In-medium properties of the low-lying bottom baryons in the QMC model

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Interesting Results for Bottom Baryons, Σ_b, Ξ_b

1. K. Tsushima, Phys. Rev. D 99, 014026 (2019)

2. G. Krein, A. W. Thomas, K. Tsushima (Quarkonia-A)
Prog. Part. Nucl. Phys. 100, 161 (2018)

3. K. Saito, K. Tsushima and A. W. Thomas (QMC model)
Prog. Part. Nucl. Phys. 58, 1 (2007)

References:

In-medium properties of the low-lying strange, charm, and bottom baryons in the quark-meson coupling model (Heavy Baryons):
K. Tsushima
Phys. Rev. D 99, 014026 (2019)

Quarkonia-nuclear bindings (QMC model brief summary):
G. Krein, A. W. Thomas, K. Tsushima
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QMC model summary:
K. Saito, K. Tsushima and A. W. Thomas

Prog. Part. Nucl. Phys. 58, 1 (2007)

1. Motivations
2. Introduction: QMC
3. Low-lying Strange, Charm, Bottom baryons
4. Summary, Perspective

Motivations, and Introduction of QMC model

- Complete and update the in-medium properties of the low-lying strange, charm, bottom baryons (in the QMC model)

- Detailed comparison of the strange, charm, and bottom sectors

- To get idea, opinions, and suggestions from audiences

- Highlight: Effective masses of $\Sigma_b(qqb)$ and $\Xi_b(qsb)$,

$$\boxed{m_{\Sigma_b} > m_{\Xi_b} \rightarrow m^*_{\Sigma_b} < m^*_{\Xi_b}}$$ reverses in medium !!!

$\rightarrow$ but issue of the repulsive vector potentials

QMC model 1: Hadron level

$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}[i\gamma\cdot\partial - m_N^*(\sigma) - g_\omega \omega^\mu \gamma_\mu]\psi + \mathcal{L}_{\rm meson}, \\
m_N^*(\sigma) &\equiv m_N - g_\sigma \underline{(\sigma)}\sigma \simeq m_N - g_\sigma \underline{[1-(a_N/2)(g_\sigma\sigma)]}\sigma \\
g_\sigma &\equiv g_\sigma(\sigma=0)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\rm meson} &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2 - \frac{1}{2}\partial_\mu\omega_\nu(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu) \\
&+ \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu \ ,
\end{aligned}
$$

$$
\begin{aligned}
\rho_B &= \frac{4}{(2\pi)^3}\int d^3k\ \theta(k_F - |\vec{k}|) = \frac{2k_F^3}{3\pi^2}, \\
\rho_s &= \frac{4}{(2\pi)^3}\int d^3k\ \theta(k_F - |\vec{k}|)\frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}},
\end{aligned}
$$

QMC model 2: Quark level

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius), $V_\sigma^q = g_\sigma^q \sigma$

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

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

$$[i\gamma \cdot \partial_x - m_Q]\, \psi_Q(x) \ (\text{or } \psi_{\overline{Q}}(x)) = 0$$

$$m_h^* = \sum_{j=q,\overline{q},Q\overline{Q}} \frac{n_j \Omega_j^* - z_h}{R_h^*} + \frac{4}{3}\pi R_h^{*3} B, \quad \left.\frac{\partial m_h^*}{\partial R_h}\right|_{R_h = R_h^*} = 0$$

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

$$\Omega_Q^* = \Omega_{\overline{Q}}^* = [x_Q^2 + (R_h^* m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

QMC model 3: From quarks

$$\omega = \frac{g_\omega \rho_B}{m_\omega^2},$$

$$\sigma = \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \frac{4}{(2\pi)^3} \int d^3k\ \theta(k_F - |\vec{k}|) \frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}}$$

$$= \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \rho_s \quad (g_\sigma \equiv g_\sigma(\sigma = 0)),$$

$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma = 0)} \left[\frac{\partial m_N^*(\sigma)}{\partial \sigma} \right],$$

$$E^{\mathrm{tot}}/A - m_N = \frac{4}{(2\pi)^3 \rho_B} \int d^3k\ \theta(k_F - |\vec{k}|) \sqrt{m_N^{*2}(\sigma) + \vec{k}^2}$$

$$+ \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2m_\omega^2} - m_N.$$

QMC model 4: Couplings etc.

m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148

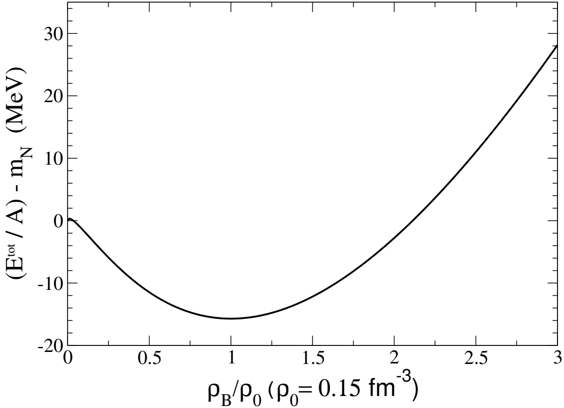
$$\frac{\partial m_N^*(\sigma)}{\partial\sigma} = -3g_\sigma^q \int_{bag} d^3r\ \overline{\psi}_q(\vec{r})\psi_q(\vec{r}) \quad \text{the lowest bag w.f.}$$

$$\equiv -\underline{3g_\sigma^q S_N(\sigma)} = -\frac{\partial}{\partial\sigma}\left[g_\sigma(\sigma)\sigma\right],$$

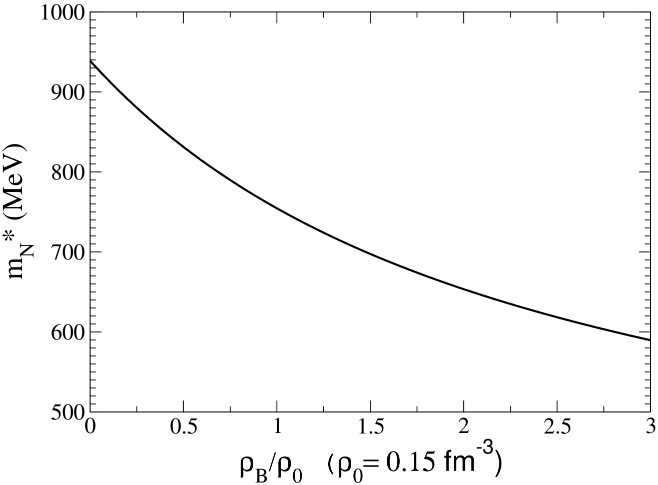
$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma=0)}\left[\frac{\partial m_N^*(\sigma)}{\partial\sigma}\right],$$

$$g_\sigma \equiv g_\sigma^N \equiv \underline{3g_\sigma^q S_N(\sigma=0)}.$$

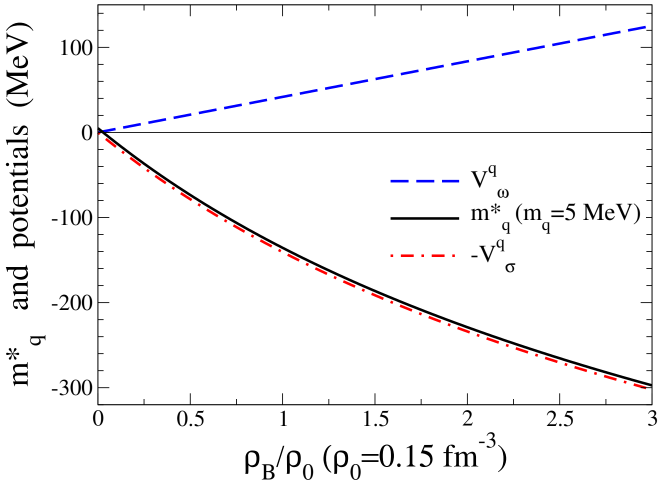
Results: Quark Meson Coupling (Standard)



- Symmetric Nuclear Matter - Biding Energy per Nucleon
- $m_q = 5$ MeV, $K = 279.3$ MeV

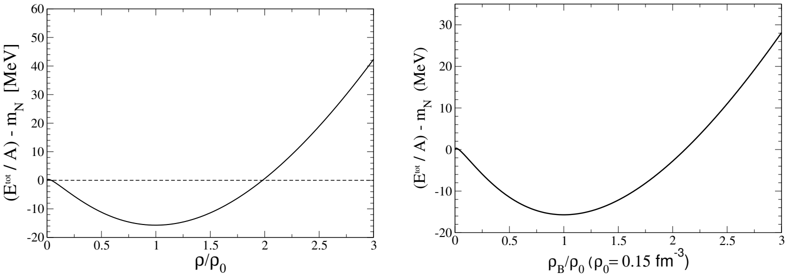


- **Nucleon effective mass: $m_q = 5$ MeV**

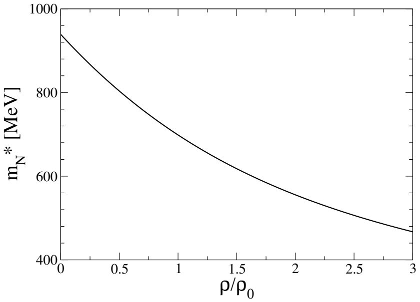


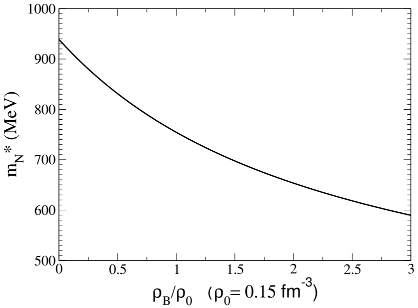
- **Effective mass of constituent quarks: $m_q = 5$ MeV**
- **All the light-quarks in any hadrons feel the same potentials !!**

Comparison of Energy/nucleon



- Symmetric Nuclear Matter - Biding Energy per Nucleon (scale !!)
- LF pion model (left): $m_q = 220$ MeV, $K = 320.9$ MeV
- Standard QMC (right): $m_q = 5$ MeV, $K = 279.3$, MeV



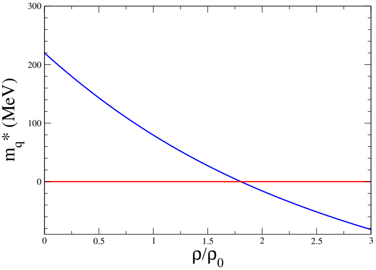


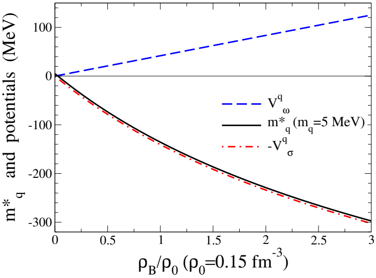
Nucleon effective mass

•LF pion model (left: $m_q = 220MeV$)

•Standard QMC (right: $m_q = 5MeV$)

LF pion model and Standard QMC: m_q^* (potentials)





- Effective mass of constituent quarks, up and down
- LF pion model: $m_q = 220$ MeV (left)
- Standard QMC $m_q = 5$ MeV (right)

Standard QMC, π, ρ in LF model parameters comparison

- **Motivation:** The present model works well (Symmetric Vertex)!

m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148
430	8.73	11.93	565.25	361.4	5.497	69.75

- Refs. LF π, ρ model:

J.P.B.C. de Melo, KT et al.,
LF π model ($m_q = 220$ MeV): Phys.Rev. C90 (2014) no.3, 035201;
Phys.Lett. B766 (2017) 125;
Few Body Syst. 58 (2017) no.2, 85
LF ρ model ($m_q = 430$ MeV): Few Body Syst. 58 (2017) no.2, 82;
arXiv:1802.06096 [hep-ph], Phys. Lett. B 788 (2019) 137

QMC: Hadron masses in medium

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius) , $V^q_\sigma = g^q_\sigma \sigma$

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

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

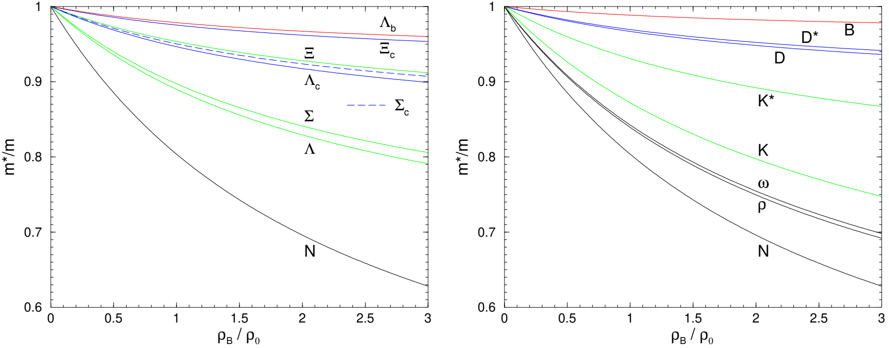
$$[i\gamma \cdot \partial_x - m_Q] \psi_Q(x) \ (\text{or } \psi_{\overline{Q}}(x)) = 0$$

$$m^*_h = \sum_{j=q,\bar{q},Q\overline{Q}} \frac{n_j \Omega^*_j - z_h}{R^*_h} + \frac{4}{3}\pi R^{*3}_h B, \quad \left. \frac{\partial m^*_h}{\partial R_h} \right|_{R_h = R^*_h} = 0$$

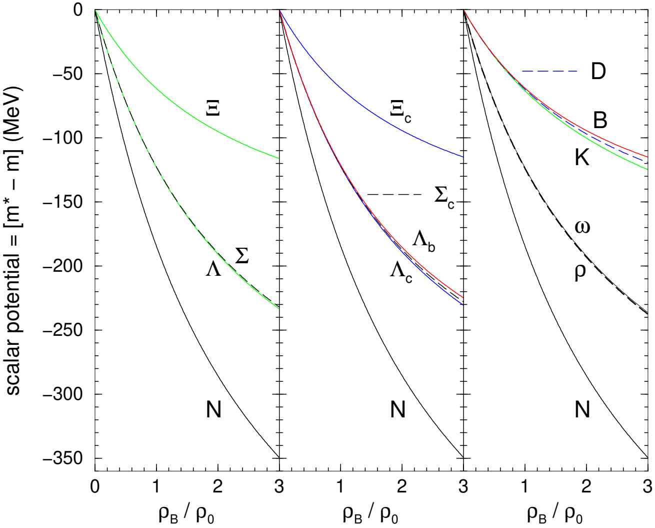
$$\Omega^*_q = \Omega^*_{\bar{q}} = [x^2_q + (R^*_h m^*_q)^2]^{1/2}, \text{with } m^*_q = m_q - g^q_\sigma \sigma$$

$$\Omega^*_Q = \Omega^*_{\overline{Q}} = [x^2_Q + (R^*_h m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

Hadron masses (ratios) in medium



Scalar potentials: $m_h^* - m_h$ (in medium)



In-medium properties of the low-lying Strange, Charm, Bottom baryons

- Effective masses (Σ_b, Ξ_b !!)
- In-medium bag radii
- In-medium bag eigenfrequencies
- Scalar and vector (plus Pauli) potentials
- Excitation (total) energies (Σ_b, Ξ_b !!)

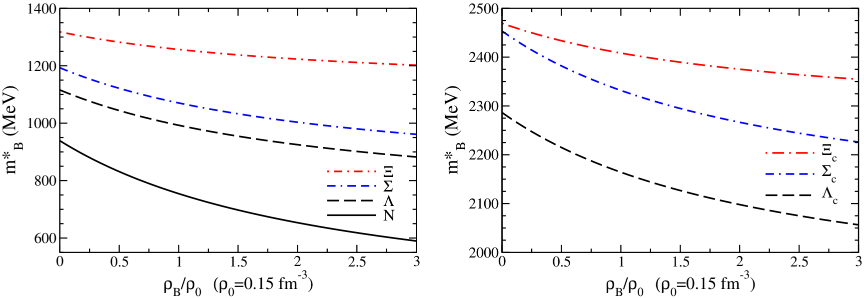
In vacuum (inputs)

$B(q_1, q_2, q_3)$	z_B	m_B	R_B	x_1	x_2	x_3
$N(qqq)$	3.295	939.0	0.800	2.052	2.052	2.052
$\Lambda(uds)$	3.131	1115.7	0.806	2.053	2.053	2.402
$\Sigma(qqs)$	2.810	1193.1	0.827	2.053	2.053	2.409
$\Xi(qss)$	2.860	1318.1	0.820	2.053	2.406	2.406
$\Omega(sss)$	1.930	1672.5	0.869	2.422	2.422	2.422
$\Lambda_c(udc)$	1.642	2286.5	0.854	2.053	2.053	2.879
$\Sigma_c(qqc)$	0.903	2453.5	0.892	2.054	2.054	2.889
$\Xi_c(qsc)$	1.445	2469.4	0.860	2.053	2.419	2.880
$\Omega_c(ssc)$	1.057	2695.2	0.876	2.424	2.424	2.884
$\Lambda_b(udb)$	-0.622	5619.6	0.930	2.054	2.054	3.063
$\Sigma_b(qqb)$	-1.554	5813.4	0.968	2.054	2.054	3.066
$\Xi_b(qsb)$	-0.785	5793.2	0.933	2.054	2.441	3.063
$\Omega_b(ssb)$	-1.327	6046.1	0.951	2.446	2.446	3.065

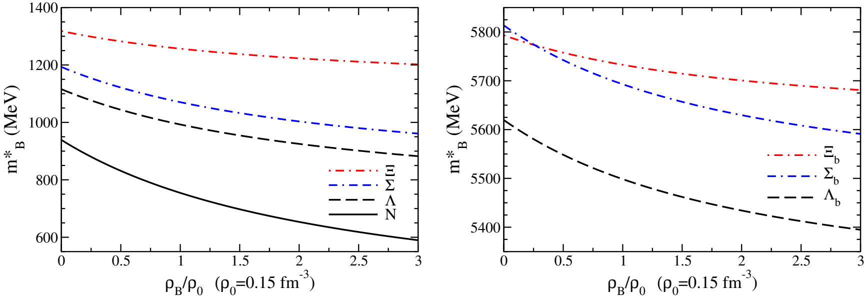
In medium at $\rho_0 = 0.15\,\mathrm{fm}^3$

$B(q_1, q_2, q_3)$	m_B^*	R_B^*	x_1^*	x_2^*	x_3^*
$N(qqq)$	754.5	0.786	1.724	1.724	1.724
$\Lambda(uds)$	992.7	0.803	1.716	1.716	2.401
$\Sigma(qqs)$	1070.4	0.824	1.705	1.705	2.408
$\Xi(qss)$	1256.7	0.818	1.708	2.406	2.406
$\Omega(sss)$	—	—	—	—	—
$\Lambda_c(udc)$	2164.2	0.851	1.691	1.691	2.878
$\Sigma_c(qqc)$	2331.8	0.889	1.671	1.671	2.888
$\Xi_c(qsc)$	2408.3	0.859	1.687	2.418	2.880
$\Omega_c(ssc)$	—	—	—	—	—
$\Lambda_b(udb)$	5498.5	0.927	1.651	1.651	3.063
$\Sigma_b(qqb)$	5692.8	0.966	1.630	1.630	3.066
$\Xi_b(qsb)$	5732.7	0.931	1.649	2.440	3.063
$\Omega_b(ssb)$	—	—	—	—	—

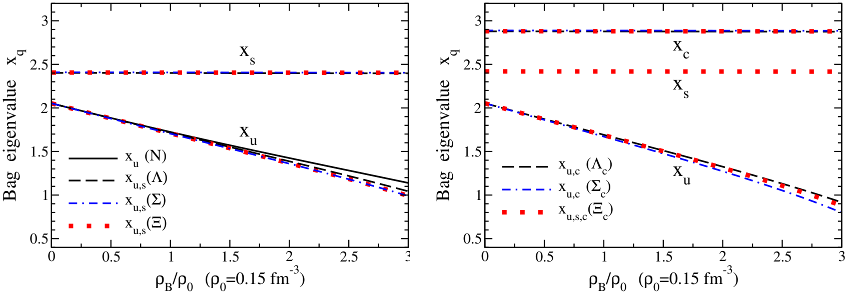
Effective masses:
Strange (left), Charm (right) baryons



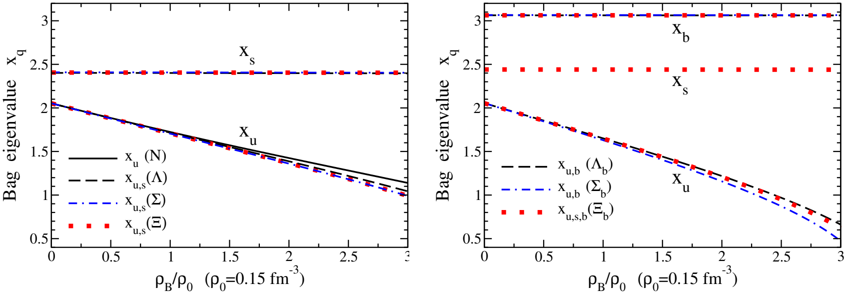
Effective masses:
Strange (left), Bottom (right) baryons



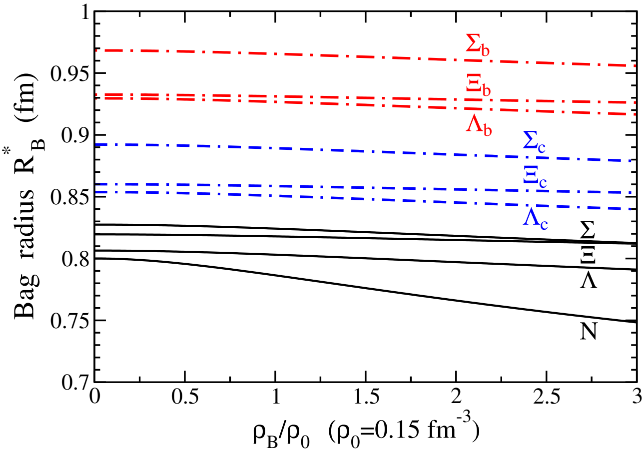
Bag eigenfrequencies:
Strange (left), Charm (right) baryons



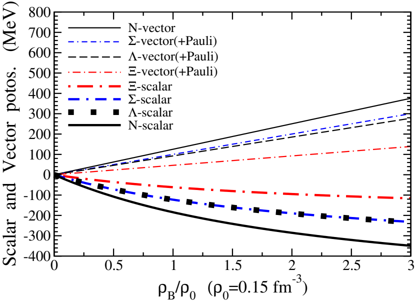
Bag eigenfrequencies: Strange (left), Bottom (right) baryons

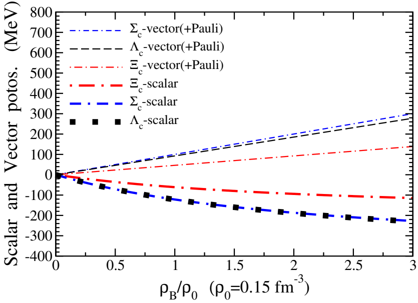


Bag radii: Strange, Charm, Bottom baryons

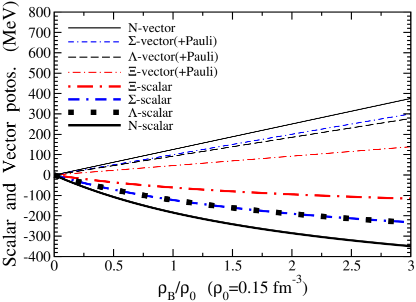


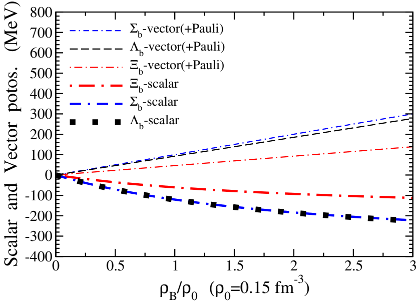
Scalar and (Vector+Pauli) potentials: Strange (left), Charm (right) baryons



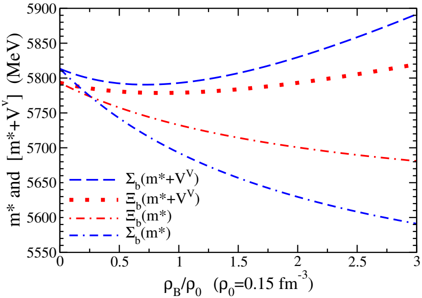


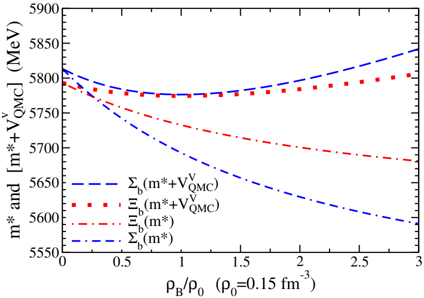
Scalar and (Vector+Pauli) potentials: Strange (left), Bottom (right) baryons





Excitation energies (scalar + vector pots.): Σ_b, Ξ_b
Vector + "Pauli" (left), Vector (right)





Summary, Perspective

•QMC model: In-medium properties of the low-lying Strange, Charm, Bottom baryons (completed)
effective masses, bag radii, bag eigenfrequencies, (two different) vector potentials, excitation (total) energies

⟹• Σ_b, Ξ_b baryon effective masses!! excitation energies !!!

⟹• EM FFs., Weak-interaction FFs. for heavy baryons in medium
⟹•in the near future !!

⟹• Heavy ion collisions involving heavy baryons!!!

⟹•Other interesting applications ??!! Your Suggestions !!!

Thank You Very Much !!!

References:

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