Toward a relativistic *ab initio* description for nuclear structure

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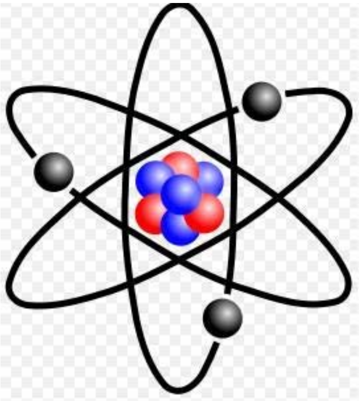
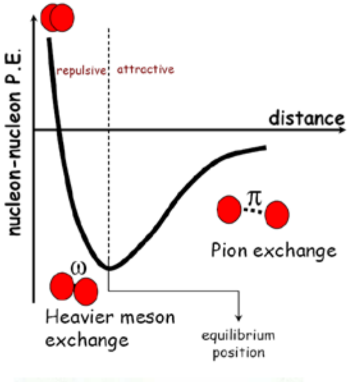
Milestone toward the nuclear model

During the hundred years' struggling, in the development of nuclear physics itself, there emerged a lot of significant milestones, including

The discovery of neutron by Chadwick which verified the composition of nucleus as protons and neutrons

The meson-exchange theory for the interaction between nucleons by Yukawa

H. Euler, Z. Physik 105, 553 (1937)
Heisenberg's student who calculated the nuclear matter in 2nd order perturbation theory

First generation nuclear model：mean field approximation

Nuclear Force

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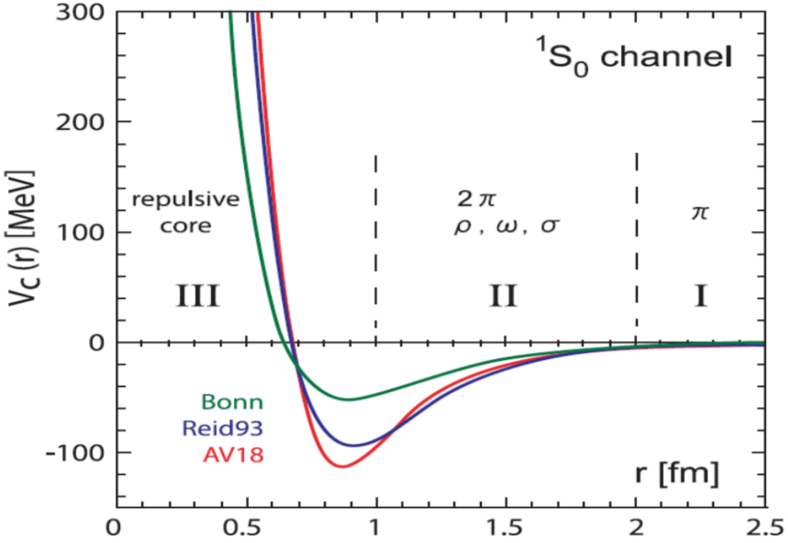
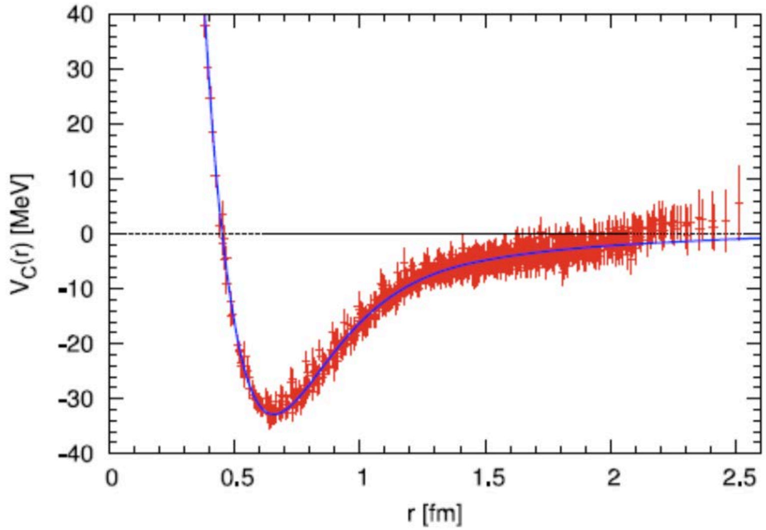
1. High precision nuclear force via fitting NN scattering - phenomenological;
2. From QCD - non-perturbative.
3. Non-perturbative QCD at low energy – novel computational approach.

各种唯象核力



格点QCD初步计算



Ishii, Aoki, Hatsuda, Phys. Rev. Lett. 92 (2007) 022001

The achievement is both a computational *tour de force* and a triumph for theory.

----- 《Nature》 2007 Research Highlights

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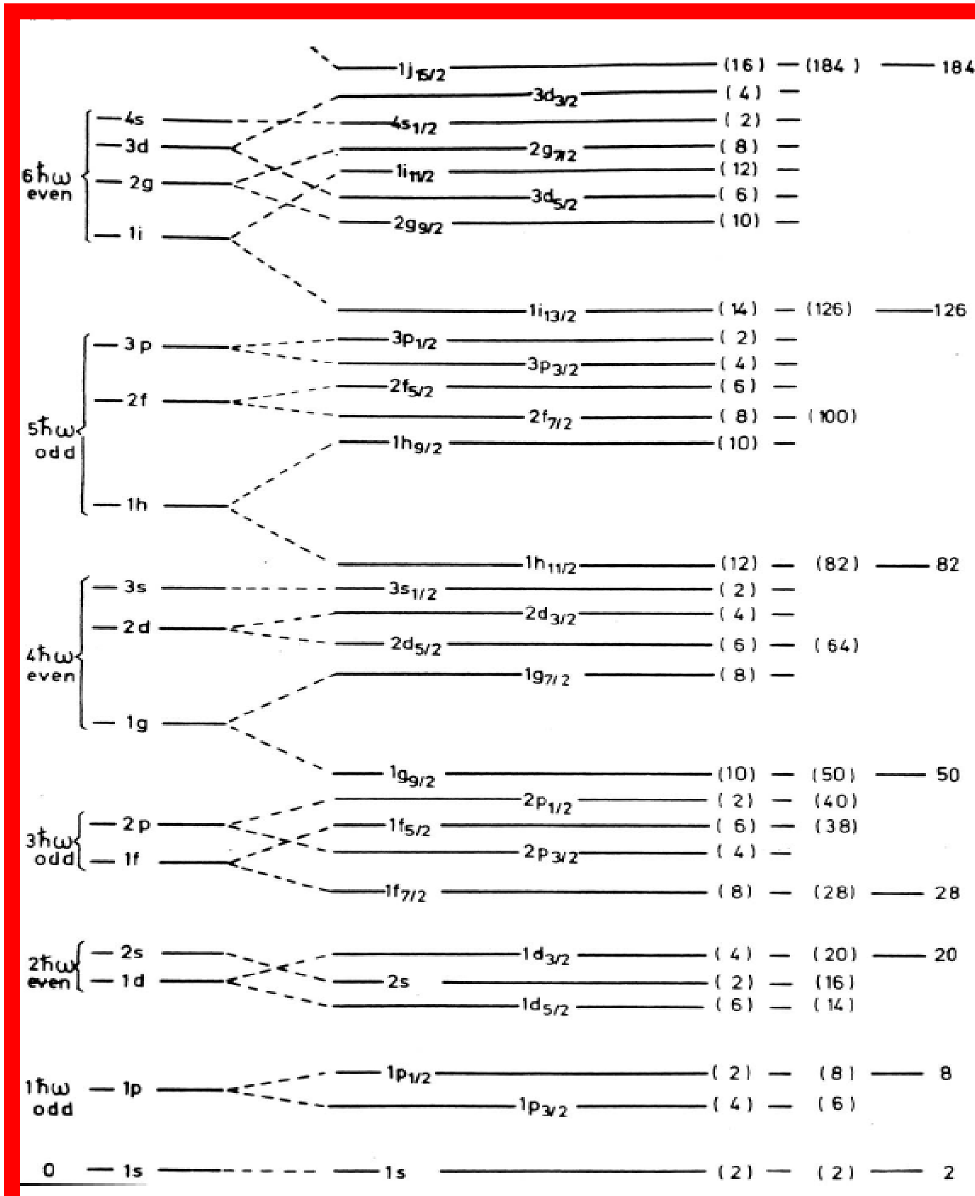
Shell Model



J. H. D. Jensen

M. G. Mayer

E. P. Wigner

Nobel Prize in Physics 1963

Strong spin-orbit interaction

Great for:

magic numbers
ground state properties
some low lying excited states

Lead to deformed Nilsson model

S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. 29, No.16(1955).
S. G. Nilssion, et al., Nucl. Phys. A131(1969) 1.

Totally fails for nuclear bulk properties

Shell Model and Collective model

The independent particle shell model of nucleus by Mayer and Jensen *et al.*, and the collective Hamiltonian for nuclear rotation and vibration by Bohr and Mottelson, etc. However, since 1950s, nuclear physics stepped into a more challenging stage.

- Although the independent particle shell model could describe the single-particle motion in a nucleus with a phenomenological mean potential, **it cannot provide even a qualitative description for the nuclear bulk properties.**

- On the contrary, a unified phenomenological description of nuclear vibration and rotation can be achieved by the collective Hamiltonian whereas **it is helpless in understanding the motion of a single nucleon.**

J. H. D. Jensen

M. G. Mayer

E. P. Wigner

Nobel Prize in Physics 1963

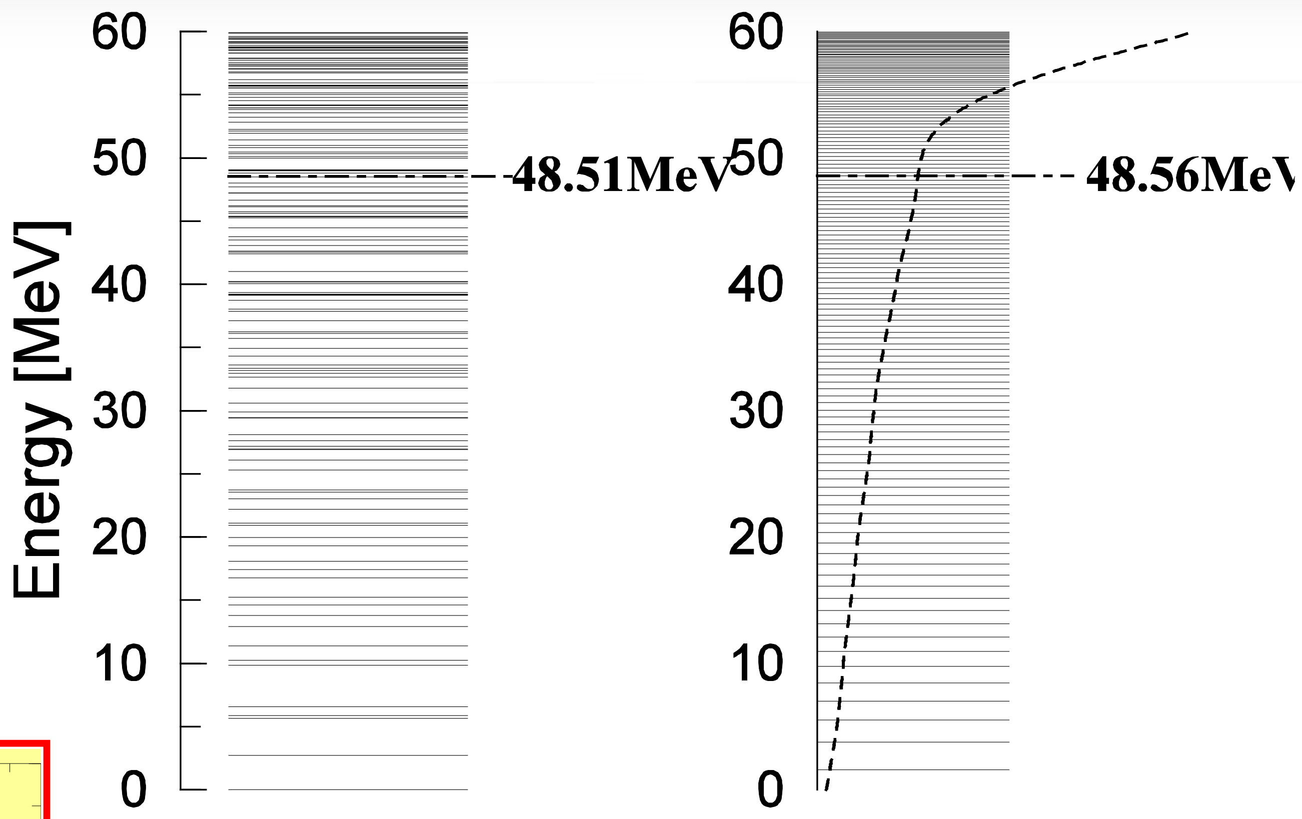
A. N. Bohr

B. R. Mottelson

J. Rainwater

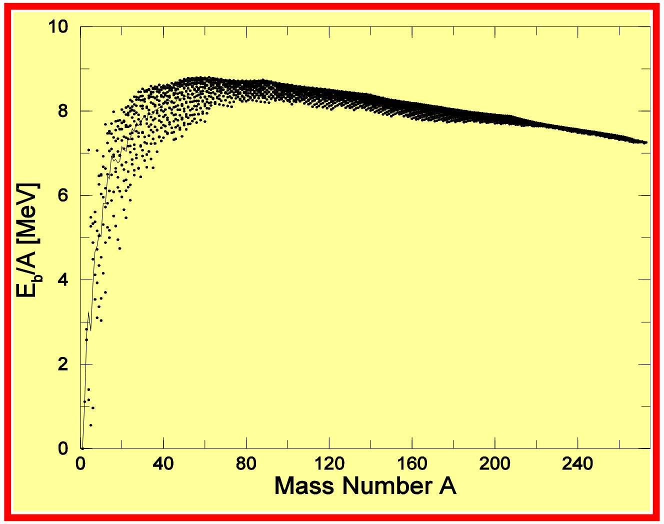
Nobel Prize in Physics 1975

Strutinsky shell correction



Compromise between Shell model and collective model

Great success for
FRDM
WS4 …



V.M. Strutinsky,
Shell effects in nuclear masses and deformation energies, Nuclear Physics A 95 (1967) 420
Times Cited: 1,664
"Shells" in deformed nuclei, Nuclear Physics A 122 (1968) 1
Times Cited: 1,040

Mass models

Finite-Range Droplet Model (FRDM)

P. Möller, J.R. Nix, W.D. Myers, W.J. Swiatecki, At. Data Nucl. Data Tables 59, 185 (1995).

Times Cited: 2,385   Error of the mass model is 0.669 MeV

Weizsäcker-Skyrme (WS) formula

"Isospin for S-O & E_sym + mirror nuclei"

inspired by the Skyrme energy-density functional and a macroscopic-microscopic mass formula, with an rms deviation of 336 keV with respect to the 2149 measured masses in 2003 Atomic Mass Evaluation.

N. Wang, M. Liu and X. Z. Wu, Phys. Rev. C 81, 044322 (2010).
N. Wang, Z. Y. Liang, M. Liu and X. Z. Wu, Phys. Rev. C 82, 044304 (2010).
M. Liu, N. Wang, Y. G. Deng, and X. Z. Wu, Phys. Rev. C 84, 014333 (2011).

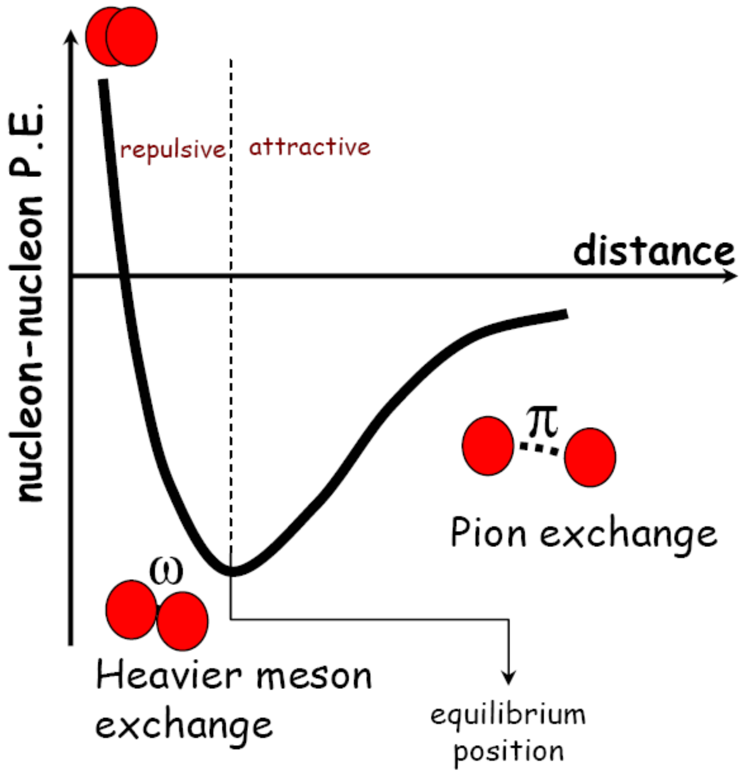
Taking into account the surface diffuseness effect, the rms deviation with 2353 known masses falls to 298 keV.

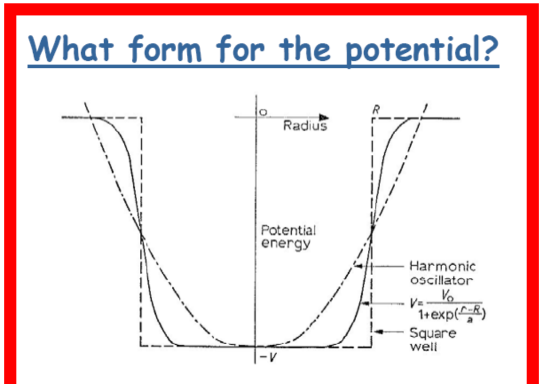
N. Wang, M. Liu, X. Z. Wu and J. Meng, Phys. Lett. B 734, 215 (2014).

Second generation nuclear model：effective NN interaction

Nuclear Force

How to achieve microscopically and self-consistently a unified description of the single-nucleon and collective motions of nucleus based on the strong interaction theory is a crucial question to be answered by nuclear scientists.





Many-body theory

Many-body problems

$$\hat{H}\Psi = \left[-\frac{\hbar^2}{2m}\sum_i \nabla_i^2 + \sum_{i>j} V_{ij} \right]\Psi = E\Psi$$

$$\hat{H} = \sum_i \left[-\frac{\hbar^2}{2m}\nabla_i^2 + U(r_i) \right] + \sum_{i>j} V_{ij} - \sum_i U(r_i)$$

Mean field potential **Residual interaction**

The **self-consistent mean-field approach to nuclear structure is** analogous to **Kohn-Sham Density Functional Theory.**

Density functional theory (DFT) , with the name comes from the use of functionals of the particle density, is aquantum mechanical theory used in physics and chemistry to investigate the structure (mainly the ground state) of many-particle systems.

Many-body theory

- *Ab inito*

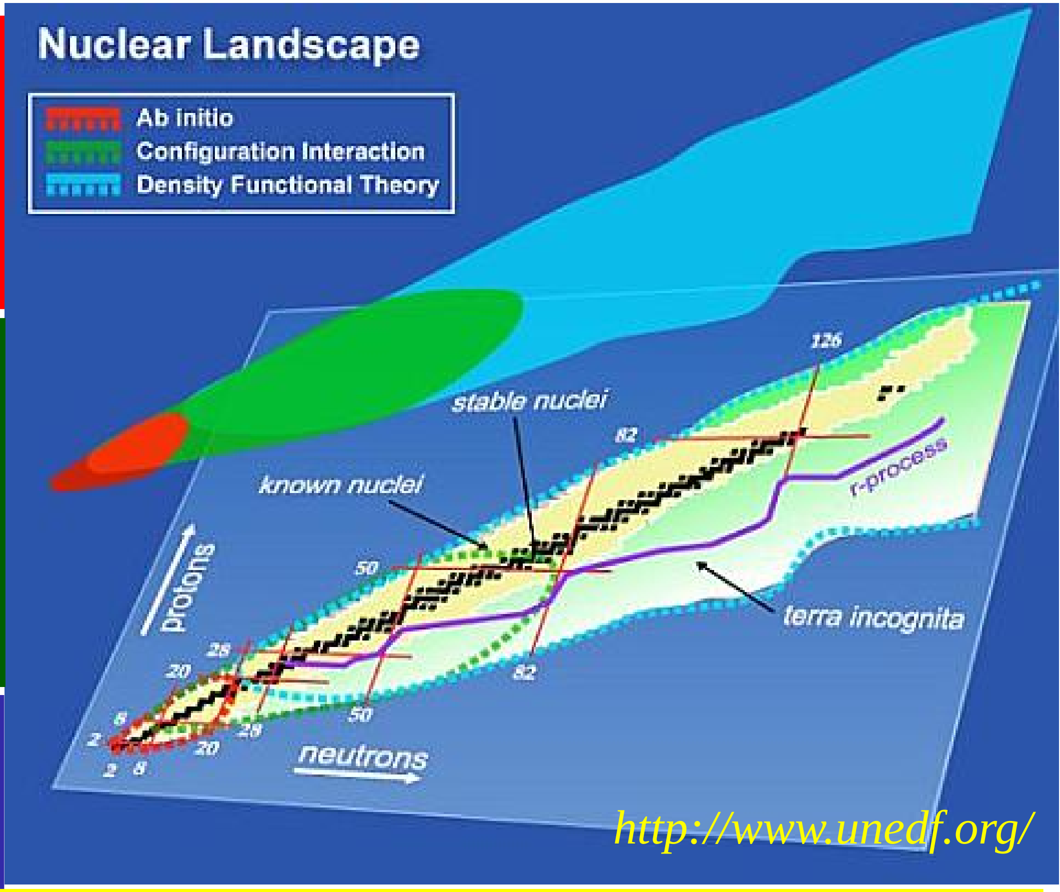
  Navratil, Vary, Barrett Phys. Rev. Lett. 84 (2000) 5728
  Bogner, Furnstahl, Schwenk
  Prog. Part. Nucl. Phys. 65 (2010) 94
  …

- Shell model

  Caurier, Martínez-Pinedo, Nowacki, Poves, Zuker,
  Rev. Mod. Phys. 77 (2005) 427
  Otsuka, Honma, Mizusaki, Shimizu, Utsuno,
  Prog. Part. Nucl. Phys.47(2001)319
  Brown, Prog. Part. Nucl. Phys. 47 (2001) 517
  …

- **Density functional theory**

  Jones and Gunnarsson,
  Rev. Mod. Phys., 61 (1989) 689
  Bender, Heenen, Reinhard,
  Rev. Mod. Phys., 75 (2003) 121
  Ring, Prog. Part. Nucl. Phys.37(1996)193
  Meng, Toki, Zhou, Zhang, Long, Geng,
  Prog. Part. Nucl. Phys. 57 (2006) 470
  …



密度泛函理论有希望给出核素图上所有原子核性质的统一描述

Relativistic Density Functional for Nuclear Structure，International Review of Nuclear Physics Vol 10（World Scientific, 2016）

Nuclear Density functional theory

Nuclear DFT has been introduced by **effective Hamiltonians**: by Vautherin and Brink (1972) using the Skyrme model as a vehicle

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

Based on the philosophy of Bethe, Goldstone, and Brueckner one has a density dependent interaction in the nuclear interior G(ρ)

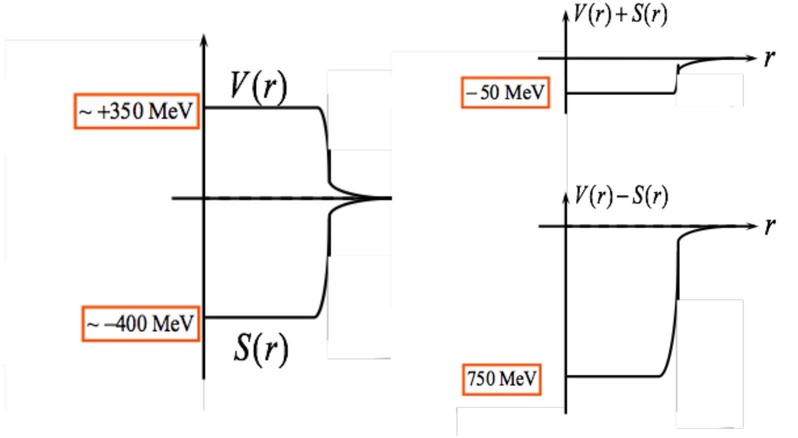
At present, the ansatz for E(ρ) is phenomenological:

- Skyrme: non-relativistic, zero range
- Gogny: non-relativistic, finite range (Gaussian)
- CDFT: Covariant density functional theory

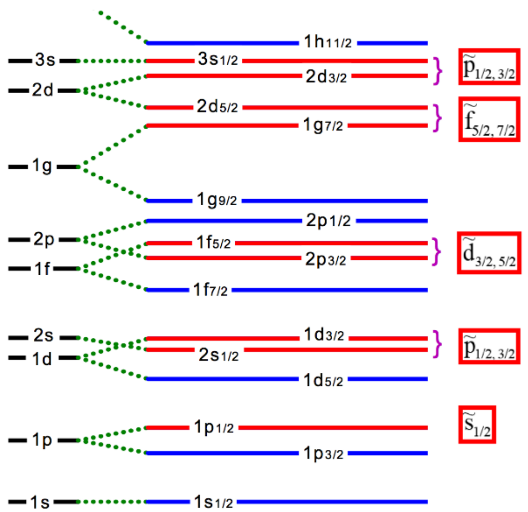
Why Covariant?

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

- ✓ Spin-orbit automatically included
- ✓ Lorentz covariance restricts parameters
- ✓ Pseudo-spin Symmetry
- ✓ Connection to QCD: big V/S ~ ±400 MeV
- ✓ Consistent treatment of time-odd fields
- ✓ Relativistic saturation mechanism
- ✓ … Liang, Meng, Zhou, Physics Reports **570** : 1-84 (2015).



Pseudospin symmetry



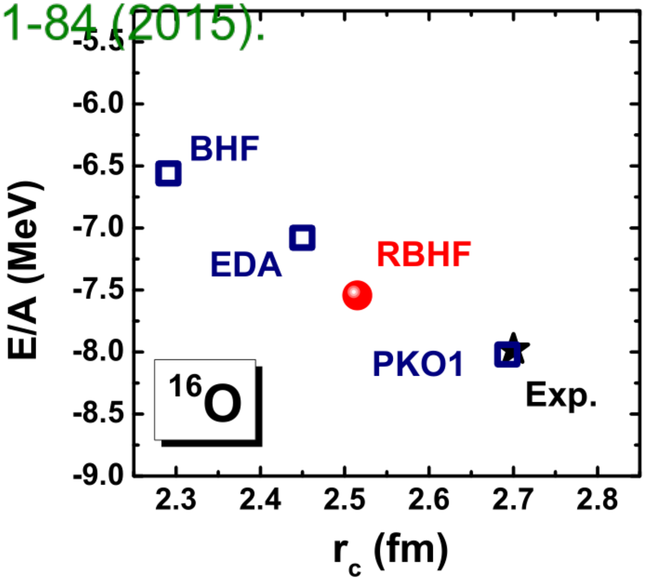
$$\begin{array}{lll} n-1, & l+2, & j=l+3/2 \\ n, & l, & j=l+1/2 \end{array}$$

$$\begin{array}{ll} \text{pseudo-orbit} : & \tilde{l}=l+1 \\ \text{pseudo-spin} : & \tilde{s}=1/2 \end{array}$$

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

Ginocchio PRL 78, 436



Shen et al Chin. Phys. Lett. 33 (2016) 102103

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

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

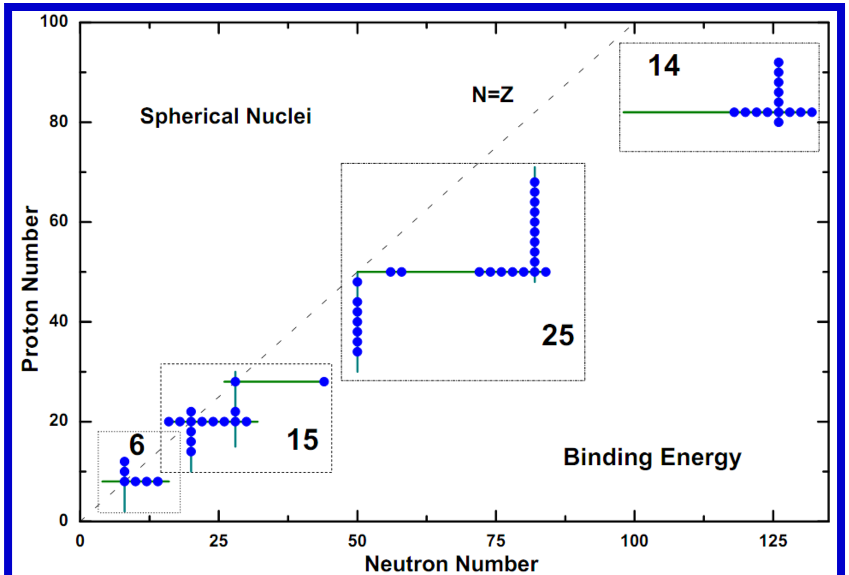
$$E_{2nd} = \frac{1}{2}\int (\alpha_S\rho_S^2 + \alpha_V\rho_V^2 + \alpha_{tV}\rho_{tV}^2)d\mathbf{r}$$

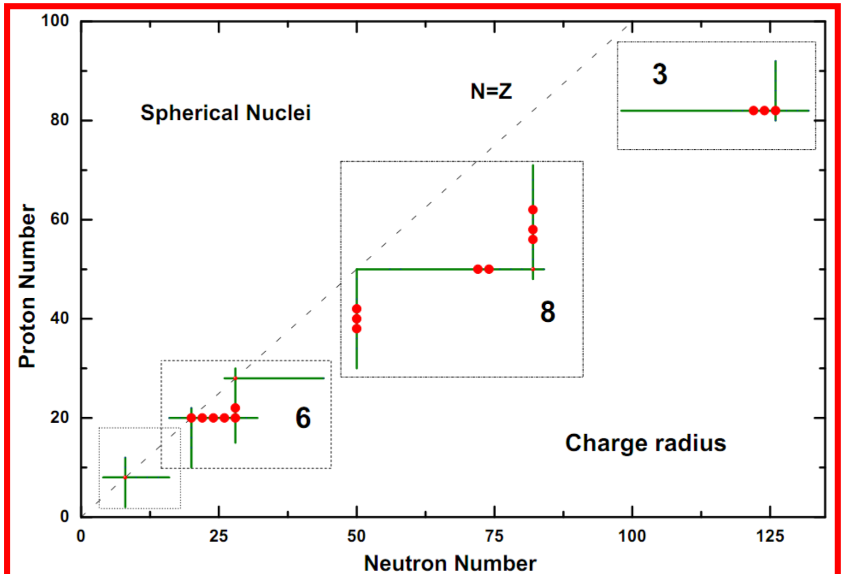
$$E_{hot} = \frac{1}{12}\int (4\beta_S\rho_S^3 + 3\gamma_S\rho_S^4 + 3\gamma_V\rho_V^4)d\mathbf{r}$$

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

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

Relativistic functional PC-PK1





Coupl.	Cons.	PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}
δ_{TV}	$[10^{-10}]$	-4.11112	MeV^{-4}
V_n	$[10^{0}]$	-349.5	$\mathrm{MeV\ fm}^{3}$
V_p	$[10^{0}]$	-330	$\mathrm{MeV\ fm}^{3}$

Zhao, Li, Yao, Meng, PRC 82, 054319 (2010)

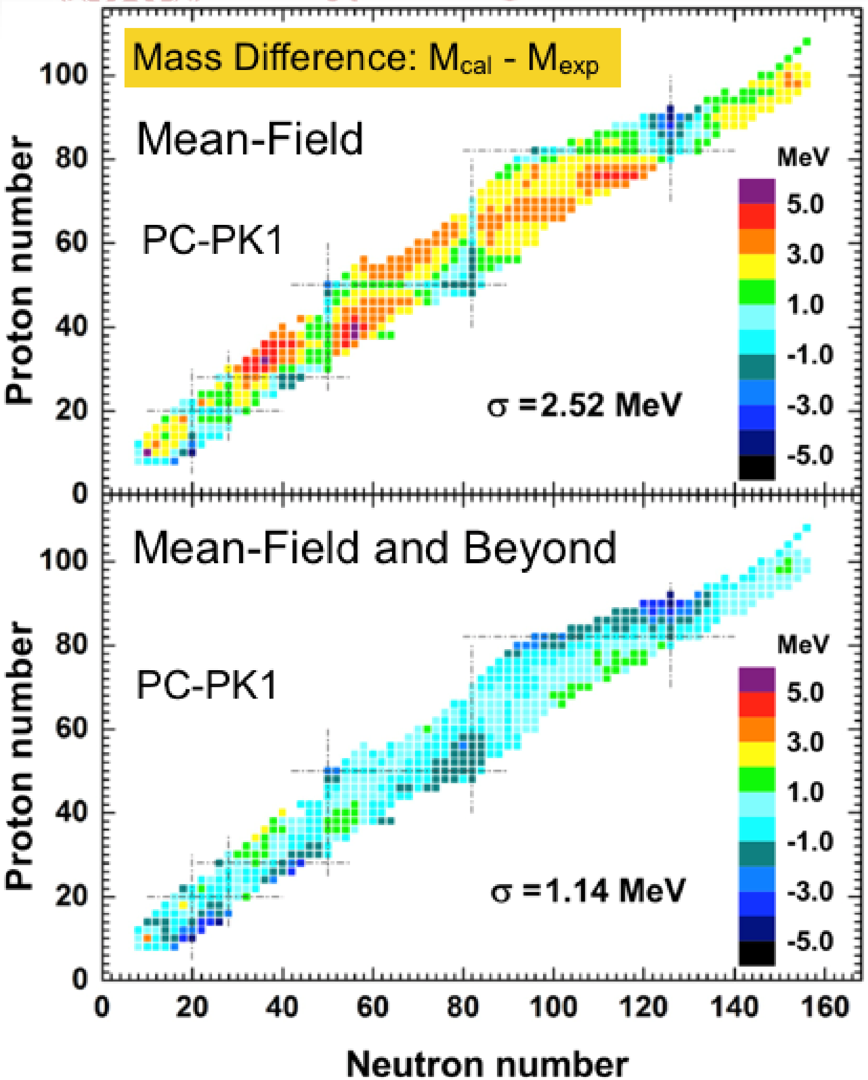
Ground state properties

CDFT, implemented with self-consistency and taking into account various correlations by spontaneously broken symmetries, provide an excellent description for the ground-state properties including

- Total energy and other physical observables as the expectation values of local one-body operators.
- Open shell nuclei with pairing correlations properly treated by generalized CDFT based on BCS or HFB approach.
- Exotic nuclei with extreme neutron or proton numbers, where novel phenomena such as halos may appear.
- …

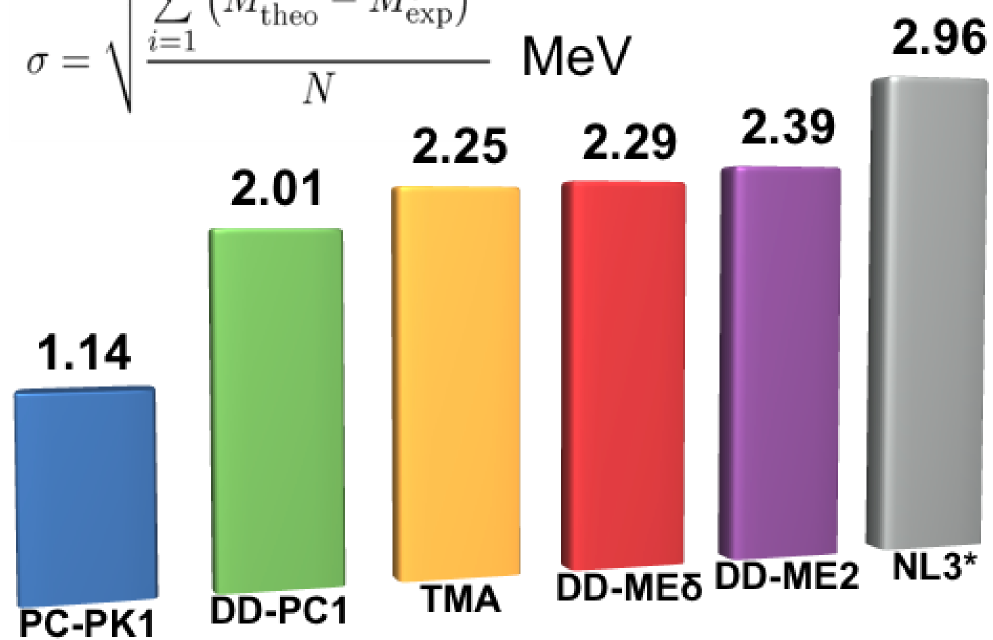
1. Meng, Toki, Zhou, Zhang, Long, Geng, Prog. Part. Nucl. Phys. 57 (2006) 470
2. Meng and Zhou, J. Phys. G: Nucl. Part. Phys. 42 (2015) 093101

Nuclear Masses



Zhao, Li, Yao, Meng, PRC 82, 054319 (2010)
Zhang, Niu, Li, Yao, Meng, Front. Phys. 9 (2014) 529
Lu, Li, Li, Yao, Meng PRC 91 (2015) 027304

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(M_{\rm theo}^{i} - M_{\rm exp}^{i}\right)^2}{N}} \text{ MeV}$$



Agbemava PRC 2014
Geng PTP 2005

Best density-functional description for nuclear masses so far!

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First mass table with the continuum

Atomic Data and Nuclear Data Tables 121–122 (2018) 1–215

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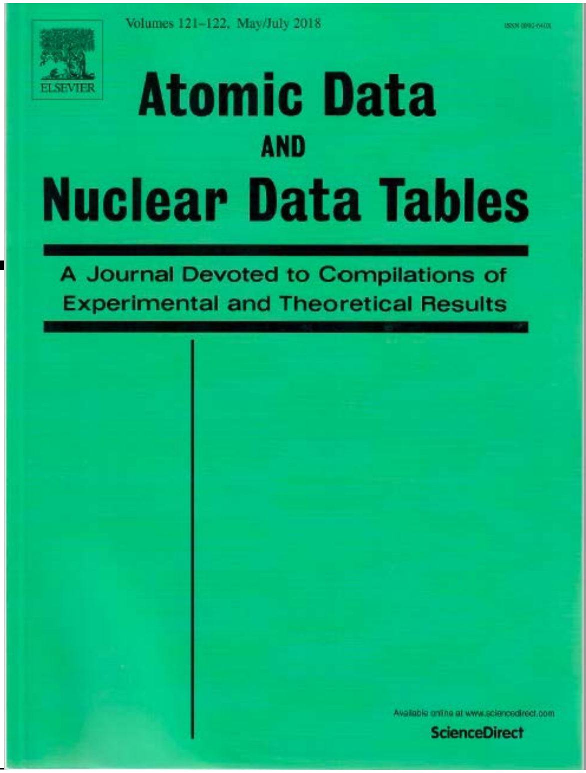

The limits of the nuclear landscape explored by the relativistic continuum Hartree–Bogoliubov theory

X.W. Xia [a], Y. Lim [b,c], P.W. Zhao [d,e], H.Z. Liang [f], X.Y. Qu [a,g], Y. Chen [d,h], H. Liu [d], L.F. Zhang [d], S.Q. Zhang [d], Y. Kim [c], J. Meng [d,a,i,*]

[a] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[b] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*
[c] *Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Republic of Korea*
[d] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[e] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[f] *RIKEN Nishina Center, Wako 351-0198, Japan*
[g] *School of Mechatronics Engineering, Guizhou Minzu University, China*
[h] *Institute of materials, China Academy of Engineering Physics, Sichuan, 621907, China*
[i] *Department of Physics, University of Stellenbosch, Stellenbosch, South Africa*

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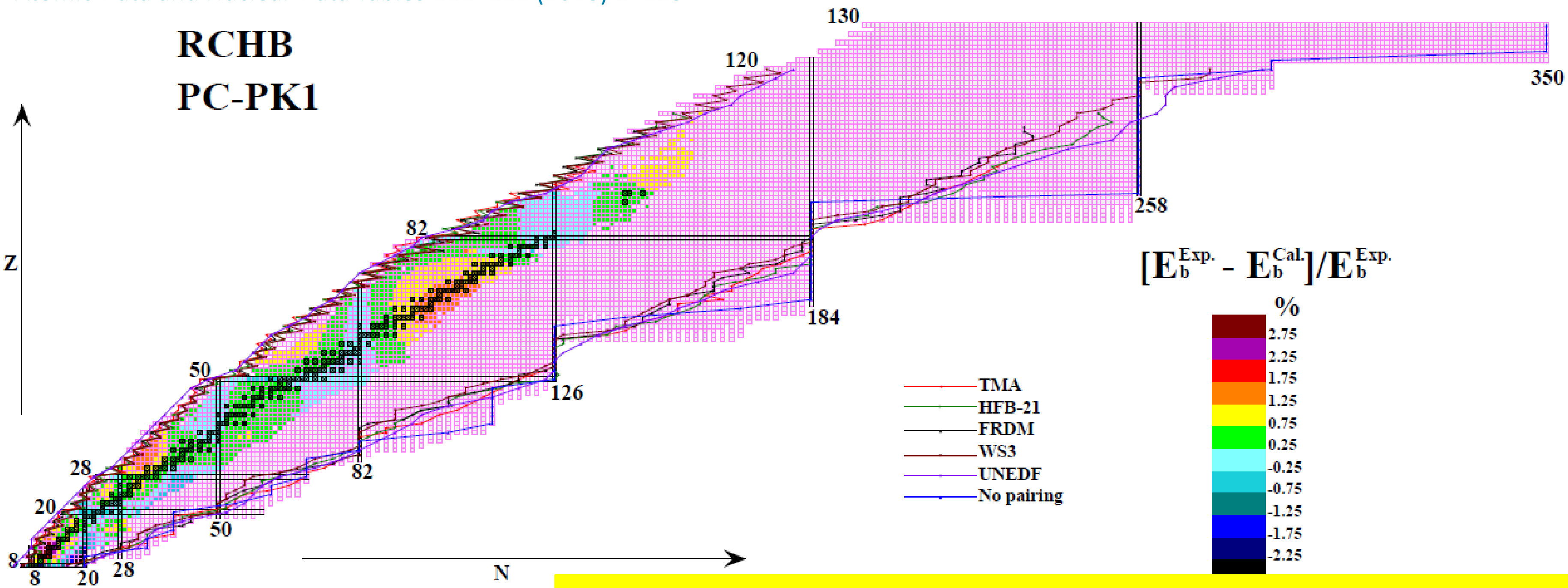
ABSTRACT

The ground-state properties of nuclei with $8 \leqslant Z \leqslant 120$ from the proton drip line to the neutron drip line have been investigated using the spherical relativistic continuum Hartree–Bogoliubov (RCHB) theory with the relativistic density functional PC-PK1. With the effects of the continuum included, there are totally 9035 nuclei predicted to be bound, which largely extends the existing nuclear landscapes predicted with other methods. The calculated binding energies, separation energies, neutron and proton Fermi surfaces,

Drip-lines in variant models

The number of bound nuclides with between 2 and 120 protons is around 7,000 28 JUNE 2012 | VOL 486 | NATURE | 509

Atomic Data and Nuclear Data Tables 121–122 (2018) 1–215



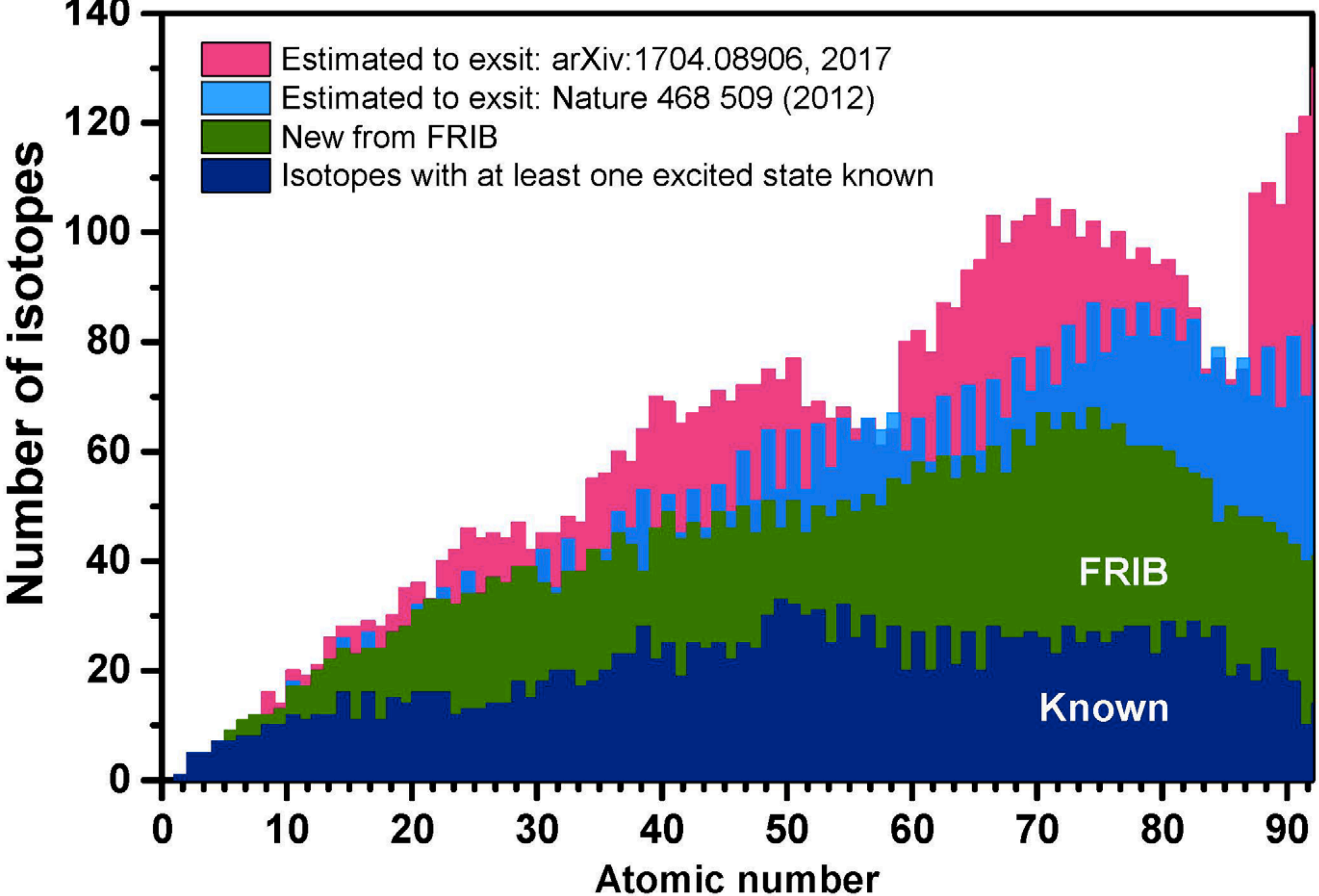
8 ⩽ Z ⩽ 120: 9035 nuclei predicted to be bound

10532 bound nuclei from Z=8 to Z=130 predicted by RCHB theory with PC-PK1. For 2227 nuclei with data, binding energy differences between data and calculated results are shown in different color. The nucleon drip-lines predicted TMA, HFB-21, WS3, FRDM , UNEDF and without pairing correlation are plotted for comparison.

See also: Afanasjev, Agbemava, Ray, Ring, PLB726(2013)680

Possible existing isotopes

Atomic Data and Nuclear Data Tables 121-122(2018)1-215

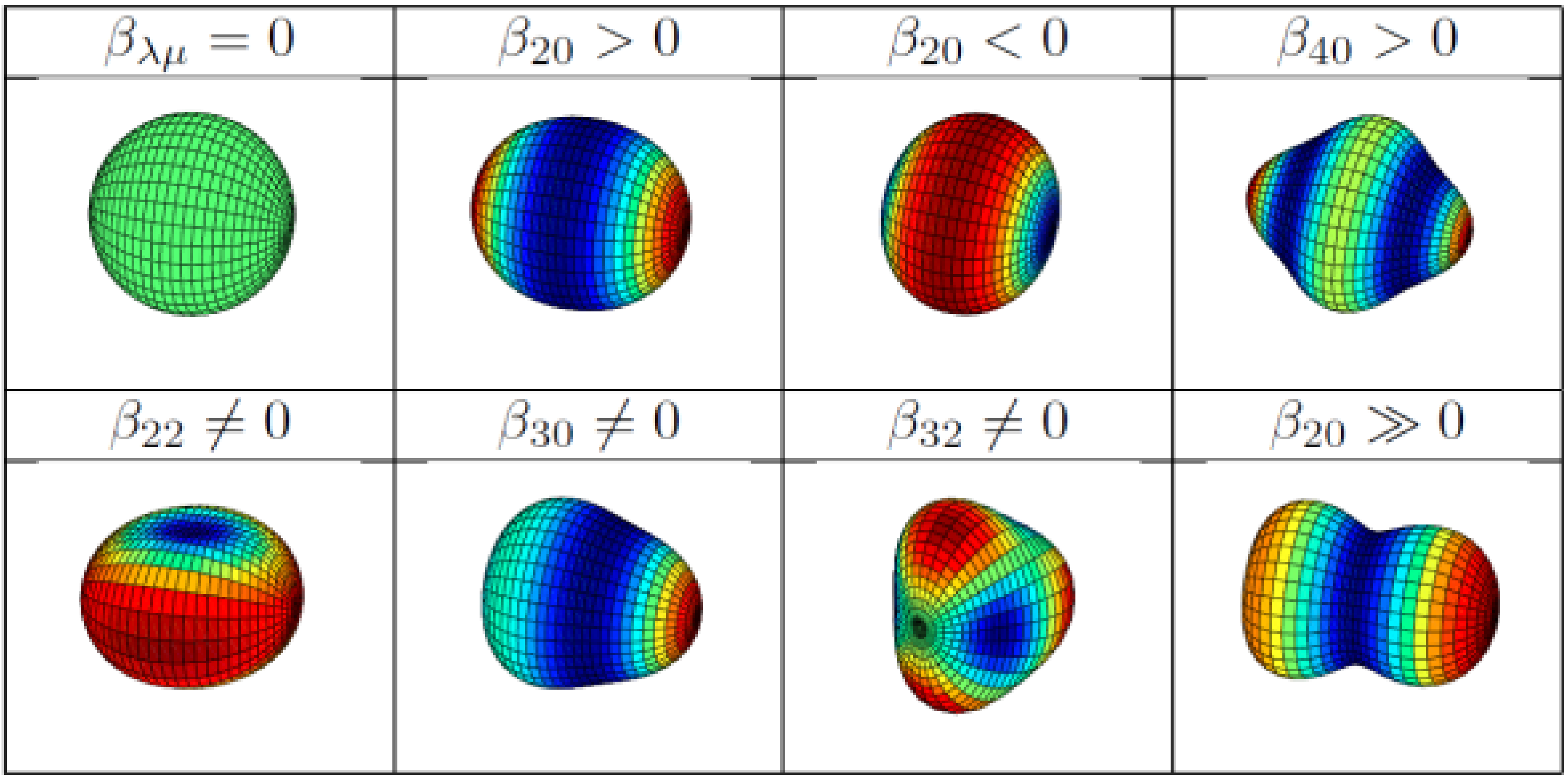


1st workshop on Deformed RHB in continuum mass table

December 05 – 07, 2018

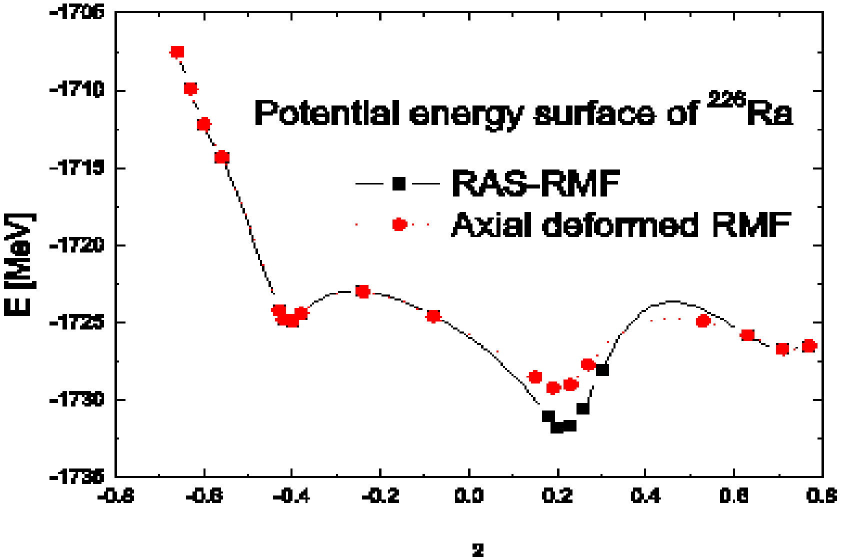
IBS, Daejeon, Korea

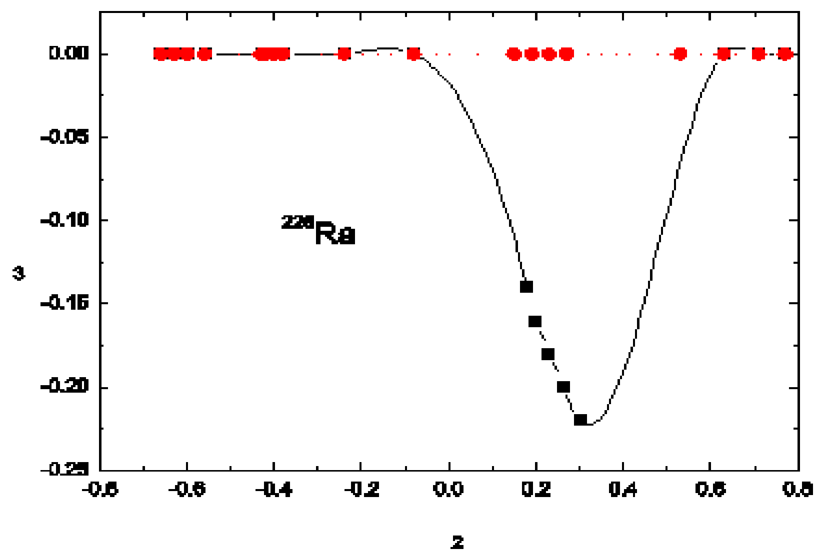
Nuclear Shape

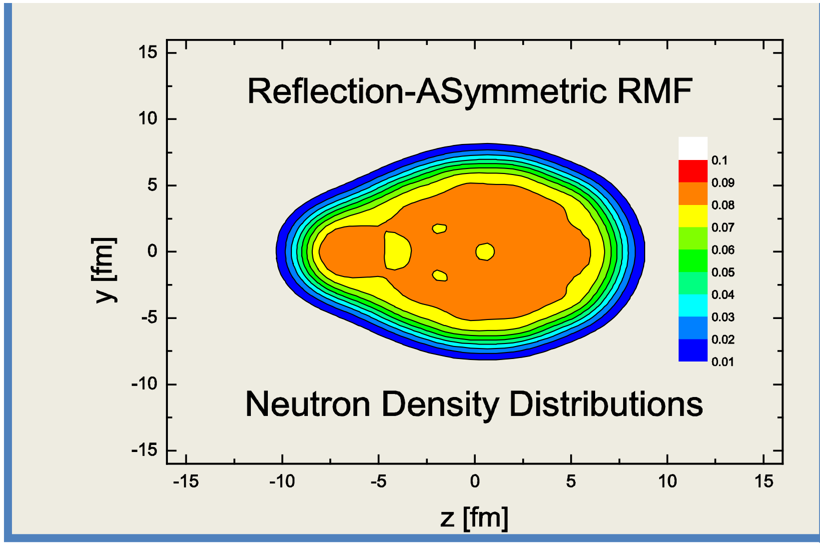


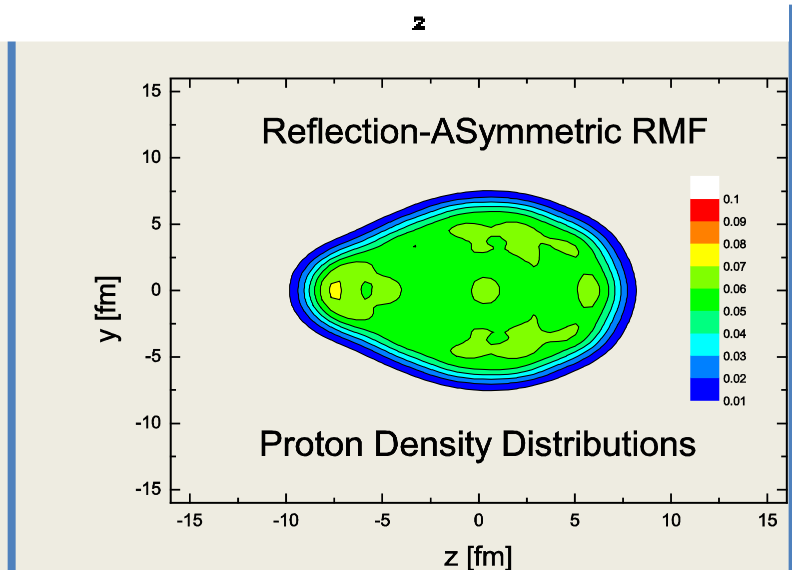
By Bing-Nan Lu

Stability against reflection asymmetry





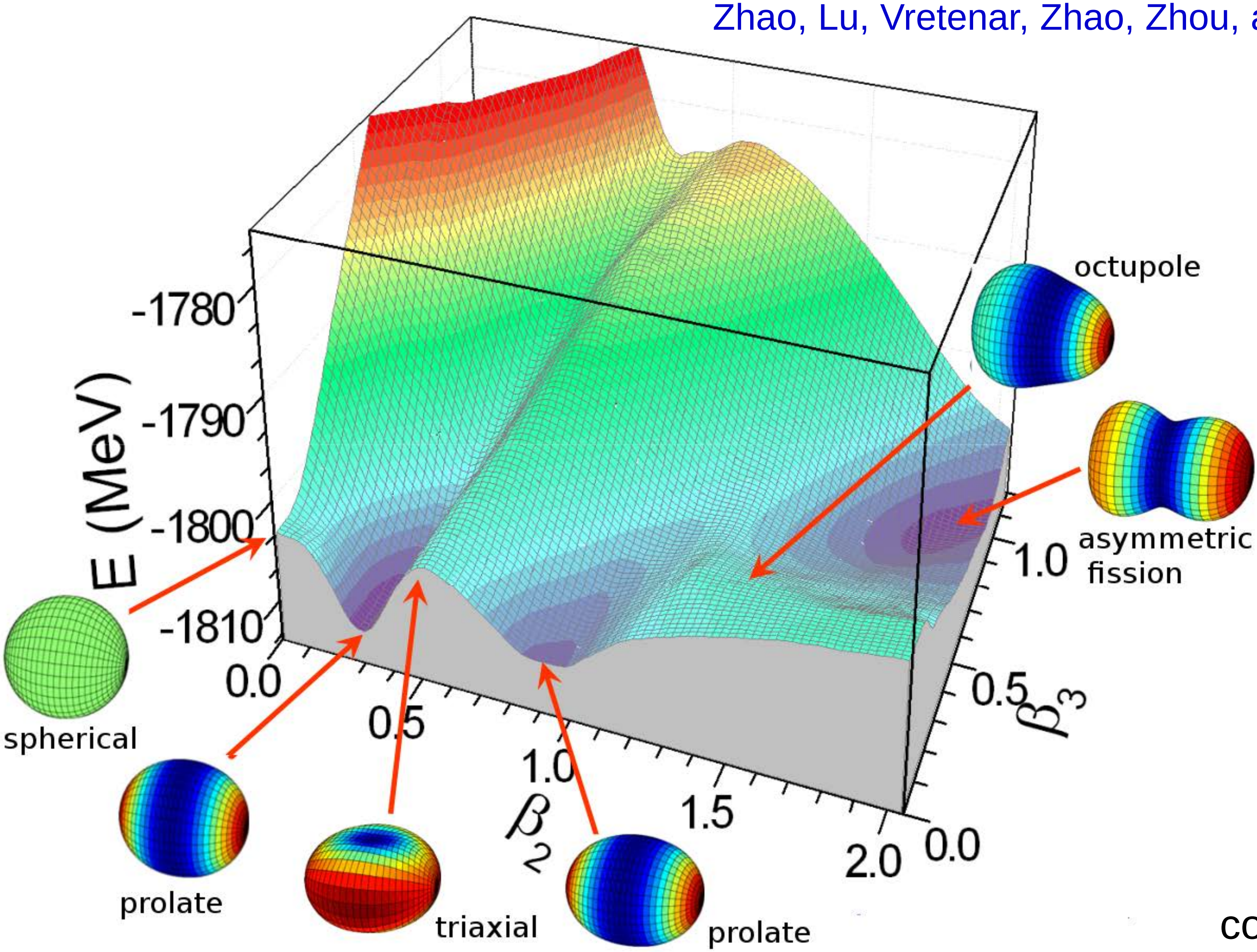




L.-S. Geng, J. Meng, and H. Toki, Chin. Phys. Lett. **24**, 1865 (2007).

Deformation map of ^{240}Pu

Lu, Zhao, Zhou, PRC 85, 011301 (2012)
Zhao, Lu, Zhao, Zhou, PRC 86, 057304 (2012)
Lu, Zhao, Zhao, Zhou, PRC 89, 014323 (2014)
Zhao, Lu, Vretenar, Zhao, Zhou, arXiv:1404.5466 (2014)



courtesy of B.N. LU

Multidimentionally constrained CDFT

- MDC-CDFT: all $\beta_{\lambda\mu}$ with even μ included
- Triaxial & octupole shapes both crucial around the outer barrier

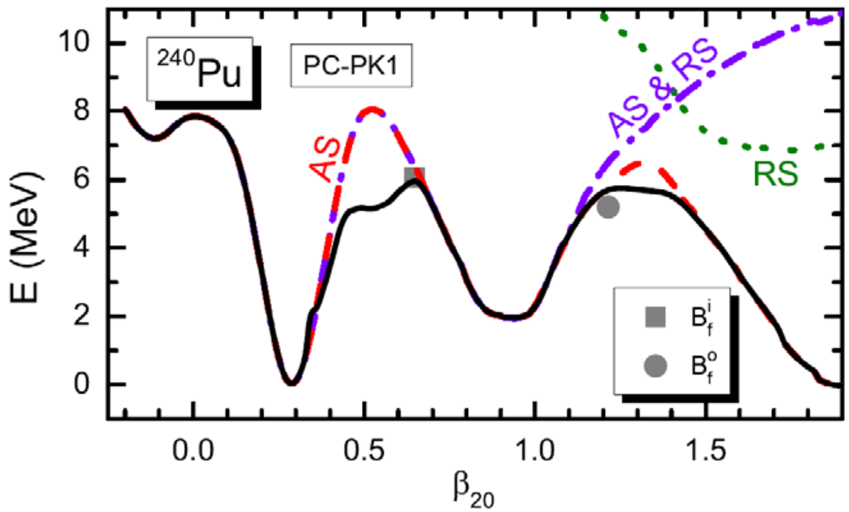
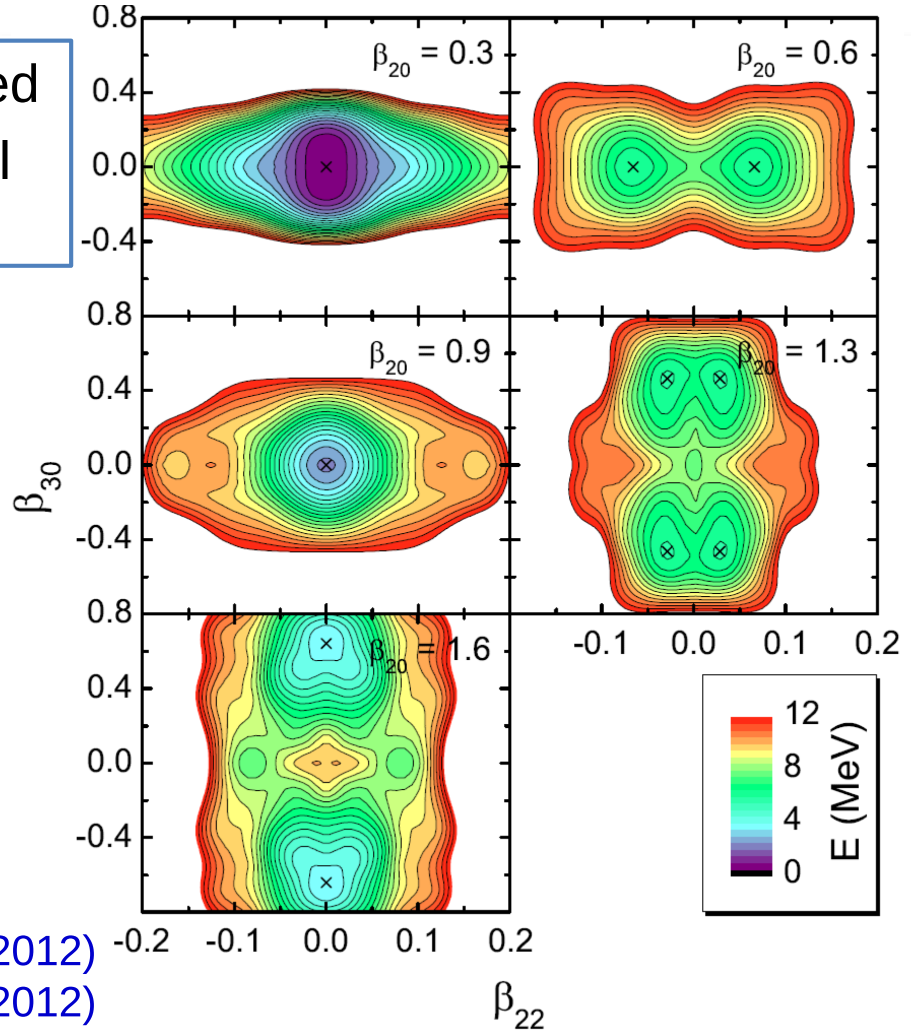


Figure: Potential energy curve of ^{240}Pu

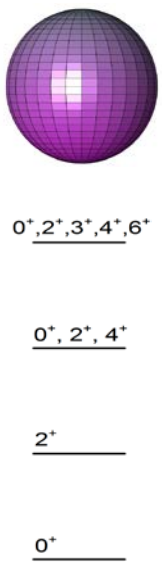


Lu, Zhao, Zhou, PRC 85, 011301 (2012)
Zhao, Lu, Zhao, Zhou, PRC 86, 057304 (2012)
Lu, Zhao, Zhao, Zhou, PRC 89, 014323 (2014)
Zhao, Lu, Vretenar, Zhao, Zhou, arXiv:1404.5466 (2014)

Figure: 3D PES of ^{240}Pu

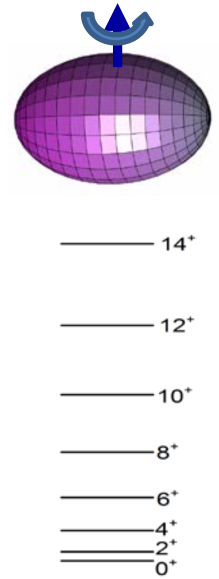
Triaxial deformation only: Abusara, Afanasjev, Ring PRC 85, 024314 (2012)

Chiral rotation and MχD



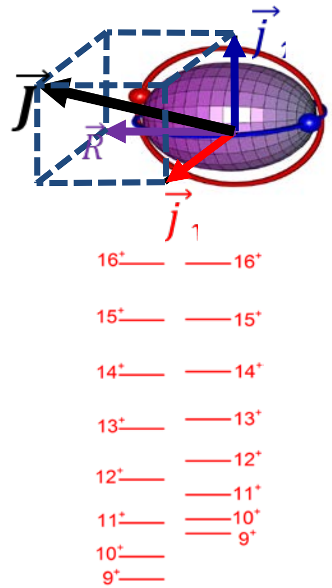
$$H = \frac{1}{2}\sum_{\mu}\{B_2|\dot{\alpha}_{2\mu}|^2 + C_2|\alpha_{2\mu}|^2\}$$

vibration



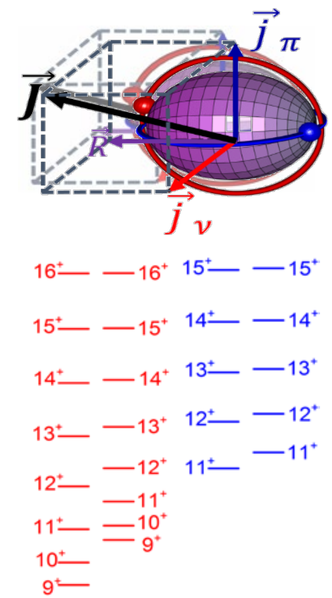
$$H = \sum_{i=1}^{3}\frac{\hat{R}_i^2}{2\mathcal{J}_i}$$

Rotation



$$H = \sum_{i=1}^{3}\frac{\hat{R}_i^2}{2\mathcal{J}_i} + \sum_{\tau\nu}\varepsilon_{\tau\nu}a^{+}_{\tau\nu}a_{\tau\nu}$$

Chiral Rotation



$$H(q) = \sum_{i=1}^{3}\frac{\hat{R}_i^2}{2\mathcal{J}_i(q)} + \sum_{\tau\nu}\varepsilon_{\tau\nu}(q)a^{+}_{\tau\nu}(q)a_{\tau\nu}(q) + V(q)$$

MχD

A. Bohr & B. Mottelson

Frauendorf & Meng,
NPA 617 (1997) 131

Meng, Peng, Zhang, Zhou,
PRC73 (2006) 037303

Prediction of MχD

Microscopic search for chiral Nucleus

PHYSICAL REVIEW C **73**, 037303 (2006)

Possible existence of multiple chiral doublets in ^{106}Rh

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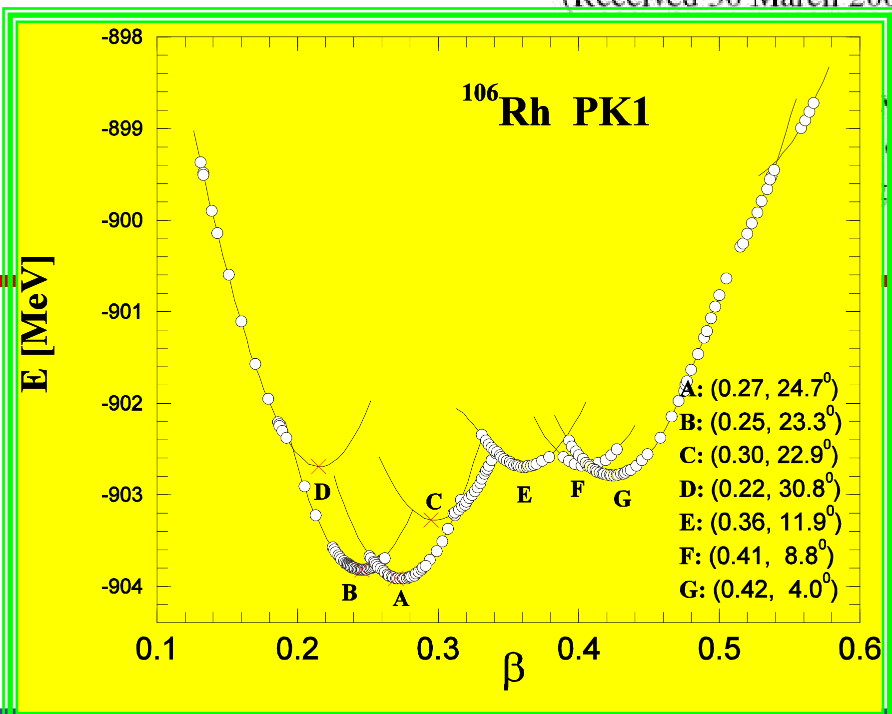
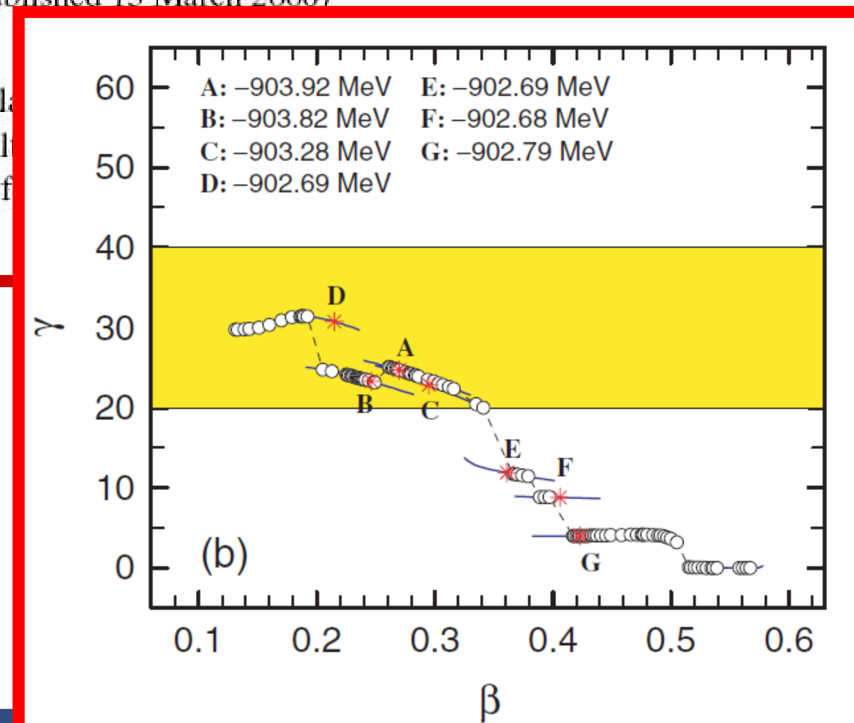
(Received 30 March 2005; published 15 March 2006)





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First observation of the MχD

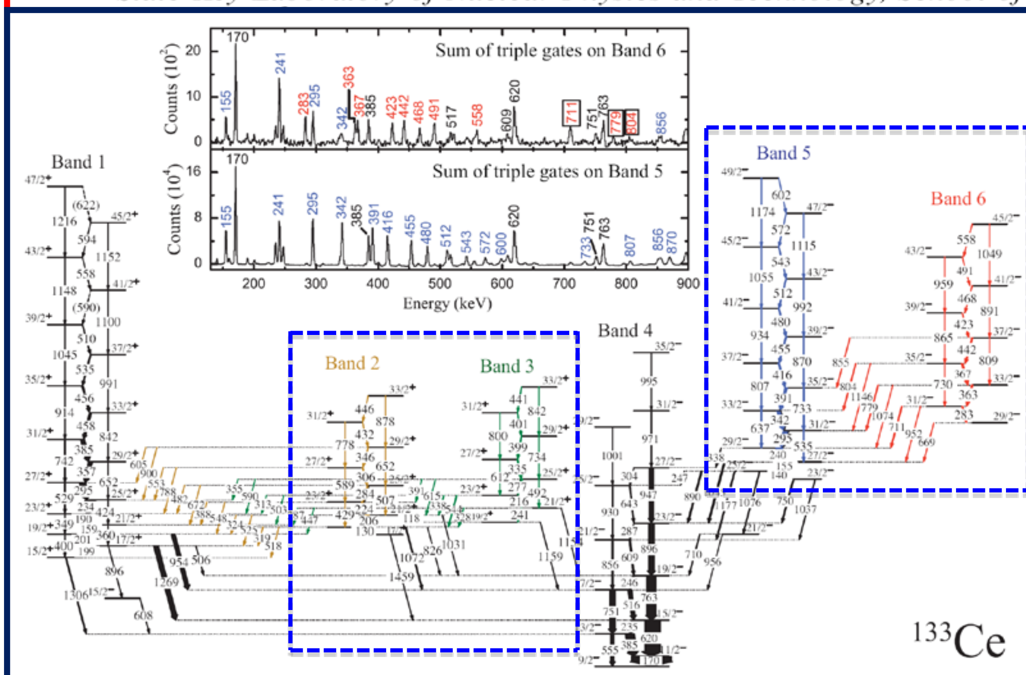
PRL 110, 172504 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

Evidence for Multiple Chiral Doublet Bands in ^{133}Ce

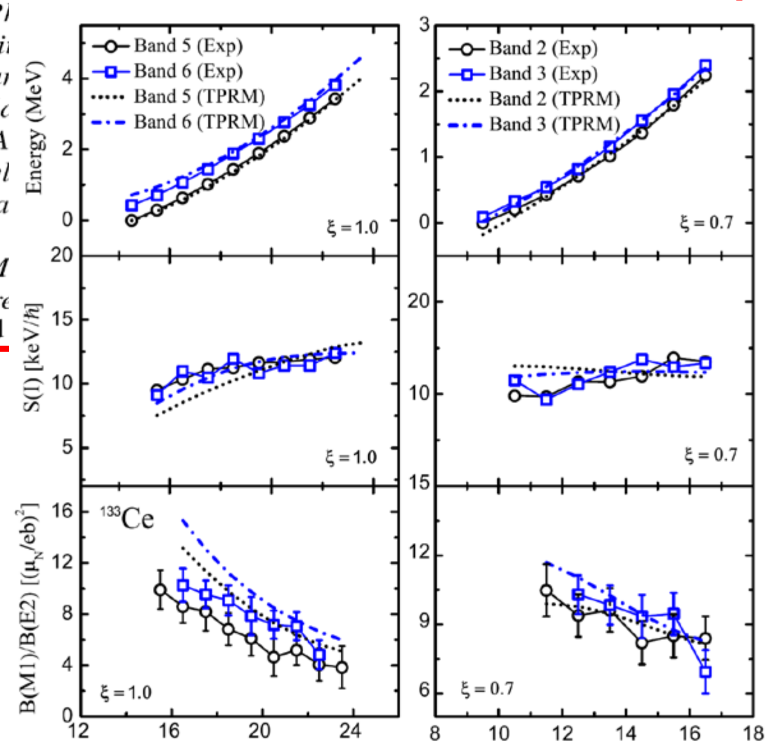
A. D. Ayangeakaa,[1] U. Garg,[1] M. D. Anthony,[1] S. Frauendorf,[1] J. T. Matta,[1] B. K. Nayak,[1,*] D. Patel,[1] Q. B. Chen (陈启博),[2] S. Q. Zhang (张双全),[2] P. W. Zhao (赵鹏巍),[2] B. Qi (亓斌),[3] J. Meng (孟杰),[2,4,5] R. V. F. Janssens,[6] M. P. Carpenter,[6] C. J. Chiara,[6,7] F. G. Kondev,[8] T. Lauritsen,[6] D. Seweryniak,[6] S. Zhu,[6] S. S. Ghugre,[9] and R. Palit[10,11]

[1]Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA

[2]State Key Laboratory of Nuclear Physics and Technology, School of Pl



Level Scheme



Theoretical description

Simultaneous chiral and parity symmetry breaking

PRL 116, 112501 (2016) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2016

Evidence for Octupole Correlations in Multiple Chiral Doublet B

C. Liu (刘晨),[1] S. Y. Wang (王守宇),[1,†] R. A. Bark,[2] S. Q. Zhang (张双全),[3,‡] J. Meng (孟杰),[3,4,5,§] B.
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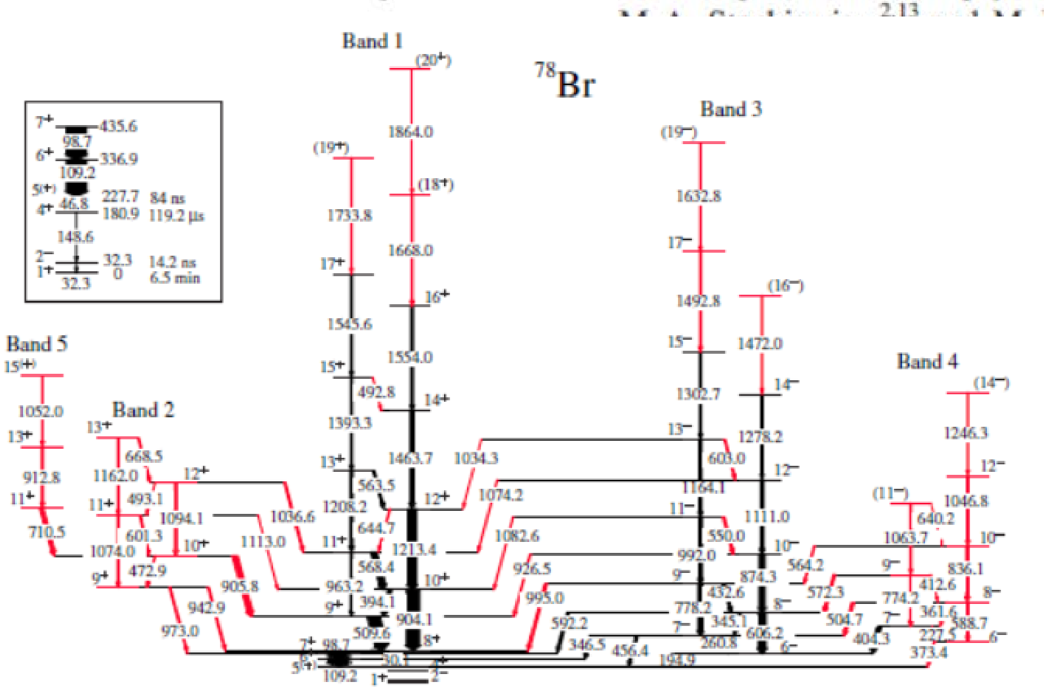
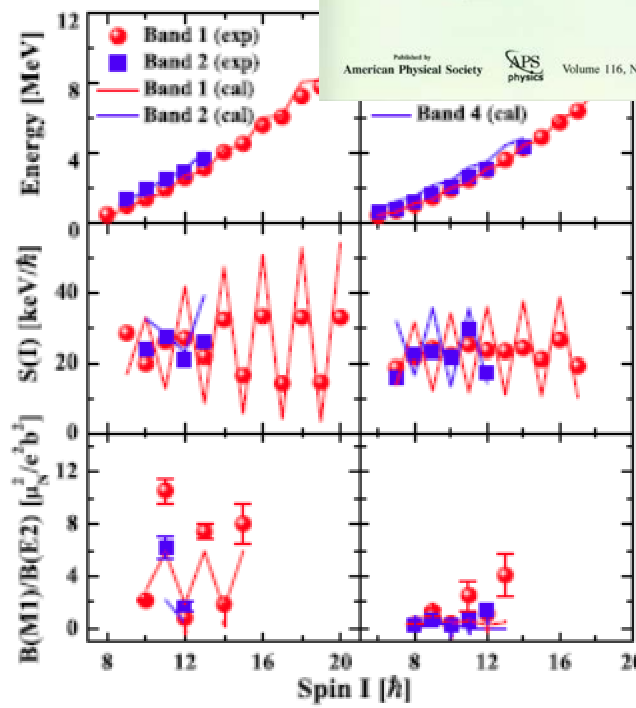
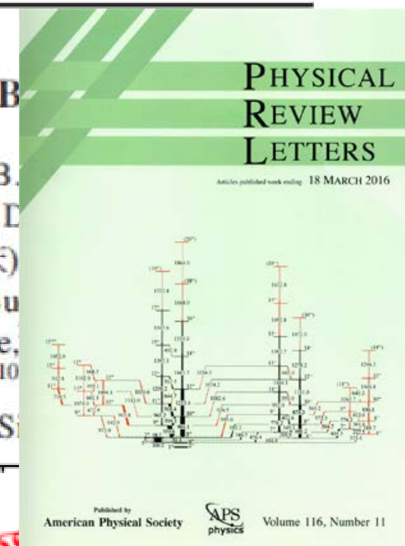
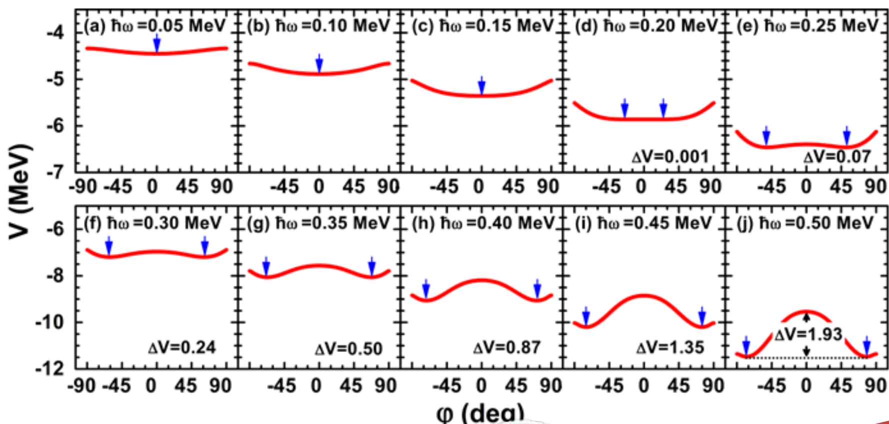
L. Liu (刘雷),[1] Z. Q. Li (李志泉),[1] N. B. Zhang (张乃波),[1] H. Jia (贾慧),[1] X. Q. Li (李湘庆)
Q. B. Chen (陈启博),[3] Z. G. Xiao (肖志刚),[8,9] H. J. Li (李红洁),[8] L. H. Zhu (竺礼华),[4] T. D. Bu
J. Easton,[2,10] K. Juhász,[11,*] A. Kamblawe,[2,5] E. Khaleel,[2,5] N. Khumalo,[2,10,12] E. A. Lawrie,
S. N. T. Majola,[2,13] S. M. Mullins,[2] S. Murray,[2] J. Ndayishimye,[2,5] D. Negi,[2] S. P. Noncolela,[2,10]
B. M. Nyakó,[14] J. N. Orce,[10] P. Papka,[2,5] J. F. Sharpey-Schafer,[2,10] O. Shirinda,[2] P. S

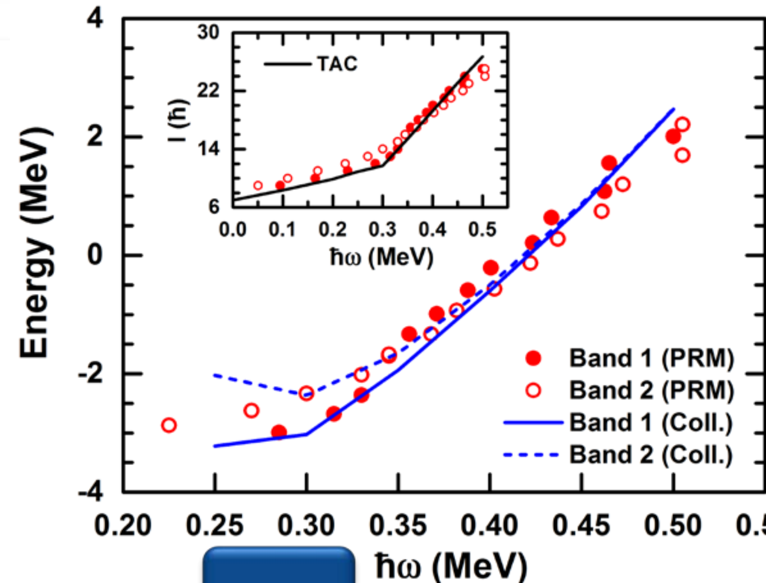




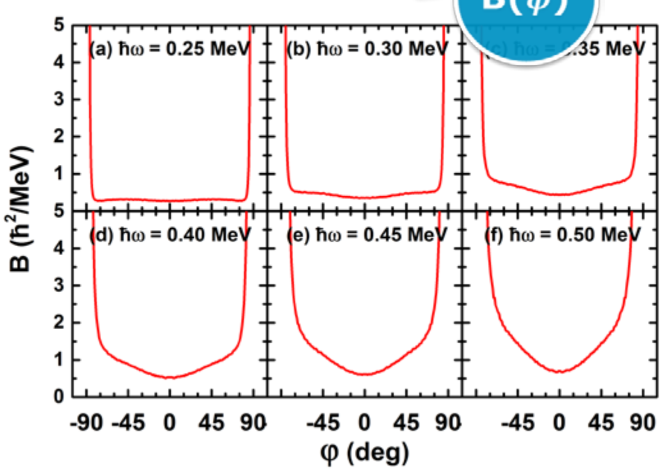


Chiral Collective Hamiltonian based on TAC





TAC → $V(\varphi)$ + $B(\varphi)$ → **Collective Hamiltonian** → E, ψ

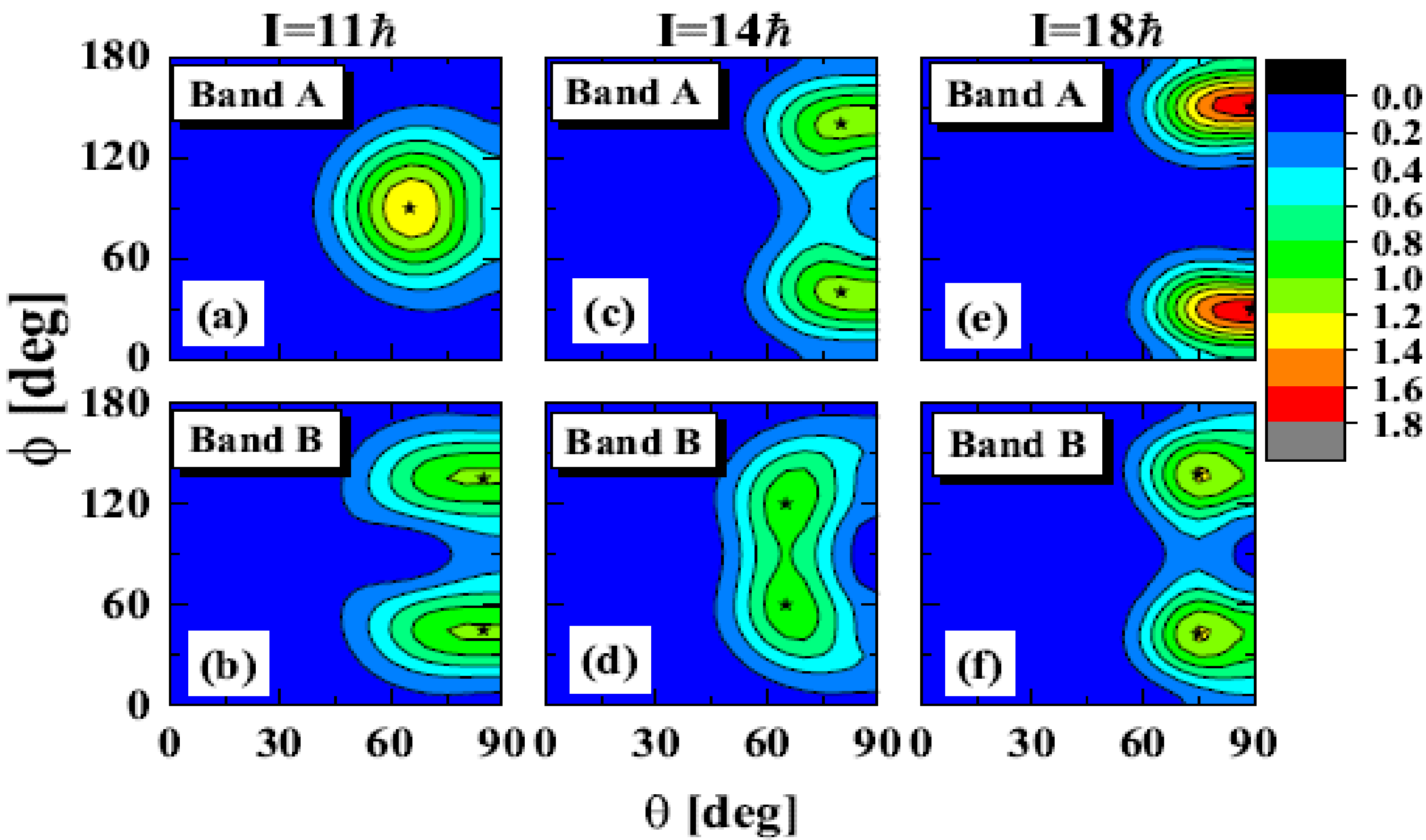


$$\hat{H}_{\rm coll} = -\frac{\hbar^2}{2\sqrt{B(\varphi)}}\frac{\partial}{\partial\varphi}\frac{1}{\sqrt{B(\varphi)}}\frac{\partial}{\partial\varphi} + V(\varphi)$$

Q. B. Chen, S. Q. Zhang, P. W. Zhao, R. V. Jolos, J. Meng

Phys. Rev. C 87, 024314 (2013)

Chiral geometry: Azimuthal Plot



Azimuthal Plot for I = 11, 14 and 18 to examine AM orientation

Chiral geometry in symmetry-restored states: Chiral doublet bands in 128Cs
F. Q. Chen (陈芳祁), Q. B. Chen (陈启博), Y. A. Luo (罗延安), J. Meng (孟杰), and S. Q. Zhang (张双全)
Phys. Rev. C 96, 051303(R) – Published 20 November 2017

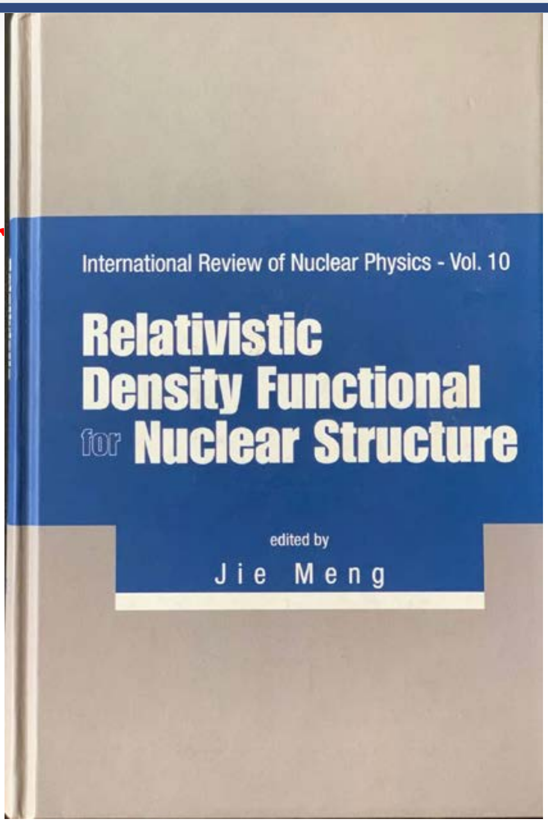
International Review of Nuclear Physics (Vol 10)

Relativistic Density Functional for Nuclear Structur

World Scientific, Singapore (2016)

700 Pages

Editor: Jie Meng



Authors include:

China: J. Y. Guo, Z. P. Li , W. H. Long, Z.M. Niu, B.H.Sun, S.Q. Zhang, E.G. Zhao, S.-G. Zhou
Croatia: N. Paar, T. Niksic, D. Vretenar, J. Zhao
France: N. Van Giai
Germany: B.N. Lv, P. Ring, P.-G. Reinhard
Italy: Y. Niu,
Japan: K. Hagino, H. Z. Liang, J. M. Yao
USA: A. V. Afanasjev, E. Litvinova, J. Piekarewicz, P. W. Zhao

Open questions regarding in the existing functionals

- Properties such as symmetry energy are difficult to be constrained from data:.
- No unique ansatz to write down a functional, e.g., the role of tensor terms within nuclear DFT.
- Difficult in connecting observables to the tensor force uniquely.
- Difficult in disentangling the effects of the isovector-scalar and isovector-vector channels by the nuclear ground-state properties。
- Additional adjustment is needed for charge-exchange spin-flip excitations, such as Gamow-Teller resonances and spin-dipole resonances.

***ab initio* calculations should become a benchmark.**

provide valuable information for the derivation of nuclear energy density functionals.

Third generation nuclear model： *ab initio* calculation

ab initio calculation has become one of hot topics in current nuclear physics

ab initio----- "from the beginning"

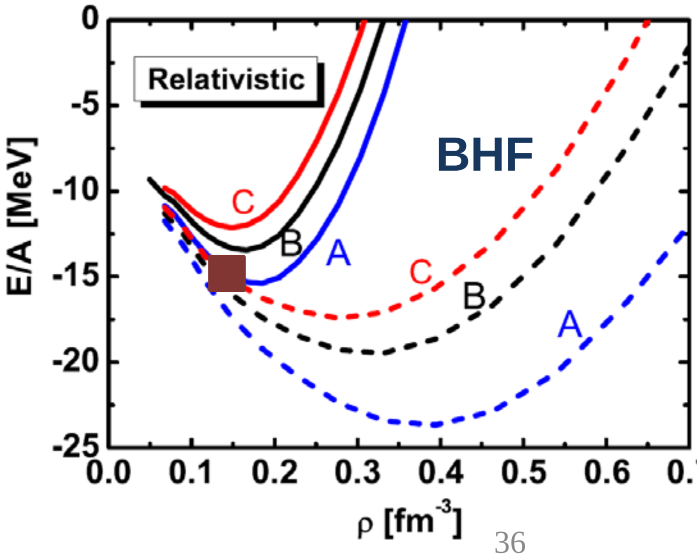
- without additional assumptions
- without additional parameters

ab initio in nuclear physics

- with realistic nucleon-nucleon interaction
- with few-body or many-body methods, such as Monte Carlo method, shell model and energy density functional theory

ab initio in nuclear matter

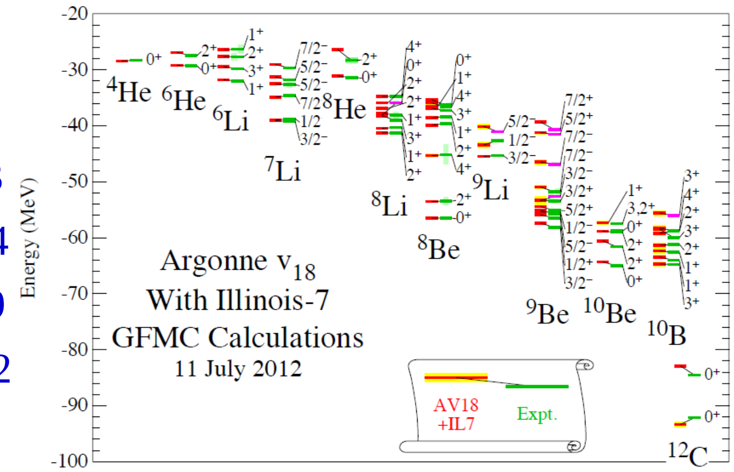
- Variational method — Akmal PRC1998
- Green's function method — Dickhoff PPNP2004
- Chiral Perturbation theory — Kaiser NPA2002
- Brueckner-Hartree-Fock (BHF) theory — Baldo RPP2012
- Relativistic BHF theory — Brockmann PRC1990
- ....



ab initio calculation for finite nucleus

ab initio calculation for light nuclei

- Gaussian Expansion Method — Hiyama PPNP2003
- Green Function Monte Carlo Method — Pieper PRC2004
- Lattice Chiral Effective Field Theory — Lee PPNP2009
- No-Core Shell Model — Barrett PPNP2012
- ……



Pieper, Wiringa, et al.

ab initio calculation for heavier nuclei

- Coupled Channel method — Hagen PRL2009
- BHF theory — Hjorth-Jensen Phys.Rep.1995
  - With HJ potential — Dawson Ann.Phys.1962
  - With Reid potential — Machleidt NPA1975
  - With Bonn potentials — Muether PRC1990

	Bonn C	Bonn B	Bonn A	Exp.
$\varepsilon_{1s_{1/2}}$	−39.73	−44.37	−50.46	−40 ± 8
$\varepsilon_{1p_{3/2}}$	−16.98	−19.49	−22.89	−18.4
$\varepsilon_{1p_{1/2}}$	−11.64	−13.24	−15.44	−12.1
E	−71.84	−85.60	−104.96	−127.68
r_c	2.465	2.380	2.291	2.737

^{16}O in BHF method in Bonn potential

ab initio calculation for finite nucleus

- Among all *ab initio* methods, the Brueckner theory is one of the most promising theories for heavy nuclei.
- Inspired by the success of early relativistic investigations for finite nucleus, the relativistic Brueckner theory is developed and achieved great success in the study of nuclear matter Anastasio PRep 1983 Brockmann PLB 1984 ter Haar PRep. 1987
- For finite nuclei , the Local Density Approximation (LDA) is used, i.e., the density dependence of the G matrix in nuclear matter is mapped onto a density-dependent relativistic Hartree or HF model. Brockmann PRC1990 Brockmann PRL 1992 Fritz PRL 1993
- This mapping is far from unique and therefore suffers from large ambiguities

ab initio calculation：

Relativistic Brueckner Hartree-Fock Theory

Shi-Hang Shen, Jin-Niu Hu,Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Relativistic Brueckner–Hartree–Fock Theory for Finite Nuclei .
Chin. Phys. Lett. 33 (2016) 102103

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Fully self-consistent relativistic Brueckner-Hartree-Fock theory for finite nuclei.
Phys. Rev. C 96, 014316 (2017)

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Effects of tensor forces in nuclear spin–orbit splittings from ab initio calculations.
Phys. Lett. B778 (2018) 344–348

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Spin symmetry in the Dirac sea derived from the bare nucleon–nucleon interaction
Phys. Lett. B781(2018)227–231

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Relativistic Brueckner-Hartree-Fock theory for neutron drops
Phys. Rev. C 97, 054312 (2018)

Hui Tong, Xiu-Lei Ren, Peter Ring, Shi-Hang Shen, Si-Bo Wang, and Jie Meng
Relativistic Brueckner-Hartree-Fock theory in nuclear matter without the average momentum approximation
Phys. Rev. C 98, 054302 (2018)

Realistic Nucleon-Nucleon Interaction

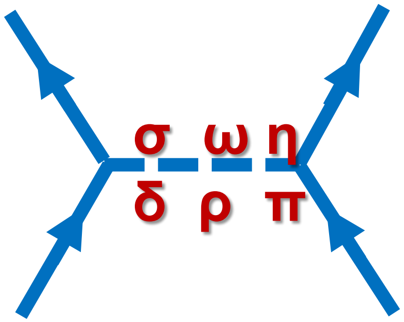
- Starting point: Bonn interaction R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989)

  The interaction Lagrangians

$$\mathscr{L}_{NNpv} = -\frac{f_{ps}}{m_{ps}}\bar{\psi}\gamma^5\gamma^\mu\psi\partial_\mu\varphi^{(ps)},$$

$$\mathscr{L}_{NNs} = g_s\bar{\psi}\psi\varphi^{(s)},$$

$$\mathscr{L}_{NNv} = -g_v\bar{\psi}\gamma^\mu\psi\varphi_\mu^{(v)} - \frac{f_v}{4M}\bar{\psi}\sigma^{\mu\nu}\psi\left(\partial_\mu\varphi_\nu^{(v)} - \partial_\nu\varphi_\mu^{(v)}\right).$$



- Bosons exchanged include σ, δ (scalar); ω, ρ (vector); η, π (pseudoscalar).
- A monopole-type form factor is attached to each vertex $\frac{\Lambda_\alpha^2 - m_\alpha^2}{\Lambda_\alpha^2 + \mathbf{q}^2}$
- Coupling constants are determined by NN scattering and deuteron properties R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989).

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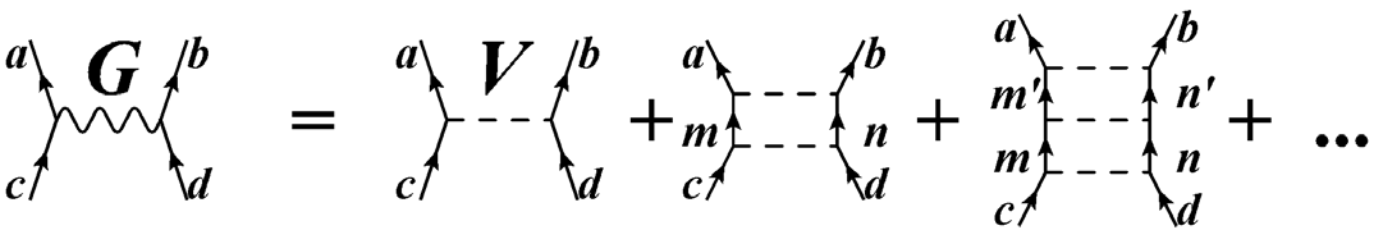
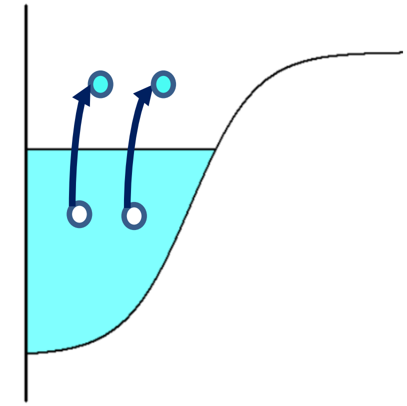
Bethe-Goldstone Equation

K. A. Brueckner, C. A. Levinson, and H. M. Mahmoud, *Phys. Rev.* **95**, 217 (1954)

- Sum up ladder diagrams to infinite order





- Bethe-Goldstone equation is solved **self-consistently**

$$\langle ab|G(W)|cd\rangle = \langle ab|V|cd\rangle + \sum_{mn} \langle ab|V|mn\rangle \frac{Q(m,n)}{W - \varepsilon_m - \varepsilon_n} \langle mn|G(W)|cd\rangle .$$

- Starting energy W depends on the position of G-matrix in the diagram.
- RHF single particle energies ε_m , ε_n.
- Pauli operator Q forbids the state scattering below Fermi surface.

Relativistic Brueckner-Hartree-Fock Theory

- Relativistic Hartree-Fock equation in complete basis, details in, e.g.

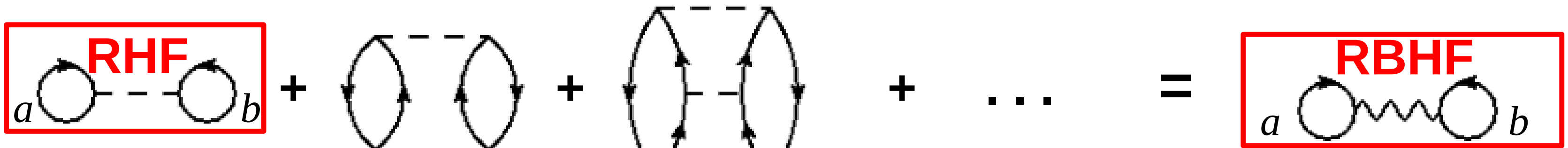
  W. Long, N. Van Giai, and J. Meng, *PLB* **640**, 150 (2006)

$$\sum_j (T_{ij} + U_{ij})\, D_{ja} = \varepsilon_a D_{ia}, \qquad U_{ij} = \sum_{c=1}^{A} \langle ic|\bar{G}(W)|jc\rangle$$

where D are the expansion coefficients:

$$|a\rangle = \sum_i D_{ia}|i\rangle.$$

- RBHF total energy



$$\frac{1}{2}\sum_{ab}^{A}\langle ab|V|ab\rangle \qquad\qquad \frac{1}{2}\sum_{ab}^{A}\langle ab|G(W)|ab\rangle$$

$$W = \varepsilon_a + \varepsilon_b.$$

together with exchange term,

$$E = \sum_a^A \langle a|T|a\rangle + \frac{1}{2}\sum_{ab}^{A}\langle ab|\bar{G}(W)|ab\rangle.$$

Numerical details for finite nuclei

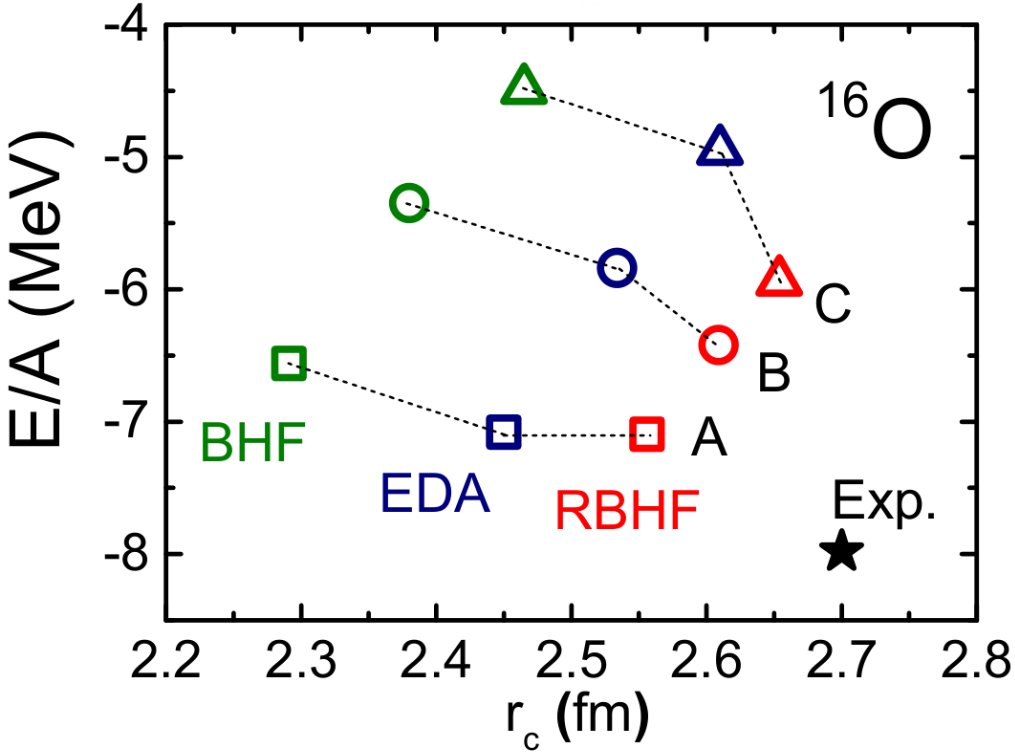
- Nuclei: ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca.
- Interaction: Bonn A potential. R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989)
- Cut-offs for basis: $l_{cut} = 20$, $\varepsilon_{cut} = 1100$ MeV, $\varepsilon_{Dcut} = -1700$ MeV.
- Basis: Dirac Woods-Saxon basis / self-consistent RHF basis.

  S. Zhou, J. Meng, and P. Ring, *PRC* **68**, 034323 (2003)
- Coulomb exchange term: relativistic local density approximation.

  H. Gu, et al., *PRC* **87**, 041301 (2013)
- Center-of-mass correction: included in variation.

  as in density functional SLy6 E. Chabanat, et al., *NPA* **635**, 231 (1998).
- Box size: R = 7 fm.

Energies and charge radii of ^{16}O in RBHF in comparison with EDA and BHF



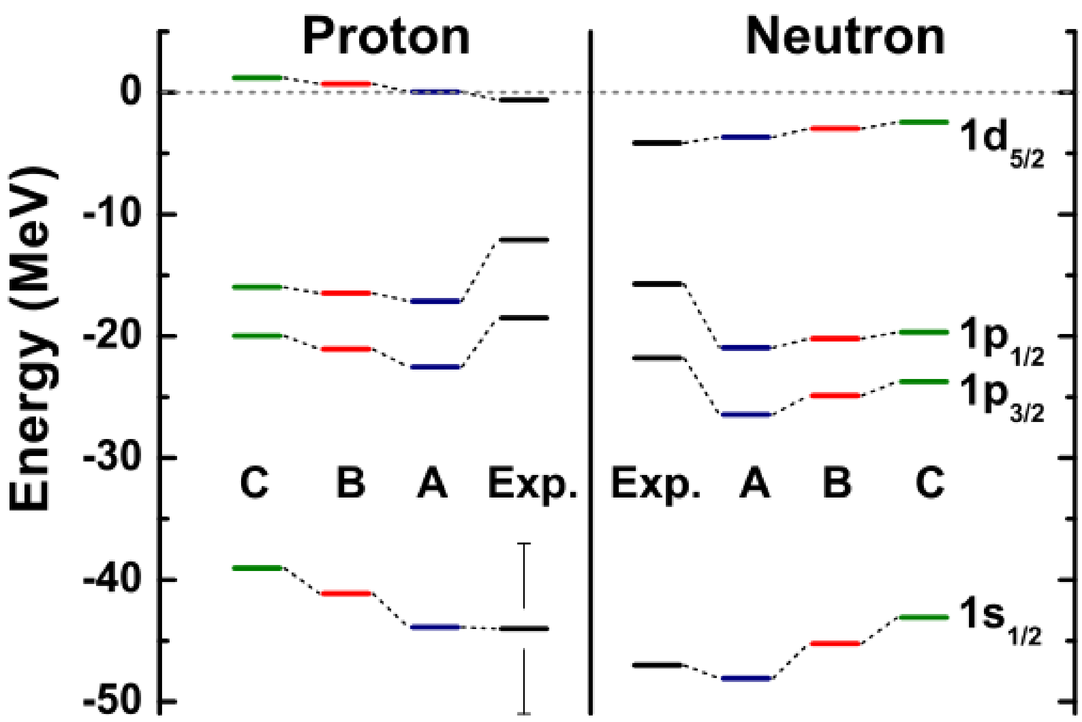
RBHF improves the description over EDA or BHF.

EDA and BHF taken from
H. Müther, R. Brockmann, and R. Machleidt, *PRC* **42**, 1981 (1990).

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Fully self-consistent relativistic Brueckner-Hartree-Fock theory for finite nuclei.
Phys. Rev. C 96, 014316 (2017)

Single particle energy in ^{16}O

Single particle energy in RBHF with Bonn A, B, C



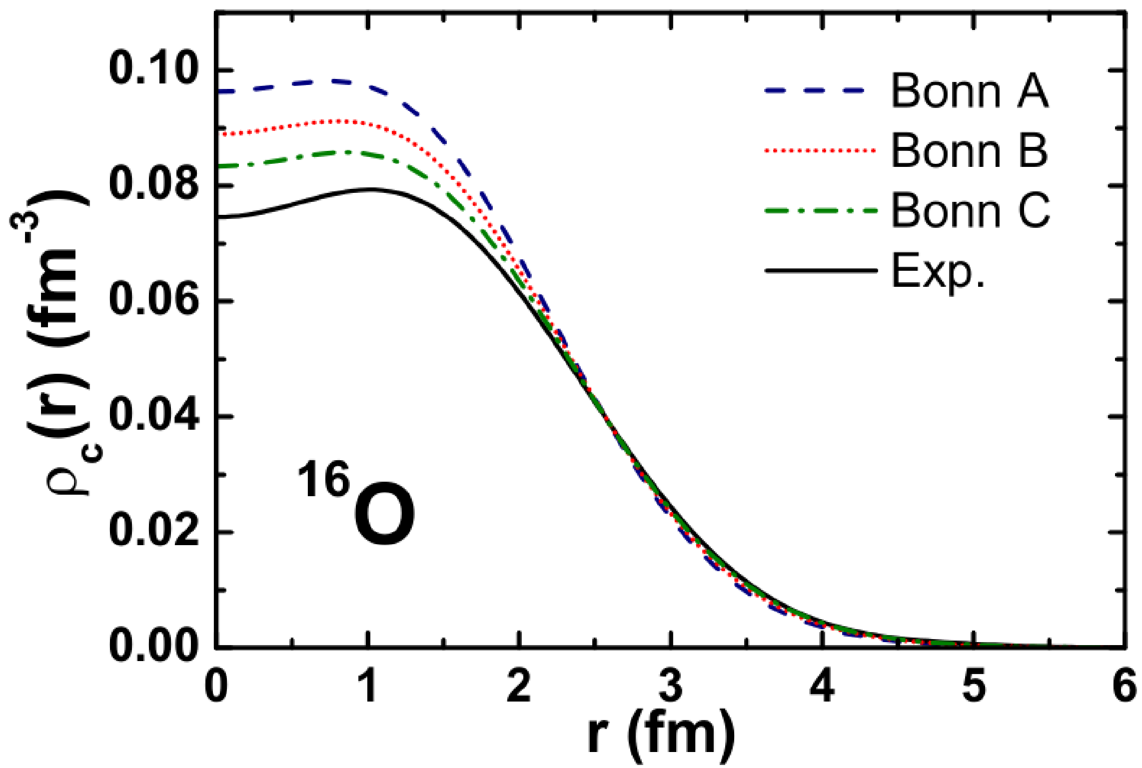
data from
L. Coraggio, et al., *PRC* **68**, 034320 (2003).

- Bonn A provides the best agreement with the data.
- The gap at Fermi surface suggests the lack of higher order configurations

E. Litvinova and P. Ring, *PRC* **73**, 044328 (2006).

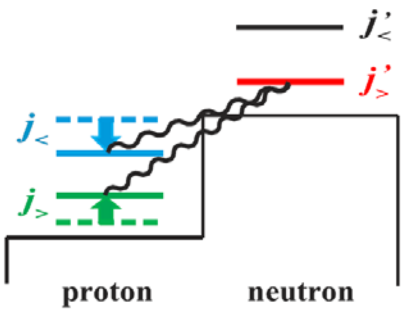
Charge density distributions for ^{16}O

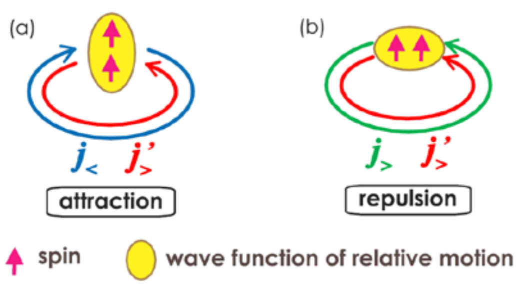
- **Charge density distributions in RBHF with Bonn A, B, C**
- **Data from** H. De Vries, C. De Jager, and C. De Vries, *At. Data Nucl. Data Tables* **36**, 495 (1987).



Effects of tensor forces in nuclear spin–orbit splittings

- As an important component in the NN interaction, the tensor force in the form of the two pion exchange provides the main part of the nuclear attraction, which is taken into account by the scalar σ meson. However, the role of the tensor force on the spin properties in finite nuclei is much less clear.
- In configuration interaction shell model it is found that the tensor force plays an important role in exotic nuclei.
- In contrast, tensor forces have been neglected in almost all the successful nuclear energy density functional, due to the difficult in data only connected to tensor forces and therefore suitable for an adjustment of their parameters.





Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005)

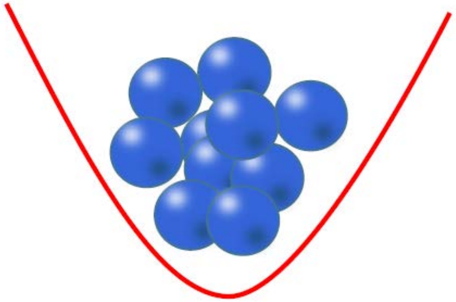
- **Neutron drop is a neutron system confined in an external field. It is an ideal and simple system to investigate the neutron-rich environment by *ab initio* methods and phenomenological density functional theory.** Pudliner et al., PRL 76, 2416 (1996). Gandolfi, Carlson, Pieper, PRL 106, 012501 (2011). Maris et al., PRC 87, 054318 (2013). Potter et al., PLB 739, 445 (2014). Zhao & Gandolfi, PRC 94, 041302(R) (2016).

……

- **A neutron drop provides also an ideal and simple system to investigate the effects of tensor forces.**

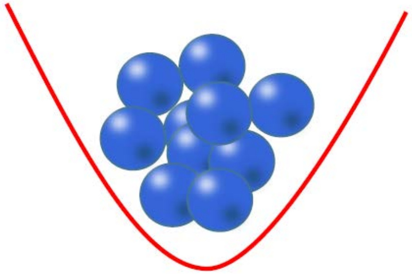
- **From fully self-consistent relativistic Brueckner theory, a systematic and specific pattern due to the tensor forces is found in spin–orbit splitting in neutron drops, which forms a guide for the derivations of relativistic and nonrelativistic nuclear energy density functional.**

Shen, Liang, Meng, Ring, Zhang,
Effects of tensor forces in nuclear spin–orbit splittings from ab initio calculations.
Phys. Lett. B778 (2018) 344–348



Numerical details for neutron drop

$$(T + U + U_{\rm ex})|a\rangle = e_a|a\rangle,$$



- Neutron drops with N from 4 to 50.
- External field: spherical harmonic oscillator (HO) potential

$$U_{\rm ex} = \frac{1}{2}M\omega^2 r^2 \qquad \text{with} \qquad \hbar\omega = 10 \text{ MeV}$$

- Interaction: Bonn A R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989)
- Cut-offs for basis space: $l_{\rm cut} = 24$, $\varepsilon_{\rm cut} = 1000$ MeV, $\varepsilon_{\rm Dcut} = -1700$ MeV.
- Total angular momentum cut-off $J_{\rm cut} = 12$.

S. Shen, *et al.*, *Phys. Rev. C* **96**, 014316 (2017)

- Basis: self-consistent RHF basis.
- Box size: R = 8 $(T + U + U_{\rm ex})|a\rangle = e_a|a\rangle,$

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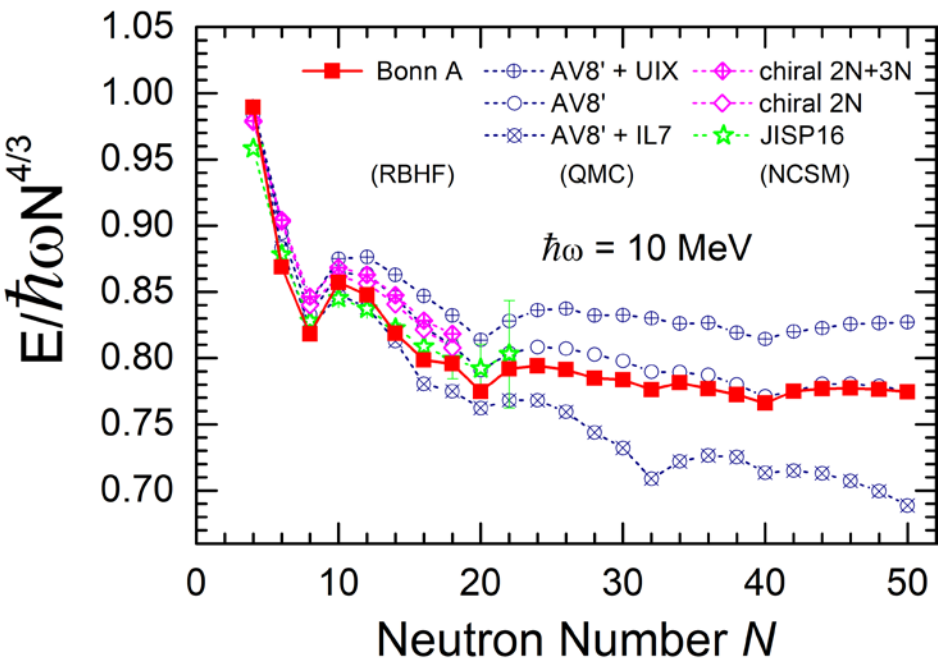
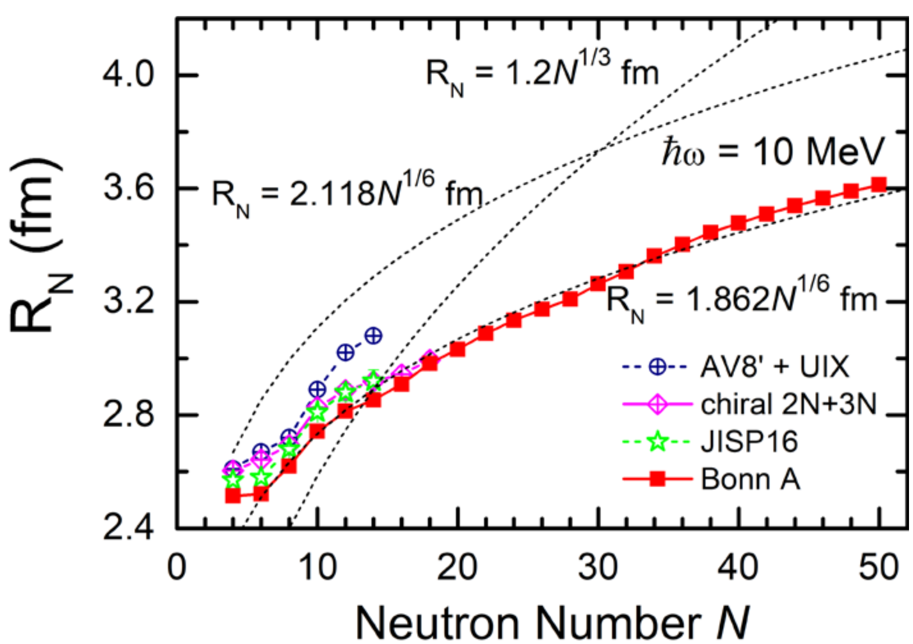
Energies and Radii

Energies and radii for N-neutron drops in RBHF with Bonn A



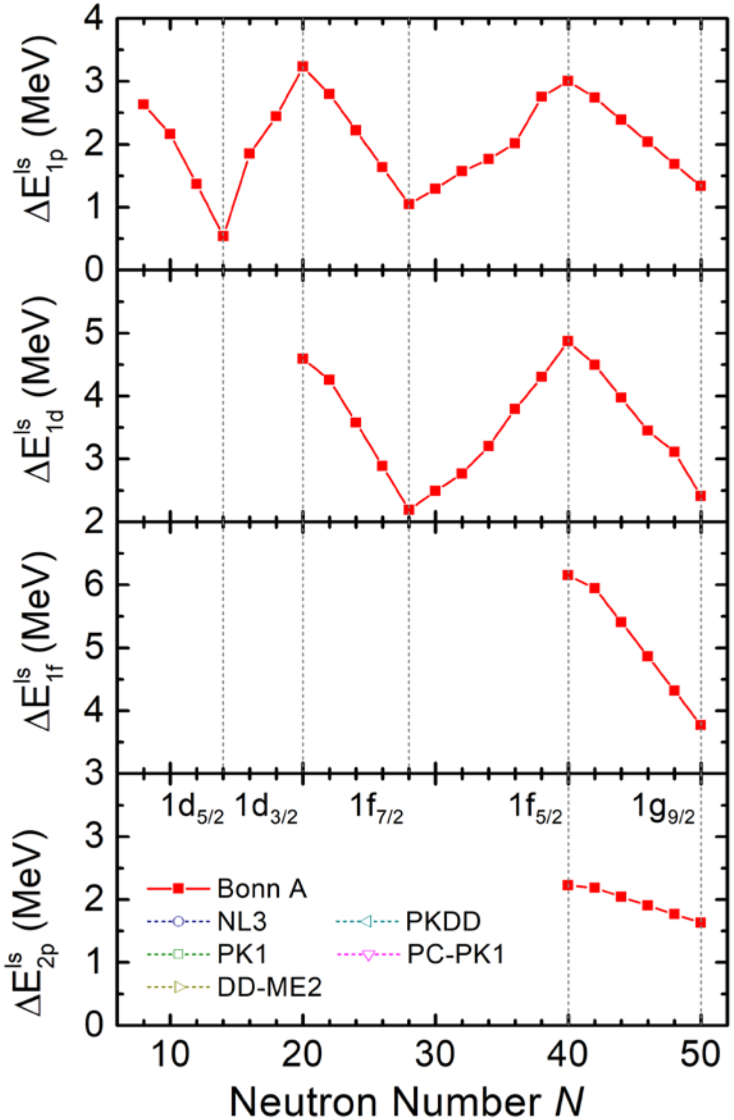


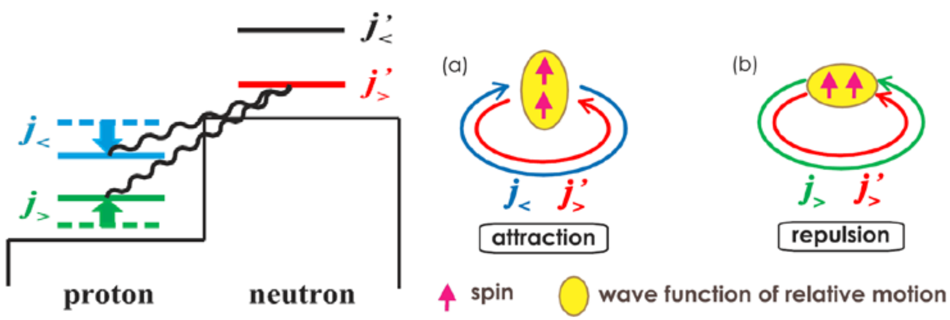
Gandolfi, Carlson, Pieper, *PRL* **106**, 012501 (2011)
Maris et al., *PRC* **87**, 054318 (2013)
Potter et al., *PLB* **739**, 445 (2014)

Shen, Liang, Meng, Ring, Zhang,
Phys. Lett. B778 (2018) 344–348

- Energies E and radii R_N are consistent with JISP16 or AV8'.
- R_N follows the $N^{1/6}$ law.

Spin-Orbit Splitting





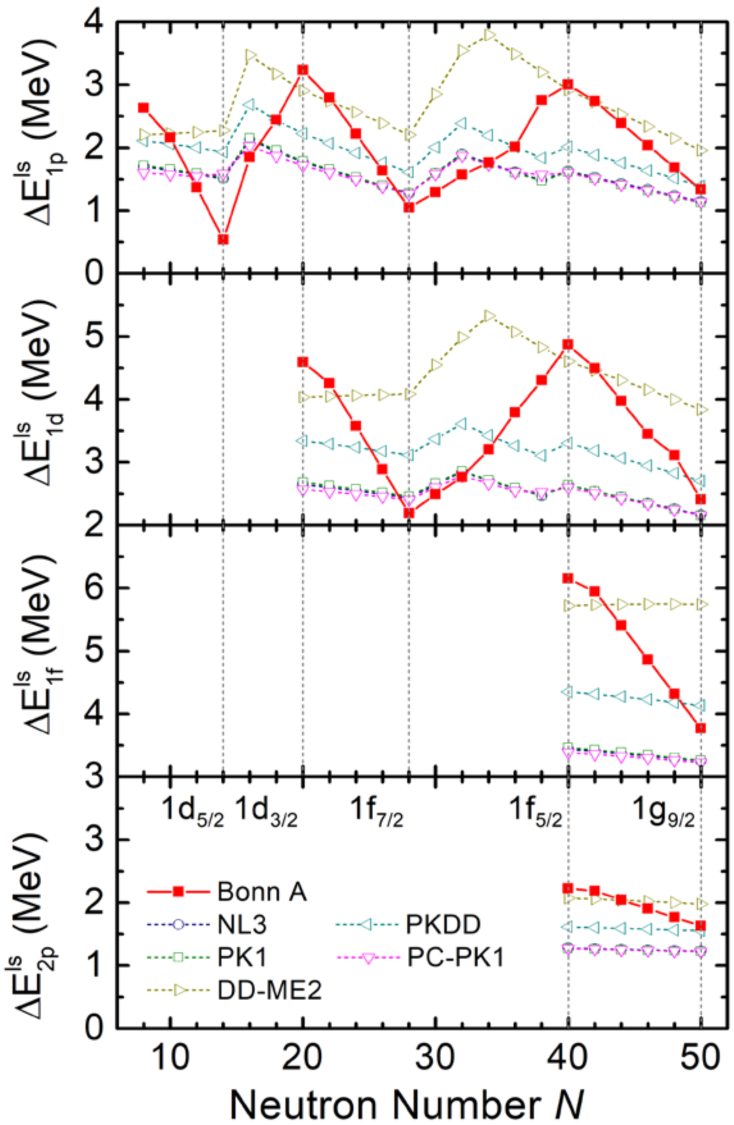
Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005)

- The SO splitting **decreases** as the spin-up $j_> = l + 1/2$ orbitals are filled, while the SO splitting **increases** as the spin-down $j_< = l + 1/2$ orbitals are filled.

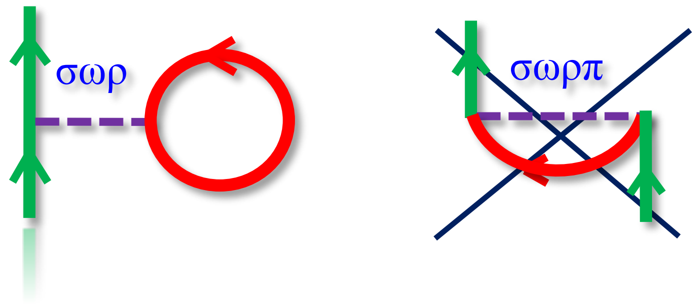
Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Effects of tensor forces in nuclear spin–orbit splittings from ab initio calculations.
Phys. Lett. B778 (2018) 344–348

Relativistic Brueckner-Hartree-Fock theory for neutron drops
Phys. Rev. C 97, 054312 (2018)

Spin-Orbit Splitting



- Comparison with the **phenomenological** relativistic density functionals.



- **None of them can reproduce this tensor behavior!**

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
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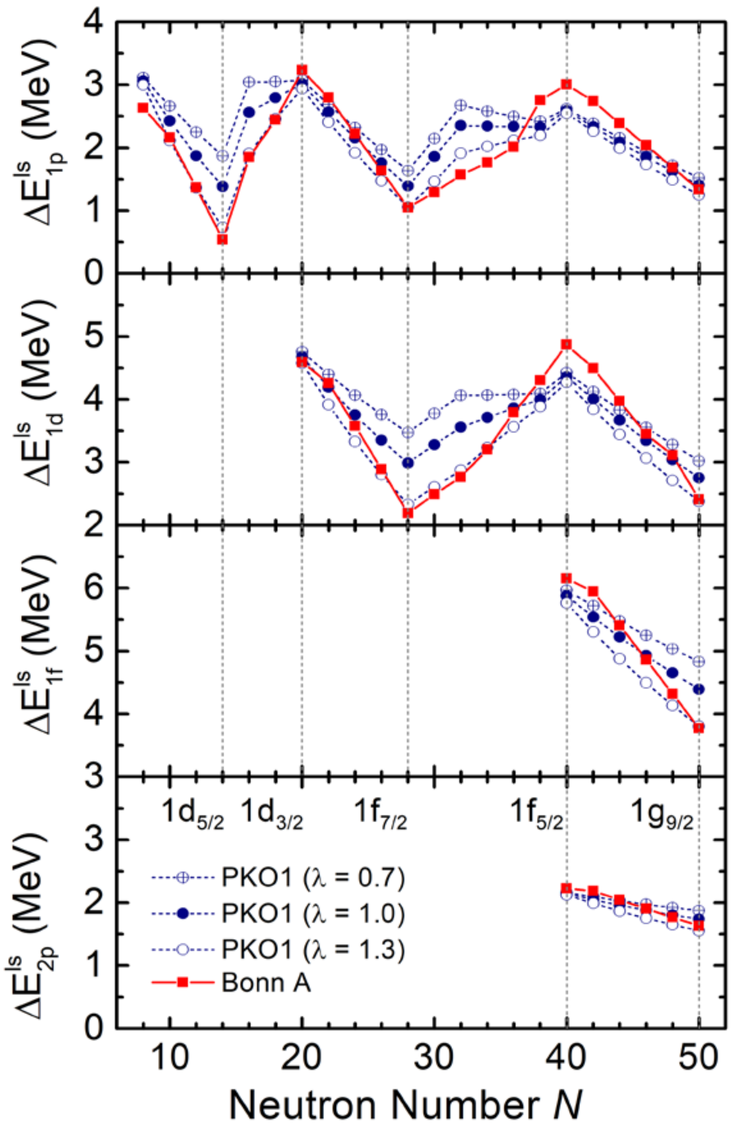
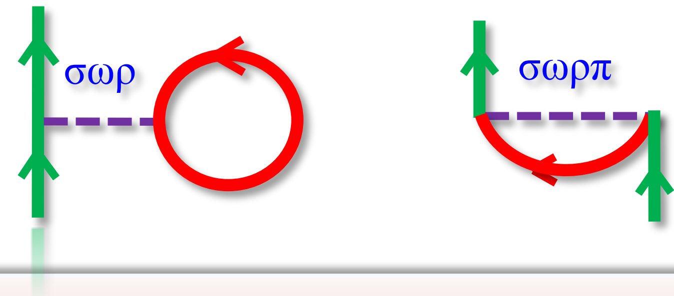


- Comparison with the **phenomenological** relativistic Hartree-Fock (**RHF**) energy density functionals (EDF).



- **RHF** shows similar pattern, mainly contributed by **πNN tensor interaction**.
- Neither RBHF nor CDFT includes **beyond-mean-field effects** ➔ **a fair comparison!**

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
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Summary & Perspectives

北京大學
PEKING UNIVERSITY

Symmetry energy at supra-saturation densities via the Gravitational Waves from GW170817

Hui Tong, Peng-Wei Zhao, Jie Meng

(Submitted on 14 Mar 2019)

Motivated by the historical detection of gravitational waves from GW170817, the neutron star and the neutron drop, i.e., a certain number of neutrons confined in an external field, are systematically investigated by ab initio calculations as well as the nonrelativistic and relativistic state-of-art density functional theories. Strong correlations are found among the neutron star tidal deformability, the neutron star radius, the root-mean-square radii of neutron drops, and the symmetry energies of nuclear matter at supra-saturation densities. From these correlations and the upper limit on the tidal deformability extracted from GW170817, the neutron star radii, the neutron drop radii, and the symmetry energy at twice saturation density are respectively constrained as $R_{1.4M_\odot} \leqslant 12.94$ km, $R_{\rm nd} \leqslant 2.36$ fm, and $E_{\rm sym}(2\rho_0) \leqslant 53.2$ MeV.

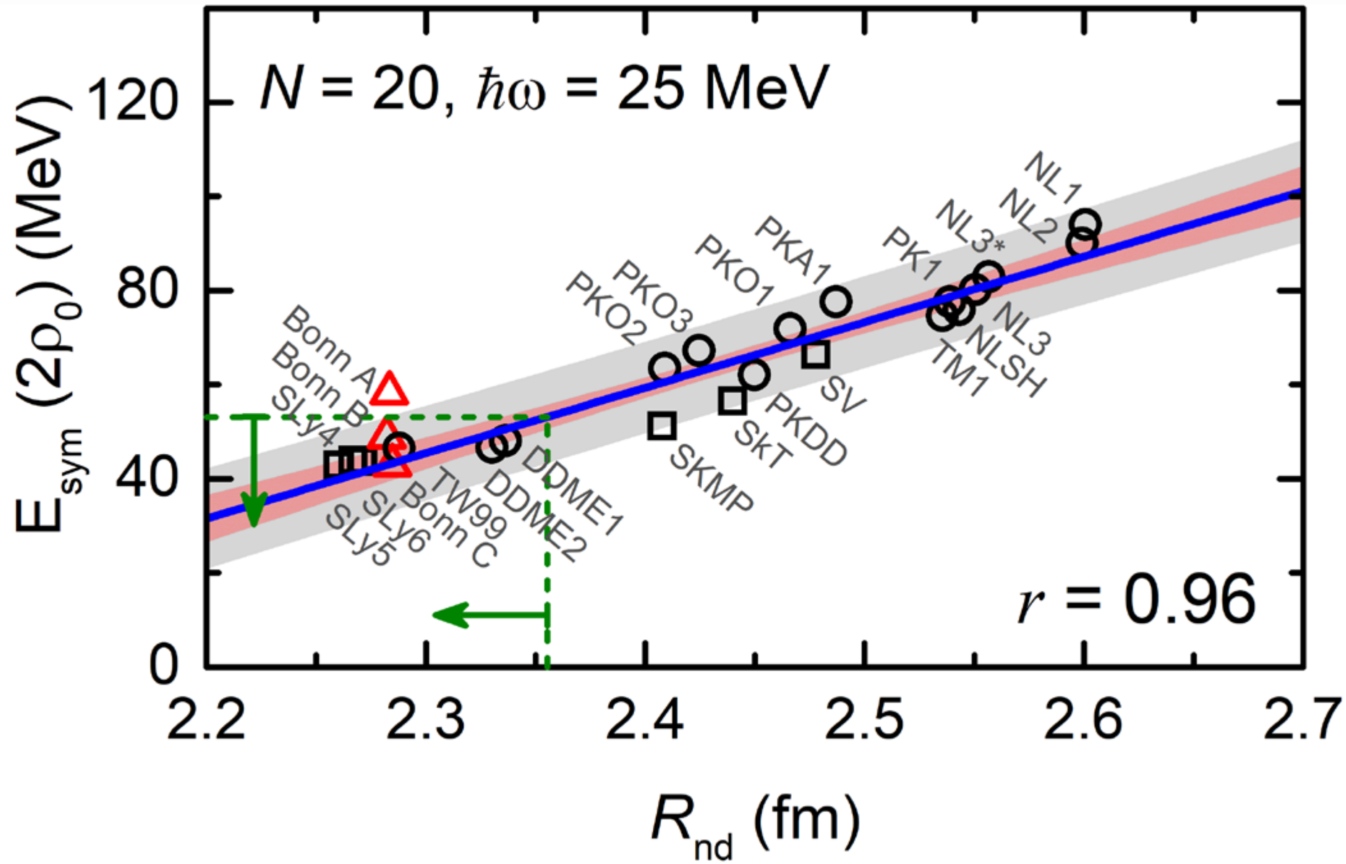
Comments: 11 pages, 4 figures

Subjects: **Nuclear Theory (nucl-th)**

Cite as: **arXiv:1903.05938 [nucl-th]**

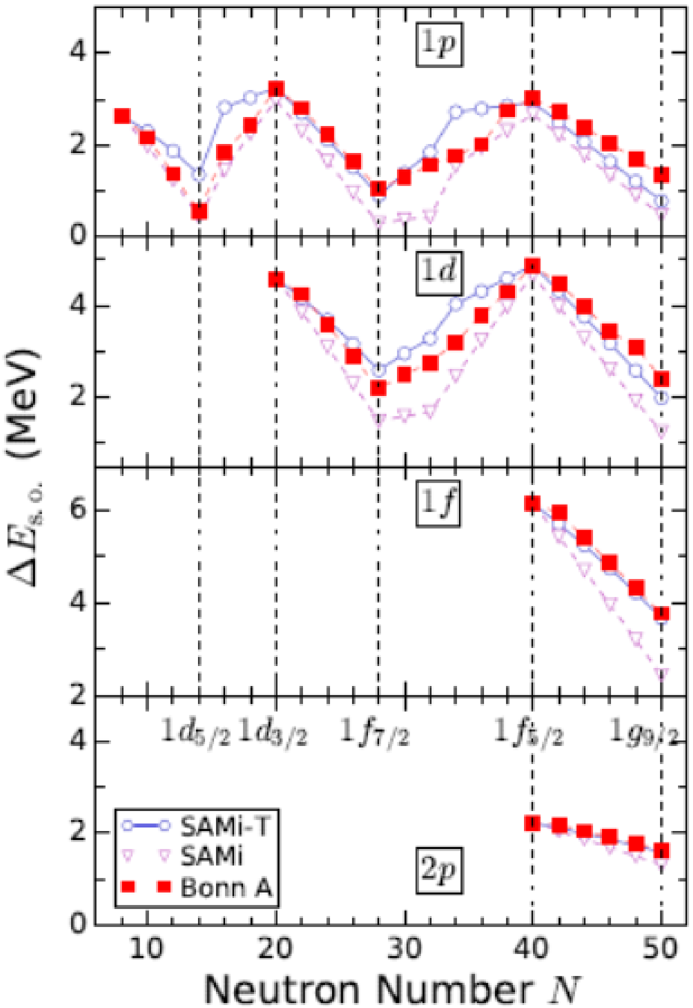
(or **arXiv:1903.05938v1 [nucl-th]** for this version)

Correlation between $E_{sym}(2\rho_0)$ and R_{nd}



1. $R_{nd} \le 2.36$ fm $\Rightarrow E_{sym}(2\rho_0) \le 53.2$ MeV
2. ASY-EOS experiment : $50.82 \text{ MeV} \le E_{sym}(2\rho_0) \le 60.39 \text{ MeV}$

P. Russotto, et al., PRC 94, 034608 (2016)



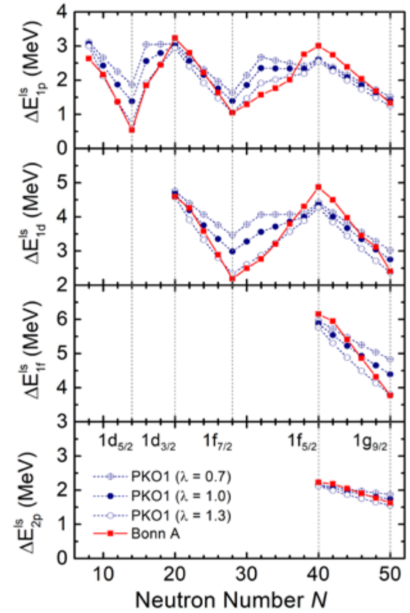
A new Skyrme functional **SAMi-T** inspired by the fitting protocol of the successful SAMi functional, with further information on ntensor terms provided by ab initio calculations.

The new functional SAMi-T does not decrease the accuracy of describing ground state properties but gives a good description of the excitation energies and sum rules of Giant Resonances.

Skyrme functional with tensor terms from ab initio calculations,
Shihang Shen, Gianluca Colò, Xavier Roca-Maza **arXiv:1810.09691 [nucl-th]**

北京大學 PEKING UNIVERSITY

- **A first *ab initio* relativistic calculation for finite nuclei** by RBHF theory
  - ✓ Binding energies and radii of ^{16}O and ^{40}Ca ➔ a **benchmark** for LDA study
  - ✓ **Spin-orbit splitting** is well reproduced 🡐 bare NN interaction together with relativistic scheme
- **Tensor effects on spin-orbit splitting in neutron drops**
  - ✓ Effects of **πNN tensor interaction**
  - ✓ **Important guideline** for phenomenological EDF



- **Future Work**
  - ✓ Expedite code to investigate isospin dependent properties in finite nuclui
  - ✓ Provide information to EDF from the G-matrix.
  - ✓ Combining with relativistic LQCD or chiral force.
  - ✓ Higher order effects beyond RBHF
  - ✓ ……

Ren et al., Chinese Physics C 42 (2018) 014103

arXiv:1904.04977 [nucl-th]

Towards an ab initio covariant density functional for nuclear structure

Shihang Shen, Haozhao Liang, Wen Hui Long, Jie Meng, Peter Ring

Nuclear structure models built from phenomenological mean fields, the effective nucleon-nucleon interactions (or Lagrangians), and the realistic bare nucleon-nucleon interactions are reviewed. The success of covariant density functional theory, which starts from effective Lagrangians, to describe nuclear ground-state and excited-state properties and its influence on Brueckner theory within the relativistic framework are focused upon. The challenges and ambiguities of predictions for unstable nuclei without data or for high-density nuclear matter, arising from covariant density functionals, are discussed. The basic ideas in building an ab initio covariant density functional for nuclear structure from ab initio calculations with realistic nucleon-nucleon interactions for both nuclear matter and finite nuclei are presented. The current status of fully self-consistent relativistic Brueckner-Hartree-Fock (RBHF) calculations for finite nuclei or neutron drops (ideal systems composed of a finite number of neutrons and confined within an external field) is reviewed. The guidance and perspectives towards an ab initio covariant density functional for nuclear structure derived from the RBHF results are provided.

Thank you for your attention!