Light hypernuclei

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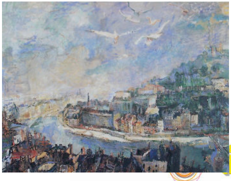

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Content

Work done in collaboration with Qiang Zhao (IHEP) and Qian Wang (Jülich)

New light hypernuclei?

- Much activity in the “molecular’ model,
- Meson-meson, baryon–baryon, baryon–antibaryon, etc.
- Stimulated by $X(3872)$ and other states in the heavy-quark sector
- Also for nucleon-hyperon systems = light hypernuclei
- Work presented at the Chinese-French meeting, April 8, 2014
- Preliminary results on arXiv:1404.3473 (April 14th, 2014)
- To be presented at the next Conference on Clusters

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Light hypernuclei: survey

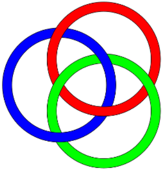
- $N\Lambda$ not bound
- $\Lambda\Lambda$ not bound, but might be attractive at short distances
- See, speculations on H dibaryon (Jaffe, ...)
- ${}^{3}_{\Lambda}\mathrm{H} = (n, p, \Lambda)$ bound slightly below ${}^{2}\mathrm{H} + \Lambda$
- This probes the ΛN interaction of the Nijmegen + Japan group fitting the (rare) scattering data and constrained from NN by $\mathrm{SU(3)_F}$
- ${}^{5}_{\Lambda}\mathrm{He} = (\alpha, \Lambda)$ bound, another example (More in Sakaguchi, 2009)
- Recent efforts on (n, n, Λ), with mixing of ΛN to ΣN included, found not bound (Gal et al., Hiyama et al., Valcarce et al.)

Light double hypernuclei: survey

- Double hypernuclei also seen
- "Nagara" event ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ seen
- Indicates a weak attraction for $\Lambda\Lambda$ in medium
- Suppression of $\Lambda\Lambda \leftrightarrow N\Xi \leftrightarrow \Lambda\Lambda$ due to Pauli principle
- Some discussion about (n, Λ, Λ)

Borromean binding

- Thomas (1935), Zhukov et al. (1993) milestones to stress the possibility of Borromean binding
- Bound state whose subsystems are unbound



- In quantum mechanics for bosons, a short-range attractive potential $g\,V(r)$
- Needs $g > g_2$ to bind (m, m)
- Needs $g > g_3$ to bind (m, m, m)
- With $\boldsymbol{g_3 < g_2}$ $[g_3, g_2]$ Booromean windows

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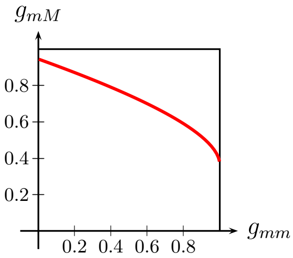
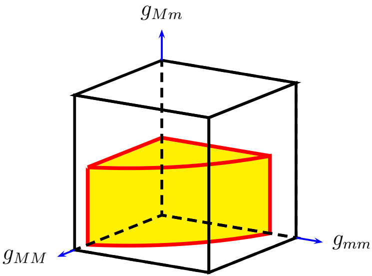
Borromean binding

- Example $^6\mathrm{He} = (\alpha, n, n)$ is stable
- while neither (α, n) nor (n, n) are bound
- Rigorous limit $2\,g_2/3 < g_3$ can be established
- And generalized to unequal masses and coupling, and to $N > 3$ body systems

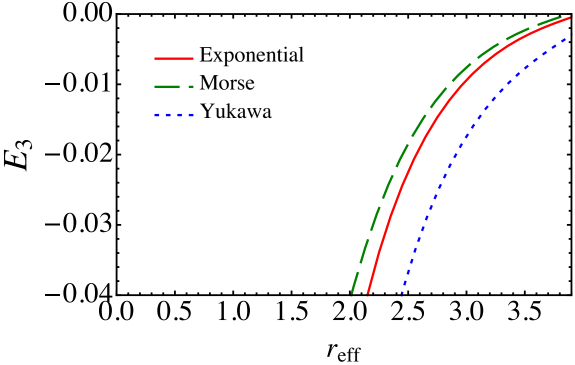




So, some hope is permitted, including 4-body binding without 3-body binding

Borromean binding

The amount of Borromean binding, for a given scattering length, depends on the effective range, a point sometimes overlooked.



Variational calculations

- Use simple central potentials (exp., Morse) reproducing $a_{\rm sc}$ and $r_{\rm eff}$, as done by several groups,
- 3-body: $\Psi = \sum_i \gamma_i \exp(-a_i\, x + b_i\, y + c_i\, z)$, $x = |\boldsymbol{r}_2 - \boldsymbol{r}_3|, \ldots$
- For given $\{a_i, b_i, c_i\}$, variational energy and $\{\gamma_i\}$ from a simple eigenvalue equation
- Non-linear parameters $\{a_i, b_i, c_i\}$ searched for numerically, as any triple inside a geometric series a, $a\,v$, $a\,v^2, \ldots$. So only a and v are varied (cf. Nakamura)
- Cross-checked with Varga and Suzuki's stochastic variational method (SVM) based on Gaussians

$$\Psi = \sum_i \gamma_i \exp[-\sum_{k<\ell} a_i^{k\ell}\,(\boldsymbol{r}_\ell - \boldsymbol{r}_k)^2]\ ,$$

- SVM also used for 4-body

Low-energy parameters

- Conventional: Nijmegen–RIKEN series of fits with meson exchanges
- More recent description of low-energy data with effective theories
- Which tend to give smaller r_{eff} and thus more binding

#	$(np)_{I=1}$	(nn)	$(np)_{I=0}$	$(\Lambda N)_{s=0}$	$(\Lambda N)_{s=1}$	$(\Lambda\Lambda)$
a	−23.735 2.694	−16.51 2.85	5.428 1.753	−2.70 2.97	−1.65 3.63	−0.97 3.88
b	−23.735 2.694	−18.9 2.75	5.428 1.753	−2.90 2.65	−1.51 2.64	−1.54 0.31

Results

- Very delicate 3-body and 4-body calculations
- With $V = -g_{ij}\exp(-r)$, r in GeV, tuned to reproduce the scattering lengths (n, p), (n, p, Λ) OK, (n, n, Λ) unbound, (n, p, Λ, Λ) and (n, n, Λ, Λ) stable, but effective range too small
- With $V = -g_{ij}\exp(-0.2\,r)$, r in GeV, (n, p), (n, p, Λ) OK, (n, n, Λ) unbound, (n, p, Λ, Λ) bound and (n, n, Λ, Λ) unstable, but effective range too large,
- With $V = -g_{ij}\exp(-\mu_{ij}\,r)$, or $V = g_{ij}\exp[-2\alpha_{ij}(r - R)] - 2\,g_{ij}\exp[-\alpha_{ij}(r - R)]$ (Morse), and a reasonable R, one can adjust g_{ij} and μ_{ij} or α_{ij} to reproduce the scattering length and effective range for each pair, then (n, p), (n, p, Λ) OK, (n, n, Λ) unbound, (n, p, Λ, Λ) bound and (n, n, Λ, Λ) very weakly bound, at least in the Jülich model [1]
- First indication for this neutral configuration which is fully Borromean

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[1] Chiral effective theory, another Jülich model was used earlier by Gloeckle et al.

Open questions- 1

- Three-body forces
  - probably very repulsive at high nuclear density (no room for additional u or d in a medium already saturated for u and d by two neighbouring nucleons
  - might be attractive for few-baryon systems
- Coupled channels
  - Often advocated
  - $\Lambda\Lambda \leftrightarrow \Xi N$ suppressed at high density, if medium saturated for Ns,
  - May be not for a very dilute (Λ, Λ, n, n)
  - Similarly, comparison of (ΛNN) with or without coupling to ΣNN meaningful only if ΛN alone and $\Lambda N + \Sigma N$ tuned to produce the same low-energy parameters. Not clear in the existing literature.

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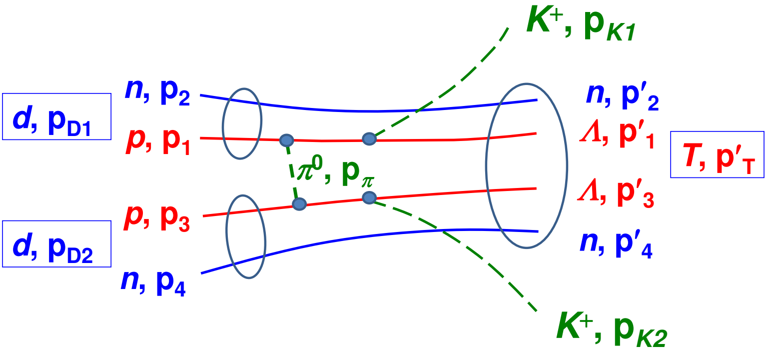
Open questions-2

- $\Lambda\Lambda$ interaction Very short-range in the "Jülich" model, with $r_{\rm eff} = 0.3\,$fm.
- If mimicked, à la Japanese, by an exponential, one gets almost a delta function, this making the numercial estimate moire delicate,
- Reminiscent of Jaffe's model for the $H = (uuddss) = \Lambda\Lambda + \cdots$, where the attraction is due the short-range part of the interquark force, the chromo-magnetic interaction.
- The existence of (n, n, Λ, Λ) would thus suggest a short-range free $\Lambda\Lambda$ interaction that is strongly suppressed in the nuclear medium.

Production mechanism

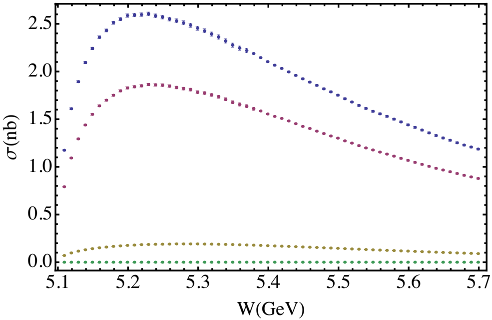
Production mechanism for the tetra-baryon state (ΛΛnn) in deuteron-deuteron collision



- **The two K^+ production is via the elementary process, $pp \rightarrow \Lambda\Lambda K^+K^+$.**
- **The intermediate S11(1535) excitations dominate the threshold production.**

Production mechanism

- Rough estimate
- Total, and Born term, double $N(1530)$, single $N(1530)$ contributions



Conclusions

$A = 3$

- A second (n, p, Λ), with $I = 0$ and $s = 3/2$ cannot be excluded
- (n, p, Λ) with $I = 1$ or (n, n, Λ) hardly bound with 2-body forces only
- (N, Λ, Λ) debated
- Three-body forces to be studied more carefully

$A = 4$

- Calculations confirms the likely existence of a (n, p, Λ, Λ)
- New light hypernuclei expected such as (n, n, Λ, Λ)
- In a regime of extreme Borromean binding
- If ΛN and $\Lambda\Lambda$ have small effective range, as suggested by effective field theories