Photoproduction of \( \Lambda \) Hypernuclei in the Quark-Meson Coupling (QMC) model


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PLB, 676, 51 (2009)
Outline

• Introduction, motivation
• \textbf{QMC} model, finite nuclei
• \textbf{Hypernuclei} in the \textit{latest} QMC model ($\Sigma, \Lambda, \Xi$): \textit{no} heavy $\Sigma$ hypernuclei as in experiments
• \textbf{Photoproduction} of $\Lambda$ hypernuclei
• Summary (Discussions)
Introduction, motivation

- (Heavy) nuclei in terms of quarks and gluons (or QCD) ???!!!
- \( NN, NNN, NNNN, NNNNN \ldots \) interactions
  \( \rightarrow \) Nucleus ? \( \leftarrow \) shell model, MF model, density functional theory…BUT ?
- Lattice QCD: still extracting NN and NY 2-body interactions, \([Y=hyperons: \Lambda, \Sigma, \Xi]\)
- Hypernucleus ? (Nucleus+Y) bound states
- Quark model based description of nucleus
Λ hypernuclei: well established Expts. up to Pb core nucleus, many states

Σ⁺ hypernuclei: only $^4\Sigma$ He confirmed

⇒ Probably no other heavy $\Sigma$ hypernuclei

Ξ hypernuclei: hints – not confirmed

⇒ Planned Expts.: (JLab?), J-PARC, GSI-FAIR
Light (u,d) quarks interact self-consistently with mean $\sigma$ and $\omega$ fields

\[ m^*_q = m_q - g_\sigma \sigma = m_q - V_\sigma \]

↓ nonlinear in $\sigma$
\[ M^*_N \cong M_N - g_\sigma \sigma + (d/2)(g_\sigma \sigma)^2 \]

1. Start
\[ [i \partial \cdot \gamma - (m - V_\sigma^q) + \gamma_0 V_\omega^q] q = 0 \]

\[ [i \partial \cdot \gamma - M^*_N + \gamma_0 V_\omega^N] N = 0 \]

Self-consistent!

Nuclear Binding!!

(For a review, PPNP 58, 1 (2007))

K. Tsushima
Nucleon response to a chiral invariant scalar field is then a nucleon property of great interest...

\[ M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2} \left( g_\sigma \sigma(\vec{R}) \right)^2 \]

Non-linear dependence: scalar polarizability
\((d)^{**}_4 = 0.22 \, \text{R} \) in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the **ONLY** place the response of the internal structure of the nucleon enters.
New saturation mechanism!
Incompressibility
(~ spring constant)

$K \approx 280 \text{ MeV}$
(200 ~ 300 MeV)

PLB 429, 239 (1998)
Finite nuclei: $^{208}$Pb energy levels

NPA 609, 339 (1996)

Heavy mass nuclei

Based on quarks!

↓

Hypernuclei

(the latest version of QMC)
QMC ↔ QHD

- QHD shows importance of **relativity**: mean $\sigma$, $\omega$ and $\rho$ fields
- **QMC** goes far beyond QHD by incorporating effect of hadron **internal structure**

- Minimal model couples these mesons to **quarks** in relativistic quark model – e.g. MIT bag, or confining NJL

- $g_\sigma^q$, $g_\omega^q$, $g_\rho^q$ fitted to $\rho_0$, $E/A$ and **symmetry energy**

- **No additional parameters**: predict change of structure and binding in nuclear matter of **all hadrons**: e.g. $\omega$, $\rho$, $\eta$, $J/\psi$, $N$, $\Lambda$, $\Sigma$, $\Xi$ → see next!
Scalar potentials in QMC respects SU(3) (light quark # !)
\( \Lambda \) and \( \Sigma \) ↔ Self-consistent OGE color hyperfine interaction

• \( \Lambda \) and \( \Sigma \) hypernuclei are more or less similar (channel couplings) ↔ improve!

• \( \Xi \) potential: weaker (~1/2) of \( \Lambda \) and \( \Sigma \) (Light quark #, or SU(3))

• Very small spin-orbit splittings for \( \Lambda \) hypernuclei ↔ SU(6) quark model
Bag mass and color mag. HF int. contribution (OGE)

T. DeGrand et al., PRD 12, 2060 (1975)

\[ M = \frac{[N_q \Omega_q + N_s \Omega_s]}{R} - \frac{Z_0}{R} + \frac{4\pi BR^3}{3} \]
\[
+ (F_s)^n \Delta E_M (f) \quad (f = N, \Delta, \Sigma, \Lambda, \Xi \ldots)
\]

\[ \Delta E_M = -3\alpha_c \sum \lambda_i \lambda_j \overrightarrow{\sigma}_i \cdot \overrightarrow{\sigma}_j M(m_i, m_j, R) \]

\[ \Delta E_M(\Lambda) = -3\alpha_c M(m_q, m_q, R), \quad (q = u, d) \]

\[ \Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R) - 4\alpha_c M(m_q, m_s, R) \]
Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

\[ N - \Delta \text{ and } \Sigma - \Lambda \text{ splitting arise from one-gluon-exchange in MIT Bag Model: as } \sigma \text{ so does this splitting...} \]

\[ \Sigma - \Lambda \text{ splitting} \]

\[ \Sigma \text{-hypernuclei unbound!!} \]

\[ \Sigma^0 \text{ potentials} \]
\[ (1s_{1/2}) \]

**Repulsion**
- in center

**Attraction**
- in surface

**No \( \Sigma \) nuclear bound state!**

HF couplings for hyperons \( \Leftrightarrow \) successful for high density neutron star

(NPA 792, 341 (2007))
### Hypernuclei spectra 2

<table>
<thead>
<tr>
<th></th>
<th>(^{89}\text{Yb}_{\Lambda}) Exp.</th>
<th>(^{91}\text{Zr}_{\Lambda})</th>
<th>(^{91}_{\Xi}\text{Zr})</th>
<th>(^{208}\text{Pb}_{\Lambda}) Exp.</th>
<th>(^{209}\text{Pb}_{\Lambda})</th>
<th>(^{209}_{\Xi}\text{Pb})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s(_{1/2})</td>
<td>-23.1</td>
<td>-24.0</td>
<td>-9.9</td>
<td>-26.3</td>
<td>-26.9</td>
<td>-15.0</td>
</tr>
<tr>
<td>1p(_{3/2})</td>
<td>-19.4</td>
<td>-19.4</td>
<td>-7.0</td>
<td>-24.0</td>
<td>-24.0</td>
<td>-12.6</td>
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<tr>
<td>1p(_{1/2})</td>
<td>-16.5</td>
<td>-19.4</td>
<td>-7.2</td>
<td>-21.9</td>
<td>-24.0</td>
<td>-12.7</td>
</tr>
<tr>
<td>1d(_{5/2})</td>
<td>-9.1</td>
<td>-13.4</td>
<td>-3.1</td>
<td>-16.8</td>
<td>-20.1</td>
<td>-9.6</td>
</tr>
<tr>
<td>2s(_{1/2})</td>
<td>-9.1</td>
<td>-9.1</td>
<td>–</td>
<td>-17.1</td>
<td>-8.2</td>
<td></td>
</tr>
<tr>
<td>1d(_{3/2})</td>
<td>(-9.1)</td>
<td>-13.4</td>
<td>-3.4</td>
<td>(-16.8)</td>
<td>-20.1</td>
<td>-9.8</td>
</tr>
</tbody>
</table>
Summary: hypernuclei

• The latest version of QMC (OGE color hyperfine interaction included self-consistently in matter) ⇒

• $\Lambda$ single-particle energy $1s_{1/2}$ in Pb is -26.9 MeV (Exp. -26.3 MeV) ⇐ no extra parameter!

• Small spin-orbit splittings for the $\Lambda$

• No $\Sigma$ nuclear bound state !!

• $\Xi$ is expected to form nuclear bound state
Photoproduction of $\Lambda$ hypernuclei

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)

$\Lambda$ and $K^+$ are produced via s-channel.
$N^*$ excitation (dominant)
$S_{11}(1650)$, $P_{11}(1710)$
$P_{13}(1720)$

Energy region of interests, hypernuclei production
($\sim 10\%$ ambiguity due to the other background $\Rightarrow$)
Elementary $\gamma p \rightarrow K^+ \Lambda$ reaction

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)
Differential cross sections: $^{12}C(\gamma,K^+)_{\Lambda}B$

PLB 676, 51 (2009)

$\frac{d\sigma}{d\Omega}$ at
Kaon angle $\theta = 10^\circ$

$1^-, 2^- \leftrightarrow (1p_{3/2}^-, 1s_{1/2}^\Lambda)$
(wave functions!)

$2^+, 3^+ \leftrightarrow (1p_{3/2}^-, 1p_{3/2}^\Lambda)$
(potentials!)

$\text{Dirac}_p$
(phenomenological)

$\text{QMC}$

$|q| \approx [1.4, 1.7]$ fm$^{-1}$

$E_{\gamma} \approx 695$ MeV
Summary: $\Lambda$ hypernuclei photoproduction

1. **First attempt** to study photoproduction of $\Lambda$ hypernuclei ($^{12}_{\text{C}}(\gamma,K)^{12}_{\Lambda B}$ reaction) via **quark-based model** (QMC)

2. $d\sigma/d\Omega$ at Kaon angle $\theta = 10^\circ$ shows **distinguishable difference**!

3. **Background** inclusion (higher energies)

4. **Heavier** $\Lambda$ hypernuclei
Discussions

1. Study of $\Xi$ hypernuclei
   \[ \uparrow \Rightarrow A(K^-, K^+) \Xi B \] reaction

2. Elementary $K^- p \rightarrow \Xi K^+$ reaction

3. Heavier $\Lambda$ hypernuclei photoproduction

4. Electroproduction of $\Lambda$ hypernuclei

5. $\Lambda_c$ hypernuclei ???!!!
Bound quark Dirac spinor \((1s_{1/2})\)

**Quark Dirac spinor in a bound hadron:**

\[
q_{1s}(r) = \begin{pmatrix}
U(r) \\
\hat{i} \sigma \cdot r \ L(r)
\end{pmatrix} \chi
\]

Lower component is **enhanced**!

\[\implies g_{A}^{*} < g_{A} : \sim |U|^{2} - \frac{1}{3} |L|^{2},\]

\[\implies \text{Decrease of scalar density} \implies\]
Decrease in Scalar Density

Scalar density (quark): $\sim |U|^2 - |L|^2$,

$\downarrow$

$M_N^*, N$ wave function, Nuclear scalar density etc., are self-consistently modified due to the N internal structure change!

$\implies$ Novel Saturation mechanism!
### Hypernuclei spectra 1

#### NPA 814, 66 (2008)

<table>
<thead>
<tr>
<th></th>
<th>$^{16}_\Lambda$ O</th>
<th>$^{17}_\Lambda$ O</th>
<th>$^{17}_0\Lambda$ O</th>
<th>$^{40}_\Lambda$ Ca</th>
<th>$^{41}_\Lambda$ Ca</th>
<th>$^{41}_0\Lambda$ Ca</th>
<th>$^{49}_\Lambda$ Ca</th>
<th>$^{49}_0\Lambda$ Ca</th>
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</thead>
<tbody>
<tr>
<td>1s$^{1/2}$</td>
<td>-12.4</td>
<td>-16.2</td>
<td>-5.3</td>
<td>-18.7</td>
<td>-20.6</td>
<td>-5.5</td>
<td>-21.9</td>
<td>-9.4</td>
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<tr>
<td>1p$^{3/2}$</td>
<td>-6.4</td>
<td>-</td>
<td>-</td>
<td>-13.9</td>
<td>-13.9</td>
<td>-1.6</td>
<td>-15.4</td>
<td>-5.3</td>
</tr>
<tr>
<td>1p$^{1/2}$</td>
<td>-1.85</td>
<td>-6.4</td>
<td>-</td>
<td>-13.9</td>
<td>-13.9</td>
<td>-1.9</td>
<td>-15.4</td>
<td>-5.6</td>
</tr>
<tr>
<td>1d$^{5/2}$</td>
<td>-</td>
<td>-5.5</td>
<td>-</td>
<td>-5.5</td>
<td>-</td>
<td>-7.4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2s$^{1/2}$</td>
<td>-</td>
<td>-1.0</td>
<td>-</td>
<td>-1.0</td>
<td>-</td>
<td>-3.1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1d$^{3/2}$</td>
<td>-</td>
<td>-5.5</td>
<td>-</td>
<td>-5.5</td>
<td>-</td>
<td>-7.3</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
### $^{12}_{\Lambda}B$ hypernucleus (MeV)

<table>
<thead>
<tr>
<th>State</th>
<th>Exp.</th>
<th>QMC</th>
<th>$V_V$ (W.S)</th>
<th>$V_S$ (W.S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}<em>{\Lambda}B1s</em>{1/2}$</td>
<td>11.37</td>
<td>14.93</td>
<td>171.78</td>
<td>-212.69</td>
</tr>
<tr>
<td>$^{12}<em>{\Lambda}B1p</em>{3/2}$</td>
<td>1.73</td>
<td>3.62</td>
<td>204.16</td>
<td>-252.28</td>
</tr>
<tr>
<td>$^{12}<em>{\Lambda}B1p</em>{1/2}$</td>
<td>1.13</td>
<td>3.62</td>
<td>227.83</td>
<td>-280.86</td>
</tr>
<tr>
<td>$(p1p_{3/2})^{-1}_{12}C$ Sep. energy</td>
<td>15.96</td>
<td>(≈OK)</td>
<td>382.60</td>
<td>-472.34</td>
</tr>
</tbody>
</table>
• **Hyperons** enter at just 2-3 $\rho_0$

• Hence need effective $\Sigma$-$N$ and $\Lambda$-$N$ forces in this density region!

• **Hypernuclear data is important input** (J-PARC, FAIR, JLab)

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From Schaffner-Bielich (2005)

Thomas Jefferson National Accelerator Facility
Consequences for Neutron Star

New QMC model, fully relativistic, Hartree-Fock treatment