Emergence of ^{4}H($J^{\pi} = 1^{-}$) resonance in contact theories (Phys. Lett. B 840 (2023) 137840)

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Introduction

LO $\pi\!\!\!/$EFT

$$\hat{V} = \sum_{ST} C_0^{ST} \sum_{i<j} e^{-\frac{\Lambda^2}{4} r_{ij}^2}$$

$$\hat{W} = D_0 \sum_{i<j<k} \sum_{cyc} e^{-\frac{\Lambda^2}{4}(r_{ij}^2 + r_{ik}^2)}$$

Impresive amount of various studies for $A \leq 3$ at LO $\pi\!\!\!/$EFT and its higher orders.

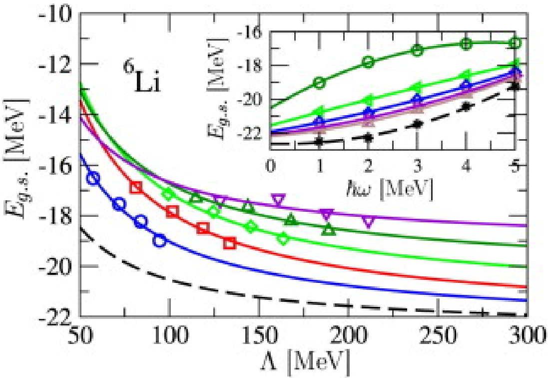
At this conference :

LO $\pi\!\!\!/$EFT for hypernuclei (talk of L. Contessi)
Few-nucleon scattering at NLO $\pi\!\!\!/$EFT for $A \leq 4$ (talk of B. Bazak)
S-wave $n^4\mathrm{He}$ scattering at NLO $\pi\!\!\!/$EFT (poster of M. Bagnarol)
Getting LQCD calculations outside the box (poster of T. Weiss-Attia)

... **What about p-shell or even heavier nuclear systems ?**

LO $\not\pi$EFT calculation of $^6\mathrm{Li}$

(I. Stetcu, B. R. Barrett, and U. van Kolck, Phys. Lett. B 653 (2007) 358)



→ NCSM calculation

→ 3 LECs in LO $\not\pi$EFT fitted such that exp. ground state $B(^2\mathrm{H})$, $B(^3\mathrm{H})$, and $B(^4\mathrm{He})$ are reproduced

→ for large Λ $B(^6\mathrm{Li})$ estimated as ~ 23 MeV

LO $\not\pi$EFT calculation of ^{16}O

(L. Contessi, A. Lovato, F. Pederiva, A. Roggero, J. Kirscher, and U. van Kolck, Phys. Lett. B 772 (2017) 839)

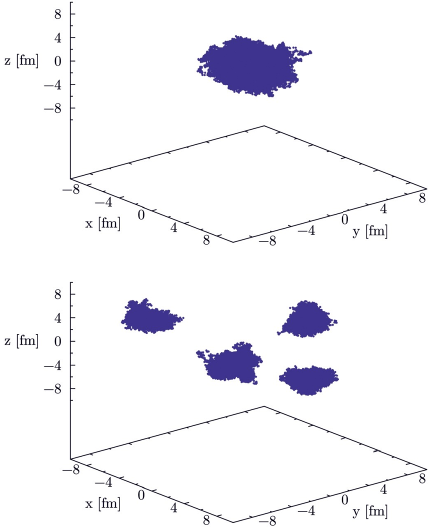
→ AFDMC (Monte Carlo)

→ ground state binding energy for $\Lambda = 2,\ 4,\ 6,\ 8\ \mathrm{fm}^{-1}$

→ bound at $\Lambda = 2\ \mathrm{fm}^{-1}$

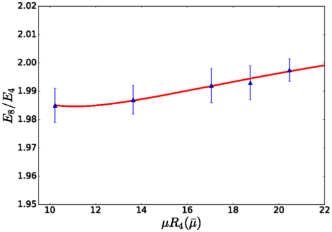
→ for $\Lambda \geq 4\ \mathrm{fm}^{-1}$ wave function of ^{16}O breaks into 4 mutually unbound α clusters

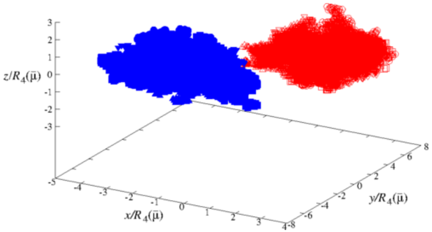
→ the same outcome for ^{16}O and ^{40}Ca using coupled-cluster method
(A. Bansal, S. Binder, A. Ekström, G. Hagen, G. R. Jansen, and T. Papenbrock, Phys. Rev. C 98, 054301, 2018)



LO contact EFT calculation of 8 four-component unitary fermions (W. G. Dawkins, J. Carlson, U. van Kolck, and A. Gezerlis, Phys. Rev. Lett. 124 (2020) 143402)

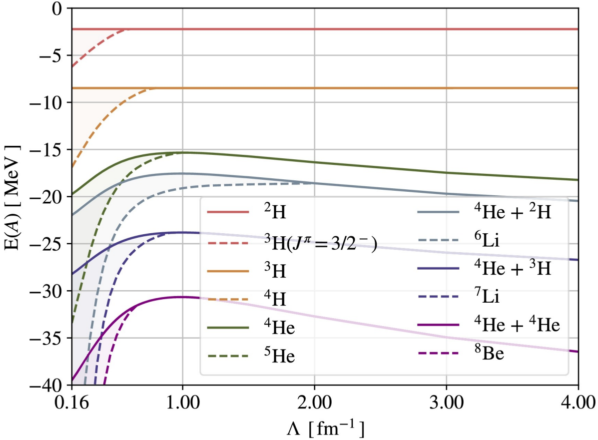
- $\rightarrow$ ressemblence to Wigner LO SU(4)-symmetric $\not\pi$EFT ($^{8}\mathrm{Be}$)
- $\rightarrow$ DMC (Monte Carlo)
- $\rightarrow$ zero-range limit $\mu R_4(\bar{\mu}) \rightarrow \infty$
- $\rightarrow$ $E_8/E_4(\infty) = 2.04 \pm 0.05$
- $\rightarrow$ $E_8/E_4(\infty)$ ratio consistent with the disintegration threshold into two 4-body clusters





LO $\not\pi$EFT calculations of several *p*-shell nuclei up to ^{8}Be

(M. Schäfer, L. Contessi, J. Kirscher, and J. Mareš, Phys. Lett. B 816 (2021) 136194)



At certain small and finite Λ all *p*-shell nuclear systems up to ^{8}Be break into mutually unbound *s*-shell subclusters.

Intermezzo (M. Schäfer, L. Contessi, J. Kirscher, and J. Mareš, Phys. Lett. B 816 (2021) 136194)

Conjecture based on the numerical evidence :

Beyond *s*-shell nuclear systems break in the zero-range limit into *p*, *n*, $^2\mathrm{H}$, $^3\mathrm{H}/^3\mathrm{He}$, and $^4\mathrm{He}$. (free nucleon(s) + spherically-symmetric fragments)

Option 1 :
LO shallow continuum pole; RG invariant; can be mutated into a bound state with perturbative insertions of sub-leading operators.

Option 2 :
Identical as above; nonperturbative mechanism required to move the pole into a bound-state region.

Option 3 :
No LO RG invariant continuum pole in the EFT's convergence radius; must be created nonperturbatively by modifying the LO.

^{4}H resonances

Experimental evidence :

→ n^3H elastic cross-sections

(Ann. Phys. 74 (1972) 250;Phys. Rev. C 22 (1980) 384)

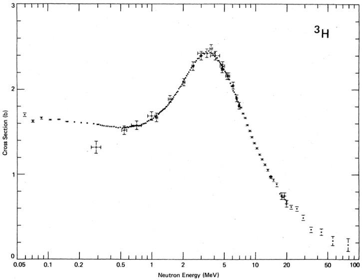
→ π^- absorption experiments

(Phys. Lett. B 103 (1981) 409; Nucl. Phys. A 531 (1991) 613)

→ transfer reactions

(Phys. Rev. C 33 (1986) 2204; Nucl. Phys. A 719 (2003) C229)

→ extracted resonance positions significantly differ



Theory :

→ RGM with complex scaling

(Phys. Rev. C 68 (2003) 034303)

→ Spin-dipole strength functions

(Phys. Rev C 87 (2013) 034001)

→ Faddeev-Yakubovsky equations

(Phys. Lett. B 791 (2019) 335)

→ No-core Gamov Shell Model

(Phys. Rev. C 104 (2021) 024319)

J^π	E_r [MeV]	Γ [MeV]
2^-	1.15(5)	3.97(7)
1^-_I	0.90(3)	3.80(8)
0^-	0.78(15)	7.7(7)
1^-_{II}	0.2(2)	4.6(1)

INOY; (Phys. Lett. B 791 (2019) 335)

One LO interaction ... three different methods

(L. Contessi, M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonell, Phys. Lett. B 840 (2023) 137840)

SU(4)-symmetric LO $\not\pi$EFT

$$\hat{V} = C_0 \sum_{i<j} e^{-\frac{r_{ij}^2 \Lambda^2}{4}}$$

$$\hat{W} = D_0 \sum_{i<j<k} \sum_{cyc} e^{-\frac{(r_{ij}^2 + r_{ik}^2)\Lambda^2}{4}}$$

$B(^2\mathrm{H})$/*unitarity* and $B(^3\mathrm{H})$

Faddeev-Yakubovsky formalism

(Phys. Rev. C 70 (2004) 044002)

(Front. Phys. (2020) 251)

$n^3\mathrm{H}$ scattering, $^4\mathrm{H}$ S-matrix pole

Harmonic oscillator trap

(Phys. Rev. A 80 (2009) 033601)

(Phys. Rev. C 85 (2012) 034003)

(Phys. Rev. Lett. 125 (2020) 112503)

$n^3\mathrm{H}$ scattering

Resonating group method

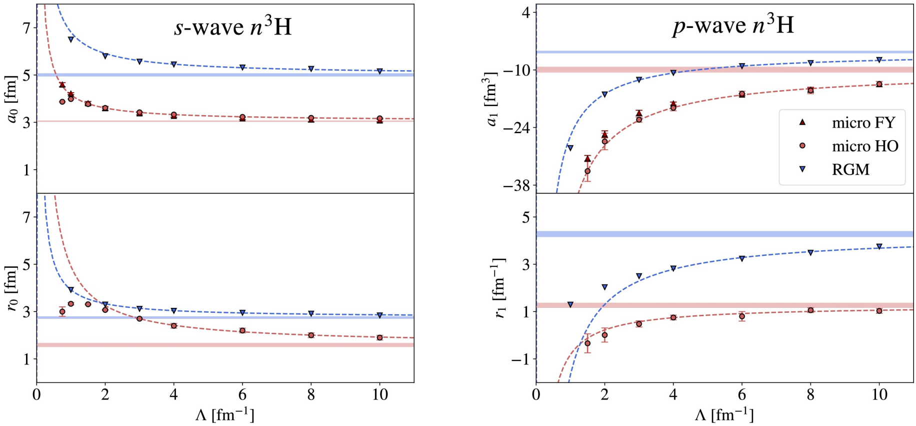
(Phys. Rev. 52 (1937) 1107)

(K. Wildermuth, Y. T'ang, *A unified theory of the nucleus* (1977) Vieweg+Teubner Verlag)

$n^3\mathrm{H}$ scattering

S-wave and p-wave $n^3\mathrm{H}$ elastic scattering

(L. Contessi, M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonell, Phys. Lett. B 840 (2023) 137840)



RGM insight into $n^3\mathrm{H}$ potential

(L. Contessi, M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonell, Phys. Lett. B 840 (2023) 137840)

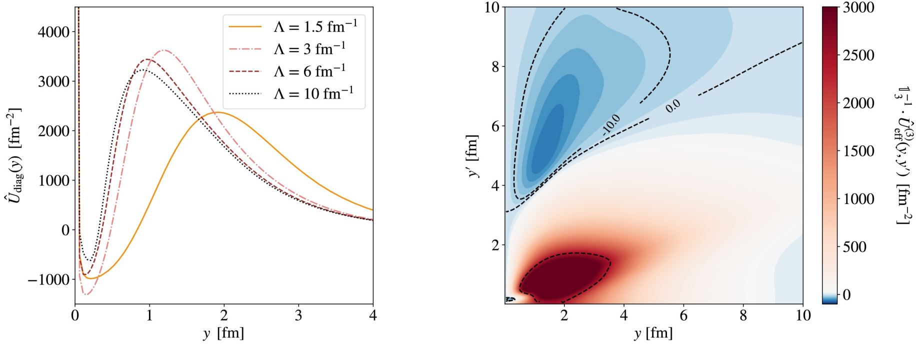
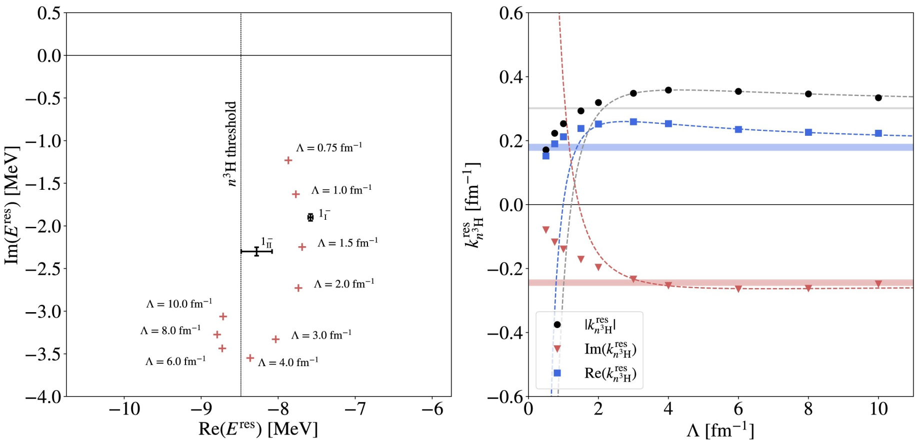


Figure: Left panel: Diagonal part of the effective "nuclear" RGM potential in the $L = 1$ partial wave, $\hat{U}_{\mathrm{diag}}(y) := L(L+1)y^{-2} + \frac{2\mu}{\hbar^2}\left[\hat{U}^{(2)}_{\mathrm{eff}}(y) + \hat{U}^{(3)}_{\mathrm{eff}}(y,y)y^2\right]\frac{1\mathrm{fm}}{N_3}$, where N_3 is the norm of the triton wave function and $1.5\,\mathrm{fm}^{-1} \leq \Lambda \leq 10\,\mathrm{fm}^{-1}$. Right panel: Topography of the non-local part $\hat{U}^{(3)}_{\mathrm{eff}}(y,y')$ ($\Lambda = 10$ fm^{-1}) exhibiting an off-diagonal attractive pocket (second quadrant of the contour plot) which does not vanishes in the zero-range limit. The potentials were obtained at $E = 0$ with a five-dimensional Gaussian calibration of the core wave function to SVM ground states.

Emergence of $^4\mathrm{H}$ $J^\pi = 1^-$ resonance in LO $\not\pi$EFT

(L. Contessi, M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonell, Phys. Lett. B 840 (2023) 137840)



$$k_{\mathrm{res}} = \sqrt{2\mu \tilde{E}_{\mathrm{res}}}, \qquad \tilde{E}_{\mathrm{res}} = E_{\mathrm{res}} - E_t$$

Summary

- Beyond *s*-shell nuclear systems break in the zero-range limit into *p*, *n*, $^{2}\mathrm{H}$, $^{3}\mathrm{H}/^{3}\mathrm{He}$, and $^{4}\mathrm{He}$ (conjecture based on the numerical evidence)
- Suprisingly, the same type of instability for $^{6}\mathrm{Li}$ and $^{16}\mathrm{O}$ found using RG-invariant power-counting scheme at LO in χEFT (Phys. Rev. C 103 (2021) 054304)
- Calculation of $^{4}\mathrm{H}$ $J^{\pi} = 1^{-}$ resonance within SU(4)-symmetric LO $\not{\pi}$EFT using three different methods
- Numerical evidence of stabilization of $^{4}\mathrm{H}$ $J^{\pi} = 1^{-}$ resonance pole with increasing momentum cutoff

→ Reasonable to expect that the same stabilization occurs also in heavier *p*-shell systems, if so, we can speculate :

$^{6}\mathrm{Li} \rightarrow \alpha + \mathrm{d}$	(likely 4+2 virtual(antibound) state)
$^{6}\mathrm{He} \rightarrow \alpha + \mathrm{n} + \mathrm{n}$	(likely 4+1+1 resonance)
$^{7}\mathrm{Li} \rightarrow \alpha + \mathrm{t}$	(likely 4+3 resonance)
$^{8}\mathrm{Be} \rightarrow \alpha + \alpha$	(likely 4+4 virtual(antibound) state)
$^{16}\mathrm{O} \rightarrow \alpha + \alpha + \alpha + \alpha$	(likely 4+4+4+4 resonance)