Baryon Interactions from Lattice QCD with physical masses

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for HAL QCD Collaboration
The journey from Quarks to Universe

- QCD vacuum
- Baryons
- Nuclei
- Neutron Stars / Supernovae

QCD

1st-principle Lattice QCD

Baryon Forces

ab-initio nuclear calc.

Nuclear Forces / Hyperon Forces

EoS of Dense Matter

J-PARC

ASTRO-H

KAGRA/ aLIGO

© Leinweber
The journey from unphysical to physical quark masses

We were here

\[ \pi_L = 0.4 \text{ GeV} \]
\[ L = 3 \text{ fm} \]

\[ \rightarrow \] lighter \( m_q \)

\textbf{Phys. point}

\textbf{K-computer}

\textbf{Hadrons to Atomic nuclei from Lattice QCD (HAL QCD Collaboration)}

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T. Doi, T. Hatsuda, Y. Ikeda (RIKEN)
F. Etminan (Univ. of Birjand)
T. Inoue (Nihon Univ.)
T. Iritani (Stony Brook Univ.)
N. Ishii, K. Murano (RCNP)
H. Nemura, K. Sasaki (Univ. of Tsukuba)

+ Collaboration in HPCI Field5 Project 1
• **Outline**
  
  — Introduction
  
  – Theoretical framework
  
  – Results at heavy quark masses
  
  – Reliability test of LQCD methods
  
  – Results at physical quark masses
  
  – Summary / Prospects
**HAL QCD method**

**NBS wave func.**

\[ \psi_{NBS}(\vec{r}) = \langle 0 | N(\vec{r}) N(\vec{0}) | N(\vec{k}) N(-\vec{k}), in \rangle \]

\[ = R e^{i\delta_i(k)} \sin(kr - l\pi/2 + \delta_i(k))/(kr) \]

(at asymptotic region)

**Lat Nuclear Force**

\[ (k^2/m_N - H_0) \psi(\vec{r}) = \int d\vec{r}' U(\vec{r}, \vec{r}') \psi(\vec{r}') \]

**E-indep (& non-local) Potential:** Faithful to phase shifts

**Analog to ...**

**Phase shifts**

**Phen. Potential**
Recent Crucial Development

- **Time-dependent HAL method**
  - [Luscher’s method] (traditional) \(\Rightarrow\) ground state saturation \(\Rightarrow\) very bad S/N
    \[ S/N \sim \exp[-A \times (m_N - 3/2m_\pi) \times t] \]
  - [HAL method] \(\Rightarrow\) ground state saturation NOT required w/ E-indep pot
    \(\Rightarrow\) “exponential” S/N Improvement
    \[ S/N \sim \exp[-A \times (m_N - 3/2m_\pi) \times t] \]

- **Coupled Channel systems**
  - Coupled channel potentials can be extracted above inelastic threshold
    \(\Rightarrow\) Essential for YN/YY-forces

- **Unified Contraction Algorithm (UCA)**
  - Drastically faster algorithm by unifying Wick and color/spinor contractions
    Speedup: \(\times 192\) for \(^3\text{H}/^3\text{He}\), \(\times 20736\) for \(^4\text{He}\), \(\times 10^{11}\) for \(^8\text{Be}\)
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SU(3) study

**BB potentials**

### NN sector

- $^1S_0$
  - Strong repulsive core

- $^3S_1 - ^3D_1$
  - $27,10^*$: Same as NN

### YN/YY sector

- $^8s,10$: Strong repulsive core
  - Attractive core!

- $^8s,10$: Deep attractive pocket

**SU(3) lat → Physical point**

- $m_{BB} = 2380\text{MeV}$
- $m_{NN} = 2260\text{MeV}$
- $m_H = 120\text{MeV}$
- $m_{\Delta\Delta} = 2230\text{MeV}$

**Repulsive core \(\leftrightarrow\) Pauli principle!**

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a=0.12fm, L=3.9fm, $m(PS) = 0.47$-$1.2\text{GeV}$

T.Inoue et al. (HAL), NPA881(2012)28

M.Oka et al., NPA464(1987)700
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\[
\begin{array}{ll}
\text{NN } \left( ^1S_0, ^3S_1 \right) \text{ @ heavy masses:} & \\
\text{HAL method} \quad \text{(HAL)} & : \text{unbound} \\
\text{Luscher’s method} \quad \text{(Yamazaki et al./ NPL/ CalLat)} & : \text{bound}
\end{array}
\]

– Results at physical quark masses
– Summary / Prospects
Reliability Test of LQCD methods

- High-stat study for BB-system (@m(\pi)=0.5GeV)
  - Benchmark w/ two LQCD setup (wall & smeared src)

\[ \Delta E = m\Xi \Xi(1S_0) - 2m \Xi \Xi(1S_0) \]

\[ S/N \sim \exp[-\alpha t] \]

Inconsistent “signal” (red (wall) vs blue (smeared))
- cannot judge which (or neither) is reliable

\[ V_{\text{eff}}(r) \text{ from wall & } V^{\text{LO}}(r) \text{ from wall+smeared} \]
- are consistent

HAL method (new !)

T. Iritani et al. (HAL Coll.)
Understand the origin of “fake plateaux”

**Potential**

- $t = 15$
- $t = 13$
- $t = 11$

**NBS correlator $\Psi(r,t)$**

- smeared src.: $t = 14$
- $t = 13$
- $t = 12$
- wall src.: $t = 13$
- $t = 15$

**Solve Schrödinger eq. in Finite V**

**Eigen-wave functions**

**Eigen-energies**

<table>
<thead>
<tr>
<th>$n$-th A1</th>
<th>$\Delta E_n$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2.58(1)</td>
</tr>
<tr>
<td>1</td>
<td>52.49(2)</td>
</tr>
<tr>
<td>2</td>
<td>112.08(2)</td>
</tr>
<tr>
<td>3</td>
<td>169.78(2)</td>
</tr>
<tr>
<td>4</td>
<td>224.73(1)</td>
</tr>
</tbody>
</table>

**Decompose NBS correlator to each eigenstates**
Decompose NBS correlator to each eigenstates

NBS correlator $\Psi(r,t)$

Contribution from each (excited) states (@ t=0)

R-correlator $R(t) = \sum_r \Psi(r,t)$

(R(t) w/ smeared has been used in Luscher’s method)

Contribution from each (excited) states (@ t=0)

Excited States

G.S.

Blue: smeared

Red: wall

excited states NOT suppressed

excited states suppressed

Excited States
Understand the origin of “fake plateaux”

We are now ready to “predict” the behavior of $m(\text{eff})$ of $\Delta E$ at any “$t$”

“prediction” reproduce the real data well

To obtain a “real plateau”, $t/\alpha > 100$ ($t > 10\text{fm}$) is necessary

Extreme care is necessary for the results from the Luscher’s method
Understand the origin of “fake plateaux”

We are now ready to “predict” the behavior of $m(\text{eff})$ of $\Delta E$ at any “$t$”

To obtain a “real plateau”, $t/a > 100$ ($t > 10\text{fm}$) is necessary

Extreme care is necessary for the results from the Luscher’s method
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Simulations w/ ~ physical masses

HPCI Strategic Program Field 5
“The origin of matter and the universe”
FY2010-15

Gauge Config Generation

- Nf = 2+1 full QCD
  - clover fermion + Iwasaki gauge w/ stout smearing
  - volume: 96^4 ~ (8 fm)^4
  - 1/a ~ 2.3 GeV (a ~ 0.085 fm)
  - m_π ~ 145 MeV, m_K ~ 525 MeV
  - #traj ~ 2000 generated

Baryon Forces

⇒ HAL QCD method
Strategy for phys point BB-forces calc

• Focus on the most important forces:
  – Central/tensor forces for all NN/YN/YY in P=(+) (S, D-waves)
  • Hyperon forces provide precious “predictions”

<table>
<thead>
<tr>
<th>S=0</th>
<th>S=-1</th>
<th>S=-2</th>
<th>S=-3</th>
<th>S=-4</th>
<th>S=-5, -6</th>
</tr>
</thead>
</table>

- **NN**
- **ΛN, ΣN**
- **ΛΛ, ΛΣ, ΣΣ, ΞΞ**
- **ΛΞ, ΣΞ**
- **ΞΞ**
- **ΩΩ**

“milestone-postdiction”

Hypernuclear phys @ J-PARC
H-dibaryon ?, Ξ-hypernuclei

Λ appearance in NS & EoS ?

New bound state(s) ?

**Code:**
Efficient implementation of UCA
Performance on K @ 2048node:
~25% of peak (~65 Tflops sustained)

**Setup:**
Wall source w/ Coulomb gauge + temporal DBC
#stat ~= 200conf x 4rot x 20-44src ➔ ~x2-4 in FY2015

**Weak scaling**
(total of Hadron-Force code, w/o IO)
ΩΩ system in $^1S_0$

A new exotic dibaryon

⇒ HIC experiments?

[S. Gongyo / K. Sasaki]

B.E.(QCD) ~ = a few - 10 MeV
$^1S_0 \quad \Xi \Xi$-Potentials

$^3S_1-^3D_1$

- $^1S_0 \sim 27$-plet
  $\Leftrightarrow$ NN($^1S_0$) + SU(3) breaking

- $^3S_1-^3D_1 \sim 10$-plet
  $\Leftrightarrow$ unique w/ hyperon DoF
  $\Leftrightarrow$ $\Sigma^-$ in neutron star

Preliminary

Central Tensor
phase shifts ($^{1}S_{0}$)

($^{1}S_{0}$) is unbound

(t-dependence will be checked again w/ larger #stat)

➔ HIC experiments?

c.f. Phen. model (Nijmegen) : possibly bound
EFT (Haidenbauer et al. ‘14) : unbound favored

(2-gauss + 2-OBEP fit)
(200conf x 4rot x 44src)
\( \Lambda \Lambda, N \Xi, \Sigma \Sigma \) coupled channel (I=0) \( ^1S_0 \)

**H-dibaryon channel**

**Diagram**

- **Diagonal**
  - \( m_{\Sigma \Sigma} = 2380 \text{MeV} \)
  - 120 MeV
- **Off-diagonal**
  - \( m_{N \Xi} = 2260 \text{MeV} \)
  - 30 MeV
- **Strong Attraction in flavor-singlet channel**

\[ m_{\Lambda \Lambda} = 2230 \text{MeV} \]

[K. Sasaki]
$\Lambda\Lambda$, $N\Xi$ (effective) 2x2 coupled channel analysis

$\Lambda\Lambda$, $N\Xi$ phase shifts

H-dibaryon may exist as a resonance just below $N\Xi$ threshold

N.B. systematics from time-dependence should be checked

$\Sigma\Sigma$ mass: 2380 MeV

$N\Xi$ mass: 2260 MeV

$\Lambda\Lambda$ mass: 2230 MeV

Preliminary

[K. Sasaki]
**NΞ-Potentials**

KISO-event (2014): $\Xi^{-}\rightarrow^{14}\text{N} : \text{B.E.} = 4.38(25) \text{ MeV} (\text{or } 1.11(25) \text{ MeV})$

- $N\Xi (l=0, ^3S_1)$: Attractive
- $N\Xi - \Lambda\Sigma (l=1, ^1S_0)$: Repulsive
- $N\Xi - \Lambda\Sigma - \Sigma\Sigma (l=1, ^3S_1)$: Attractive

Is interaction net attractive? Stay tuned!

(net attractive @ $m(\pi)=0.66-88\text{GeV}$)
NN-Potentials

\[ {^1S_0} \]

\[ {^3S_1-^3D_1} \]

Vc: repulsive core
+ long-range attraction

Vt: tensor force clearly visible

Preliminary

(200conf x 4rot x 44src)
NN-Potentials (tensor)

- Similar structure to phenomenological potential
- Larger $t$ w/ larger #stat is desirable
The 1st LQCD calc of Baryon Interactions at ~ phys. point
- $m(\pi) \sim 145$ MeV, $L \sim 8$ fm, $1/a \sim 2.3$ GeV
- Central & Tensor forces calculated for all NN/YN/YY in $P=(+)$ channel
- Various exciting results from precise prediction to semi-quantitative arguments

HAL QCD method
- t-dep HAL method avoids S/N issue by g.s. saturation
- Suitable for coupled channel systems
- Unified contraction algorithm for computations
- (Difficulty in Lushcer’s method shown explicitly)

Prospects
- Measurement in progress $\Rightarrow$ #stat will be $\sim 2-4$ in FY2015
- LS-forces, $P=(-)$ channel, 3-baryon forces $\Rightarrow$ towards post K
- Resonances / Exotics (talk by Y. Ikeda, on Tue.) & more