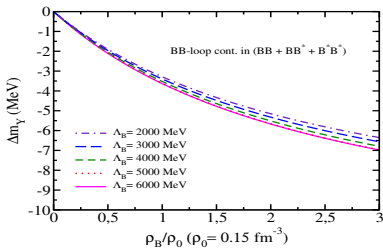
$$q = (q^0, \mathbf{q}) \quad k = (m_\Upsilon, 0)$$

Results for Υ mass shift



- $\Delta m_\Upsilon = -16$ to -22 MeV at ρ_0



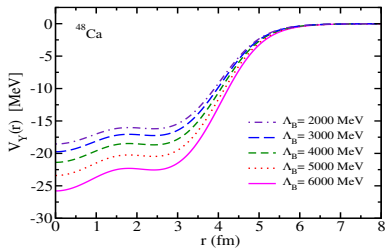
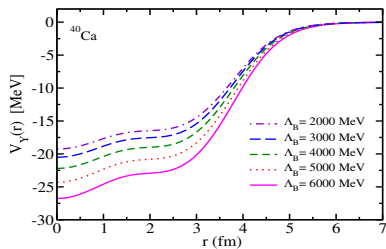
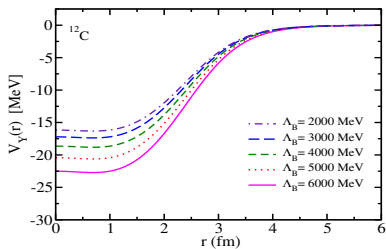


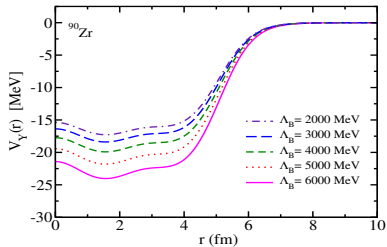
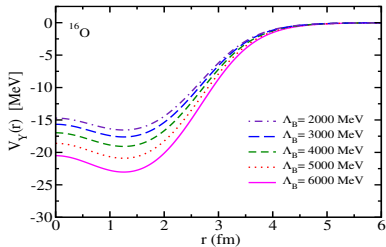
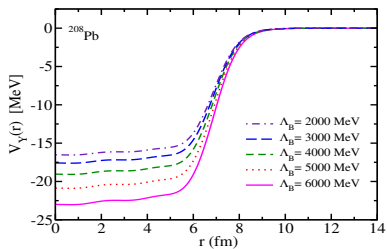
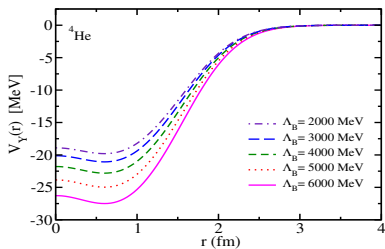
- The negative mass shift increases with Λ_B
- BB loop only = -16.22 to -22 MeV \rightarrow our prediction!
- $(BB + BB^*) = -26$ to -35 MeV
- $(BB + BB^* + B^*B^*) = -74$ to -84 MeV
- The larger contribution from the heavier meson pair indicates the need to consider either different form factors, or adopt an alternative regularization method
- Our prediction, therefore, regards only the minimal meson loop contribution

Υ nuclear potentials

$$V_{\Upsilon A}(r) = \Delta m_{\Upsilon} (\rho_B^A(r)) \rightarrow \text{Local density approximation!!!}$$

- $A = {}^4\text{He}, {}^{12}\text{C}, {}^{16}\text{O}, {}^{40}\text{Ca}, {}^{48}\text{Ca}, {}^{90}\text{Zr}, {}^{208}\text{Pb}$
- Nuclear density distributions calculated within the QMC model





Bound state energies

Bound states are found (in MeV) for various nuclei by solving the KG equation

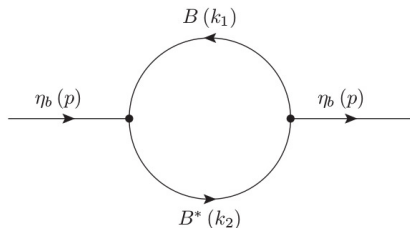
		Bound state energies				
$n\ell$		$\Lambda_B = 2000$	$\Lambda_B = 3000$	$\Lambda_B = 4000$	$\Lambda_B = 5000$	$\Lambda_B = 6000$
${}^4_{\Upsilon}\text{He}$	1s	-5.6	-6.4	-7.5	-9.0	-10.8

		Bound state energies				
$n\ell$		$\Lambda_B = 2000$	$\Lambda_B = 3000$	$\Lambda_B = 4000$	$\Lambda_B = 5000$	$\Lambda_B = 6000$
${}^{12}_{\Upsilon}\text{C}$	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

Study of η_b

- η_b mass shift studied on the same footing as that for Υ
- SU(5) universal coupling constant

BB^* loop cont. to $\Sigma_{\eta_b}(k^2) \longrightarrow$



- Only the BB^* meson loop contribution is considered (minimal prediction)
- Same range for the cutoff mass values

$$\mathcal{L}_{\eta_b BB^*} = ig_{\eta_b BB^*} \{ (\partial^\mu \eta_b) (\overline{B^*}_\mu B - \overline{B} B^*_\mu) - \eta_b [\overline{B^*}_\mu (\partial^\mu B) - (\partial^\mu \overline{B}) B^*_\mu] \}$$

$$g_{\eta_b BB^*} = g_{\Upsilon BB} = g_{\Upsilon B^* B^*} = \frac{5g}{4\sqrt{10}} \rightarrow \text{SU}(5) \text{ scheme}$$

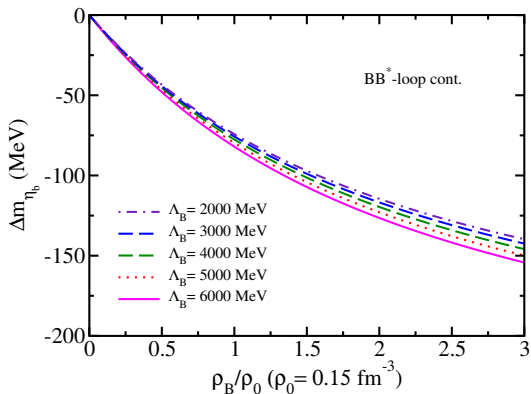
$$\Sigma_{\eta_b}^{BB^*}(\mathbf{q}^2) = \frac{8g_{\eta_b BB^*}^2}{\pi^2} \int_0^\infty dq \mathbf{q}^2 \tilde{F}_{BB^*}(\mathbf{q}^2) I_{BB^*}(\mathbf{q}^2)$$

$$I_{BB^*}(\mathbf{q}^2) = \frac{m_{\eta_b}^2 (-1 + (q^0)^2 / m_{B^*}^2)}{(q^0 + \omega_{B^*})(q^0 - \omega_{B^*})(q^0 - m_{\eta_b} - \omega_B)} \Big|_{q^0 = m_{\eta_b} - \omega_B} + \frac{m_{\eta_b}^2 (-1 + (q^0)^2 / m_{B^*}^2)}{(q^0 - \omega_{B^*})(q^0 - m_{\eta_b} + \omega_B)(q^0 - m_{\eta_b} - \omega_B)} \Big|_{q^0 = -\omega_{B^*}}$$

$$\omega_{B, B^*} = (\mathbf{q}^2 + m_{B, B^*}^2)^{1/2}, \tilde{F}_{BB^*}(\mathbf{q}^2) = \tilde{u}_B(\mathbf{q}^2) \tilde{u}_{B^*}(\mathbf{q}^2)$$

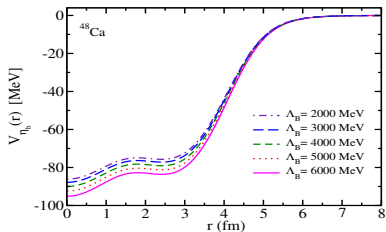
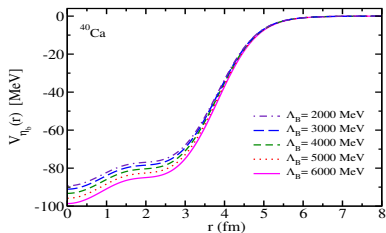
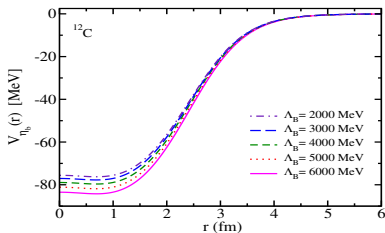
$$\tilde{u}_{B, B^*}(\mathbf{q}^2) = \left(\frac{\Lambda_{B, B^*}^2 + m_{\eta_b}^2}{\Lambda_{B, B^*}^2 + 4\omega_{B, B^*}^2(q^2)} \right)^2$$

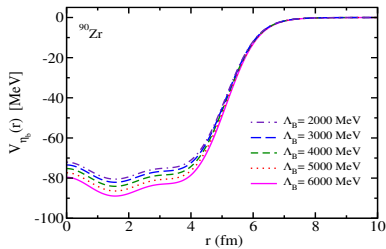
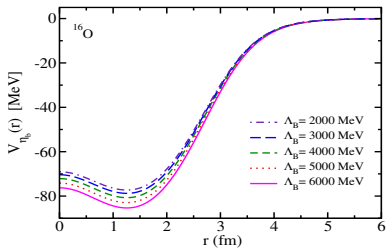
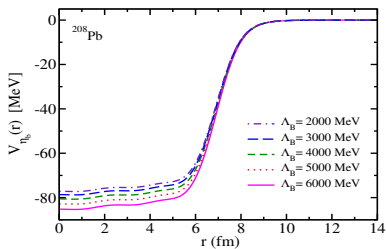
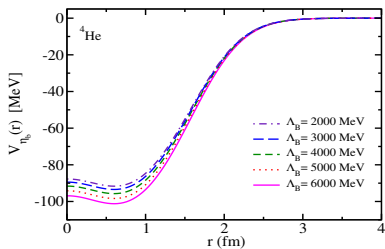
Result for η_b mass shift



- $\Delta m_{\eta_b} = -75 \text{ to } -82 \text{ MeV at } \rho_0$

η_b nuclear potentials





Bound state energies

η_b also form bound states with all nuclei considered

		Bound state energies				
	$n\ell$	$\Lambda_B = 2000$	$\Lambda_B = 3000$	$\Lambda_B = 4000$	$\Lambda_B = 5000$	$\Lambda_B = 6000$
${}^4_{\eta_b}\text{He}$	1s	-63.1	-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

		Bound state energies				
$n\ell$		$\Lambda_B = 2000$	$\Lambda_B = 3000$	$\Lambda_B = 4000$	$\Lambda_B = 5000$	$\Lambda_B = 6000$
$^{12}_{\eta_b}\text{C}$	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
	2s	-46.3	-47.5	-49.1	-51.0	-53.0
	1f	-37.5	-38.7	-40.2	-42.0	-43.9
	2p	-36.0	-37.1	-38.6	-40.3	-42.2
	1g	-27.1	-28.2	-29.6	-31.3	-33.1
	2d	-25.7	-26.7	-28.1	-29.7	-31.4
	3s	-25.1	-26.2	-27.5	-29.1	-30.8
	1h	-16.6	-17.7	-18.9	-20.4	-22.0
	2f	-15.7	-16.6	-17.8	-19.2	-20.8
	3p	-15.4	-16.3	-17.4	-18.8	-20.3
	1i	-6.1	-6.9	-8.1	-9.4	-10.9
	4s	-6.9	-7.6	-8.5	-9.5	-10.7
	3d	-6.7	-7.4	-8.3	-9.4	-10.6
	2g	-6.3	-7.1	-8.1	-9.3	-10.6
	4p	-1.0	-1.3	-1.8	-2.5	-3.2
	3f	n	-0.3	-0.9	-1.6	-2.4
2h	n	n	n	-0.2	-1.2	

Summary and Conclusion

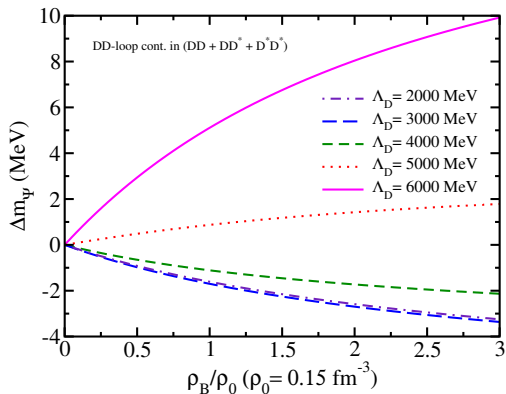
- We have calculated Υ and η_b mass shifts in nuclear matter by an effective Lagrangian approach
- B and B^* meson masses and the density distributions in nuclei are calculated within the quark-meson coupling model
- The attractions resulted from the negative shifts are strong enough to bind these mesons to various nuclei
- Bound state energies were calculated for all nuclei studied

Acknowledgements



Λ_B range

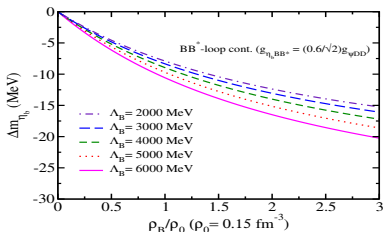
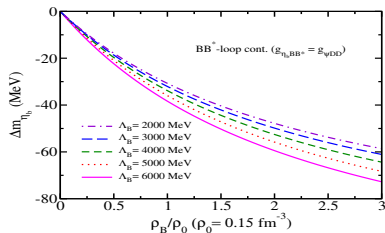
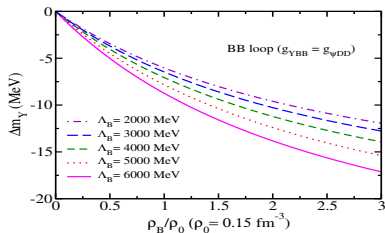
- It gives more choice and wider information for the readers
- If we omit some and show only the narrower range of the cutoff mass values, readers cannot reproduce the missing results easily
- As long as the form factors reflects the finite sizes of the mesons, one cannot say that the range varies too large



- $\Lambda_D = 5000$ and 6000 MeV may not be justified in this case

- The closer the cutoff mass values get to the J/Ψ mass, less pronounced the negative mass shift becomes, until it reaches a transition point (when Λ_D is larger than the J/Ψ free space mass), where the potential starts to become positive. At this point, the Compton wavelengths associated with the values of Λ_D become the sizes of the mesons, and the use of the form factors does not make reasonable sense.
- Such behavior is observed for the BB and BB^* meson loop contributions, for the cutoff mass values larger than 10000 MeV.

$$g_{\Upsilon BB} = g_{\eta_b BB^*} = g_{J/\psi DD} \quad \text{and} \quad g_{\eta_b BB^*} = (0.6/\sqrt{2})g_{J/\psi DD}$$



- Using different couplings for the vertices ΥBB and $\eta_b BB^*$ considering the heavy quark/meson symmetry
- $g_{\Upsilon BB} = g_{J/\psi DD} \rightarrow BB$ loop cont. for $\Upsilon = -6$ to -8.74 MeV
- $g_{\eta_b BB^*} = g_{J/\psi DD} \rightarrow BB^*$ loop cont. for $\eta_b = -30.73$ to -38.36 MeV
- $g_{\eta_b BB^*} = (0.6/\sqrt{2})g_{J/\psi DD} \rightarrow BB^*$ loop cont. for $\eta_b = -18.8$ to -24.32 MeV

Different form factor

$$u_{B,B^*}(\mathbf{q}^2) = \left(\frac{\Lambda_{B,B^*}^2}{\Lambda_{B,B^*}^2 + \mathbf{q}^2} \right)^2$$

