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

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R. Shyam, P. Guichon, A.W. Thomas
PLB, 676, 51 (2009)
Outline

1. **QMC** model, finite nuclei
2. **Hypernuclei** in the latest QMC model \((\Sigma, \Lambda, \Xi)\): no heavy \(\Sigma\)–hypernuclei as in experiment
3. **Photoproduction** of \(\Lambda\)–hypernuclei
4. Summary (Discussions)
Introduction, motivation

- **(Heavy) nuclei** in terms of **quarks** and **gluons** (or **QCD**) ????!!!
- **NN, NNN, NNNN, NNNNN.....** interactions
  - ⇒ **Nucleus ? ↔** shell model, **MF** model, **density** functional theory... **BUT ?**
- **Lattice QCD:** **still** extracting **NN** and **NY**
- **2-body** interactions, \( [Y=\text{hyperons: } \Lambda, \Sigma, \Xi] \)
- **Hypernucleus ?** (Nucleus+Y) bound states
- **Quark** model based description of **nucleus**
Hypernuclei: $SU(3)$ so bad?

$\Lambda$ hypernuclei: well established Expts. up to $\text{Pb}$ core nucleus, many states

$\Sigma^+$ hypernuclei: only $^4\Sigma\text{He}$ confirmed

$\Xi$ hypernuclei: hints – not confirmed

$\Rightarrow$ Probably no other $\Sigma$ hypernuclei

$\Rightarrow$ Planned Expts.: (JLab?), J-PARC, GSI-FAIR
The QMC model

P. Guichon, PLB 200, 235 (1988)

Light \((u,d)\) quarks interact self-consistently with mean \(\sigma\) and \(\omega\) fields

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

\(\leftarrow\) nonlinear in \(\sigma\)

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

\[ [i \partial \cdot \gamma - (m^*_q - V^q_\sigma) + \gamma_0 V^q_\omega] q = 0 \]

1. Start

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

\(\omega\) nuclear binding

Solomon consistent

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

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At Nucleon Level Response to the Applied Scalar Field is the **Scalar Polarizability**

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

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

Non-linear dependence: **scalar polarizability**

\( (d)^{**1/4} = 0.22 \ R \) 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 
(\sim spring constant)

K \approx 280 MeV
(200 \sim 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)
\[ R = \frac{(p' x)}{(p' z)} = \frac{G_E^p}{G_M^p} : ^4\text{He}/^1\text{H} \]


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 light quark number!
$\Lambda$, $\Sigma$ \textcolor{red}{\Leftrightarrow} \text{Self-consistent OGE color hyperfine interaction}

$\Lambda$ and $\Sigma$ hypernuclei are more or less similar (channel couplings) \textcolor{blue}{\Leftrightarrow} \text{improve!}

$\Xi$ potential: \textcolor{red}{\text{weaker (}\sim 1/2\text{) of } \Lambda \text{ and } \Sigma}$

(Light quark #)

Very \textcolor{blue}{\text{small spin-orbit splittings}} for

$\Lambda$ hypernuclei \textcolor{red}{\Leftrightarrow} \text{SU(6) quark model}
Bag mass and color mag. HF int. contribution (OGE)

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

\[ M = \frac{[N_q \Omega_q + N_s \Omega_s]}{R} - \frac{Z_0}{R} + \frac{4\pi BR^3}{3} \]

+ \((Fs)^n \Delta E_M(f)\) \hspace{1cm} (f=N,\Lambda,\Lambda,\Sigma,\Xi,\ldots)

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

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

\[ \Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R) \]

- \[4\alpha_c M(m_q, m_s, R)\]

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Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

$N - \Delta$ and $\Sigma - \Lambda$ splitting arise from one-gluon-exchange in MIT Bag Model: as “$\sigma$” so does this splitting...

Difference of Sigma and Lambda effective mass

$\Sigma - \Lambda$ splitting

$\Sigma$-hypernuclei unbound!!

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

**Repulsion**  
in center

**Attraction**  
in surface

**No \Sigma nuclear bound state!**

HF couplings for **hyperons** ↔ **successful** for high density neutron star  
(NPA 792, 341 (2007))
### Hypernuclei spectra 2

<table>
<thead>
<tr>
<th></th>
<th>$^{89}$Yb$_{\Lambda}$ Exp.</th>
<th>$^{91}$Zr$_{\Lambda}$</th>
<th>$^{91}$Zr$_{\Xi^0}$</th>
<th>$^{208}$Pb$_{\Lambda}$ Exp.</th>
<th>$^{209}$Pb$_{\Lambda}$</th>
<th>$^{209}$Pb$_{\Xi^0}$</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>
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<tr>
<td>1p$_{3/2}$</td>
<td>-19.4</td>
<td>-19.4</td>
<td>-7.0</td>
<td>-21.9</td>
<td>-24.0</td>
<td>-12.6</td>
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<tr>
<td>1p$_{1/2}$</td>
<td>-16.5</td>
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<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>-17.1</td>
<td>-8.2</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>

**NPA 814, 66 (2008)**
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
\( \Lambda \) and \( K^+ \) are produced via s-channel
\( N^* \) excitation (dominant)
\( S_{11}(1650), P_{11}(1710) \)
\( P_{13}(1720) \)

\[ \Downarrow \]

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: $^{12}\text{C}(\gamma, K^+) \ ^{12}\Lambda\text{B}$

**PLB 676, 51 (2009)**

\[ d\sigma/d\Omega \text{ at} \]

Kaon angle $\theta = 10^\circ$

$1^-, 2^- \iff (1p_{3/2}^{p}, 1s_{1/2}^{\Lambda})$

(wave functions!) $\Rightarrow$

$2^+, 3^+ \iff (1p_{3/2}^{-p}, 1p_{3/2}^{\Lambda})$

(potentials!) $\Rightarrow$

**Dirac**

(phenomenological)

**QMC**

\[ |q| \approx [1.4, 1.7] \text{ fm}^{-1} \]
Summary: $\Lambda$ hypernuclei photoproduction

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

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

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

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

1. Study of $E$ hypernuclei
   \[ A(K^- ,K^+) E B \] reaction
2. Elementary $K^- N \rightarrow E K^+$ reaction
3. Heavier $\Lambda$ hypernuclei photoproduction
4. Electroproduction of $\Lambda$ hypernuclei
5. $\Lambda c$ hypernuclei ???!!!
Happy Birthday Tony!
Bound quark Dirac spinor (1s<sub>1/2</sub>)

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!

\[g_A^* < g_A : \sim |U|^{**2} - (1/3) |L|^{**2},\]

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

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

\( M_{N^*}, N \) wave function, Nuclear scalar density etc., are self-consistently modified due to the \( N \) internal structure change!

\( \Rightarrow \) Novel Saturation mechanism!
### Hypernuclei Spectra 1

<table>
<thead>
<tr>
<th></th>
<th>$^{16}$O</th>
<th>$^{17}$O</th>
<th>$^{17}$O $^0$O</th>
<th>$^{40}$Ca</th>
<th>$^{41}$Ca</th>
<th>$^{41}$O $^0$Ca</th>
<th>$^{49}$Ca</th>
<th>$^{49}$O $^0$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></td>
<td>-6.4</td>
<td></td>
<td>-13.9</td>
<td>-1.6</td>
<td>-15.4</td>
<td>-5.3</td>
<td></td>
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<tr>
<td>$1p_{1/2}$</td>
<td>-1.85</td>
<td>-6.4</td>
<td></td>
<td>-13.9</td>
<td>-1.9</td>
<td>-15.4</td>
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<td></td>
</tr>
<tr>
<td>$1d_{5/2}$</td>
<td></td>
<td></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></td>
<td></td>
<td>-1.0</td>
<td></td>
<td>-3.1</td>
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</tr>
<tr>
<td>$1d_{3/2}$</td>
<td></td>
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<td>-7.3</td>
<td></td>
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</tbody>
</table>

**NPA 814, 66 (2008)**

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### $^{12}_\Lambda B$ 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>$^{12}<em>\Lambda B^1s</em>{1/2}$</td>
<td>11.37</td>
<td>14.93</td>
<td>171.78</td>
<td>-212.69</td>
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<tr>
<td>$^{12}<em>\Lambda B^1p</em>{3/2}$</td>
<td>1.73</td>
<td>3.62</td>
<td>204.16</td>
<td>-252.28</td>
</tr>
<tr>
<td>$^{12}<em>\Lambda B^1p</em>{1/2}$</td>
<td>1.13</td>
<td>3.62</td>
<td>227.83</td>
<td>-280.86</td>
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<tr>
<td>$(p^1p_{3/2})^{-1}$</td>
<td>15.96</td>
<td>(≈OK)</td>
<td>382.60</td>
<td>-472.34</td>
</tr>
</tbody>
</table>

K. Tsushima
• **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 ⇒ J. Carroll

New QMC model, fully relativistic, Hartree-Fock treatment