Light hypernuclei

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Content

- Collaboration with Qiang Zhao (IHEP) and Qian Wang (Jülich)
- Work presented at the Chinese-French meeting, April 8, 2014
- Meeting on Strangeness, Frascati, May 14, 2014
- Workshop on Clusters, Yokohama, May 2014
- Preliminary results on
  - arXiv:1404.3473 [nucl-th]
  - arXiv: arXiv:1408.1323 [nucl-th] (May 23rd, 2014)

Strangeness, hyperons

- Late 40s, 50s, new hadrons, pair produced
- Strangeness introduced, conserved by strong interactions,
- Violated in weak decays
- Generalized isospin, to account for new hadrons, SU(2) $\to$ SU(3)
- Eightfold way (Gell-Mann & Ne'eman) $\to$ quarks, see also ZWeig
- Successful prediction of the Ω^- with strangeness -3;
- Hyperons = baryons with strangeness

$S = -1$ Λ, Σ plus spin, radial and orbital excitations
$S = -2$ Ξ plus excitations
$S = -3$ Ω^- plus excitations

- Very early: interaction of the hyperons among themselves and with nucleons

Light hypernuclei: survey

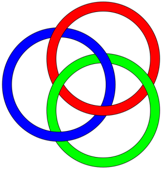
- $N\Lambda$ not bound
- $\Lambda\Lambda$ not bound, but might be attractive at short distances
- See, speculations on H dibaryon (Jaffe, ...)
- ${}^{3}_{\Lambda}\mathrm{H} = (n, p, \Lambda)$ bound slightly below ${}^{2}\mathrm{H} + \Lambda$
- This probes the ΛN interaction of the Nijmegen + Japan group 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 recent reviews)
- 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 $\boldsymbol{g_3 < g_2}$ $[g_3, g_2]$ Borromean windows

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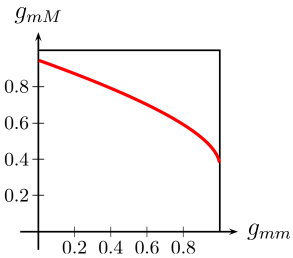
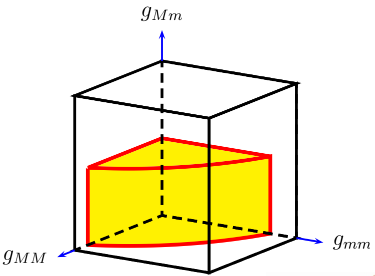
Borromean binding

- 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 such as (mmM) and $(mmMM)$



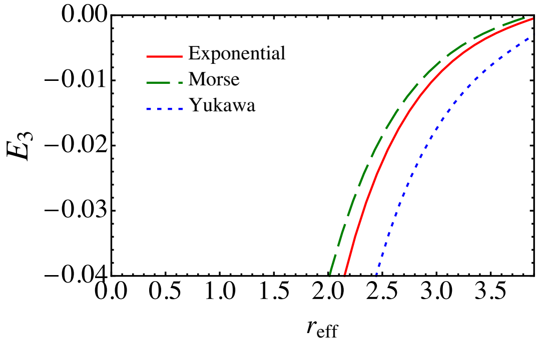


Optimist view

- So, some hope is permitted, as the ‘allowed” domain is large for (m, m, M, M)
- Including 4-body binding without 3-body binding
- As in atomic physics
  - Positronium hydride stable (Øre, 1951): (p, e^+, e^-, e^-) stable though (p, e^+, e^-) is unstable
  - (M^+, m^+, M^-, m^-) stable for $M \sim 2\,m$, though none of the 3-body subsystems such as (M^+, m, m^-) is stable (R., Phys. Rev. A 67, 034702)
- Will the magic of 4-body systems work once more?

Borromean binding

- for a given scattering length a_{sc},
- Amount of Borromean binding depends on effective range
- Already stressed (Gibson + Lehman, Gal et al., ...)
- But the effect differs according to the sign of a_{sc}



- Figure: E_3 vs. r_{eff} at fixed a_{sc}
- Here for negative a_{sc}

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Variational calculations

- Use simple central potentials (exp., Morse) reproducing $a_{\rm sc}$ and $r_{\rm eff}$, as done by several groups,
- 3-body: $\Psi = \sum_i \gamma_i \exp(-a_i\, x - b_i\, y - c_i\, z), \quad x = |\boldsymbol{r}_2 - \boldsymbol{r}_3|, \ldots$
- 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 et al.)
- 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

- $N-R$ Nijmegen–RIKEN series of fits with meson exchanges
- *CEFT Chiral Effective Field Theory*
  Which tend to give smaller $r_{\rm eff}$ and thus more binding

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

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Results

- Very delicate 3-body and 4-body calculations
- Warm-up without tuning of $r_{\rm eff}$
  - 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 tuning of $r_{\rm eff}$ $V = -g_{ij}\,\exp(-\mu_{ij}\,r)$, 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 with CEFT,
- First indication for this neutral configuration which is fully Borromean

Open questions: 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
- Evolution along the years:
- In the early 70s, a hard core was assumed for any baryon–baryon interaction
- Now the core is softer, and is understood as coming from the Pauli principle for quarks
- Repulsive core e.g., for $(u, u, d) + (u, d, d)$
- No repulsion for $(u, d, s) + (u, d, s)$
- But onset of repulsion if more Λ are put together

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Open questions: coupled channels

- $\Lambda\Lambda \leftrightarrow \Xi N$ suppressed at high density, if medium saturated for *N*s,
- May be not for a very dilute (Λ, Λ, n, n)
- Comparison of (ΛNN) with or without coupling to ΣNN when ΛN alone and $\Lambda N + \Sigma N$ give the same $a_{\rm sc}$ and $r_{\rm eff}$
- Extra attraction if new spin-isospin configurations (Gibson, ...)
- For instance, leading *s*-wave decomposition schemes

$$(n, p, \Lambda)_{I=0,s=3/2} = (np)_{0,1}\Lambda_{0,1/2} + (np)_{0,1}\Sigma_{1,1/2}$$
$$(n, p, \Lambda)_{I=0,s=1/2} = (np)_{0,1}\Lambda_{0,1/2} + (np)_{0,1}\Sigma_{1,1/2} + (NN)_{1,0}\Sigma_{1,1/2}$$

- Similarly, for the example of the $\Sigma\Sigma$ sector

$$(n, p, \Lambda\Lambda)_{I=0,s=1} = (np)_{0,1}(\Lambda\Lambda)_{0,0} + (np)_{0,1}(\Sigma\Sigma)_{0,0} + (NN)_{1,0}(\Sigma\Sigma)_{1,1}$$
$$(n, p, \Lambda\Lambda)_{I=1,s=0} = (nn)_{0,0}(\Lambda\Lambda_{0,0} + (nn)_{0,0}(\Sigma\Sigma)_{0,0} + (np)_{0,1}(\Sigma\Sigma)_{1,1}$$

both can get some small downwards shift.

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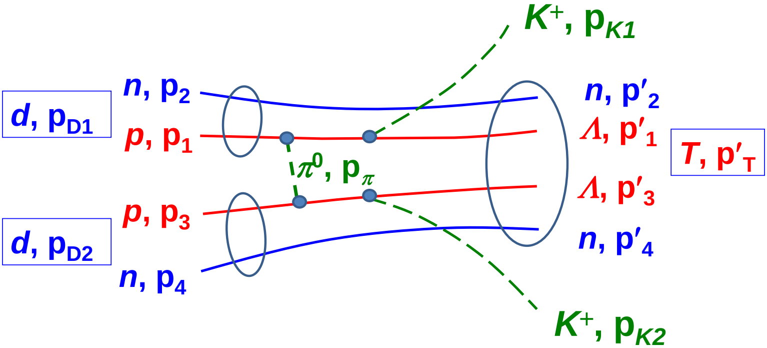
Open questions: $\Lambda\Lambda$ interaction

- Very short-range in the CEFT model, with $r_{\rm eff} = 0.3\,$fm.
- If mimicked by an exponential, one gets almost a delta function, this making the numerical estimate more 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, attractive $\Lambda\Lambda$ interaction that is strongly suppressed in the nuclear medium
  - No medium effect for the dilute (n, n, Λ, Λ)
  - Suppression of $\Lambda\Lambda \leftrightarrow N\Xi$ for heavier double hypernuclei

Production mechanism

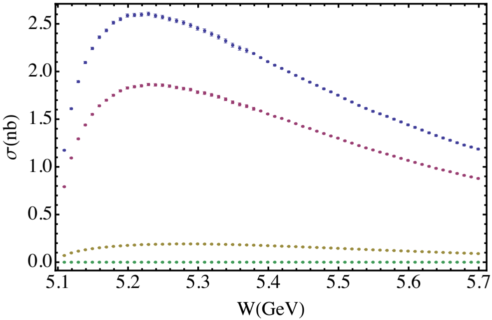
Production mechanism for the tetra-baryon state ($\Lambda\Lambda$nn) in deuteron-deuteron collision



- **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



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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