Universal few-body correlations in four-particle halo structures

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Four-neutron halo

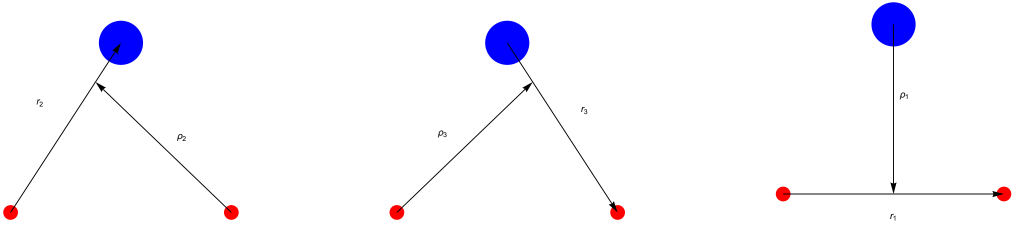
- ^{22}C and ^{19}B are halos, usually treated as three-body systems (core $+\, n + n$)
- Something curious: their cores ^{20}C and ^{17}B are themselves two-neutron halo candidates
- We want to build an analytical five-body wave function that takes into consideration the halo structure of the core

$$^{22}\mathrm{C} \sim \underbrace{\left(^{18}\mathrm{C} + n + n\right)}_{^{20}\mathrm{C}} + n + n$$

$$^{19}\mathrm{B} \sim \underbrace{\left(^{15}\mathrm{B} + n + n\right)}_{^{17}\mathrm{B}} + n + n$$

K. Tanaka et al., Phys. Rev. Lett. **104**, 062701 (2010) — **D. L. Canham, H.-W. Hammer**, Eur. Phys. J. A **37**, 367 (2008) — **E. Hiyama et al.**, Phys. Rev. C **106**, 064001 (2022)

- To isolate the influence of the structured core in the behavior of the system and obtain analytical results, we keep things simple
- We use two three-body building blocks to construct the five-body wave function
- We use s-wave contact interactions at unitarity for the two-body subsystems
- The wave function is written in terms of Jacobi coordinates



Three-body building blocks

- Subsystems A (inner) and B (outer) in hyperspherical variables:

$$\underbrace{\mathcal{R}_X^2 = r_X^2 + \rho_X^2}_{\text{overall size}} \qquad \underbrace{\tan\alpha_X^{(\beta)} = r_X^{(\beta)}/\rho_X^{(\beta)}}_{\text{shape (dineutron vs. cigar)}}$$

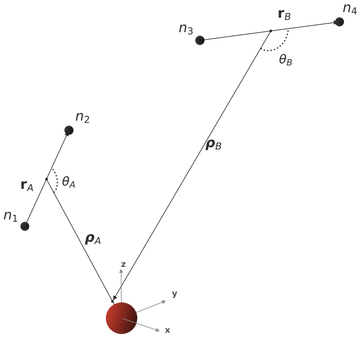
- For zero-range s-wave interactions at unitarity:

$$\Phi_X\left(\mathcal{R}_X, \alpha_X^{(\beta)}\right) = \frac{K_{\mathrm{i}s_0^X}\left(\sqrt{2}\, k_X \mathcal{R}_X\right)}{\mathcal{R}_X^2} \sum_{\beta=1}^{3} C_X^{(\beta)} \frac{\sin\left[\mathrm{i}s_0^X\left(\frac{\pi}{2} - \alpha_X^{(\beta)}\right)\right]}{\sin 2\alpha_X^{(\beta)}}$$

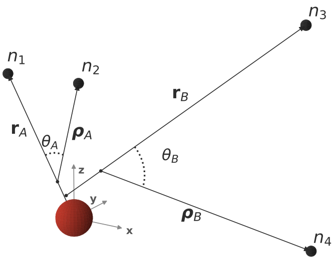
- The masses fix the Efimov parameter s_0^X and the Faddeev weights $C_X^{(\beta)}$ through the Bethe–Peierls boundary conditions

A. Bulgac and V. Efimov, Sov. J. Nucl. Phys. **22**, 153 (1976) [Yad. Fiz. 22, 296 (1975)] — **F. Werner, Y. Castin**, Phys. Rev. A **83**, 063614 (2011)

Jacobi coordinates for the five-body system



T-type tree



Y-type tree

The two-scale four-neutron halo model

- An antisymmetrized product of two three-body wave functions:

$$\Psi_{4n} = \mathcal{P}\left[\Psi_{ij}^{A} \otimes \Psi_{kl}^{B}\right], \qquad \Psi_{ij}^{X} = \Phi_X(\boldsymbol{r}_{X_{ij}}, \boldsymbol{\rho}_{X_{ij}})\,|S_{ij}\rangle$$

$|S_{ij}\rangle$: neutron-pair spin singlet; $\mathcal{P}$: antisymmetrizer over the four valence neutrons

$$S_{2n}^{(X)} = \frac{\hbar^2 k_X^2}{m_n}, \qquad X = A, B$$

- k_B/k_A controls the hierarchy: small ratios give well-separated inner and outer scales; ratios near unity give comparable scales

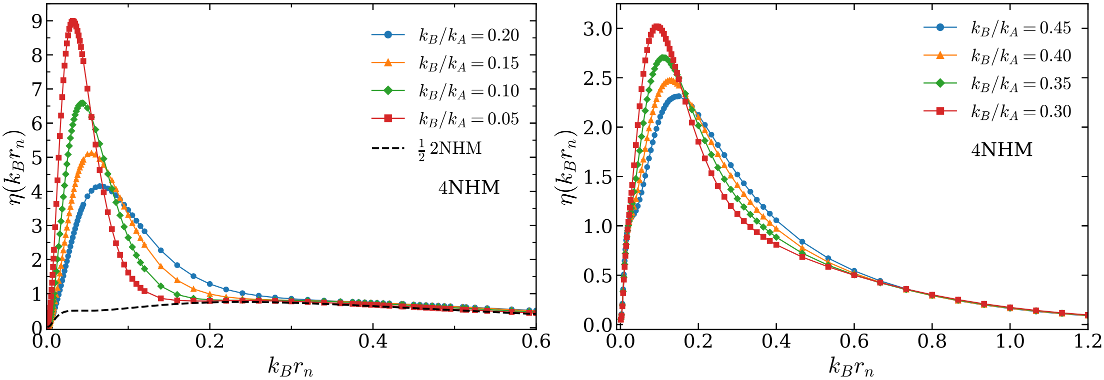
- Grouping the six terms by singlet pairing gives

$$\Psi_4^{(F)} = \mathcal{N}^{(F)}\left[G_1|\xi_1\rangle - G_2|\xi_2\rangle + G_3|\xi_3\rangle\right]$$

G_i: spatial pair combinations; $|\xi_i\rangle$: products of two spin singlets

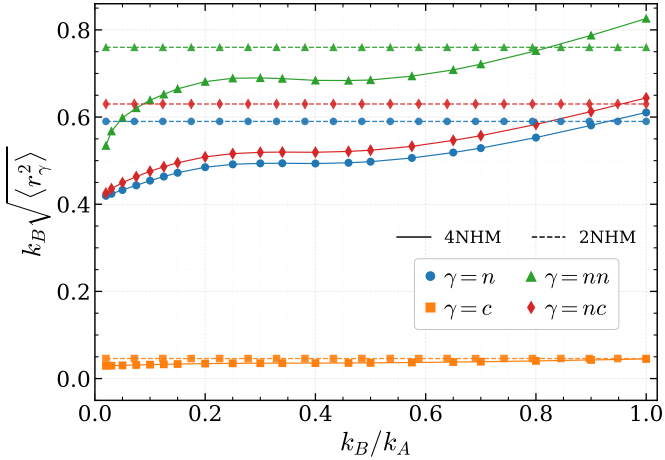
R. M. Francisco, D. S. Rosa, G. Hupin, T. Frederico, M. T. Yamashita — arXiv:2608.11964 (2026)

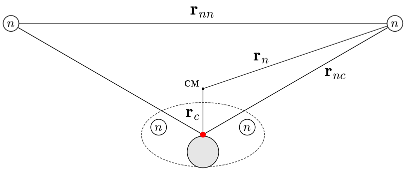
One-body density: four-neutron halo



- 4NHM stands for four-neutron halo model
- **Left**, small ratios: inner and outer halos decouple, and the tail approaches $\frac{1}{2}\times$ the 2NHM profile (dashed)
- **Right**, moderate ratios: the curves barely change as k_B/k_A varies

Dimensionless rms distances

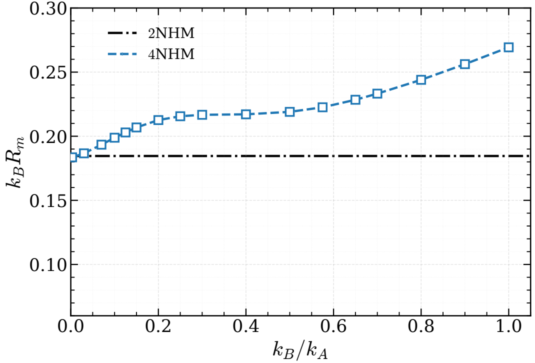




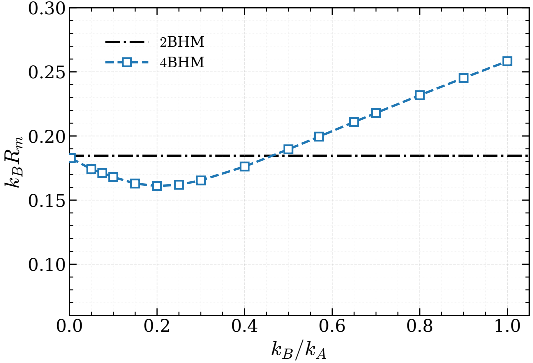
The inner block (dashed) acts as a *structured core* for the outer neutrons

- $k_B/k_A = 1$: almost coincident with 2NHM (Pauli principle)
- Moderate k_B/k_A: insensitive to the binding-momenta ratio

Dimensionless matter radius



Neutron halo



Bosonic halo

- The plateau is caused by the Pauli exclusion
- Both curves present the correct asymptotic limit

From dimensionless to physical nuclei

- Inner scale fixed by the core subsystem; outer scale varied through $S_{2n}^{(B)} = S_{2n}^{(A)}\,(k_B/k_A)^2$
- Physical radii include the intrinsic core size in quadrature:
  $R_m^{(\mathrm{phys})} = \left[R^2_{m,\mathrm{4NHM}} + \frac{18}{22} R_m[^{18}\mathrm{C}]^2\right]^{1/2}$ for ^{22}C with the 4NHM

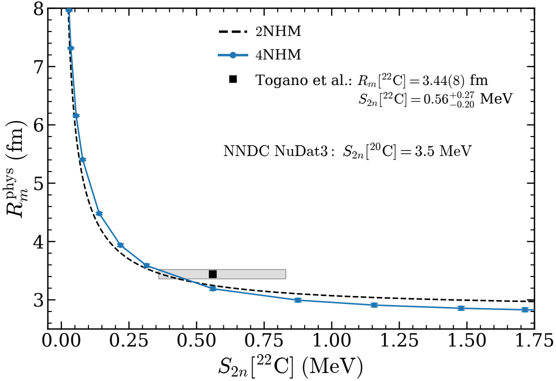
	$S_{2n}^{(A)}$	Core radius input
^{22}C	3.5 MeV	$R_m[^{18}\mathrm{C}] = 2.86(4)$ fm
^{19}B	1.38 MeV	$R_m[^{15}\mathrm{B}] = 2.59(3)$ fm

$S_{2n}[^{22}\mathrm{C}]$ varies in the radius comparison

These ratios probe a regime with finite inner–outer overlap

NNDC, NuDat 3.0 — **AME2020** — **A. Ozawa et al.**, Nucl. Phys. A **691**, 599 (2001) — **R. Kanungo et al.**, Phys. Rev. Lett. **117**, 102501 (2016)

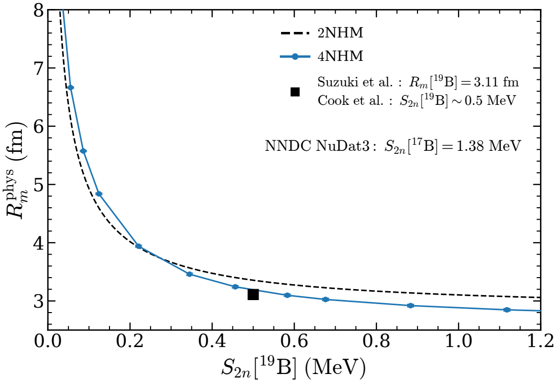
^{22}C: matter radius



- We fix the two-neutron separation energy for the internal halo: $S_{2n}[^{20}\mathrm{C}] = 3.5\mathrm{MeV}$
- $k_B/k_A = 0.40$ considering Togano et al. value for $S_{2n}[^{20}\mathrm{C}]$
- $S_{2n}[^{22}\mathrm{C}]$ is treated as a free scale parameter
- Compatible with Togano *et al.* (interaction cross section + Glauber analysis: they tune the nucleus' size until the calculated cross section matches the measured one.)

Y. Togano et al., Phys. Lett. B **761**, 412 (2016)

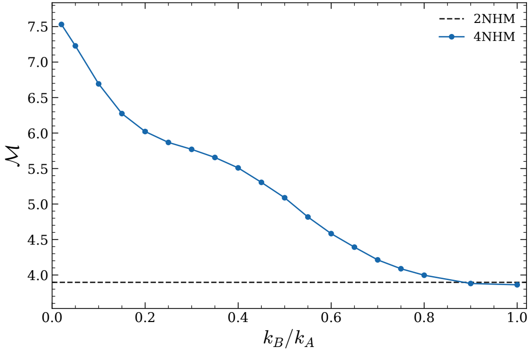
^{19}B: matter radius



- $k_B/k_A = 0.60$
- Compatible with Cook et al.
- The matter radius do not discriminate between the two models
- The tail dominates the integral, while the important part is at short distances

T. Suzuki et al., Nucl. Phys. A **658**, 313 (1999) — **K. J. Cook et al.**, Phys. Rev. Lett. **124**, 212503 (2020)

Neutron-density shape beyond the radius



$$\mathcal{M} = \frac{\langle r_n^4 \rangle}{\langle r_n^2 \rangle^2}$$

- Independent of an overall rescaling of distances
- One-scale 2NHM: constant reference
- 4NHM: $\mathcal{M}$ increases as the scales separate

Future work: momentum-space structure and reaction calculations

Conclusions

- Two-scale phenomenological ansatz for four-neutron halos, controlled by the ratio k_B/k_A
- Intermediate k_B/k_A: a Pauli-driven window where the scaled rms distances barely depend on the scale hierarchy
- Consequently, radii alone cannot discriminate the three-body from the five-body description

Outlook

- Shape-sensitive observables are the discriminator: core momentum distribution, to be compared with fast-removal data
- Refine the three-body building blocks: finite scattering length, finite-range corrections, higher partial waves

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Thank you for your attention!