The 5th International Conference on
Collective Motion in Nuclei under Extreme Conditions (COMEX5)

Krakow, September 14 -18, 2015

Rod-shaped nuclei at extreme spin and isospin

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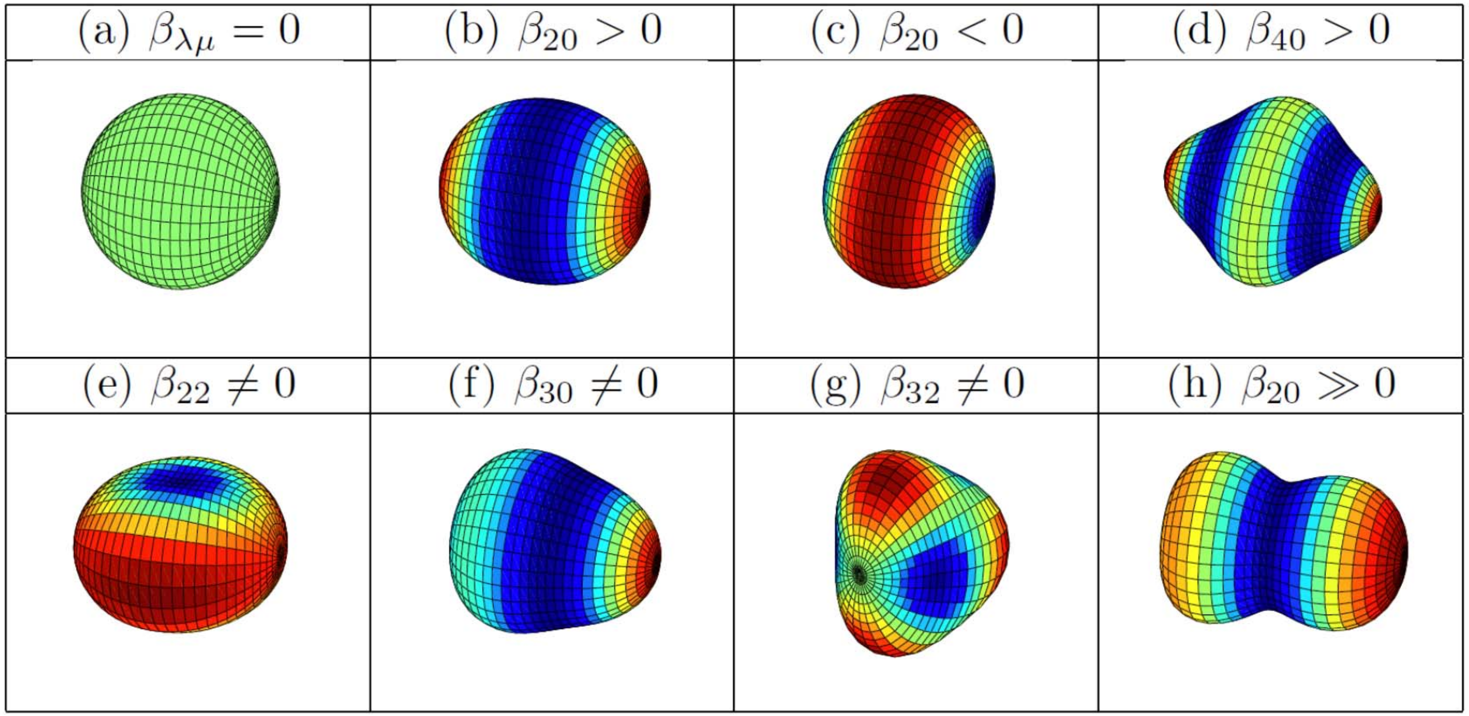
- Introduction
- Theoretical Framework
- Results and Discussion
- Summary

Nuclear deformations provide us an excellent framework to investigate the fundamental properties of quantum many-body systems.

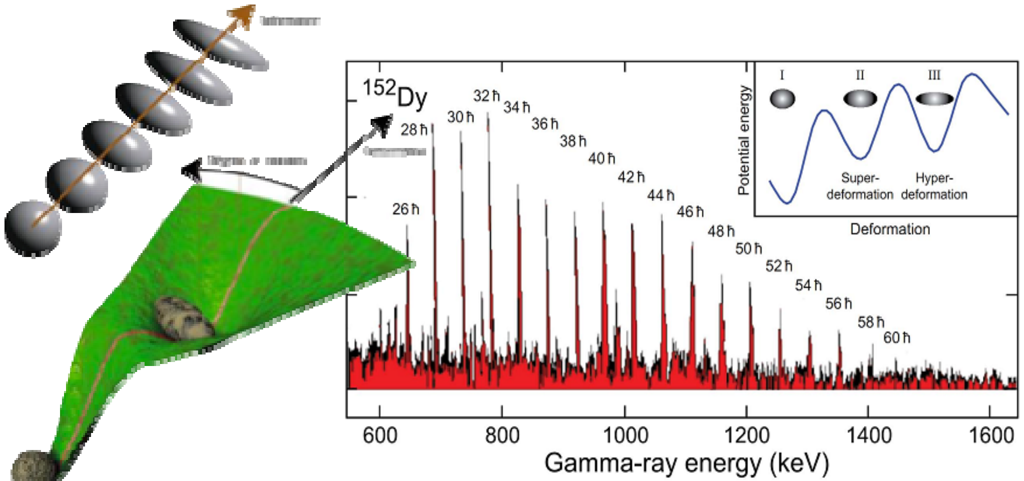
$$R(\theta,\varphi) = R_0\left[1+\beta_{00}+\sum_{\lambda=1}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\beta^*_{\lambda\mu}Y_{\lambda\mu}(\theta,\varphi)\right]$$



Courtesy of Bing-Nan Lu (吕炳楠)

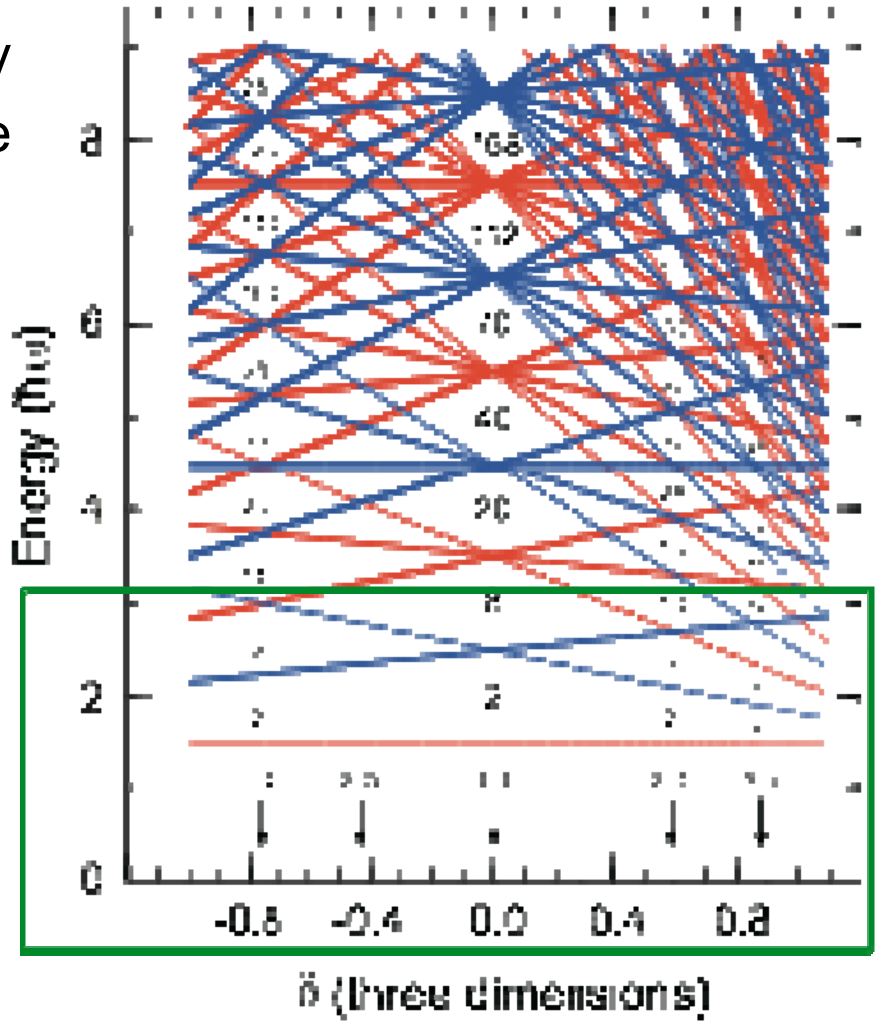
Nuclear super- (hyper) deformation

Evidence for the super- and hyper-deformation provide unique opportunity to study nuclear structure under extreme conditions



Twin PRL 1986

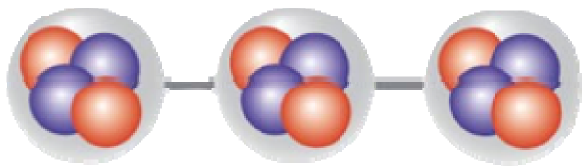
Harmonic oscillator



Nuclear super- (hyper) deformation

There have been indications that even more exotic states above 1：3 might exist in light N = Z nuclei due to the a cluster structure.

Towards hyperdeformation

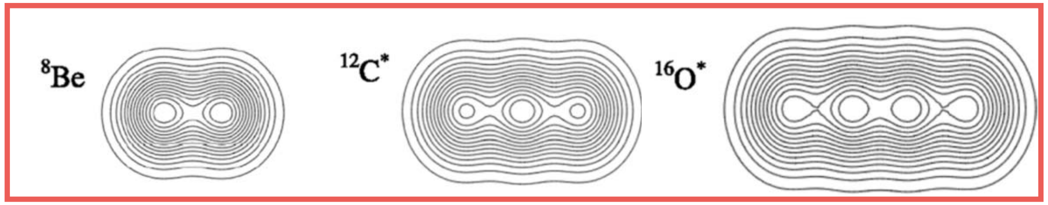


Cluster structure in light nuclei

- Clustering in nuclei is an old story: John Archibald Wheeler, Molecular Viewpoints in Nuclear Structure, Physical Review **52** (1937) 1083
- Lots of works have been done by, e.g. Ikeda, Horiuchi, Kanada-enyo, Freer, Itagaki, Khan, Maruhn, Schuck, Tohsaki, Zhou, Ichikawa, Funaki, Von Oertzen, …
- Linear-chain structure of three-α clusters was suggested about 60 years ago Morinaga, Phys. Rev. 101, 254 (1956) to explain the structure of the Hoyle state (the second 0^+ state at 7.65 MeV in ^{12}C) Hoyle, Astrophys J. Sup. 1, 121 (1954).
- However, Hoyle state was later found to be a mixing of the linear-chain configuration and other three-α configurations, and recently reinterpreted as an α-condensate-like state Fujiwara et al, PTP Sup. 68, 29 (1980). Tohsaki et al PRL 87, 192501 (2001). Suhara et al PRL 112, 062501 (2014).

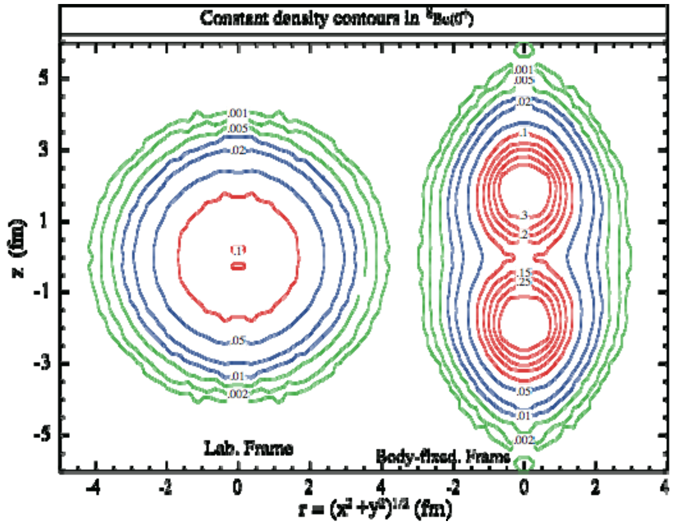
Alpha cluster chain and rod shape

Harmonic oscillator density



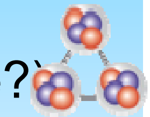
Freer RPP 2007

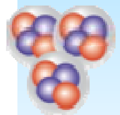
Green Function Monto Carlo

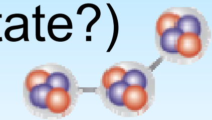


Wiringa PRC 2000

- ✓ Be-8
  - ✴ 1st 0+ (ground state)
- ✓ C-12
  - ✴ 1st 0+ (ground state?)
  - ✴ 2nd 0+ (Hoyle state?)
  - ✴ 3rd 0+ (?)







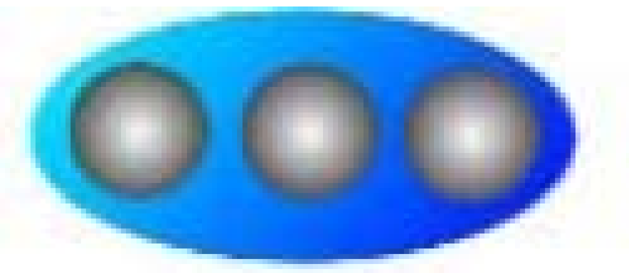
- ✓ O-16? Ne-20? Mg-24?
- ✓ …?

Because of ✓ **antisymmetrization effects**

✓ **weak-coupling nature**

it is difficult to stabilize the rod-shaped configuration in nuclear systems.

Long existing problem: how can we stabilize geometric cluster shapes for instance linear alpha chain?



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- Most of the linear chain structure have been predicted by the conventional cluster model with effective interactions determined from the binding energies and scattering phase shifts of the clusters.
- Since the DFTs do not a priori assume the existence of α clusters, it is highly desirable to have investigations based on different approaches, such as density functional theories (DFTs).

- ab initio calculation of the low-lying states of carbon-12 using effective field theory Evgeny Epelbaum, Hermann Krebs, Dean Lee, and Ulf-G. Meißner, Phys. Rev. Lett. 106, 192501 (2011)
- ab initio lattice calculations of the low-energy even-parity states of 16O using chiral nuclear effective field theory.

Cluster structures in (C)DFT

Studies have shown that the nucleons are prone to form cluster structure in the nuclear system with

- high excitation energy and high spin with large deformation

  W. Zhang, H.-Z. Liang, S.-Q. Zhang, and J. Meng, Chin. Phys. Lett. 27, 102103 (2010).
  T. Ichikawa, J. A. Maruhn, N. Itagaki, and S. Ohkubo, Phys. Rev. Lett. 107, 112501 (2011).
  L. Liu & P. W. Zhao, CPC36, 818 (2012)

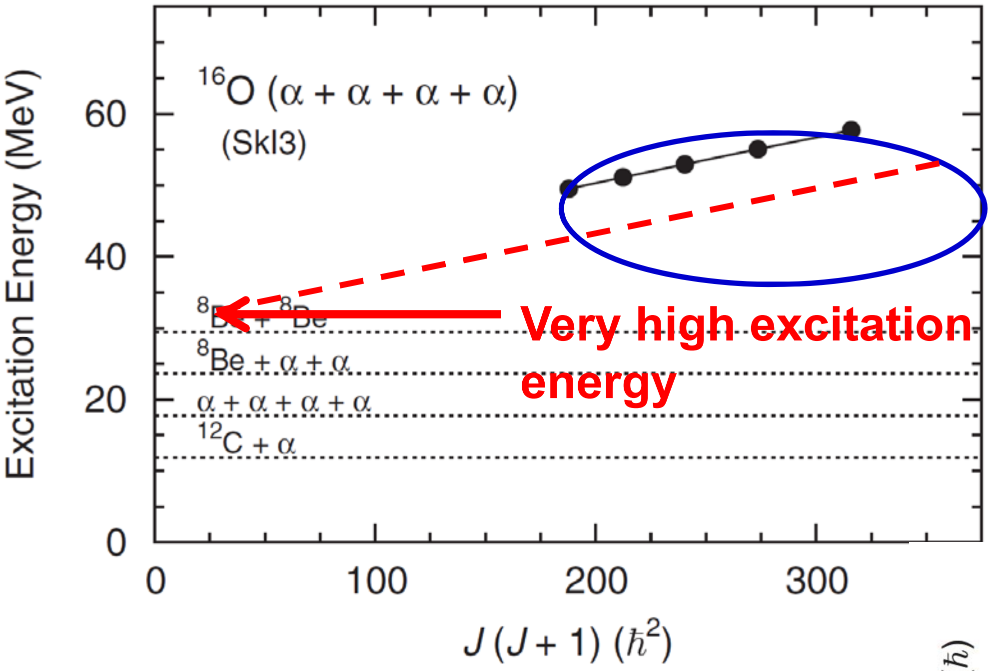
- deep confining nuclear potential

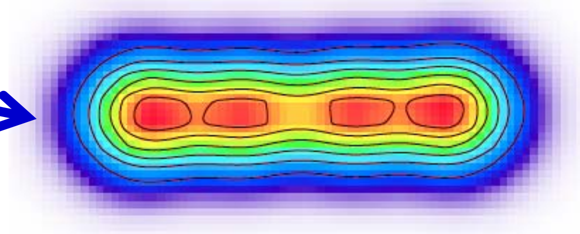
  J.-P. Ebran, E. Khan, T. Niksic, and D. Vretenar, Nature 487, 341 (2012).
  J.-P. Ebran, E. Khan, T. Niksic, and D. Vretenar, Phys. Rev. C 87, 044307 (2013).

- or expansion with low density

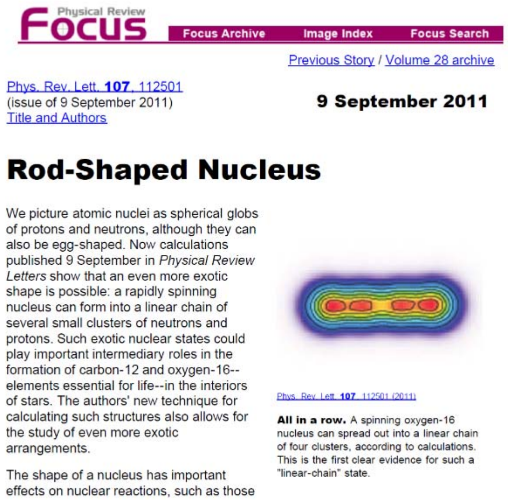
  M. Girod and P. Schuck, Phys. Rev. Lett. 111, 132503 (2013).

4α-LCS in high-spin states of ^{16}O from the cranking SHF calculation





T. Ichikawa, J. A. Maruhn, N. Itagaki, and S. Ohkubo, PRL107, 112501 (2011)



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Phys. Rev. Lett. **107**, 112501
(issue of 9 September 2011)
Title and Authors

9 September 2011

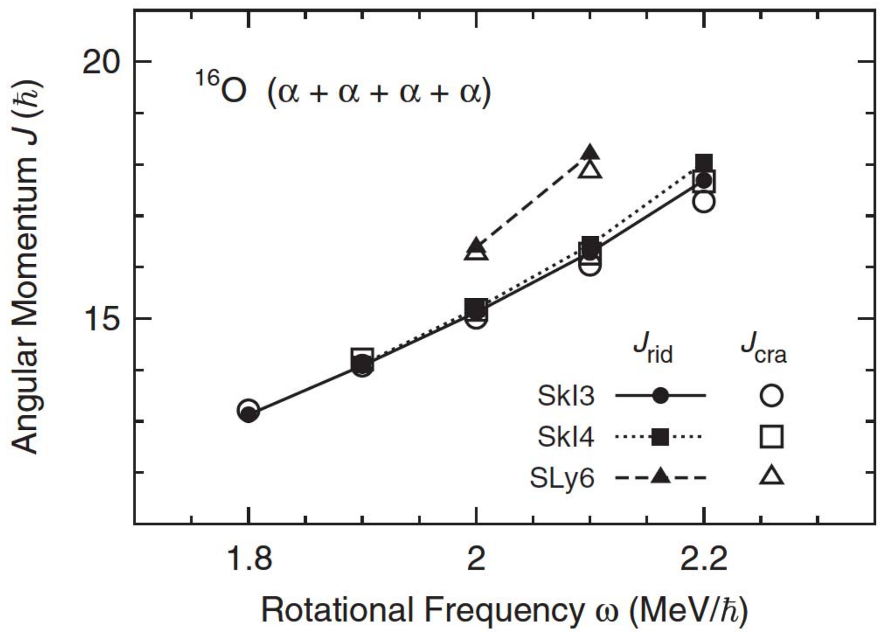
Rod-Shaped Nucleus

We picture atomic nuclei as spherical globs of protons and neutrons, although they can also be egg-shaped. Now calculations published 9 September in *Physical Review Letters* show that an even more exotic shape is possible: a rapidly spinning nucleus can form into a linear chain of several small clusters of neutrons and protons. Such exotic nuclear states could play important intermediary roles in the formation of carbon-12 and oxygen-16--elements essential for life--in the interiors of stars. The authors' new technique for calculating such structures also allows for the study of even more exotic arrangements.

Phys. Rev. Lett. **107**, 112501 (2011)

All in a row. A spinning oxygen-16 nucleus can spread out into a linear chain of four clusters, according to calculations. This is the first clear evidence for such a "linear-chain" state.

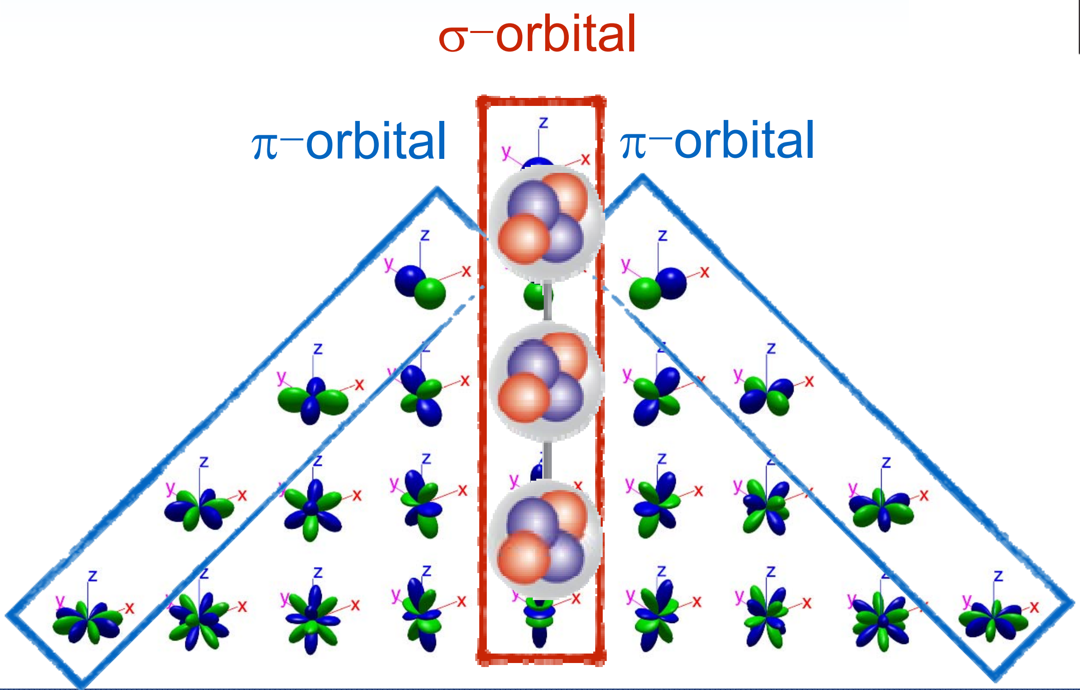
The shape of a nucleus has important effects on nuclear reactions, such as those

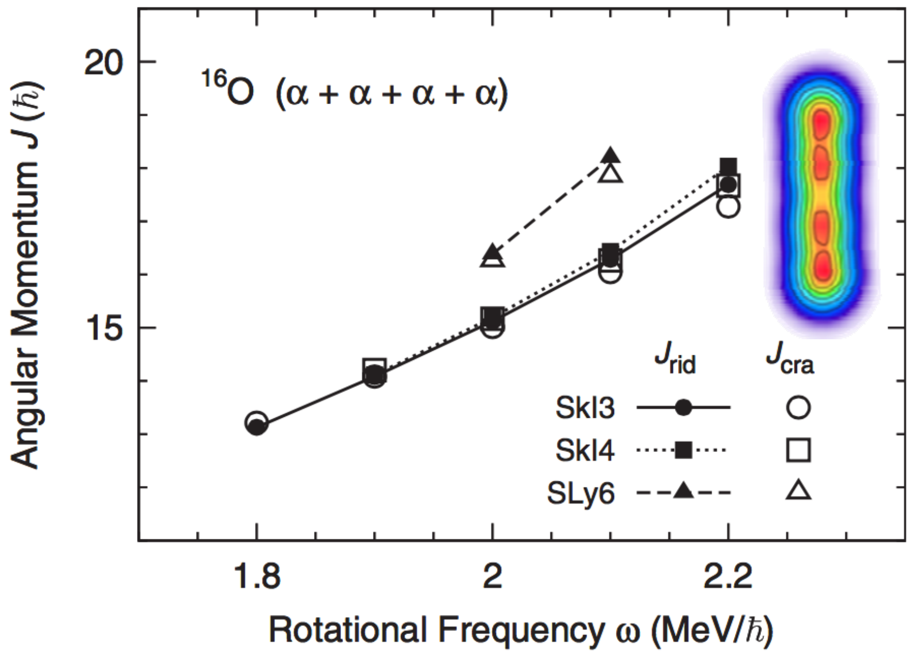


How to stabilize linear chain configurations?

Two important mechanisms

- Adding valence neutrons
  Itagaki, PRC2001
- Rotating the system
  Ichikawa, PRL2011



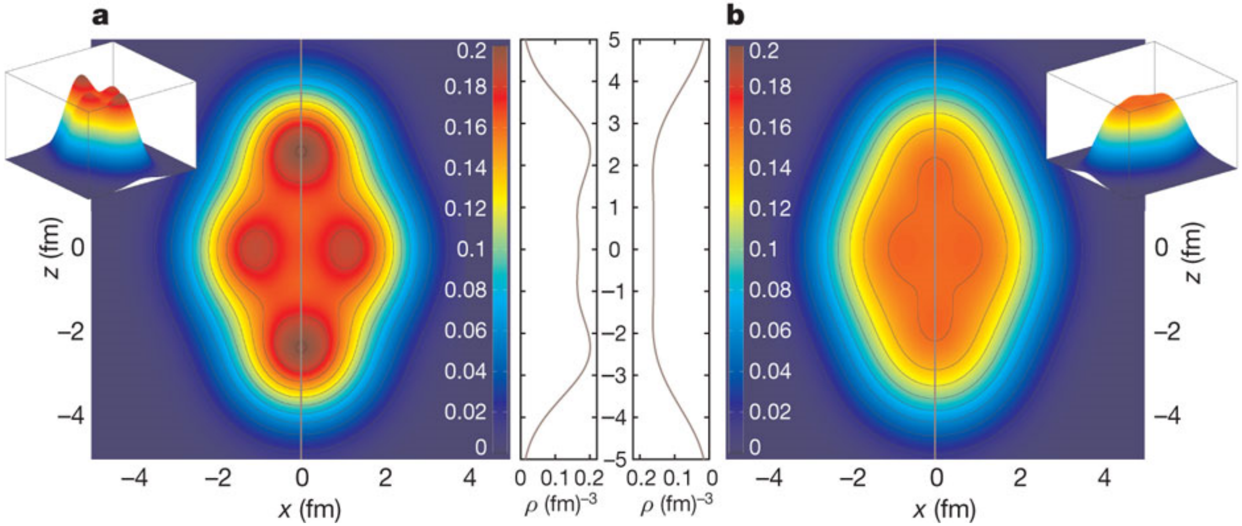


Coherent effects exist?

It facilitates the stabilization?

Self-consistent ground-state densities of ^{20}Ne.

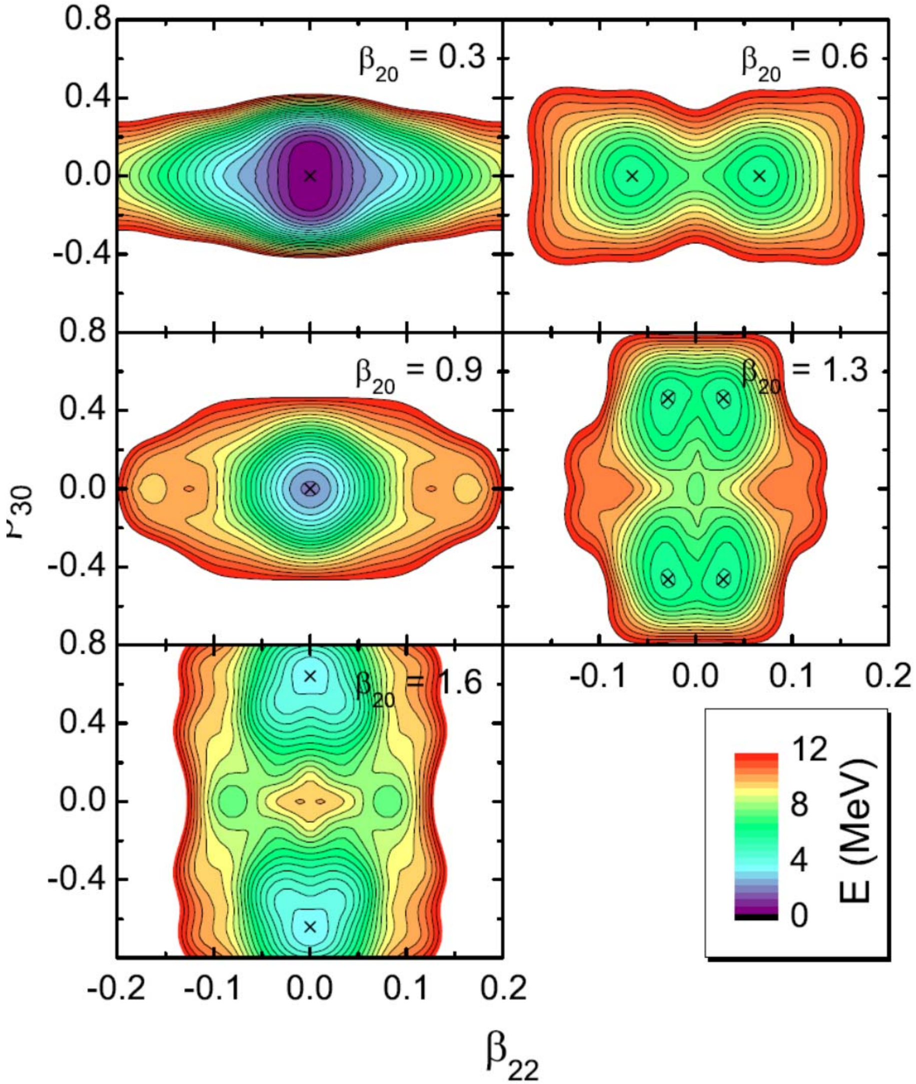
Using the nuclear energy density functional, the conditions for single nucleon localization and formation of cluster structures in finite nuclei are examined.



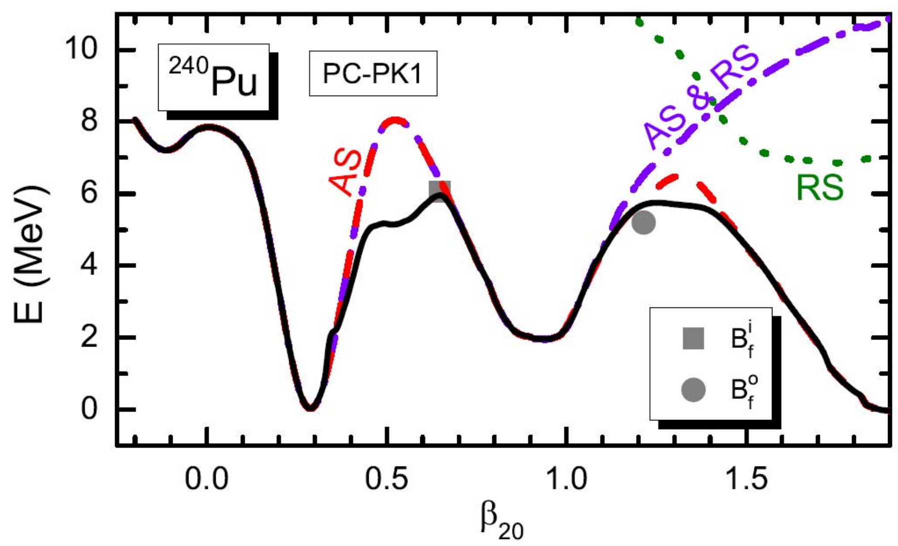
A localized equilibrium density and the formation of cluster structures are visible in (a) DD-ME2 but not in (b) Skyrme SLy4

J-P Ebran et al. Nature **487**, 341-344 (2012) doi:10.1038/nature11246

^{240}Pu: 3-dim. PES (β_{20}, β_{22}, β_{30})

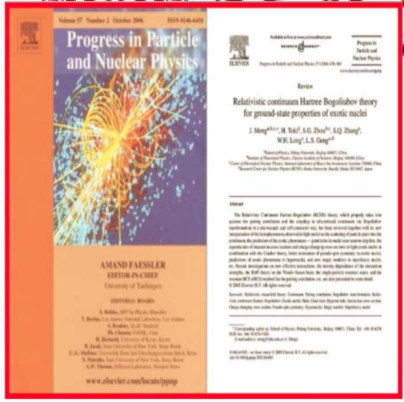


- AS & RS for g.s. & isomer, the latter is stiffer
- Triaxial & octupole shape around the outer barrier
- Triaxial deformation crucial around barriers



Lu, Zhao, Zhou Phys. Rev. C 85, 011301(R)
Zhao, Lu, Vretenar, Zhao, and Zhou, Phys. Rev. C 91 014321 (2015)

Related review paper



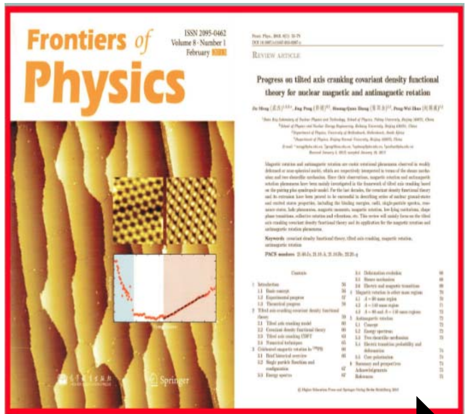
J. Meng, H. Toki, S.-G. Zhou, S.Q. Zhang, W.H. Long, ang L.S. Geng, Prog. Part. Nucl. Phys. 57 (2006) 470-563

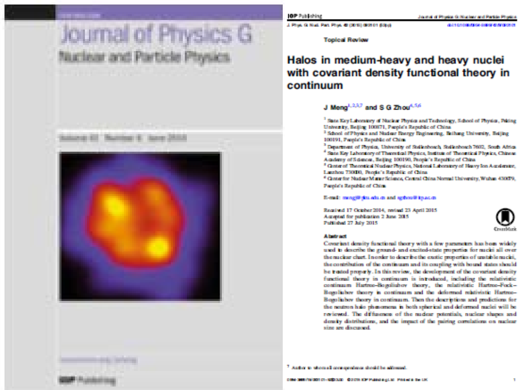
孟杰, 郭建友, 李剑, 李志攀, 梁豪兆, 龙文辉, 牛一斐, 牛中明, 尧江明, 张颖, 赵鹏巍, 周善贵, 原子核物理中的协变密度泛函理论, 物理学进展, 第31卷04期 (2011) 199-336

J. Meng, J. Peng, S.Q. Zhang, and P.W. Zhao, Front. Phys. 8 (2013) 55-79

H. Z. Liang, J. Meng, and S.-G. Zhou, Phys. Rep. 570 (2015) 1-84

J. Meng and S.-G. Zhou, J. Phys. G: Nucl. Part. Phys. 42 (2015) 093101





Hyperdeformed Rod shaped α-Linear Chain Structure

Current talk:

- Cranking CDFT to investigate the stabilization of rod shape at extreme spin and isospin in a fully self-consistent and microscopic way.
- By adding valence neutrons and rotating the system, the mechanism stabilizing the rod shape will be explored.
- CDFT configuration mixing of PN-AM projected calculation will be carried out to find evidence for 4α linear cluster structure.

Yao, Itagaki, Meng, Phys. Rev. C **90**, 054307 (2014)

Zhao, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

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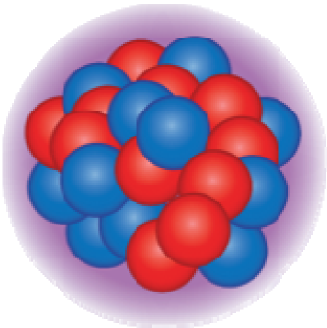
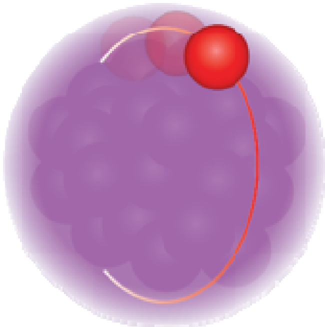
Density functional theory

The many-body problem is mapped onto an one-body problem without explicitly involving inter-nucleon interactions!





Kohn-Sham Density Functional Theory

For any interacting system, there exists a **local single-particle potential *h(r)*,** such that the exact ground-state density of the interacting system can be reproduced by **non-interacting particles** moving in this local potential.

$$E[\rho] \Rightarrow \boxed{\hat{h} = \frac{\delta E}{\delta \rho}} \Rightarrow \boxed{\hat{h}\varphi_i = \varepsilon_i \varphi_i} \Rightarrow \boxed{\rho = \sum_{i=1}^{A} |\varphi_i|^2}$$

The practical usefulness of the Kohn-Sham scheme depends entirely on whether **Accurate Energy Density Functional** can be found!

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Density functional theory in nuclei

- For nuclei, the energy density functional has been introduced by effective Hamiltonians

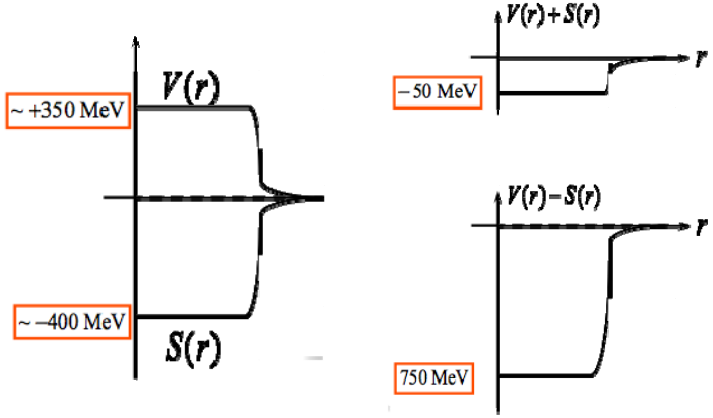
$$E = \langle \Psi | H | \Psi \rangle \approx \langle \Phi | \hat{H}_{eff}(\hat{\rho}) | \Phi \rangle = E[\hat{\rho}]$$

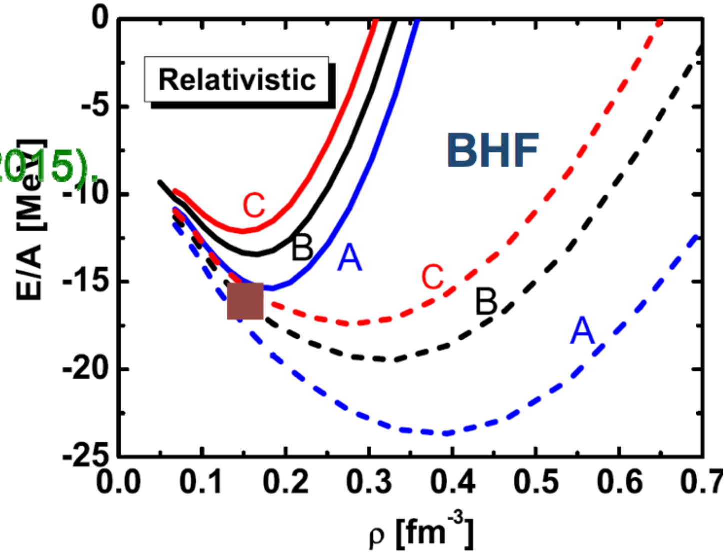
- More degrees of freedom: spin, isospin, pairing, …
- Nuclei are self-bound systems;
  ρ(r) here denotes the intrinsic density.
- Density functional is probably not exact, but a very good approximation.
- The functional are adjusted to properties of nuclear matter and/or finite nuclei and (in future) to ab-initio results.

Why Covariant?

P. Ring Physica Scripta, T150, 014035 (2012)

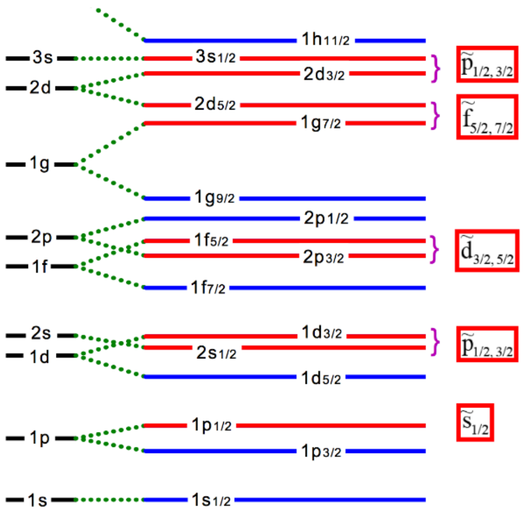
- ✓ Large spin-orbit splitting in nuclei
- ✓ Pseudo-spin Symmetry
- ✓ Success of Relativistic Brueckner
- ✓ Consistent treatment of time-odd fields
- ✓ Large fields V≈350 MeV , S≈-400 MeV
- ✓ Relativistic saturation mechanism
- ✓ … Liang, Meng, Zhou, Physics Reports **570** : 1-84 (2015)





Brockmann & Machleidt, PRC42, 1965 (1990)

Pseudospin symmetry



$$n-1,\quad l+2,\quad j=l+3/2$$
$$n,\quad l,\quad j=l+1/2$$

$$\text{pseudo-orbit} \;:\; \tilde{l}=l+1$$
$$\text{pseudo-spin} \;:\; \tilde{s}=1/2$$

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

Ginocchio, Phys. Rev. Lett. 78 (1997) 436

Covariant Density Functional Theory

Elementary building blocks

$$(\bar{\psi}\mathcal{O}_\tau\Gamma\psi) \qquad \mathcal{O}_\tau \in \{1, \tau_i\} \qquad \Gamma \in \{1, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

Densities and currents

Isoscalar-scalar	$\rho_S(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\psi_k(\mathbf{r})$
Isoscalar-vector	$j_\mu(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\gamma_\mu\psi_k(\mathbf{r})$
Isovector-scalar	$\vec{\rho}_S(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\vec{\tau}\psi_k(\mathbf{r})$
Isovector-vector	$\vec{j}_\mu(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\vec{\tau}\gamma_\mu\psi_k(\mathbf{r})$

Energy Density Functional

$$E_{kin} = \sum_k v_k^2 \int \bar{\psi}_k\left(-\gamma\nabla + m\right)\psi_k d\mathbf{r}$$

$$E_{2nd} = \frac{1}{2}\int (\alpha_S\rho_S^2 + \alpha_V\rho_V^2 + \alpha_{tV}\rho_{tV}^2)d\mathbf{r}$$

$$E_{hot} = \frac{1}{12}\int (4\beta_S\rho_S^3 + 3\gamma_S\rho_S^4 + 3\gamma_V\rho_V^4)d\mathbf{r}$$

$$E_{der} = \frac{1}{2}\int (\delta_S\rho_S\Delta\rho_S + \delta_V\rho_V\Delta\rho_V + \delta_{tV}\rho_{tV}\Delta\rho_{tV})d\mathbf{r}$$

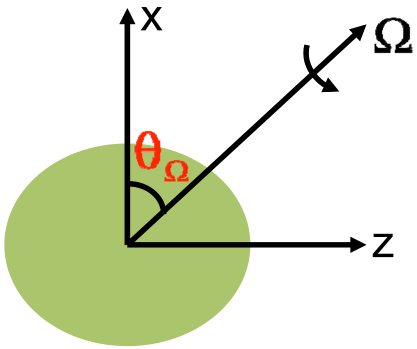
$$E_{em} = \frac{e}{2}\int j_\mu^p A^\mu d\mathbf{r}$$

Cranking Covariant Density Functional Theory

Transform to the frame rotating with a uniform velocity

$$x^{\alpha} = \begin{pmatrix} t \\ \boldsymbol{x} \end{pmatrix} \to \tilde{x}^{\mu} = \begin{pmatrix} \tilde{t} \\ \tilde{\boldsymbol{x}} \end{pmatrix} = \begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & R_x(t) \end{pmatrix} \begin{pmatrix} t \\ \boldsymbol{x} \end{pmatrix}$$

Rotating Density Functional



Peng, Meng, P. Ring, and S. Q. Zhang, **Phys. Rev. C** 78, 024313 (2008).
Zhao, Zhang, Peng, Liang, Ring, and Meng, **Phys. Lett. B** 699, 181 (2011).
Zhao, Peng, Liang, Ring, and Meng, **Phys. Rev. Lett.** 107, 122501 (2011).
Zhao, Peng, Liang, Ring, and Meng, **Phys. Rev. C** 85, 054310 (2012).
Meng, Peng, Zhang, and Zhao, **Front. Phys. 8**, 55 (2013).

Kohn-Sham/Dirac Equation:

Dirac equation for single nucleon

$$\begin{pmatrix} m+S+V-\Omega\cdot J & \sigma(p-\mathbf{V}) \\ \sigma(p-\mathbf{V}) & -m-S+V-\Omega\cdot J \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix} = \varepsilon \begin{pmatrix} f \\ g \end{pmatrix}$$

$$V(r) = \alpha_V \rho_V + \gamma_V \rho_V^3 + \delta_V \Delta\rho_V + \tau_3 \alpha_{TV} \rho_{TV} + \tau_3 \delta_{TV} \Delta\rho_{TV} + e\frac{1-\tau_3}{2}A$$

$$\mathbf{V}(r) = \alpha_V \mathbf{j}_V + \gamma_V \mathbf{j}_V^3 + \delta_V \Delta\mathbf{j}_V + \tau_3 \alpha_{TV} \mathbf{j}_{TV} + \tau_3 \delta_{TV} \Delta\mathbf{j}_{TV} + e\frac{1-\tau_3}{2}\mathbf{A}$$

$$S(r) = \alpha_S \rho_S + \beta_S \rho_S^2 + \gamma_S \rho_S^3 + \delta_S \Delta\rho_S$$

V(r) vector potential time-like

V(r) vector potential space-like

S(r) scalar potential

Observables

Binding energy

$$E_{\text{tot}} = \sum_{k=1}^{A} \epsilon_k - \int d^3r \Bigg\{ \frac{1}{2}\alpha_S \rho_S^2 + \frac{1}{2}\alpha_V j_V^{\mu} (j_V)_\mu + \frac{1}{2}\alpha_{TV} j_{TV}^{\mu}(j_{TV})_\mu + \frac{2}{3}\beta_S \rho_S^3 + \frac{3}{4}\gamma_S \rho_S^4 + \frac{3}{4}\gamma_V \left(j_V^{\mu}(j_V)_\mu\right)^2 + \frac{1}{2}\delta_S \rho_S \Delta \rho_S + \frac{1}{2}\delta_V (j_V)_\mu \Delta j_V^{\mu} + \frac{1}{2}\delta_{TV} j_{TV}^{\mu} \Delta (j_{TV})_\mu + \frac{1}{2} e j_p^0 A_0 \Bigg\} + \sum_{k=1}^{A} \langle k | \boldsymbol{\Omega} \hat{\boldsymbol{J}} | k \rangle + E_{\text{c.m.}}.$$

Angular momentum

$$J = \sqrt{\langle \hat{J}_x \rangle^2 + \langle \hat{J}_z \rangle^2} \equiv \sqrt{I(I+1)}$$

Quadrupole moments and magnetic moments

$$Q_{20} = \sqrt{\frac{5}{16\pi}} \langle 3z^2 - r^2 \rangle, \qquad Q_{22} = \sqrt{\frac{15}{32\pi}} \langle x^2 - y^2 \rangle,$$

$$\boldsymbol{\mu} = \sum_{i=1}^{A} \int d^3r \left[\frac{mc^2}{\hbar c} q \psi_i^{\dagger}(\boldsymbol{r}) \boldsymbol{r} \times \boldsymbol{\alpha} \psi_i(\boldsymbol{r}) + \kappa \psi_i^{\dagger}(\boldsymbol{r}) \beta \boldsymbol{\Sigma} \psi_i(\boldsymbol{r}) \right],$$

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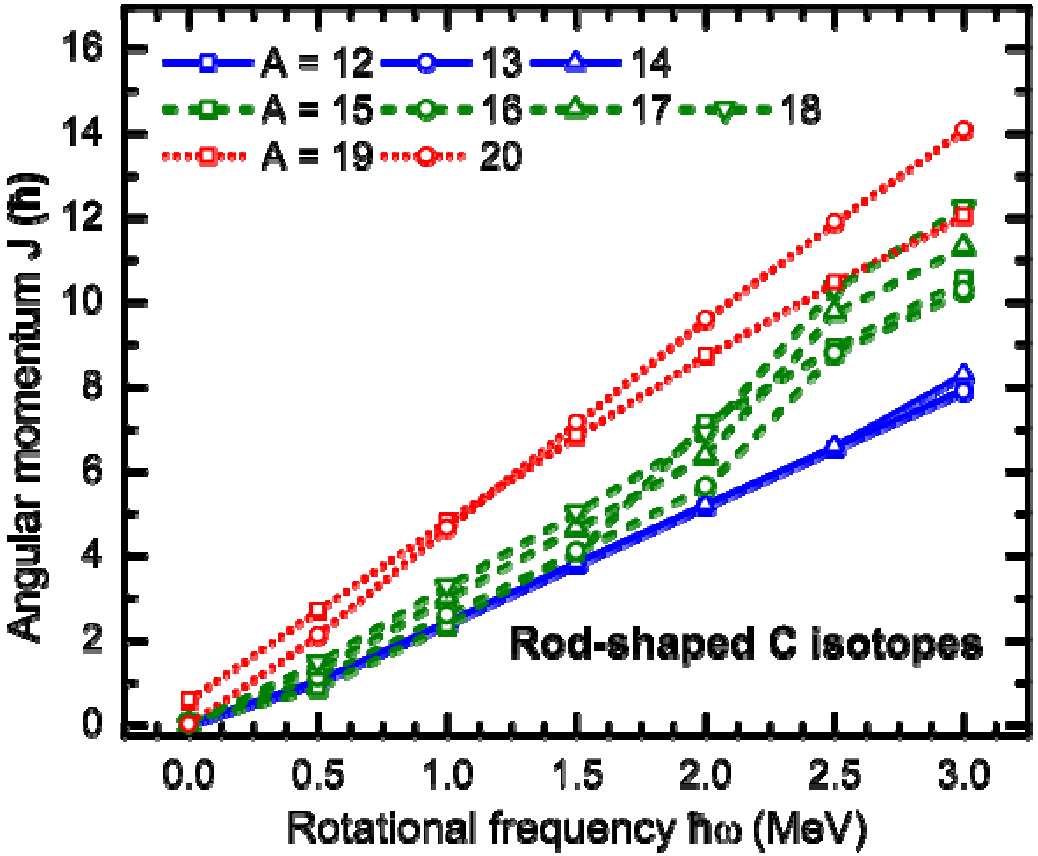
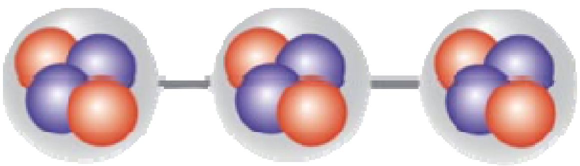
Angular momentum

DD-ME2, 3D HO basis with N = 12 major shells



- C-12, C-13, C-14
  constant moments of inertia (MOI); like a rotor
- C-15, C-16, C-17, C-18
  abrupt increase of MOI; some changes in structure
- C-19; C-20
  constant moments of inertia; much larger

Rod shape are obtained in all isotopes by tracing the corresponding rod-shaped configuration.



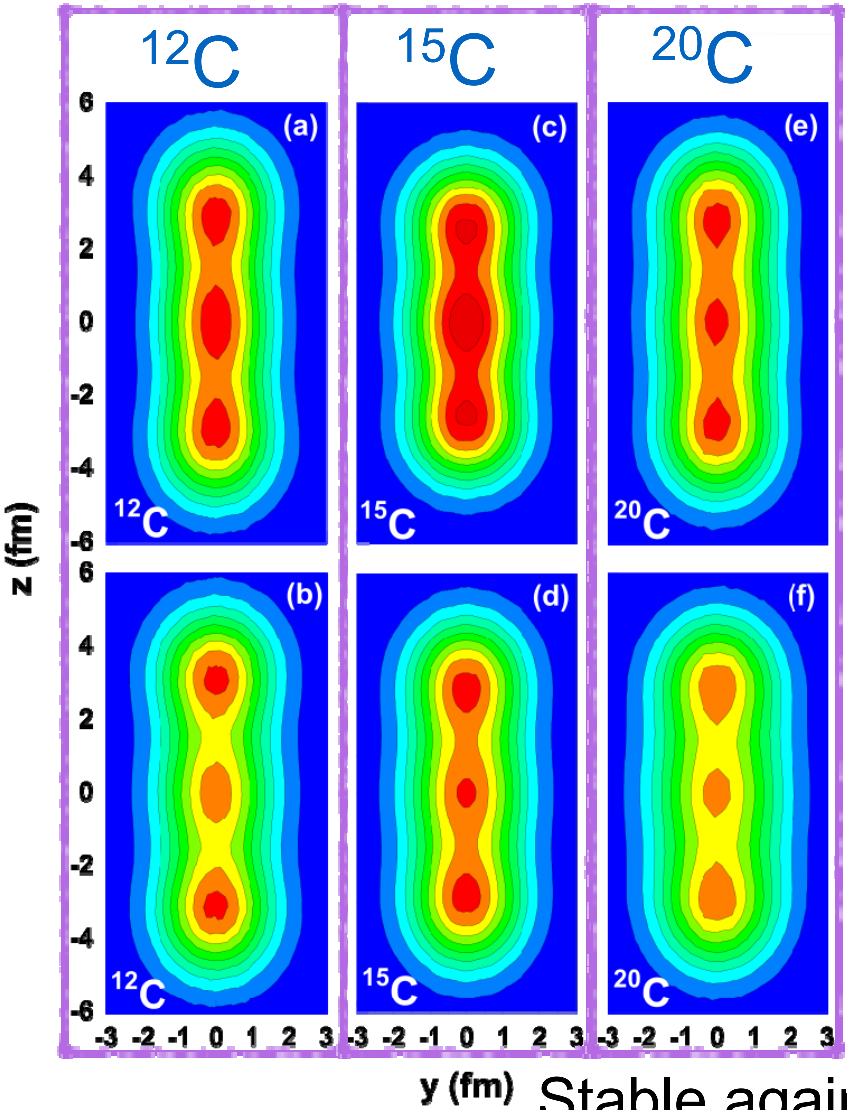
Zhao, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

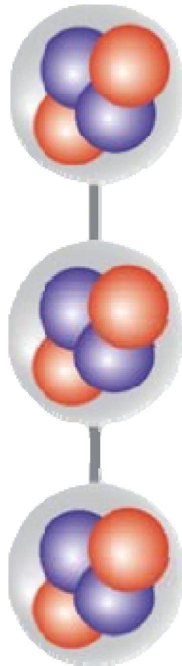
Proton density distribution

$\hbar\omega$

0.0 MeV

3.0 MeV





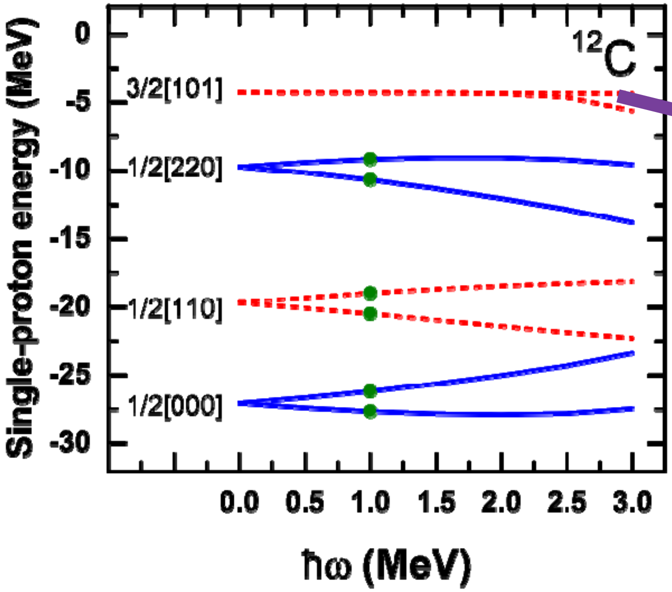
Larger deformation

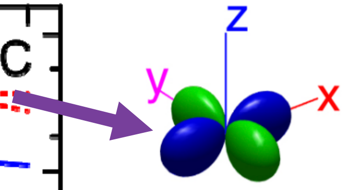
Clearer clustering

Stable against particle-hole deexcitations?

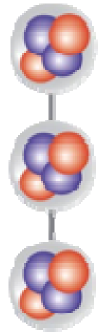
Zhao, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

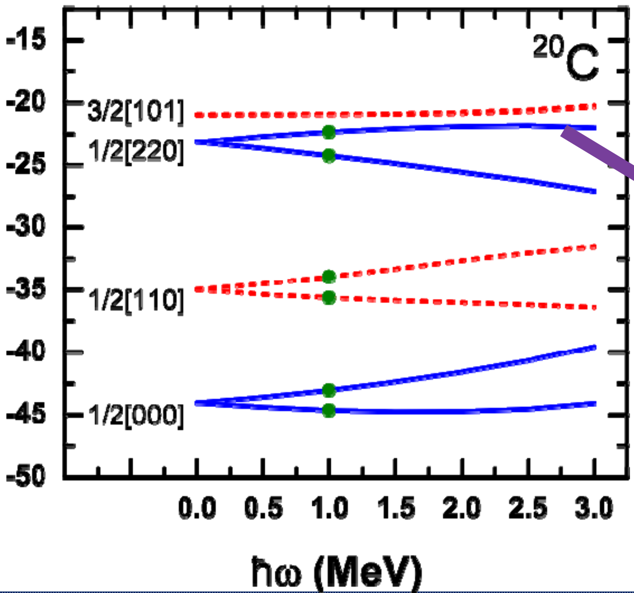
Single-proton energy : configurations stabilized against particle-hole deexcitations.

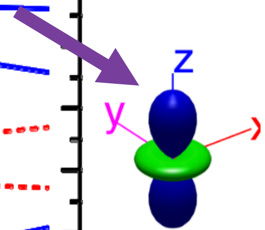




π−orbital

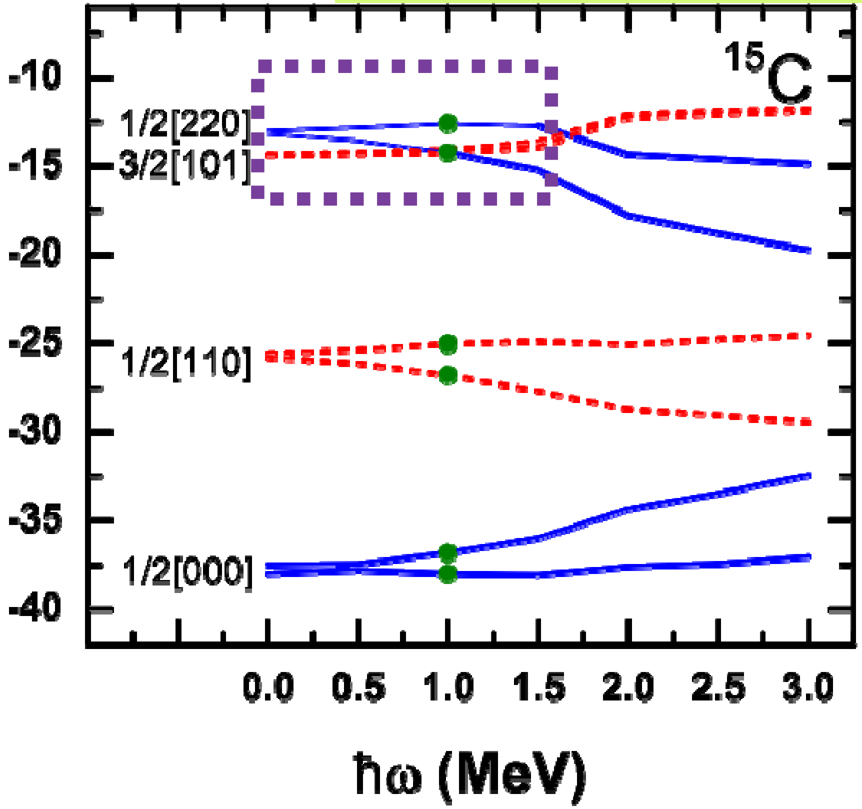






σ−orbital

spin effects?

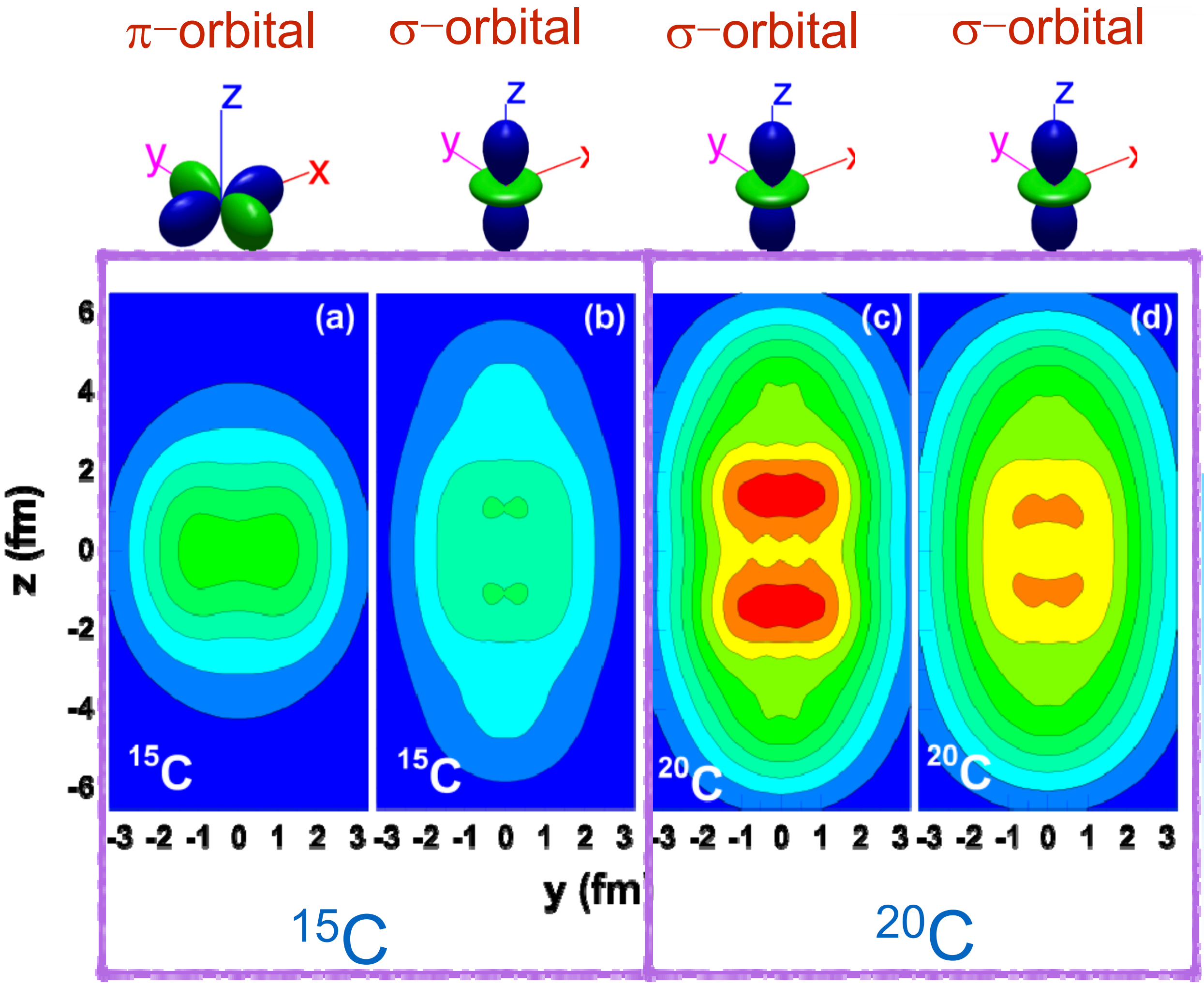


For C-15:

Low spin: deexcitations easily happen

High spin: More stable against deexcitations

Valence neutron density distribution



Isospin effects?

C-15: valence neutrons

Low spin: π−orbital; proton unstable

High spin: σ−orbital; proton stable

C-20: valence neutrons

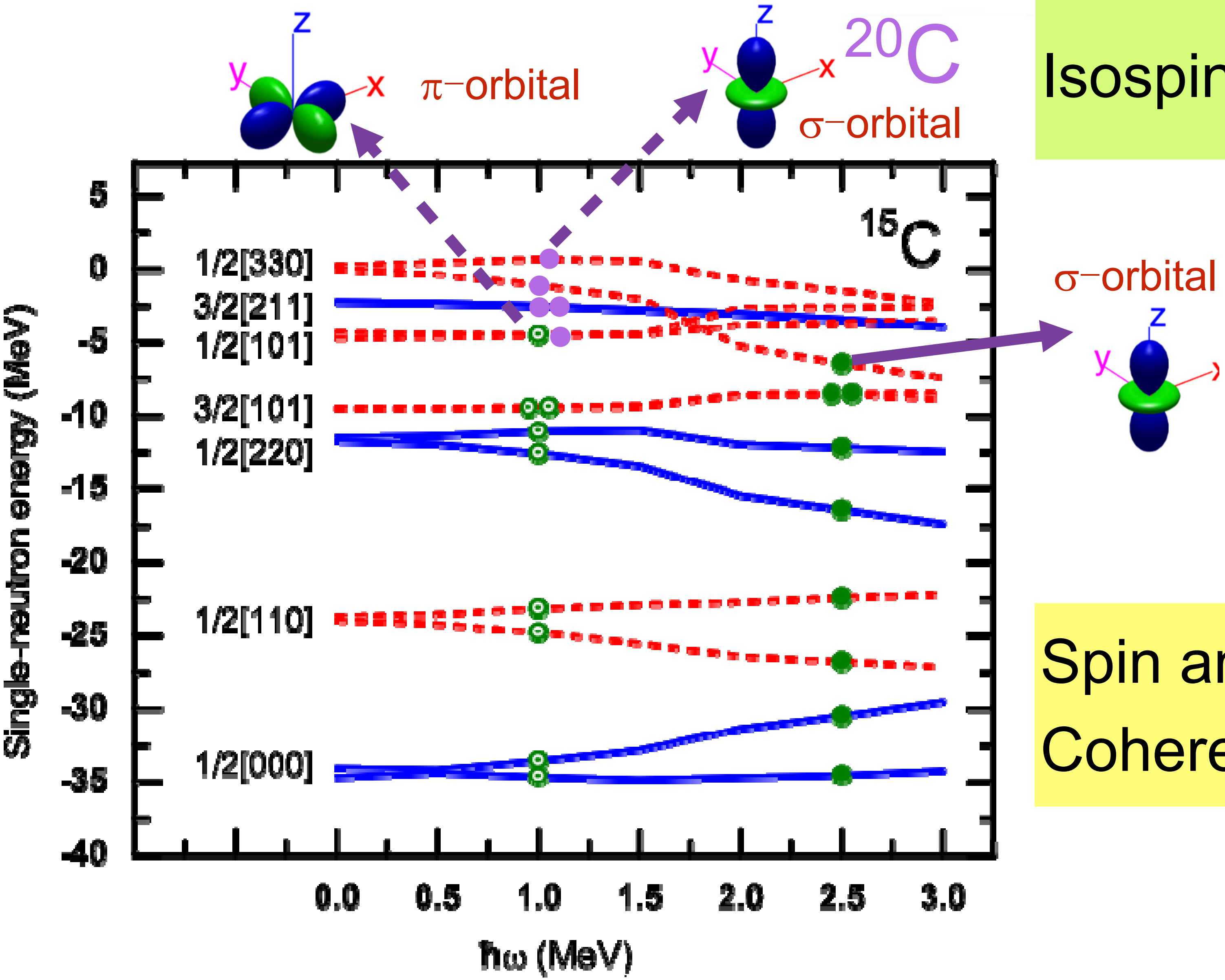
Low spin: σ−orbital; proton stable

High spin: σ−orbital; proton stable

$\hbar\omega$ 0.0 MeV → 3.0 MeV

Zhao, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

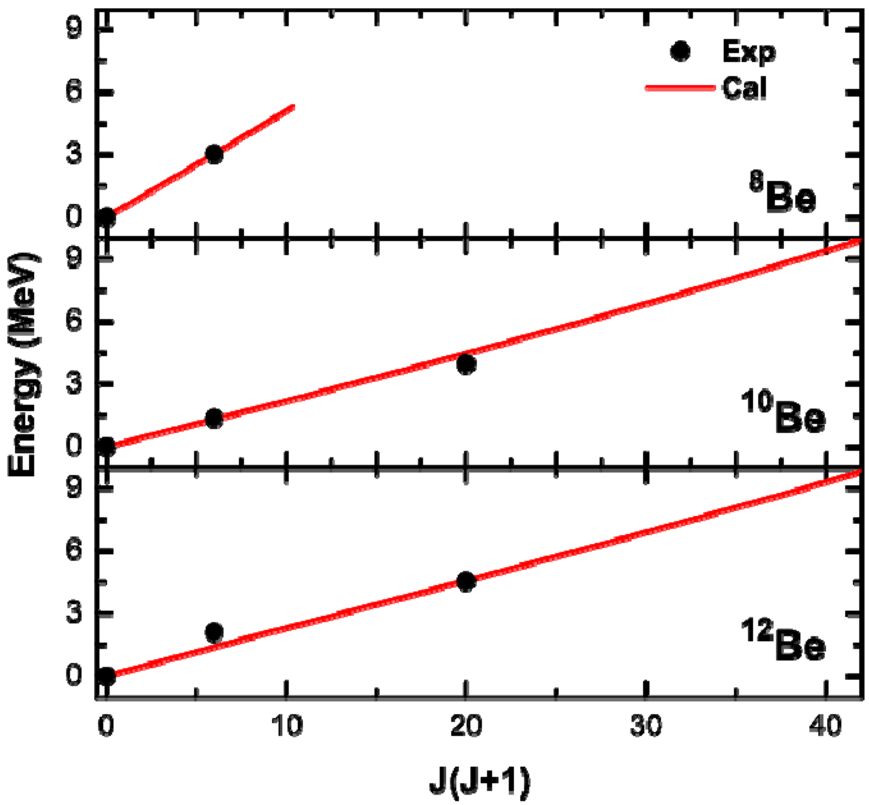
Single-neutron energy

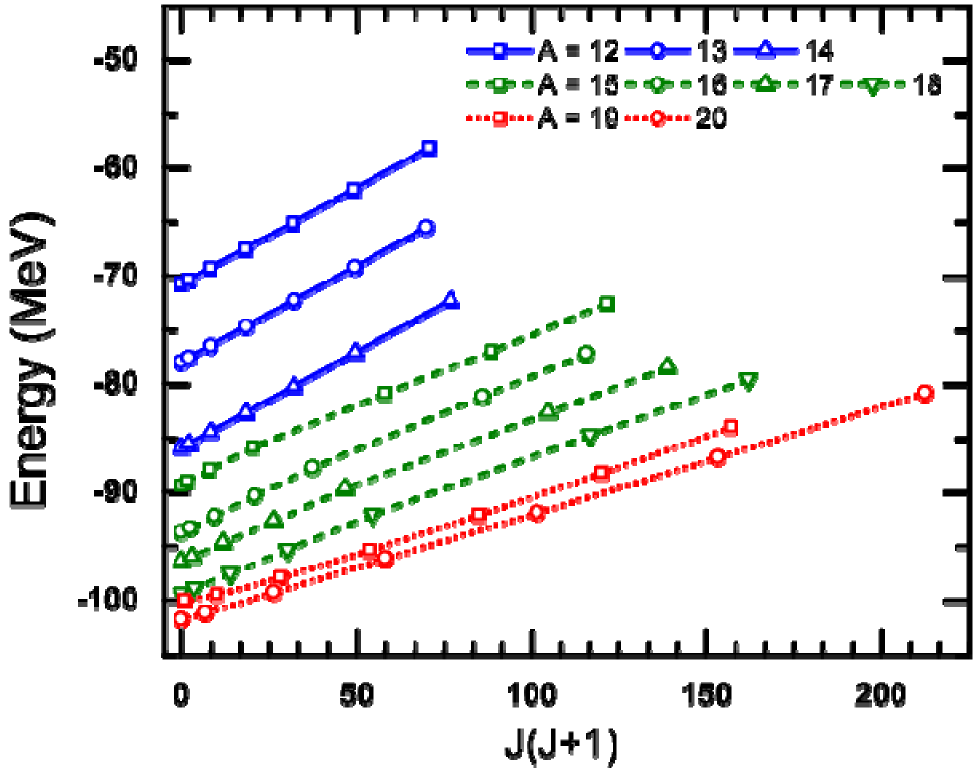


Isospin effects?

Spin and Isospin Coherent Effects

Related experiment is highly demanded !





Zhao, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

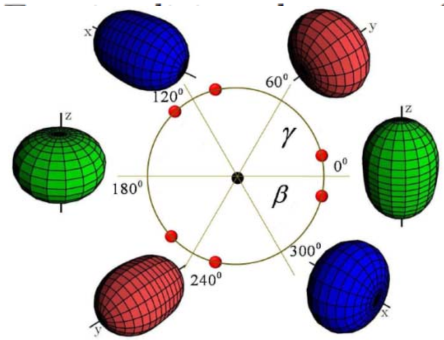
Beyond RMF calculation with GCM for low-spin states

1. **generate a large set of highly correlated RMF+BCS wave functions with triaxial deformation (β,γ) by minimizing**

$$E[\rho,\kappa]=\frac{\langle\Phi(q)|\hat{H}|\Phi(q)\rangle}{\langle\Phi(q)|\Phi(q)\rangle}-\sum_{\mu=0,2}\frac{1}{2}C_\mu(q_{2\mu}-Q_{2\mu})^2$$

$$\begin{aligned}
& E_{\rm DF}[\rho_i,\nabla\rho_i,j_i^\mu,\nabla j_i^\mu] \\
=\; & {\rm Tr}[(\alpha\cdot\mathbf{p}+\beta m)\rho_V] \\
+\; & \int d\boldsymbol{r}\left(\frac{\alpha_S}{2}\rho_S^2+\frac{\beta_S}{3}\rho_S^3+\frac{\gamma_S}{4}\rho_S^4+\frac{\delta_S}{2}\rho_S\triangle\rho_S\right. \\
+\; & \frac{\alpha_V}{2}j_\mu j^\mu+\frac{\gamma_V}{4}(j_\mu j^\mu)^2+\frac{\delta_V}{2}j_\mu\triangle j^\mu \\
+\; & \frac{\alpha_{TV}}{2}j_{TV}^\mu(j_{TV})_\mu+\frac{\delta_{TV}}{2}j_{TV}^\mu\triangle(j_{TV})_\mu \\
+\; & \left.\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-F^{0\mu}\partial_0A_\mu+e\frac{1-\tau_3}{2}j_\mu A^\mu\right),
\end{aligned}$$

mean-field states $|q(\beta,\gamma)\rangle$ are Slater determinants of single-(quasi)particle states from the RMF+BCS calculation with constraints on the mass quadrupole moments $Q_{20}=\sqrt{\frac{5}{16\pi}}\langle 2z^2-x^2-y^2\rangle$ and $Q_{22}=\sqrt{\frac{15}{32\pi}}\langle x^2-y^2\rangle$, where the deformation parameters β,γ are related to the quadrupole moments by $\beta=\frac{4\pi}{3AR^2}Q_{20}$, $\gamma=\tan^{-1}(\sqrt{2}\frac{Q_{22}}{Q_{20}})$, respectively, with $R=1.2A^{1/3}$ and A



Beyond RMF calculation with GCM for low-spin states

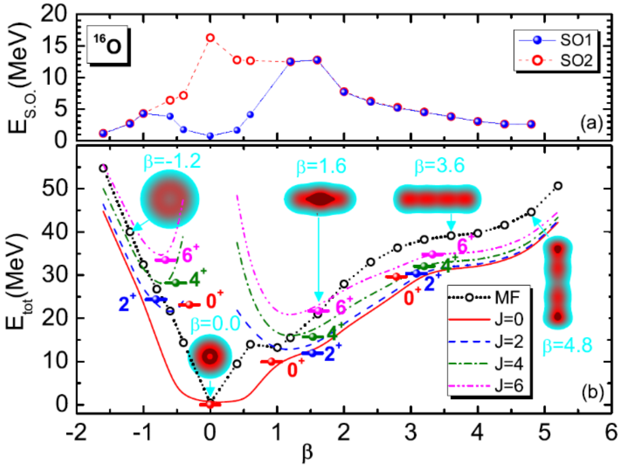
- The wave function of nuclear low-spin state is given by the superposition of a set of both particle-number and angular-momentum projected (PNAMP) quadrupole deformed mean-field states in the framework of GCM

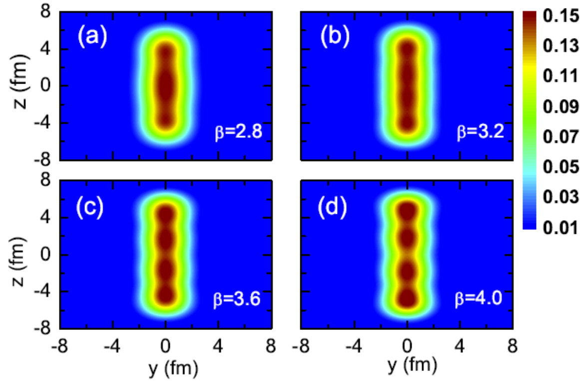
$$|JNZ;\alpha\rangle = \sum_{q,K} f_{\alpha}^{JNZK}(q)\hat{P}^{J}_{MK}\hat{P}^{N}\hat{P}^{Z}|q(\beta,\gamma)\rangle.$$

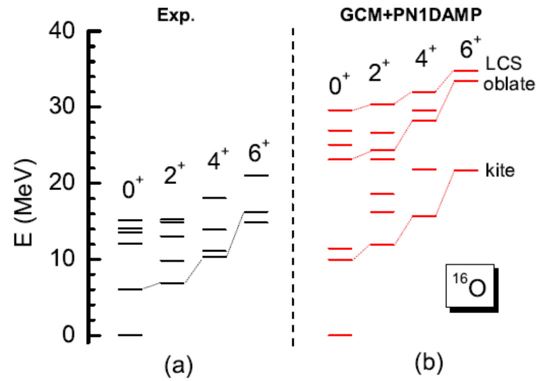
Minimization of nuclear total energy with respect to the coefficient f leads to the Hill-Wheeler-Griffin (HWG) equation (**Restricted to be axially deformed, and K=0**)

$$\sum_{\beta'}[\mathcal{H}^{J}(\beta,\beta') - E^{J}_{\alpha}\mathcal{N}^{J}(\beta,\beta')]f_{\alpha}^{JNZ}(\beta') = 0,$$

CDFT+GCM: clustering in light nuclei







- Linear-Chain-Structure (LCS) in the low-spin GCM states with moment of inertia around 0.11 MeV is found.
- 4-alpha clusters stay in z-axis and nucleons occupy the states in a nonlocal way.
- Spin and orbital angular momenta of all nucleons are parallel in the LCS states.
- Fully microscopic GCM calculation has reproduced the excitation energies and B(E2) values rather well for the rotational band built on the second 0^+ state.

Yao, Itagaki, Meng, Phys. Rev. C 90, 054307 (2014)

- Introduction
- Theoretical Framework
- Results and Discussion
- Summary

Covariant density functional

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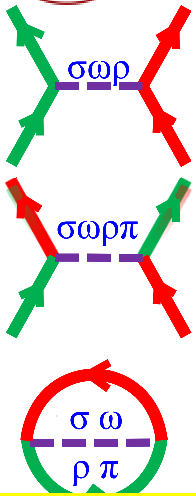
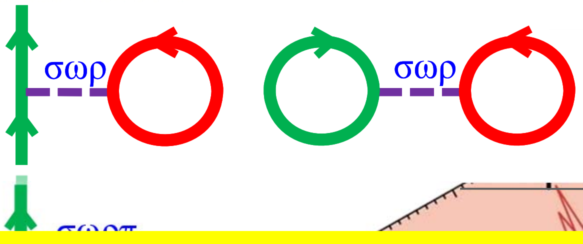
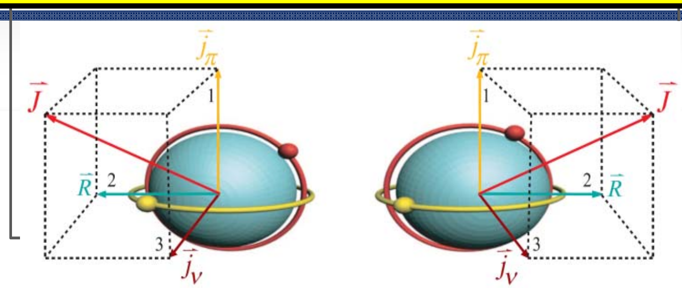
Progress in Physics. 31(2011)199-336.

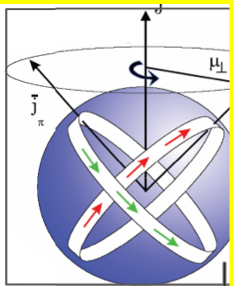


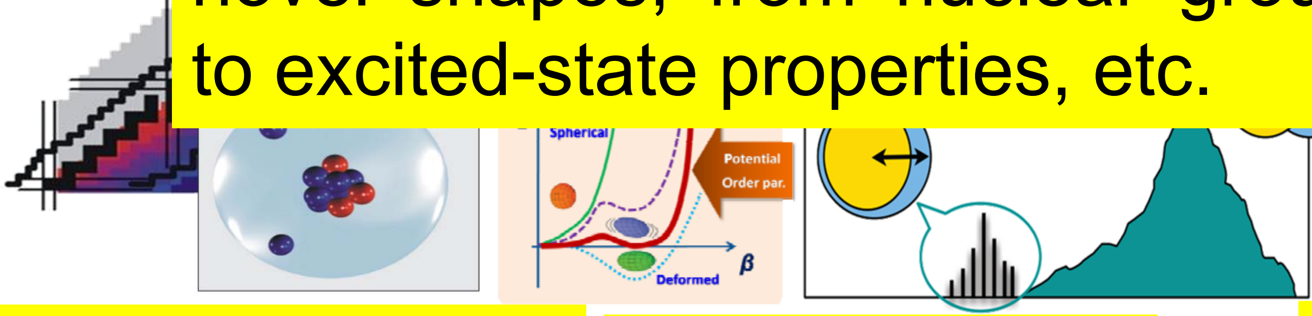


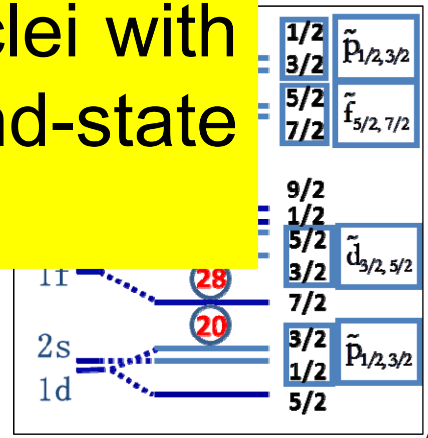


The relativistic density functional theories have been proved to be very successful in describing a large variety of nuclear phenomena from finite nuclei to nuclear matter, from stable to extreme unstable nuclei, from spherical shape to nuclei with novel shapes, from nuclear ground-state to excited-state properties, etc.

Frontiers of F







Prog. Part. Nucl. Phys. 57 (2006) 470

J. Phys. G42 (2015) 093101

Phys. Rep. 570 (2015) 1-84

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Summary

- Novel shape, rod-shaped C isotopes, known to be difficult to stabilize for a long time, has been studied
- The advantages of cranking CDFT include (i) the cluster structure is investigated without assuming the existence of clusters a priori, (ii) the nuclear currents are treated self-consistently, (iii) the density functional is universal, and (iv) a microscopic picture can be provided in terms of intrinsic shapes and single-particle shells self-consistently.
- Two mechanisms to stabilize the rod shape: rotation (high spin) and adding neutrons (high Isospin), coherently work in C isotopes
- Coherent Effects: Rotation makes the valence sigma neutron-orbital lower, and thus 1) lower the sigma proton orbitals 2) enhances the prolate deformation of protons

Outlook: bend motion? valence proton? …

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In collaboration with

Naoyuki Itagaki, Jiangming Yao, Pengwei Zhao

Thank you for your attention!