Ongoing search for the H-dibaryon in two-flavor lattice QCD

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Multi-Hadron and Nonlocal Matrix Elements in Lattice QCD
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Outline

Why the H-dibaryon?
- Experimental constraints
- The lattice perspective
- A laboratory system

Our ongoing search
- Local six-quark interpolating operators
- All-mode averaging
- Lattice results
- Extending the basis
- Hint of a bound state

Summary

Why the H-dibaryon?

Quark bag model: A stable dibaryon

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Perhaps a Stable Dihyperon*

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(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P=0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P=1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

TABLE I. Quantum numbers and masses of S-wave dibaryons.

$SU(6)_{cs}$ representation	C_6	J	$SU(3)_f$ representation	Mass in the limit $m_s=0$ (MeV)
490	144	0	$\underline{1}$	1760
896	120	1,2	$\underline{8}$	1986
280	96	1	$\underline{10}$	2165
175	96	1	$\underline{10}^*$	2165
189	80	0,2	$\underline{27}$	2242
35	48	1	$\underline{35}$	2507
1	0	0	$\underline{28}$	2799

- Stable dibaryon with: $I=0,\ S=-2,\ J^P=0^+$
- Proposed in 1976:
  - deep binding $\rightarrow$ exp. excluded
  - shallow binding $\rightarrow$ possible
- Interesting question for lattice QCD

Experimental constraints: The "Nagara"-event

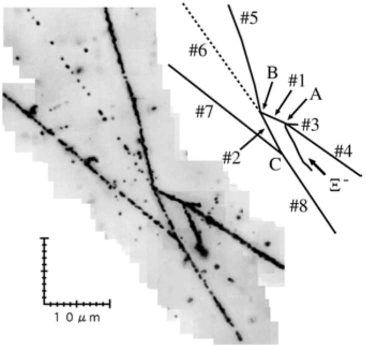


FIG. 2. Photograph and schematic drawing of NAGARA event. See text for detailed explanation.

(H. Takahashi *et al.*, PRL **87**, 212502 (2001))

"Nagara"-event at KEK (2001):

- discovery of a ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ double hypernucleus

$$E_{\Lambda\Lambda} = 6.91 \pm 0.16\mathrm{MeV}.$$

- strong constraint on the existence of the H-dibaryon, since

$$m_H \stackrel{!}{>} 2m_\Lambda - B_{\Lambda\Lambda}$$

- i.e. its binding energy E_H must be smaller than $E_{\Lambda\Lambda}$
- due to the absence of ${}^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{4}\,\mathrm{He} + H$

The lattice perspective

- Shallow binding $E_H < 7$MeV is a challenge for lattice QCD
- But: H is a good *stepping stone calculation* for lattice multi-hadron systems and lattice nuclear physics
- Number of Wick contractions required goes like $N = \prod_i^{N_f} N_{q_i}!$
  - The $H = udsuds$ has $N = 2!2!2! = 8$ Wick contraction terms
  - Can be done even by brute force
  - Ideal test-bed for advanced contraction algorithms
- No antiquarks in the operator $\Rightarrow$ No need for all-to-all propagators (counter example: $\pi\pi$-systems)
- Rule of thumb: Operators with heavy quarks are less noisy

The H-dibaryon as a laboratory: $\Delta\Delta$ from WASA@COSY

ABC Effect in Basic Double-Pionic Fusion --- Observation of a new resonance?

WASA-at-COSY Collaboration (P. Adlarson (Uppsala U.) *et al.*) *Show all 123 authors*

Apr 2011

Phys.Rev.Lett. 106 (2011) 242302
DOI: 10.1103/PhysRevLett.106.242302
e-Print: arXiv:1104.0123 [nucl-ex] | PDF

Abstract (arXiv)
We report on a high-statistics measurement of the basic double pionic fusion reaction $pn \to d\pi^0\pi^0$ over the energy region of the so-called ABC effect, a pronounced low-mass enhancement in the $\pi\pi$-invariant mass spectrum. The measurements were performed with the WASA detector setup at COSY. The data reveal the ABC effect to be associated with a Lorentzian shaped energy dependence in the integral cross section. The observables are consistent with a resonance with $I(J^P) = 0(3^+)$ in both pn and $\Delta\Delta$ systems. Necessary further tests of the resonance interpretation are discussed.

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

WASA-at-COSY Collaboration (P. Adlarson (Uppsala U.) *et al.*) *Show all 109 authors*

Feb 27, 2014 - 6 pages

Phys.Rev.Lett. 112 (2014) 202301
(2014-05-23)
DOI: 10.1103/PhysRevLett.112.202301
e-Print: arXiv:1402.6844 [nucl-ex] | PDF
Experiment: WASA-COSY

Abstract (APS)

Exclusive and kinematically complete high-statistics measurements of quasifree polarized n→p scattering have been performed in the energy region of the narrow resonancelike structure d* with I(JP)=0(3+), M≈2380 MeV, and Γ≈70 MeV observed recently in the double-pionic fusion channels pn→dπ0π0 and pn→dπ+π-. The experiment was carried out with the WASA detector setup at COSY having a polarized deuteron beam impinged on the hydrogen pellet target and utilizing the quasifree process d→p→np+pspectator. This allowed the np analyzing power, Ay, to be measured over a broad angular range. The obtained Ay angular distributions deviate systematically from the current SAID SP07 NN partial-wave solution. Incorporating the new Ay data into the SAID analysis produces a pole in the D33−G33 waves in support of the d* resonance hypothesis.

- Evidence of a resonance (dibaryon?) in the $\Delta\Delta$ channel at COSY
- Here we have $\Delta\Delta = uuuuuu$ with $6! = 720$ Wick contraction terms
- Much harder for lattice $\Rightarrow$ Gain experience with *udsuds*

Rcent lattice calculations

- Past lattice efforts have found a bound H-dibaryon at $M_\pi > M_\pi^{\mathrm{phys.}}$
- It is not clear yet if it is bound or unbound at the physical point

Group	Method	N_f	N_{vol}	$M_\pi[\mathrm{MeV}]$	$B_H[\mathrm{MeV}]$
HALQCD	B-B potentials	3	1	1171	49.1(3.4)(5.5)
			3	1015	37.2(3.7)(2.4)
			1	837	37.8(3.1)(4.1)
			1	672	33.6(4.8)(3.5)
			1	469	26(4.4)(4.8)
NPLQCD	2pt	3	3	806	74.6(3.3)(3.4)
		2+1	4	390	13.2(1.8)(4.0)
			1	230	-0.6(8.9)(10.3)

- Our search so far has been focused on $N_f = 2$ ensembles with $M_\pi = 451\mathrm{MeV}$ and $M_\pi = 1\mathrm{GeV}$ $\rightarrow$ here only $M_\pi = 1\mathrm{GeV}$ shown

Our ongoing search

Local six-quark interpolating operators

We use six parity-projected quarks to form six-quark interpolating operators of the form:

$$[abcdef] = \epsilon^{ijk}\epsilon^{lmn}(b_i^T C\gamma_5 P_+ c_j)(e_l^T C\gamma_5 P_+ f_m)(a_k^T C\gamma_5 P_+ d_n),$$

In the case $m_u = m_d$, two operators can be formed in this way that couple to the H-dibaryon:

$$H^{\mathbf{1}} = \frac{1}{48}\left([sudsud] - [udusds] - [dudsus]\right)$$
$$H^{\mathbf{27}} = \frac{1}{48\sqrt{3}}\left(3[sudsud] + [udusds] + [dudsus]\right),$$

these belong to the singlet and 27-plet irreps of flavour $SU(3)_f$.

Contractions using a blocking algorithm

An efficient way to contract the six-quark operators into correlation functions is to use a blocking algorithm:

- Form blocks of three propagators contracted into a color-singlet at the source

$$B(\alpha_1,\xi_1',\xi_2',\xi_3') = \epsilon_{c_1,c_2,c_3}(C\gamma_5 P_+)_{\alpha_2\alpha_3} S_l(\xi_1,\xi_1') S_l(\xi_2,\xi_2') S_s(\xi_3,\xi_3')$$

- Then sum over all permutations when contracting at the sink

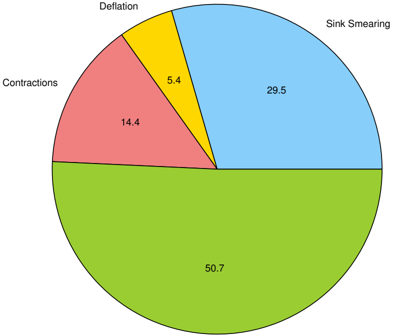
$$[sudsud] = (C\gamma_5 P_+)_{\alpha\beta} \times \epsilon_{c_1',c_2',c_3'}\epsilon_{c_4',c_5',c_6'}(C\gamma_5 P_+)_{\alpha_2'\alpha_3'}(C\gamma_5 P_+)_{\alpha_5'\alpha_6'} \sum_{\sigma_u,\sigma_d,\sigma_s} B(\alpha,\xi'_{\sigma_u(1)},\xi'_{\sigma_d(2)},\xi'_{\sigma_s(3)}) B(\beta,\xi'_{\sigma_u(4)},\xi'_{\sigma_d(5)},\xi'_{\sigma_s(6)})$$

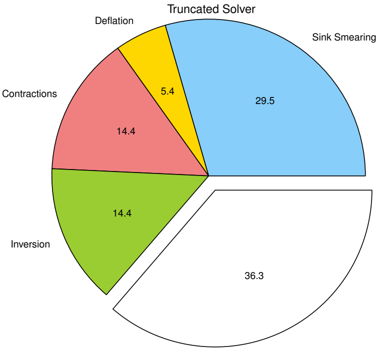
Boosting the calculation: All-mode averaging

- Computing the propagator is the most costly part of the calculation
- AMA: Reduce the precision of propagator on multiple source locations $\Rightarrow$ correct the introduced bias via

$$\mathcal{O} = \mathcal{O}_{x_0}^{\text{high prec.}} - \mathcal{O}_{x_0}^{\text{low prec.}} + \frac{1}{N_{\Delta x}} \sum_{\Delta x} \mathcal{O}_{x_0+\Delta x}^{\text{low prec.}}$$

- Depending on the ensemble we gain a factor $\sim 1.5 - 2$ in speed





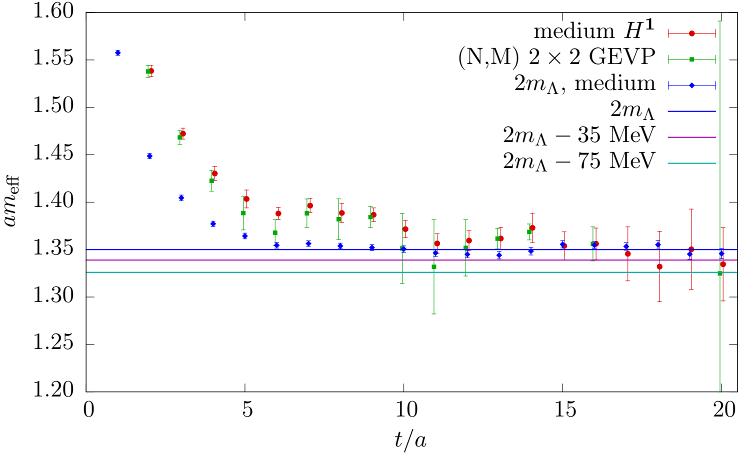
Results: E1 ensemble

- $L = 32$, $T = 64$ at $a = 0.063$fm
- $M_\pi = 1$GeV and $M_\pi L = 10$
- $N_{\rm conf} = 168$
- One high precision/low precision propagator solves for AMA bias
- $N_{src} = 128$ with low precision solves
- Double statistics using P_+ and P_- for the forward/backward propagating states
- In total this makes:

$$168 \times 128 \times 2 = 43008 \text{ measurements}$$

- $\kappa_s = \kappa_{ud}$ implies no mixing between the singlet and 27-plet irreps
- Multiple sets of smearing $\Rightarrow$ GEVP for ground state determination

Results: Effective masses



- At this point: No bound state seen with local six-quark operators

Results: Extending the basis

This was the status of our study using local six-quark operators, as presented at Lat'14. Possible issues:

- Insufficient statistics? Finite volume effects?
- Quenched strange quark

But, most importantly,

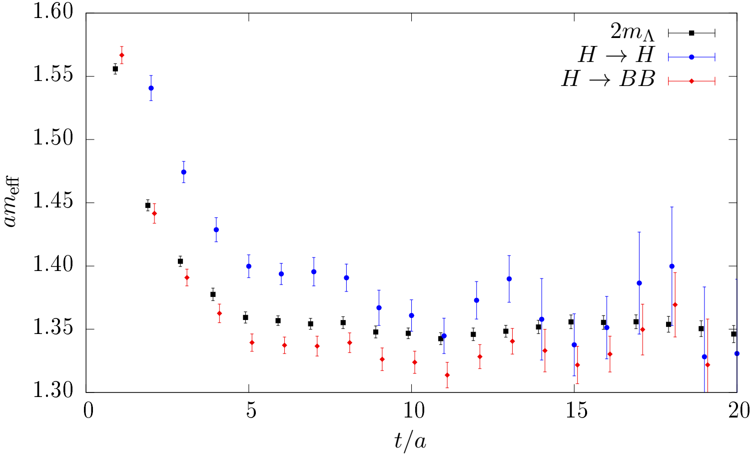
- we used only $\langle qqqqqq(x), \bar{q}\bar{q}\bar{q}\bar{q}\bar{q}\bar{q}(0)\rangle$ operators

Now, we extend our analysis and

- include $\langle qqq(x)qqq(y), \bar{q}\bar{q}\bar{q}\bar{q}\bar{q}\bar{q}(0)\rangle$ operators,
- more specifically, we compute the $SU(3)_f$ singlet combination:

$$H^1 = -\frac{1}{\sqrt{3}}\Lambda\Lambda + \Sigma\Sigma + \frac{2}{\sqrt{3}}\Xi N$$

Results: Hint of a bound state



- At this point: Hint of a bound state using the new operators
- Next step, combine both analyses (combined fit? Matrix Prony?)

Summary

Summary

Status

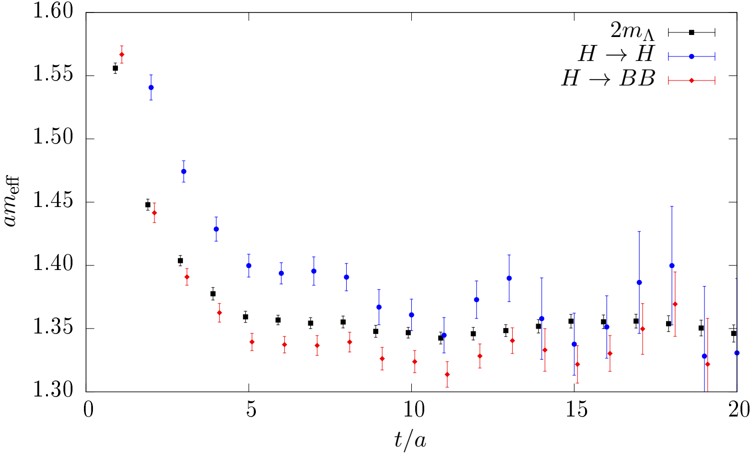
- H-dibaryon is an interesting challenge for lattice QCD
- Laboratory system for learning to do e.g. the $\Delta\Delta$ or nuclear physics
- On our heavy ($M_\pi = 1$GeV) lattice we
  - calculated $\langle qqqqqq(x), \bar{q}\bar{q}\bar{q}\bar{q}\bar{q}\bar{q}(0)\rangle$ operators
  - extended our basis to $\langle qqq(x)qqq(y), \bar{q}\bar{q}\bar{q}\bar{q}\bar{q}\bar{q}(0)\rangle$ operators

$\Rightarrow$ Hint of bound state

Outlook

- Combine analyses to determine ground state
- Reduce the mass (again) to $M_\pi = 451$MeV (E5) and further to $M_\pi = 270$ (F7)

Lots to do!



1.60
1.55
1.50
1.45
1.40
1.35
1.30
am_{eff}
0
5
10
15
20
t/a
$2m_\Lambda$
$H \to H$
$H \to BB$