August 30, 2026 to September 6, 2026
Europe/Warsaw timezone

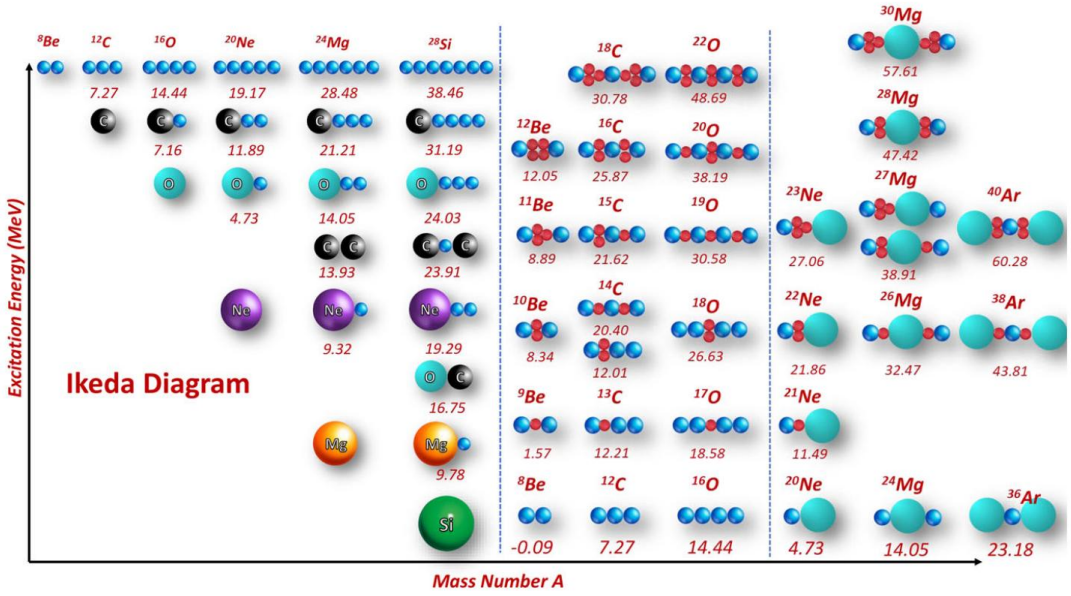
Lattice Effective Field Theory Study of Light Nuclei

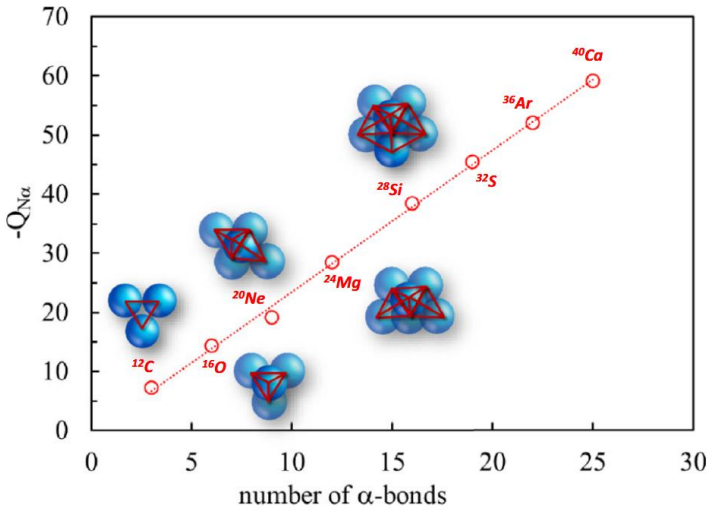
Shihang Shen
Beihang University

Clustering

Clustering plays an important role in nuclear physics, especially light nuclei

- K. Wei, Y.-L. Ye, Z.-H. Yang, Clustering in nuclei: progress and perspectives, Nucl. Sci. Tech. 35, 216 (2024)
- Y.-G. Ma and S. Zhang, α-clustering effects in relativistic heavy-ion collisions, Sci. Sin. Phys. Mech. Astron. 54, 292004 (2024)
- I. Lombardo and D. Dell'Aquila, Clusters in light nuclei: history and recent developments, Riv. Nuovo Cimento 46, 521 (2023)
- B. Zhou, Y. Funaki, H. Horiuchi, and A. Tohsaki, Nonlocalized clustering and evolution of cluster structure in nuclei, Front. Phys. 15, 14401 (2020)
- M. Freer, H. Horiuchi, Y. Kanada-En'yo et al., Microscopic clustering in light nuclei. Rev. Mod. Phys. 90, 035004 (2018)
- Z. Ren and B. Zhou, Alpha-clustering effects in heavy nuclei, Front. Phys. 13, 132110 (2018)
- ... ...

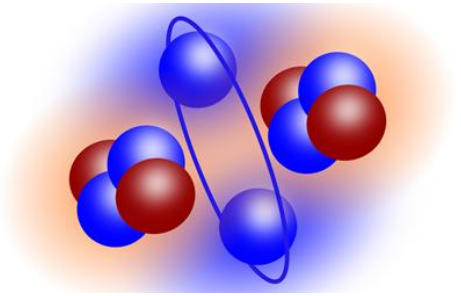




Clustering

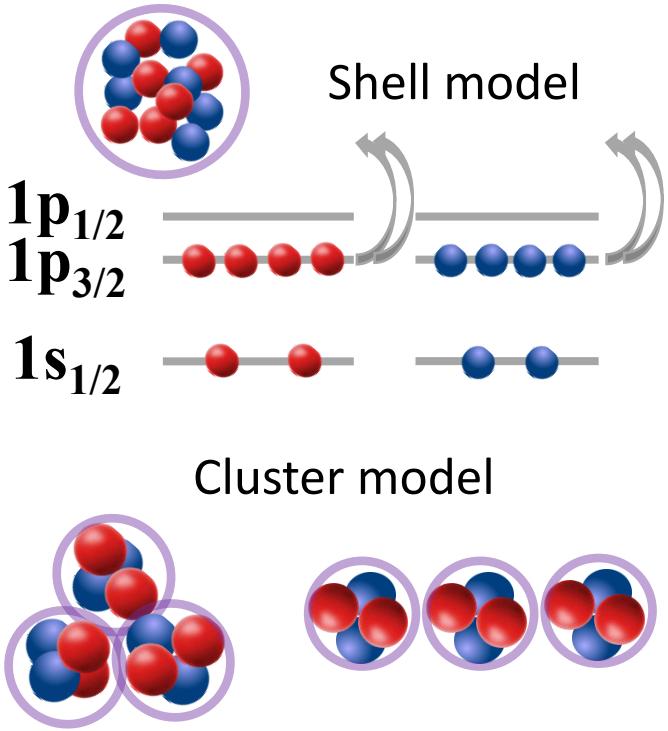
- Diverse phenomena in beryllium Isotopes: clustering, molecular orbitals, halo, …

J. Chen, et al., Phys. Rev. Lett. 134, 012502 (2025)
P. J. Li, et al., Phys. Rev. Lett. 131, 212501 (2023); Physics 16, s167 (2023)
W. von Oertzen, M. Freer, and Y. Kanada-En'yo, Phys. Rep. 432, 43 (2006)
A. Calci, et al., Phys. Rev. Lett. 117, 242501 (2016)
W. Nörtershäuser, et al., Phys. Rev. Lett. 102, 062503 (2009)
J. Chen, et al., Phys. Lett. B 781, 412 (2018)
A. Navin, et al., Phys. Rev. Lett. 85, 266 (2000)



- Structure of carbon-12, Hoyle state

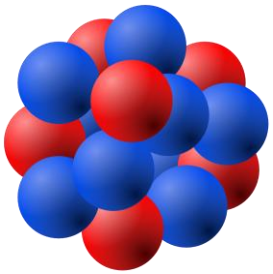
M. Freer and H.O.U. Fynbo., Prog. Part. Nucl. Phys. 78, 1 (2014)
H. Morinaga, Phys. Rev. 101, 254 (1956)
R. Bijker and F. Iachello, PRC, 61, 067305 (2000)
A. Tohsaki, et al., Phys. Rev. Lett. 87, 192501 (2001)
Y. Kanada-En'yo, Prog. Theor. Phys. 117, 655 (2007)
M. Chernykh, et al., Phys. Rev. Lett., 98, 032501 (2007)
J. Carlson, et al., Rev. Mod. Phys., 87, 1067 (2015)
T. Otsuka et al., Nature Commun., 13, 2234 (2022)

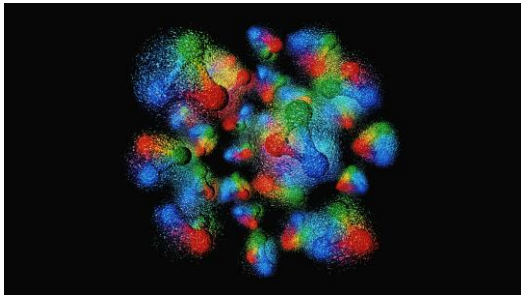


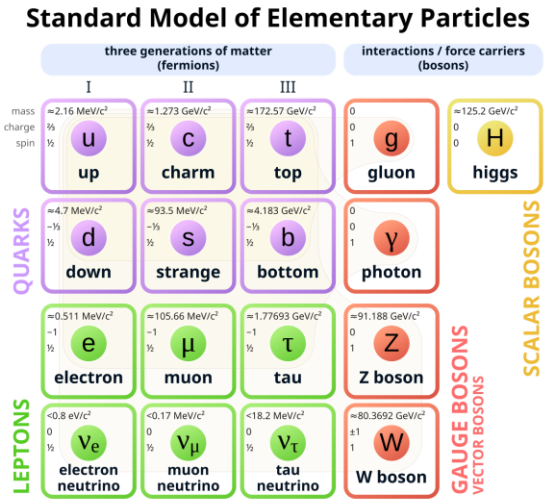
- How to describe all these phenomenon in ab initio framework, using fully correlated many-body wave function?

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)$$

ab initio in Nuclear Physics







D. Drischler, W. Haxton, K. McElvain, E. Mereghetti, A. Nicholson, P. Vranas, and A. Walker-Loud, **Towards grounding nuclear physics in QCD**, Prop. Part. Nucl. Phys. 121 (2021) 103888

https://en.wikipedia.org/wiki/Standard_Model

https://www.quantamagazine.org/colliders-and-supercomputers-force-fresh-hints-in-quark-mystery-20220214/

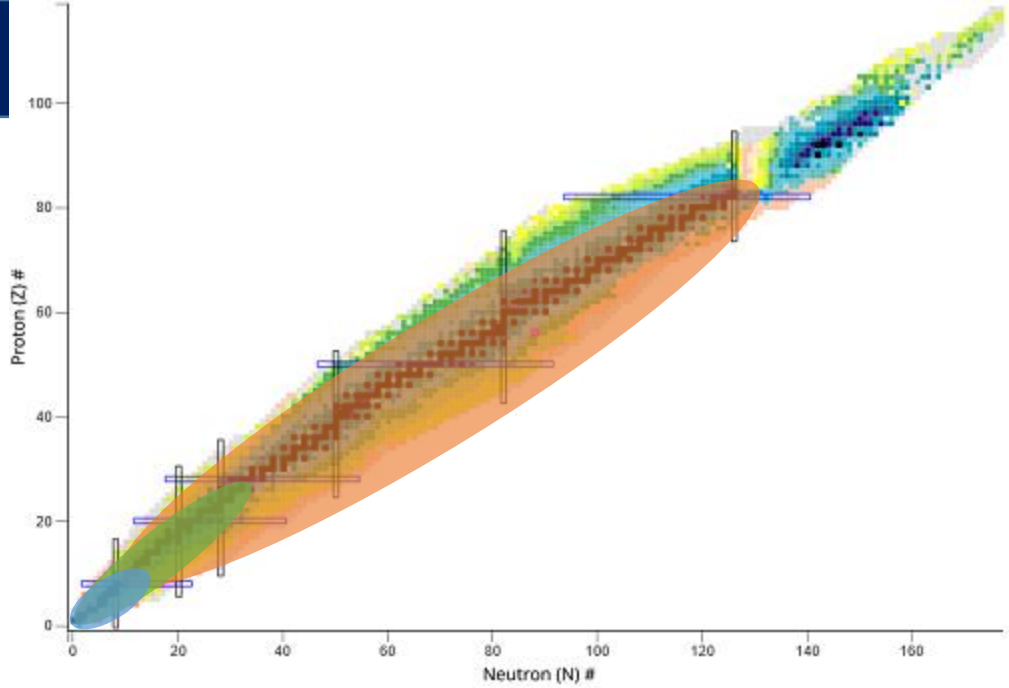
Proper degrees-of-freedom (nucleons) and energy scale

- Ekström, C. Forssén, G. Hagen, G. R. Jansen, W. Jiang and T. Papenbrock, what is ab initio in nuclear theory? Front. Phys. 11:1129094 (2023)
- R. Machleidt, what is ab initio? Few-Body Syst (2023) 64

*Do the same nuclear forces that explain **free-space scattering** experiments also explain the properties of **finite nuclei** and **nuclear matter** when applied in nuclear many-body theory?*

R. Machleidt, what is ab initio? Few-Body Syst (2023) 64

Many-Body Frameworks



- Fadeeyev equation, L.D. Faddeev, Sov. Phys. JETP 12 (1961) 101
- Faddeev–Yakubovsky equation, O.A. Yakubovsky, Sov. J. Nucl. Phys. 5 (1967) 93
- Monte-Carlo shell model, Otsuka, T. et al., Nat. Commun. 13, 2234 (2022)
- No-core shell model, B. R. Barrett, P. Navrátil, and J. P. Vary, Prog. Part. Nucl. Phys. 69, 131 (2013)
- No-core Gamow shell model, Li, J.; Ma, Y.; Michel, N.; Hu, B.; Sun, Z.; Zuo, W.; Xu, F. Physics 2021, 3, 977
- Quantum Monte-Carlo, J. Carlson, et al., Rev. Mod. Phys. 87, 1067 (2015); Y. Yang and P. Zhao, PRC 107, 034320 (2023)
- Nuclear lattice effective field theory, T. A. Lähde and U.-G. Meißner, Lect. Notes Phys. 957, 1 (2019)
- Coupled cluster, G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014)
- In-medium similarity renormalization group, H. Hergert et al., Phys. Rep. 621, 165 (2016)
- Many-body perturbation theory, A. Tichai, R. Roth, and T. Duguet, Front. Phys. 8, 164 (2020)
- Relativistic Brueckner-Hartree-Fock, SS, et al., Prog. Part. Nucl. Phys. 109, 103713 (2019)
- Self-consistent Green's function, V. Somà, Front. Phys. 8, 340 (2020)
- … …

Nuclear Lattice Effective Field Theory

- First ab initio description of Hoyle state

PRL 106, 192501 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Selected for a Viewpoint in *Physics*

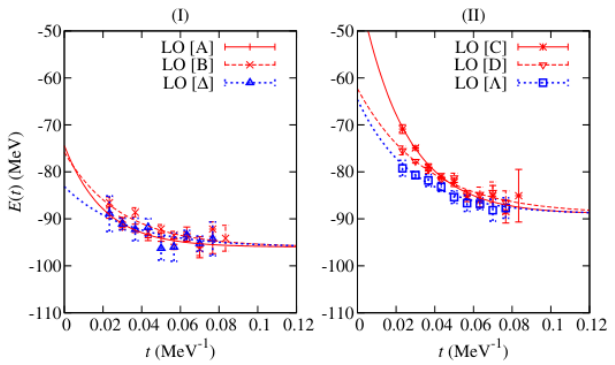
***Ab Initio* Calculation of the Hoyle State**

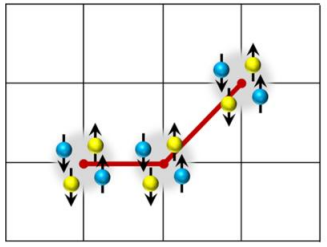
Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]

PRL 109, 252501 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Structure and Rotations of the Hoyle State

Evgeny Epelbaum,[1] Hermann Krebs,[1] Timo A. Lähde,[2] Dean Lee,[4] and Ulf-G. Meißner[5,2,3]





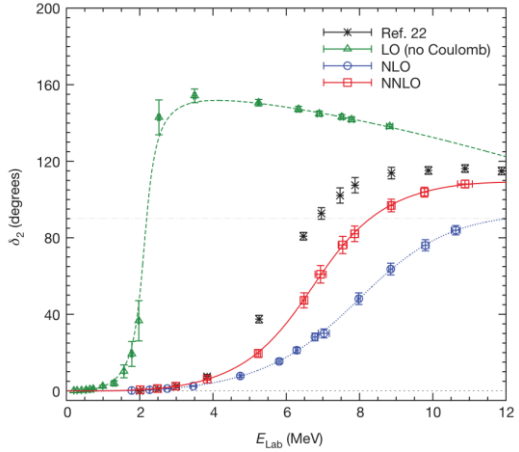
- First ab initio description of α-α scattering

Letter | Published: 02 December 2015

***Ab initio* alpha–alpha scattering**

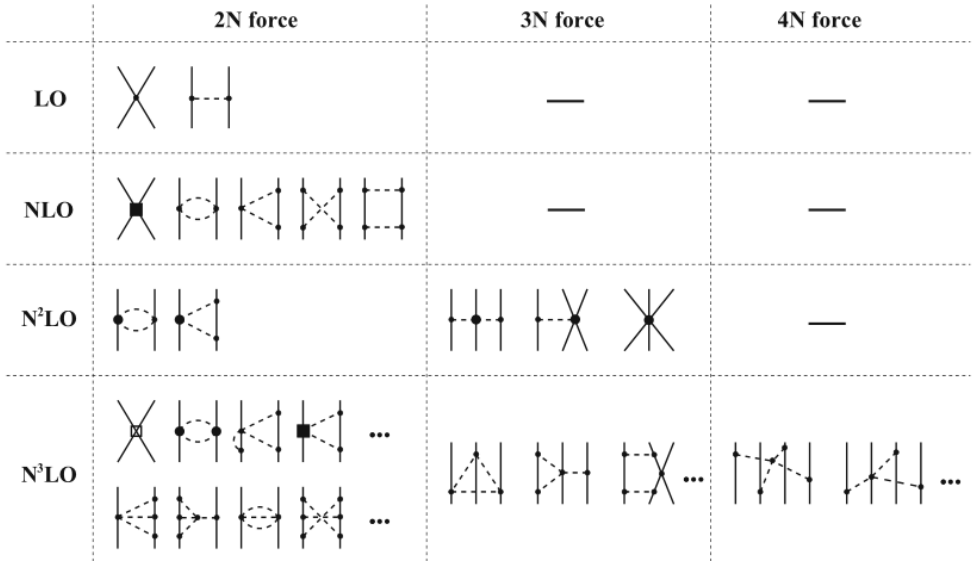
Serdar Elhatisari, Dean Lee, Gautam Rupak, Evgeny Epelbaum, Hermann Krebs, Timo A. Lähde, Thomas Luu & Ulf-G. Meißner

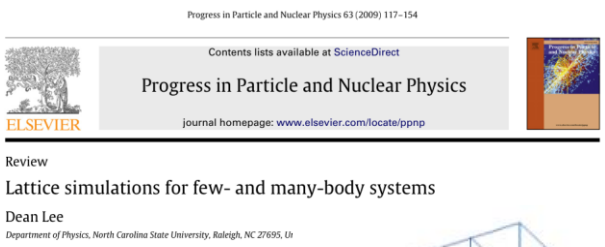
Nature **528**, 111–114 (2015) | Cite this article



- Nuclear thermodynamics B. N. Lu, et al., Phys. Rev. Lett. 125, 192502 (2020)
- Clustering in hot dilute matter Z. Ren, et al., Phys. Lett. B 850, 138463 (2024)
- Structure factors for hot neutron matter Y. Z. Ma, et al., Phys. Rev. Lett. 132, 232502 (2024)
- Hyperneutron matter H. Tong, S. Elhatisari, and U. G. Meißner, Sci. Bull. 70, 825 (2025)
- … …

Nuclear Lattice Effective Field Theory

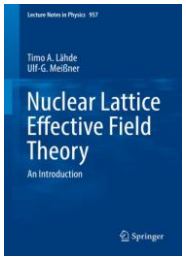


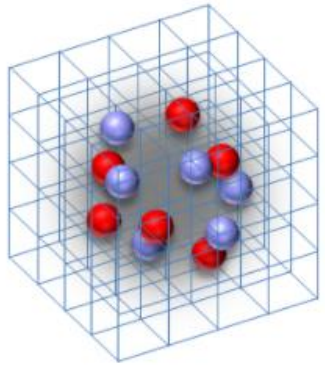

Progress in Particle and Nuclear Physics 63 (2009) 117–154
Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
ELSEVIER

Review

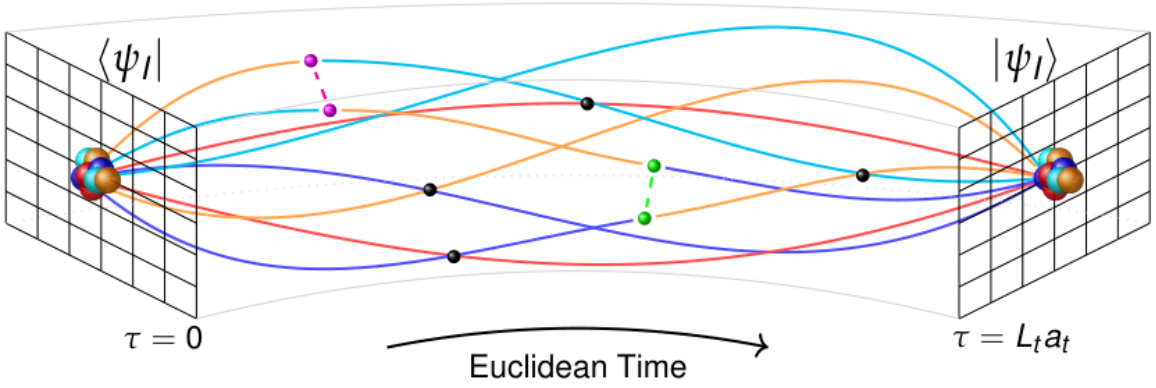
Lattice simulations for few- and many-body systems

Dean Lee
Department of Physics, North Carolina State University, Raleigh, NC 27695, Us





$$M = \exp(-a_t H) \qquad \langle \Psi_I | MM \ldots MOM \ldots MM | \Psi_I \rangle$$



Upper left figure is in courtesy of E. Epelbaum
lattice figure from https://www.physics.ncsu.edu/ntg/leegroup/research.html
Lower figure is in courtesy of S. Elhatisari

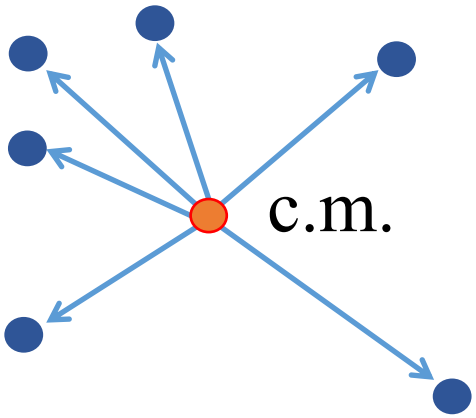
Nuclear Lattice Effective Field Theory

- Pinhole algorithm

$$\langle \Phi_0 | e^{-H\tau/2} \rho(\mathbf{n}_1, \mathbf{n}_2, \ldots, \mathbf{n}_A) e^{-H\tau/2} | \Phi_0 \rangle$$

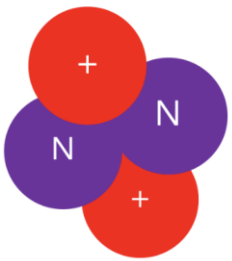
A time slice is inserted to sample the positions and spin-isospin indices in the middle time step.

S. Elhatisari et al., PRL 119, 222505 (2017)



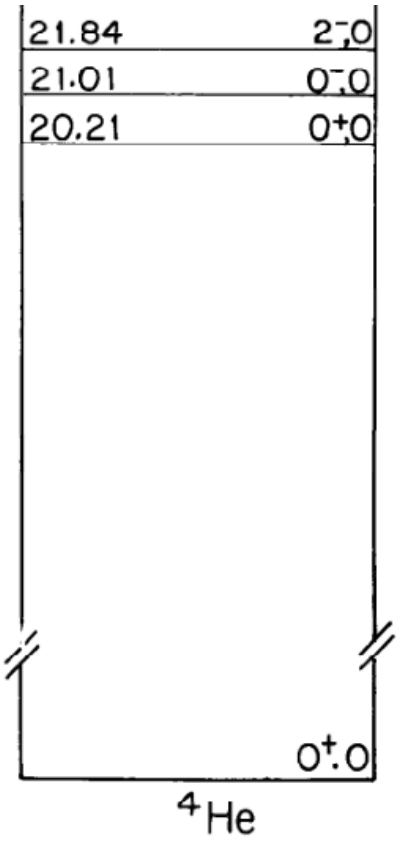
$\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots, \boldsymbol{r}_A$

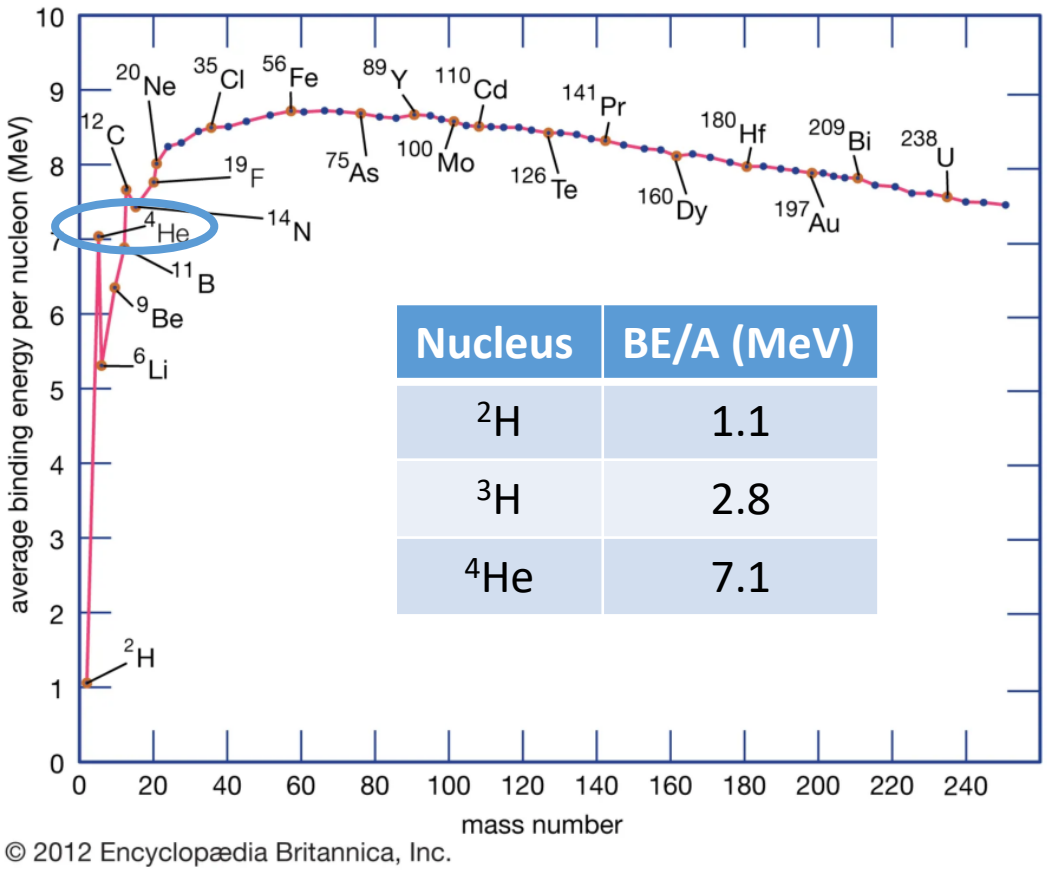
^{4}He (α)



Alpha Particle

^4_2He





© 2012 Encyclopædia Britannica, Inc.

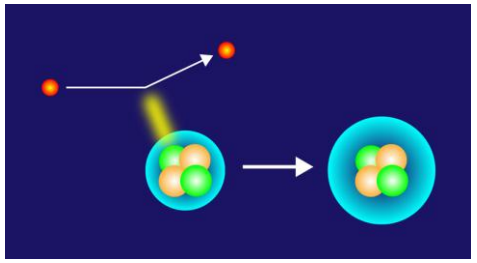
Nucleus	BE/A (MeV)
^{2}H	1.1
^{3}H	2.8
^{4}He	7.1

D.R. Tilley, H.R. Weller, and G.M. Hale, NPA, 541, 1 (1992)

^{4}He: Puzzle for Nuclear Forces?

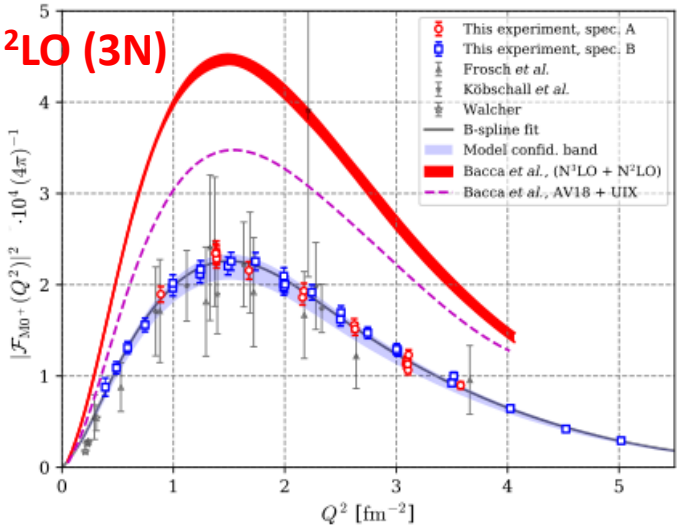
PHYSICAL REVIEW LETTERS **130,** 152502 (2023)

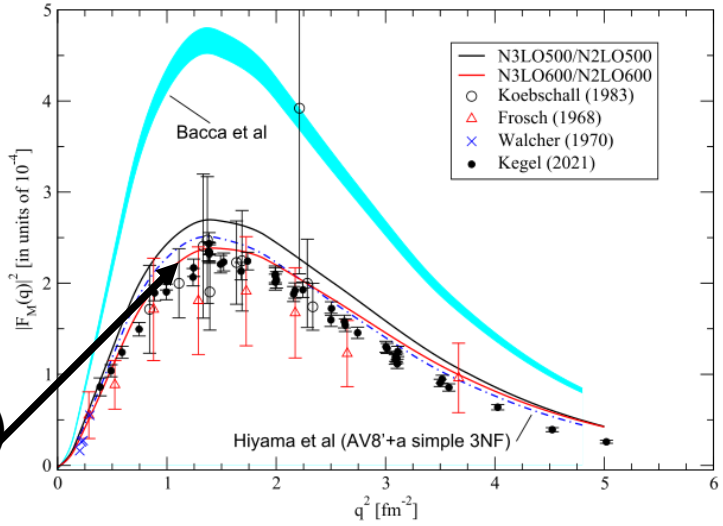
Editors' Suggestion | Featured in Physics



Measurement of the α-Particle Monopole Transition Form Factor Challenges Theory: A Low-Energy Puzzle for Nuclear Forces?

N^{3}LO (2N) + N^{2}LO (3N)



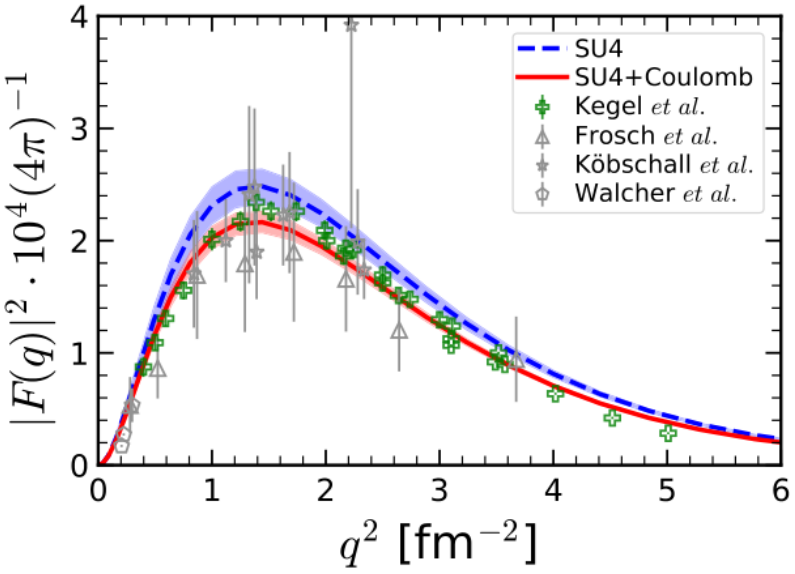


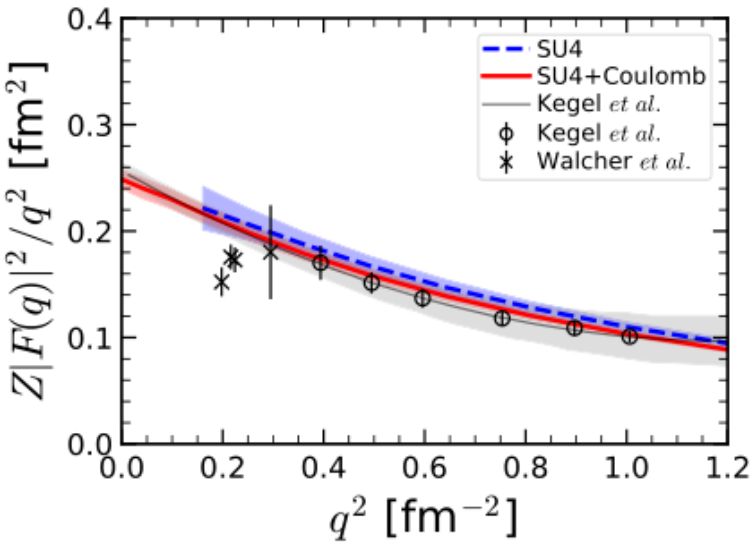
AV8' (2N) + phenomenological (3N)
N^{3}LO (2N) + N^{2}LO (3N)

E. Hiyama, B. F. Gibson, and M. Kamimura, PRC 70, 031001(R) (2004)
M. Viviani, A. Kievsky, L. E. Marcucci and L. Girlanda, Few Body Syst. 65, 74 (2024)
P. Yin et al., Phys. Rev. C 112, L031303 (2025)

NLEFT Calculation

U.-G., Meißner, SS, S. Elhatisari, D. Lee, PRL 132, 062501 (2024)





$$\frac{Z|\mathcal{F}_{\mathrm{M0^+}}(q^2)|}{q^2} = \frac{\langle r^2\rangle_{\mathrm{tr}}}{6}\left[1 - \frac{q^2}{20}\mathcal{R}^2{}_{\mathrm{tr}} + \mathcal{O}(q^4)\right]$$

	$\langle r^2 \rangle$	R
Exp.	1.53 (5)	4.56 (15)
NLEFT	1.49 (1)	4.00 (4)
Bacca et al.	1.83 (1)	3.97 (5)

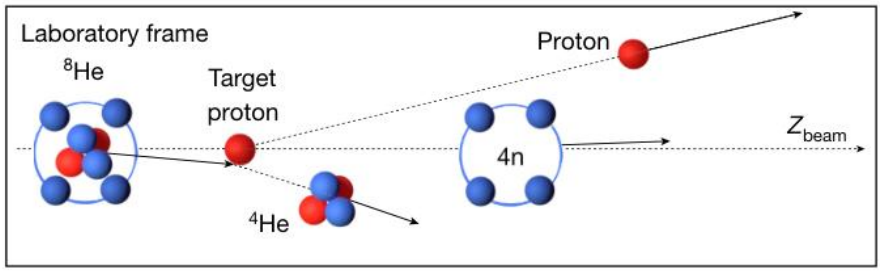
Pure-Neutron Nucleus

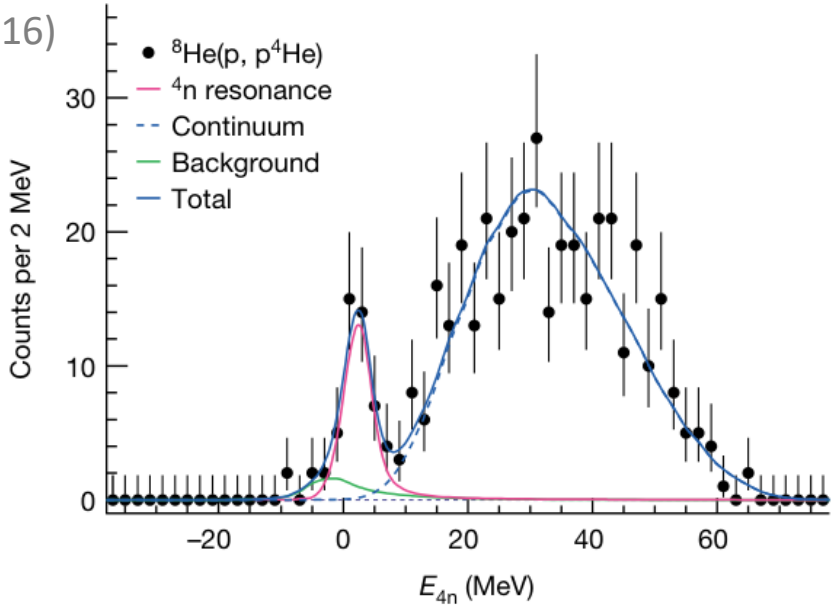
- Can neutrons form a nucleus?

  A. A Ogloblin and Y. E. Penionzhkevich, Nuclei Far from Stability. Treatise on Heavy-Ion Science, edited by D. A. Bromley (Plenum Press, New York, 1989)

- Experimental signals found low-energy peak structure in 4n spectrum

  K. Kisamori et al., Phys. Rev. Lett. 116, 052501 (2016)
  M. Duer et al., Nature (London) 606, 678 (2022)





E = 2.37 ± 0.38(stat.) ± 0.44(sys.) MeV,
Γ = 1.75 ± 0.22(stat.) ± 0.30(sys.) MeV.

- Three-neutron emission directly measured, no evidence was found for any significant three-neutron correlations

  S. W. Huang et al., Phys. Rev. Res. 8, L022003 (2026)

Theoretical Debate on the 4n Resonance

- NO resonance

  - Configuration space Faddeev-Yakubovsky (FY) equations
    R. Lazauskas and J. Carbonell, Phys. Rev. C 72, 034003 (2005)
  - FY and Gaussian expansion method
    E. Hiyama, et al., Phys. Rev. C 93, 044004 (2016)
  - Alt, Grassberger, and Sandhas equations
    A. Deltuva, PLB 782, 238 (2018); A. Deltuva and R. Lazauskas, PRC 100, 044002 (2019)
  - Adiabatic hyperspherical methods
    M. D. Higgins, et al., PRL 125, 052501 (2020); PRC 103, 024004 (2021)
  - Reaction model study ...
    R. Lazauskas, E. Hiyama, and J. Carbonell, Phys. Rev. Lett. 130, 102501 (2023)
  - Tensor-optimized antisymmetrized molecular dynamics
    N. Wan, et al., Phys. Lett. B 864, 139436 (2025)

- Resonance

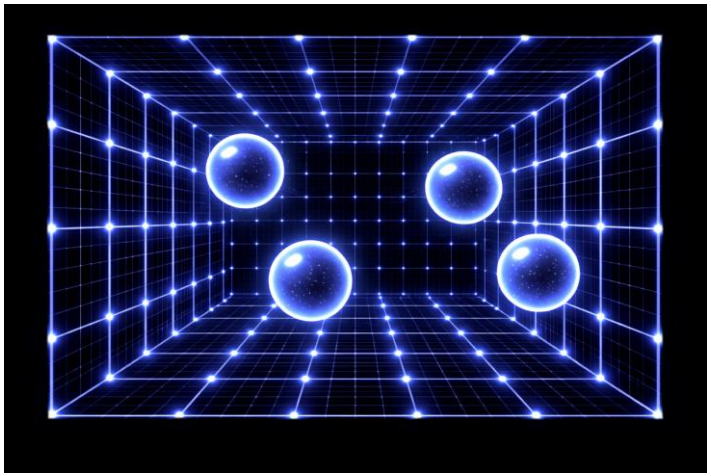
  - Quantum Monte Carlo
    S. C. Pieper, PRL 90, 252501 (2003); S. Gandolfi, et al., PRL 118, 232501 (2017)
  - No-core Gamow shell model
    J. G. Li, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu, Phys. Rev. C 100, 054313 (2019)
  - No-core shell model ...
    A. M. Shirokov, et al., Phys. Rev. Lett. 117, 182502 (2016); 121, 099901(E) (2018)

Concerns on the trap extrapolation
A. Deltuva and R. Lazauskas, Phys. Rev. Lett. 123, 069201 (2019)
S. Ishikawa, Phys. Rev. C 102, 034002 (2020)

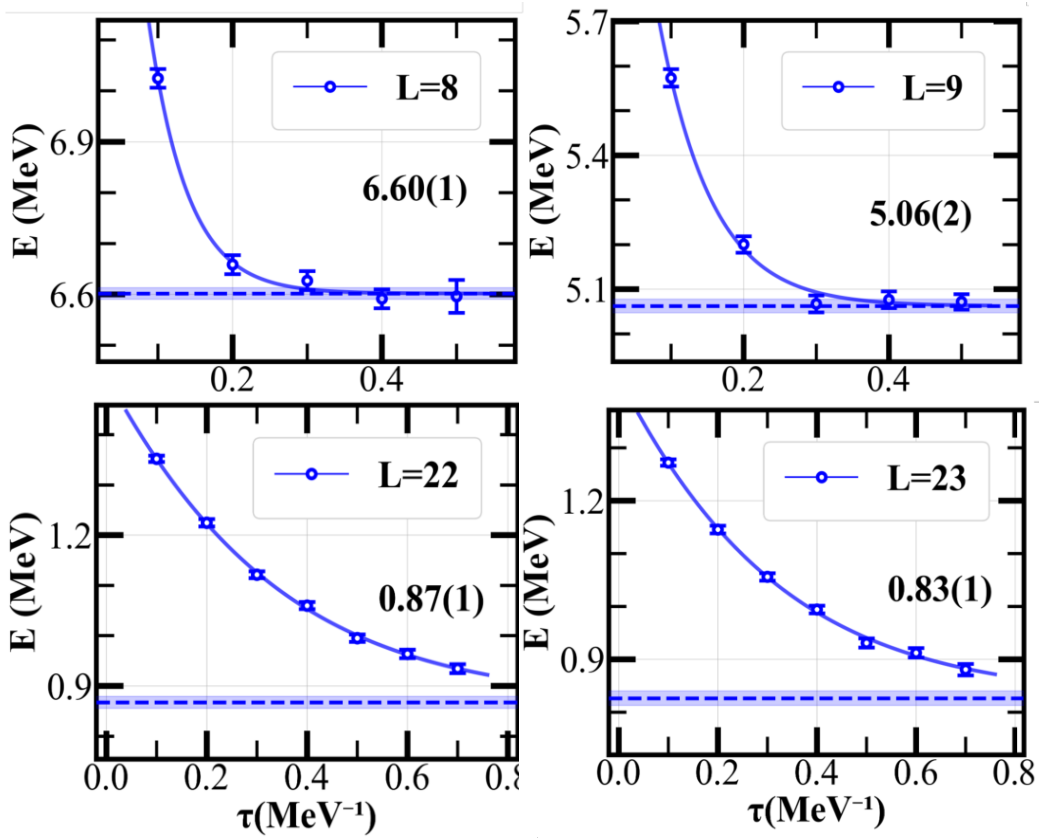
Study on the 4n System by NLEFT

- N^3LO interaction, lattice spacing $a = 1.32$ fm S. Elhatisari, et al., Nature 630, 59 (2024)
- SU(4) interaction fit to $^1S_0$ np scattering phase shift, lattice spacing $a = 1.64$ fm

Calculation from small to large box size



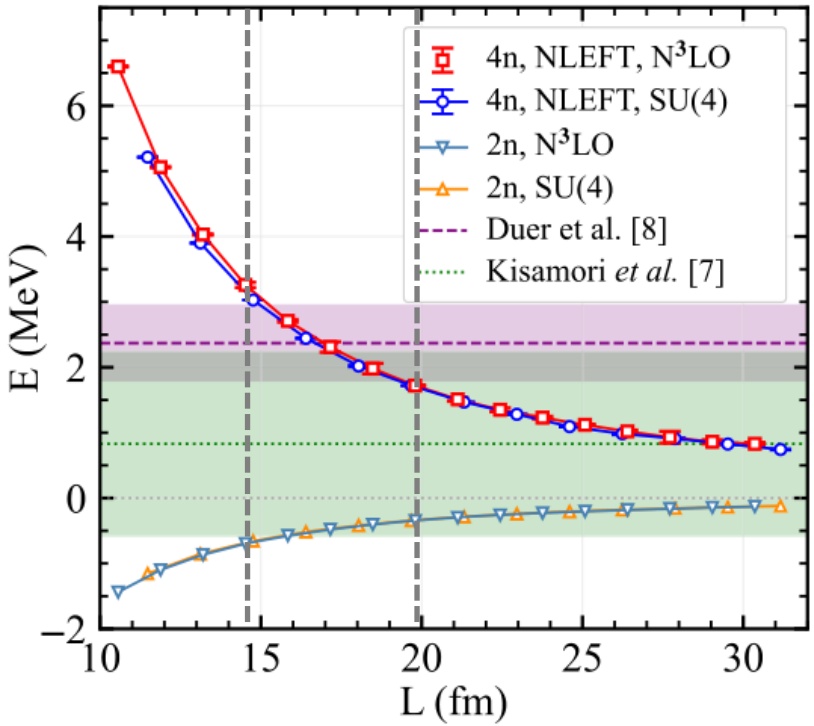
• • •

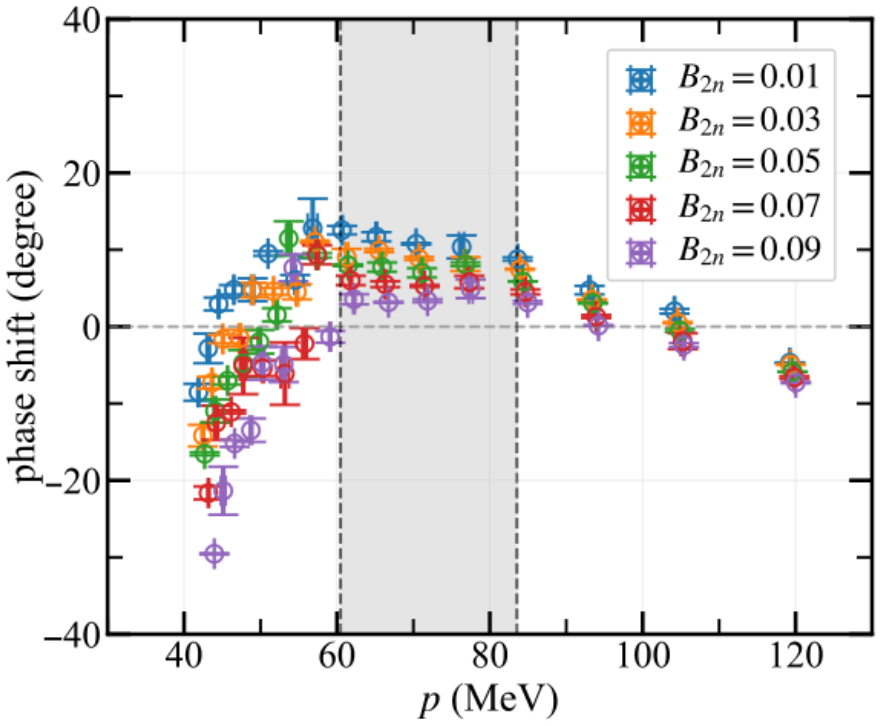


L. Wu, S. Elhatisari, U.-G. Meißner, SS, L.-S. Geng, and Y. Kim, Phys. Rev. Lett. 136, 142502 (2026)

Study on the 4n System by NLEFT

- Energies of 4n and 2n at different box size;
- 2n-2n phase shift extracted using Lüscher's method, with dineutron approximation





L. Wu, S. Elhatisari, U.-G. Meißner, SS, L.-S. Geng, and Y. Kim, Phys. Rev. Lett. 136, 142502 (2026)

- Consistent with recent theoretical studies: 2n-2n correlation from weakly bound 4n by the core

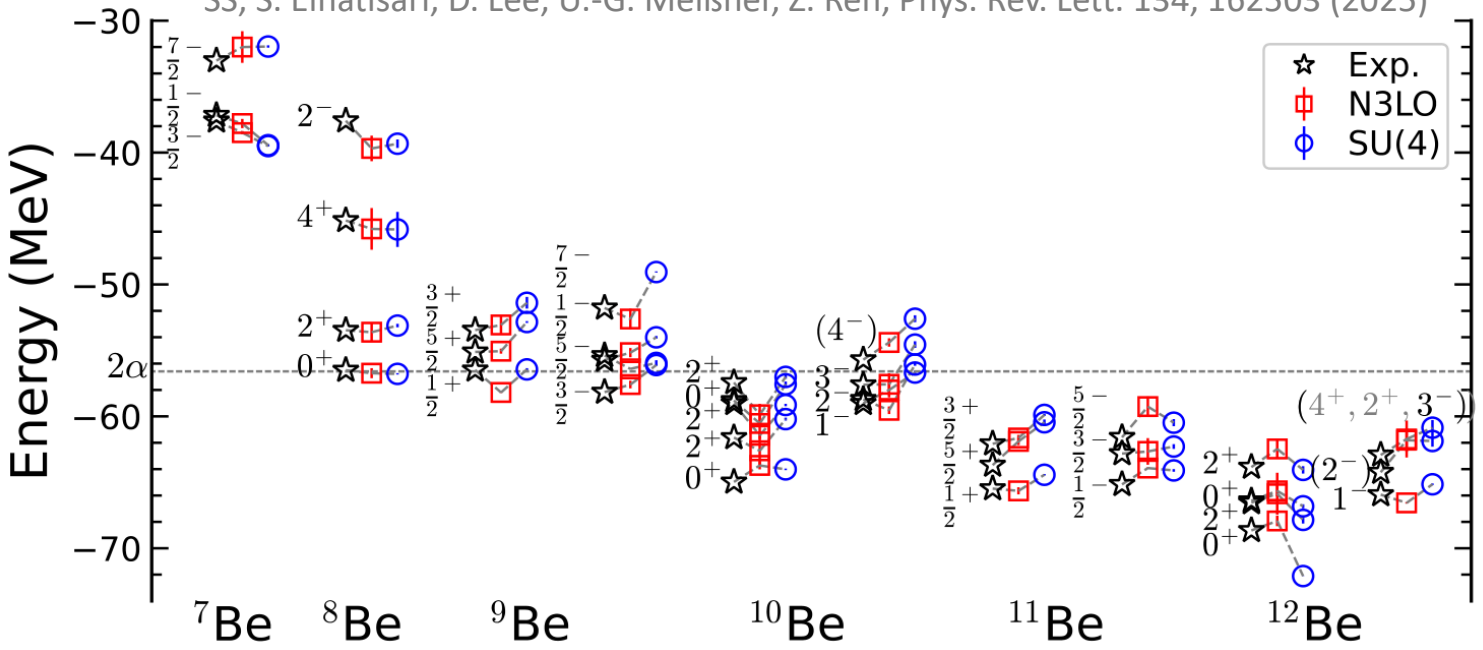
R. Lazauskas, E. Hiyama, and J. Carbonell, Phys. Rev. Lett. 130, 102501 (2023)
N. Wan, et al., Phys. Lett. B 864, 139436 (2025)

Beryllium Isotopes

- N^{3}LO interaction S. Elhatisari, et al., Nature 630, 59 (2024)
  lattice spacing $a = 1.32$ fm, box size $L = 13.2$ fm

- SU(4) interaction SS, S. Elhatisari, T. Lähde, D. Lee, B. Lu, and U.-G. Meißner, Nat. Commun. 14, 2777 (2023)
  lattice spacing $a = 1.64$ fm, box size $L = 14.8$ fm

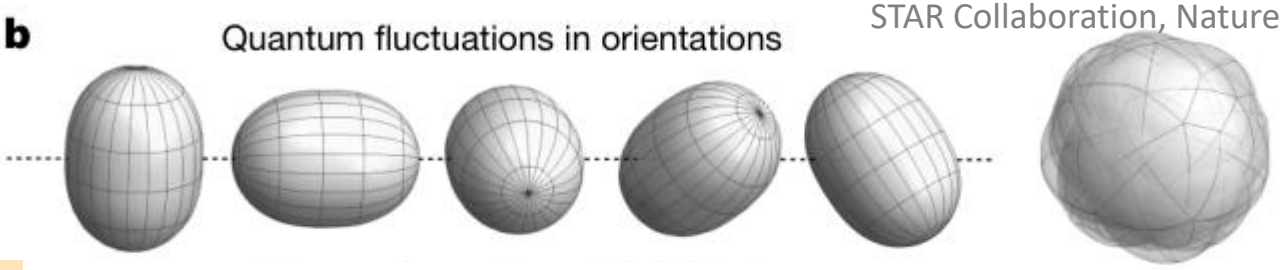
SS, S. Elhatisari, D. Lee, U.-G. Meißner, Z. Ren, Phys. Rev. Lett. 134, 162503 (2025)

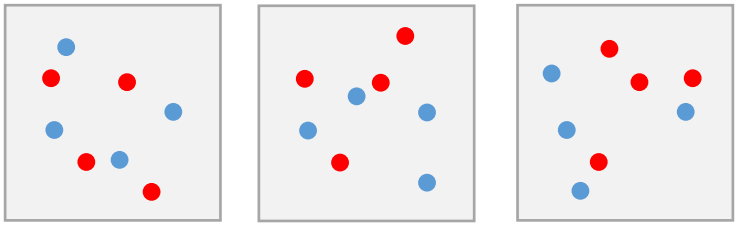


Intrinsic Density

What is intrinsic density?

STAR Collaboration, Nature 635, 67 (2024)





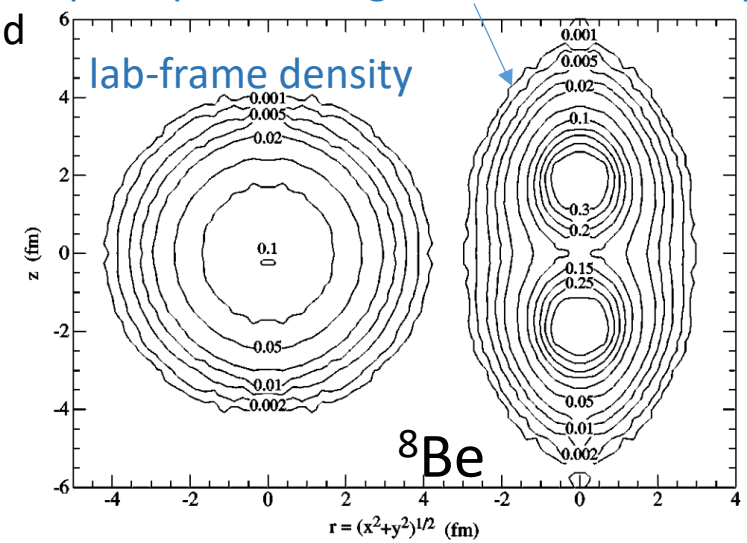
… …

In QMC study, nucleon coordinates (r_1, r_2, …, r_A) are rotated to the (long) principal axis of moment of inertia matrix

$$\mathcal{M} = \sum_{i=1}^{A} \begin{pmatrix} x_i^2 & x_i y_i & x_i z_i \\ y_i x_i & y_i^2 & y_i z_i \\ z_i x_i & z_i y_i & z_i^2 \end{pmatrix}$$

R. Wiringa, S. Pieper, J. Carlson, and V. Pandharipande, Phys. Rev. C 62, 014001 (2000)

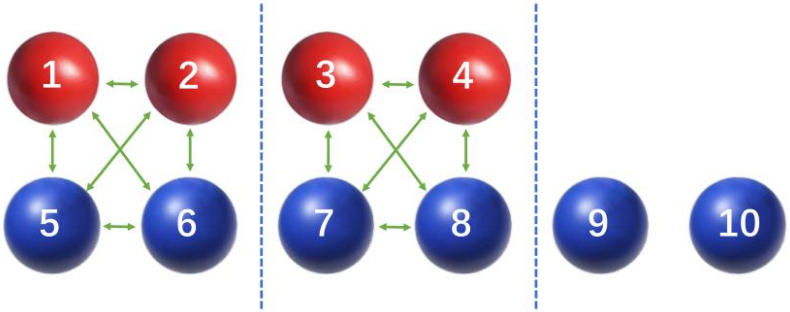
principal-axis-aligned intrinsic density



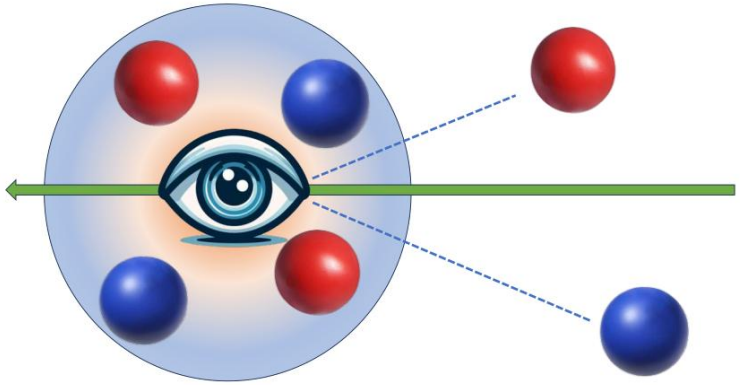
Intrinsic Density

α-view intrinsic density

1. Grouping closest 2 protons and 2 neutrons together



2. Rotate the nucleon coordinates (r_1, r_2, …, r_A) such that the cluster is aligned along the symmetry axis

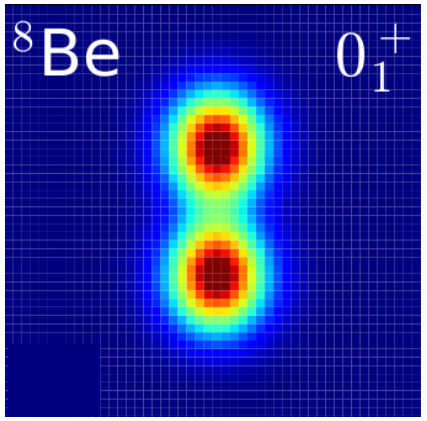


SS, S. Elhatisari, D. Lee, U.-G. Meißner, Z. Ren, Phys. Rev. Lett. 134, 162503 (2025)

Cluster, Molecular Orbital, and Halo from ab initio

α-view intrinsic density

Intrinsic total density or valence neutron density of ^{8}Be, ^{9}Be and ^{11}Be calculated by NLEFT

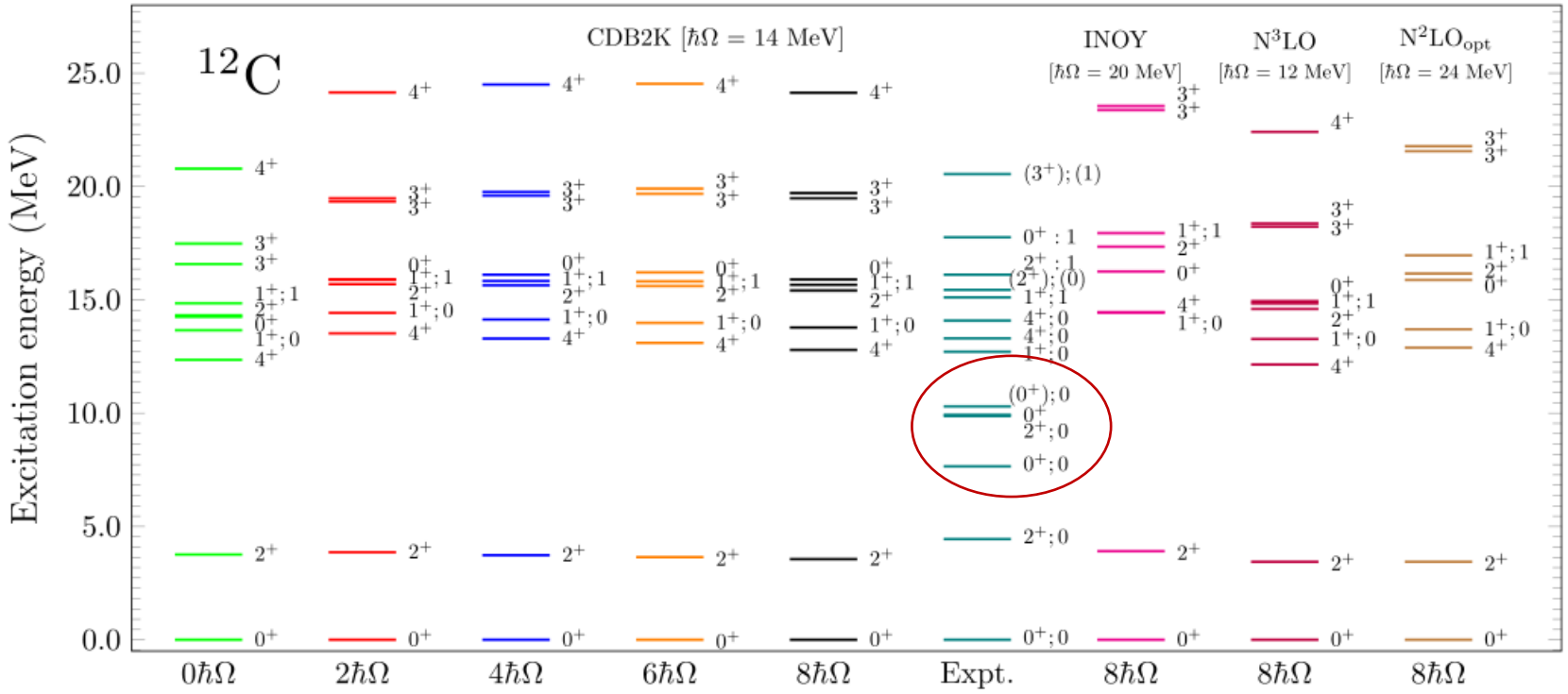


Y. Kanada-En'yo, H. Horiuchi, and A. Dote, J. Phys. G 24, 1499 (1998)

SS, S. Elhatisari, D. Lee, U.-G. Meißner, Z. Ren, Phys. Rev. Lett. 134, 162503 (2025)
SS, S. Elhatisari, D. Lee, U.-G. Meißner, Z. Ren, Particles 2026, 9, 25

Ab initio Study of ^{12}C

Hoyle state is a challenge for ab initio method



No-core shell model

P. Choudhary et al., Phys. Rev. C, 107, 014309 (2023)
P. Navrátil, J. P. Vary, and B. R. Barrett, Phys. Rev. Lett. 84, 5728 (2000)

Ab initio Study of ^{12}C

- **First successful ab initio description**: nuclear lattice effective field theory (NLEFT)

PRL **106,** 192501 (2011) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

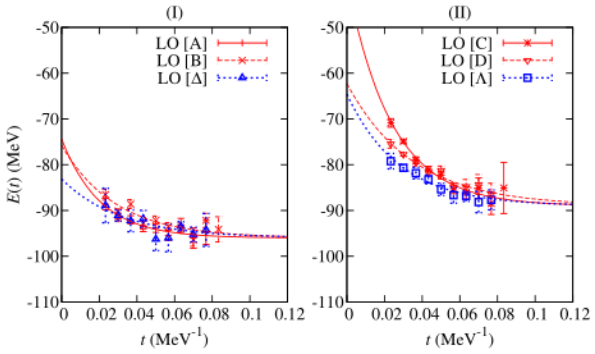
***Ab Initio* Calculation of the Hoyle State**

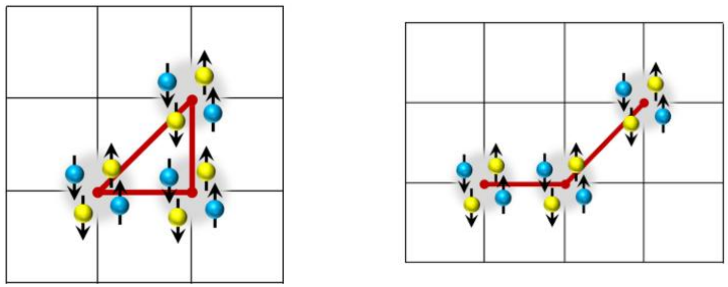
Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]

PRL **109,** 252501 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Structure and Rotations of the Hoyle State

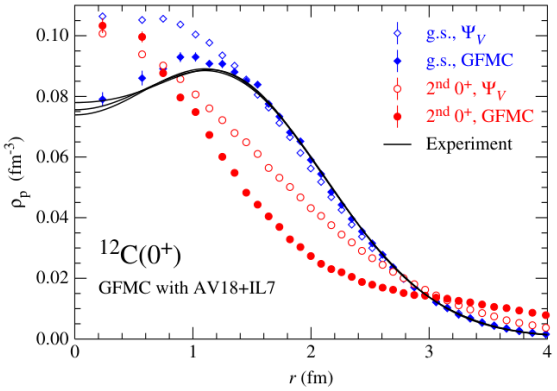
Evgeny Epelbaum,[1] Hermann Krebs,[1] Timo A. Lähde,[2] Dean Lee,[4] and Ulf-G. Meißner[5,2,3]



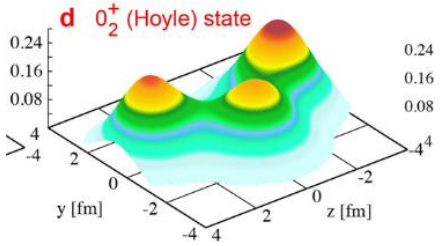


- Green's function Monte Carlo

J. Carlson, et al., Rev. Mod. Phys., 87, 1067 (2015)



- Monte Carlo Shell Model

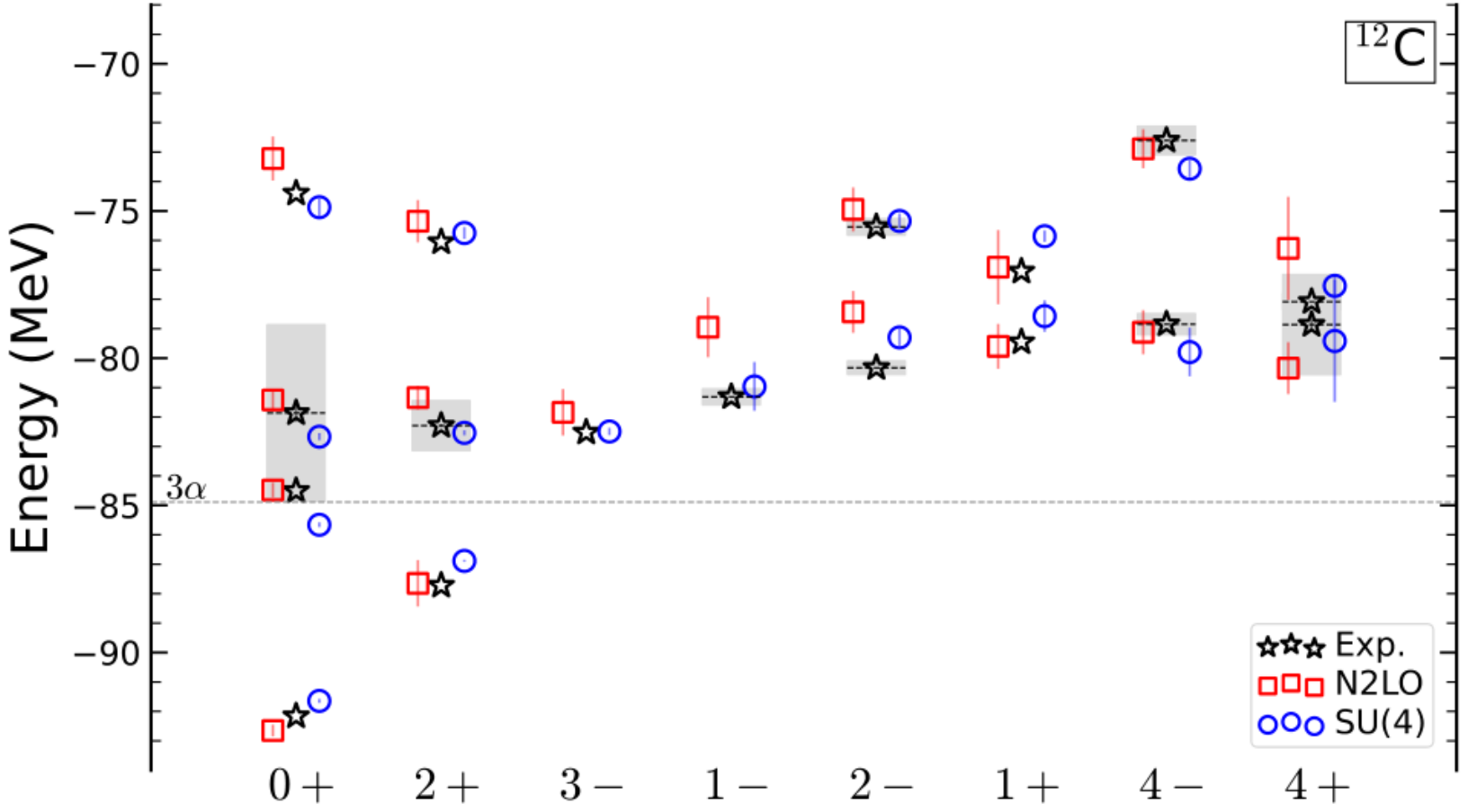


T. Otsuka et al., Nature Commun., 13, 2234 (2022)

NLEFT Study of ^{12}C

- Spectrum of ^{12}C calculated by NLEFT using N2LO and SU(4) interactions

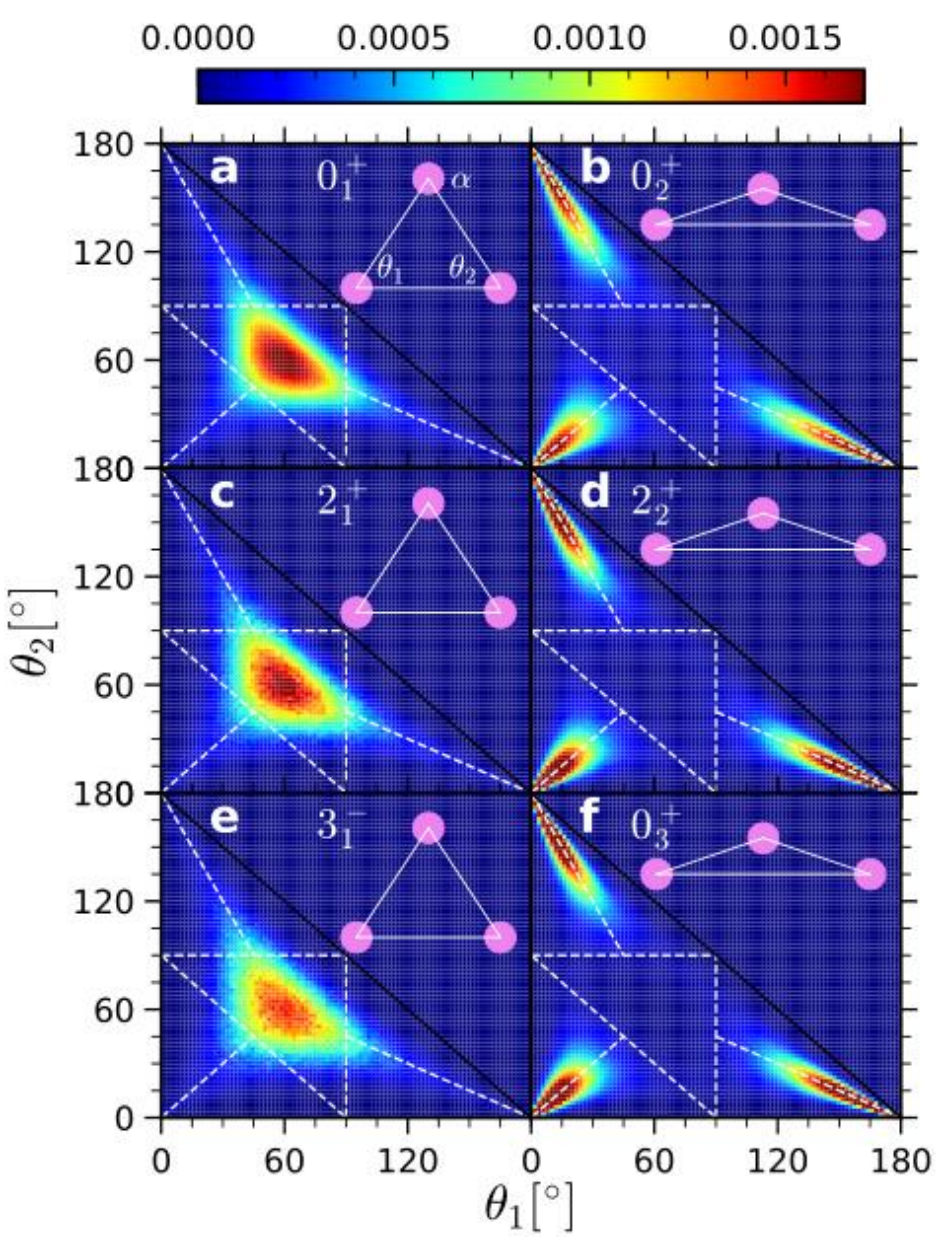
Cluster or shell-model wave functions are used as initial wave for different states

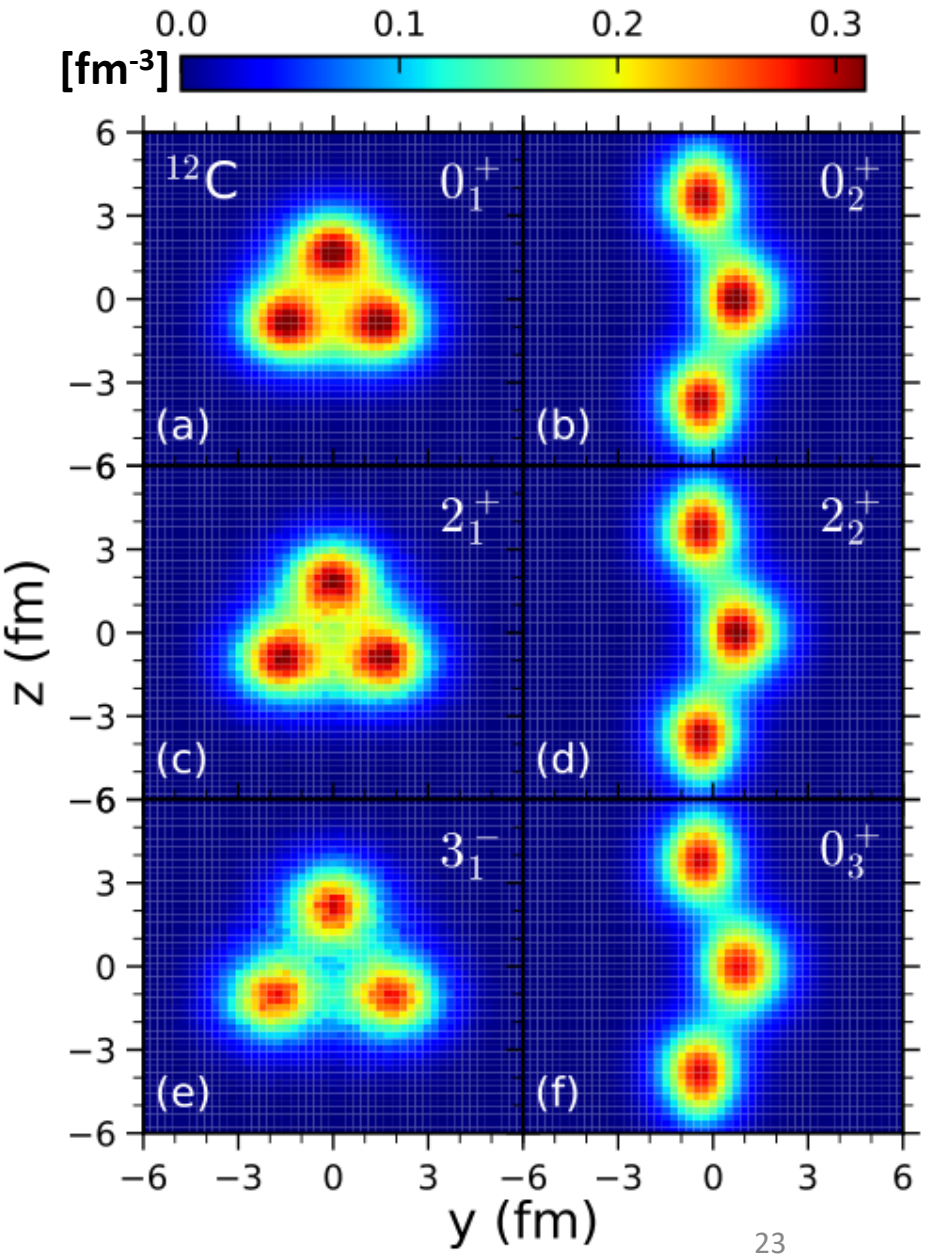


SS, T. Lähde, D. Lee, and U.-G. Meißner, Eur. Phys. J. A (2021) 57:276

SS, S. Elhatisari, T. Lähde, D. Lee, B. Lu, and U.-G. Meißner, Nat. Commun. 14, 2777 (2023)

Intrinsic Density Distribution



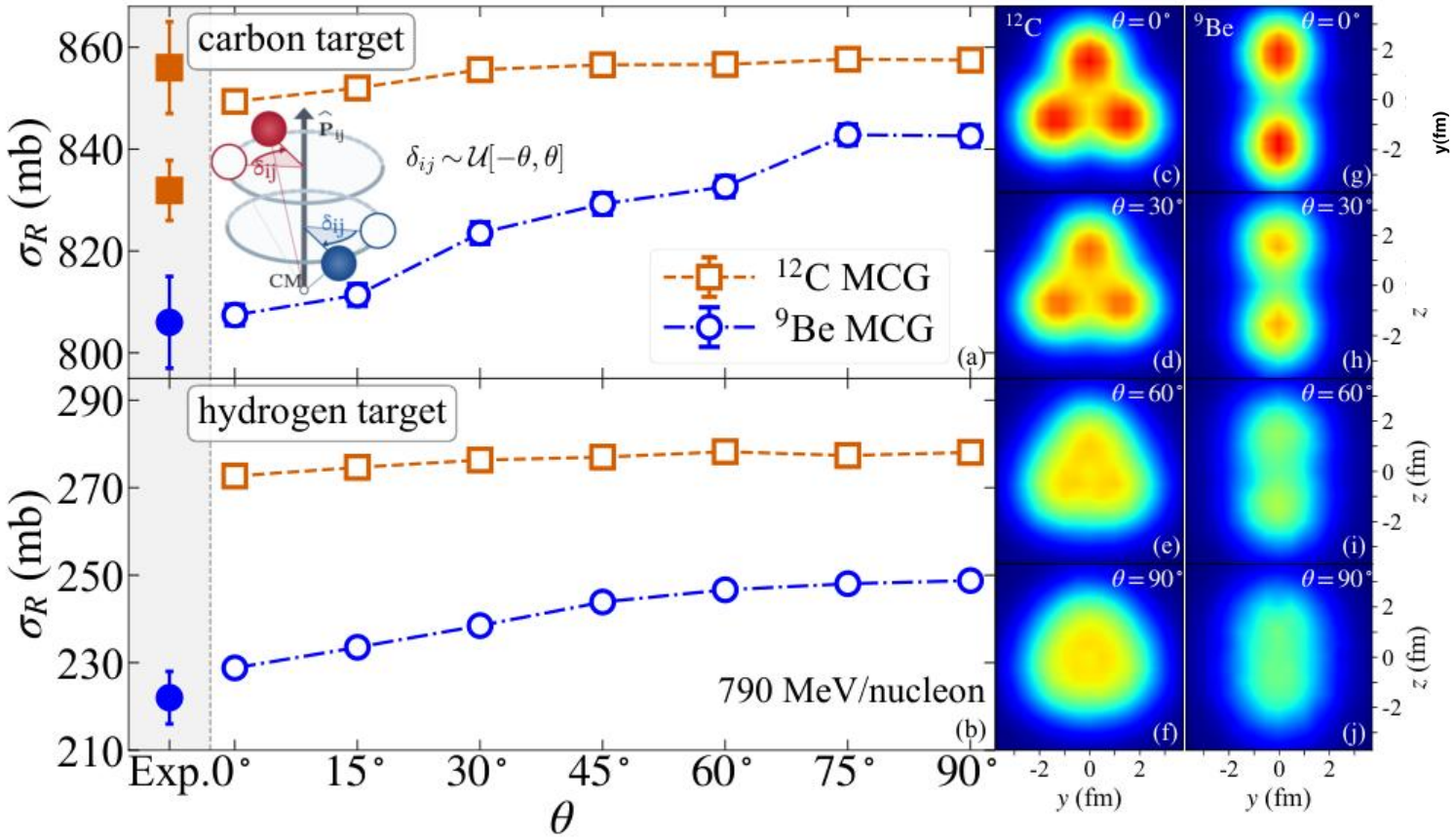


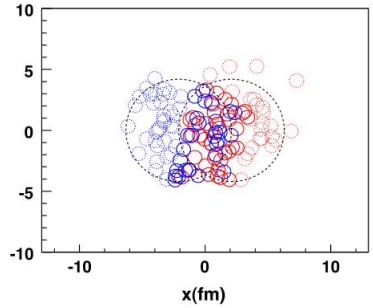
SS, S. Elhatisari, T. Lähde, D. Lee, B. Lu, and U.-G. Meißner, Nat. Commun. 14, 2777 (2023)

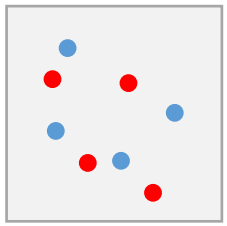
NLEFT Many-Body Density + MC Glauber Model

Reaction Cross Sections and α-Cluster Geometry in ^{12}C and Be Isotopes

C. Loizides, et. al., SoftwareX. 1, 13 (2015)





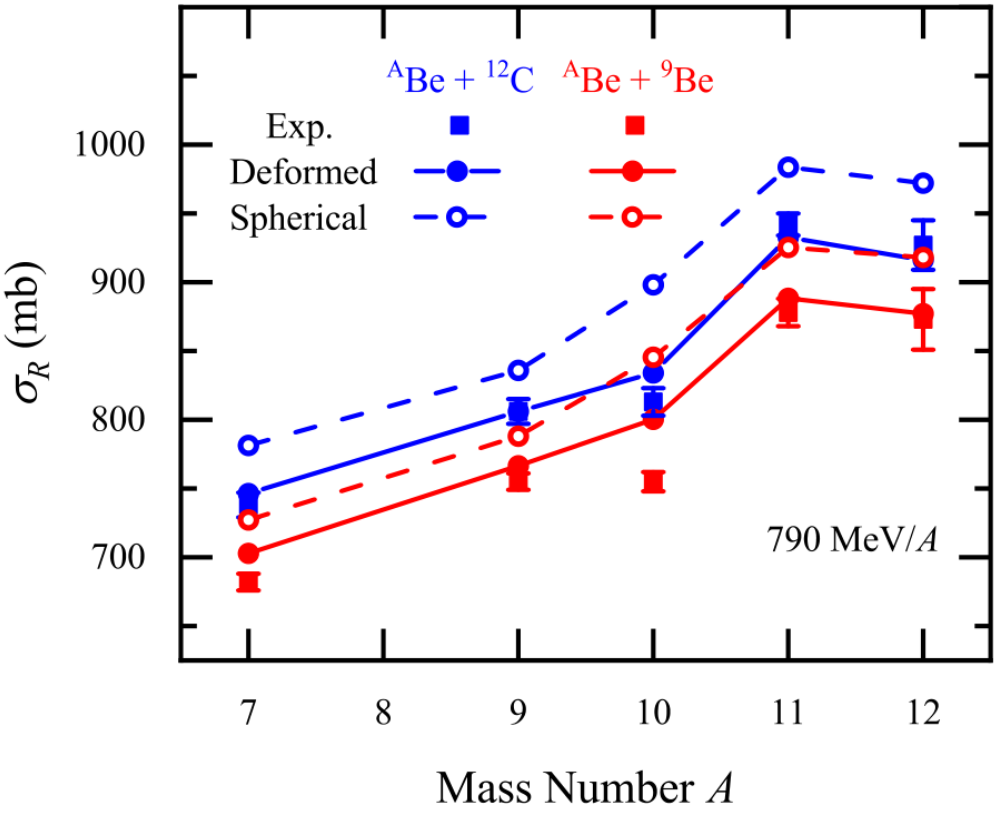


Angular decorrelation for each configuration

T. Wu, B. Sun, U.-G. Meißner, and SS, arXiv:2608.18538

NLEFT Intrinsic Density + Deformed Glauber Model

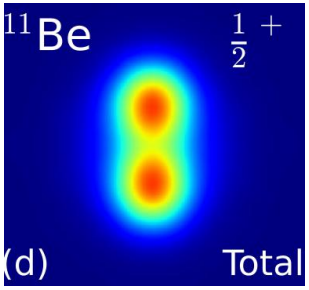
1*n* halo description from structure to reaction observables

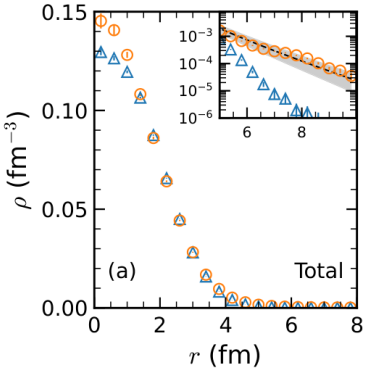


$$S_{PT}(\boldsymbol{b};\Omega) = \exp[\mathrm{i}\chi_{PT}(\boldsymbol{b};\Omega)]\,,$$

$$\mathrm{i}\chi_{PT}(\boldsymbol{b};\Omega) = -\int \mathrm{d}\boldsymbol{r} \int \mathrm{d}\boldsymbol{r}' \times \rho_P(\boldsymbol{r};\Omega)\,\rho_T(\boldsymbol{r}')\,\Gamma_{NN}(\boldsymbol{b}+\boldsymbol{s}-\boldsymbol{s}')\,,$$

$$\sigma_R(P+T) = \frac{1}{4\pi}\int \mathrm{d}\Omega \int \mathrm{d}\boldsymbol{b}\,\left[1-|S_{PT}(\boldsymbol{b};\Omega)|^2\right].$$





Q. Lu, S. Zhang, U.-G. Meißner, and SS, arXiv:2608.01131

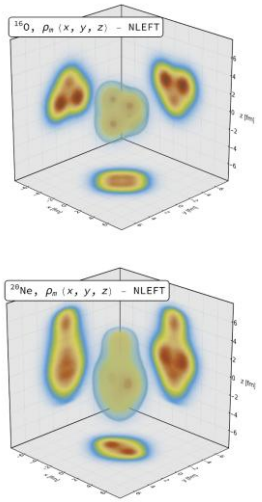
Summary

- Recent advancements in nuclear lattice effective field theory (NLEFT) offers a comprehensive ab initio understanding of light nuclei
- Helium-4, Berrylium isotopes, and carbon-12 nucleus have been investigated. Cluster structure, molecular dynamics, and geometry can be revealed intuitively
- Tetraneutron resonance was not found
- ab initio structure + reaction model

? Cluster in heavier system

? ANC

? … …



PHYSICAL REVIEW LETTERS **135,** 012302 (2025)

Exploiting ^{20}Ne Isotopes for Precision Characterizations of Collectivity in Small Systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

PHYSICAL REVIEW LETTERS **134,** 082301 (2025)

Anisotropic Flow in Fixed-Target ^{208}Pb + ^{20}Ne Collisions as a Probe of Quark-Gluon Plasma

Giuliano Giacalone,[1,*] Wenbin Zhao,[2,3,†] Benjamin Bally,[4] Shihang Shen,[5] Thomas Duguet,[6,7] Jean-Paul Ebran,[8,9] Serdar Elhatisari,[10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[16,17,5,18] Govert Nijs,[19] Jacquelyn Noronha-Hostler,[20] Christopher Plumberg,[21] Tomás R. Rodríguez,[22] Robert Roth,[23,24] Wilke van der Schee,[19,25,26] Björn Schenke,[27,‡] Chun Shen,[28,29,§] and Vittorio Somà[6]

Collaborators

- Serdar Elhatisari, KFUPM
- Timo A. Lähde, Jülich
- Dean Lee, MSU
- Bing-Nan Lu, GSCAPE
- Ulf-G. Meißner, Bonn/Jülich/Beihang
- Zhengxue Ren, Nankai
- NLEFT Collaboration

Beihang:

- Lisheng Geng
- Qi Lu
- Baohua Sun
- Linqian Wu
- Tianyu Wu
- Shisheng Zhang

Thank you for your attention!