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INT PROGRAM INT-13-3

Quantitative Large Amplitude Shape Dynamics:

fission and heavy ion fusion

September 23 - November 15, 2013

New generation of relativistic approach for nuclear structure

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EDF – CDFT – RMF – RHF – RBHF

Outline

- Introduction
- CDFT at the Hartree level (success)
- CDFT at the Hartree-Fock level (new learning)
- Full Dirac Brueckner-Hartree-Fock (expection)
- *DBHF* calculation for ^{16}O, ^{40}Ca, ^{48}Ca and ^{56}Ni
- Summary & Perspectives

Nuclear Energy Density Functional

Nuclear Energy Density Functionals: the many-body problem is mapped onto a 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.

$$E[\hat{\rho}] = \langle \Psi | H | \Psi \rangle \qquad \hat{h} = \frac{\delta E}{\delta \hat{\rho}}$$

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

Density functional theory in nuclei

- Nuclear 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, relativistic, 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 characteristic properties of nuclear matter and/or finite nuclei and (in future) to ab-initio results.

Nuclear functional usually used:

- non-relativistic zero range forces (Skyrme)
- non-relativistic finite range forces of Gaussian shape (Gogny)
- relativistic (covariant) density functional theory (RMF)

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CDFT with non-linear point coupling interaction

$$(\bar{\psi}\, O\, \Gamma\, \psi),\ O \in \{1, \vec{\tau}\},\ \Gamma \in \{1, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

Lagrangian density: For the nucleon Dirac spinor field ψ, there are ten building blocks characterized by their transformation characteristics in isospin and Minkowski space.

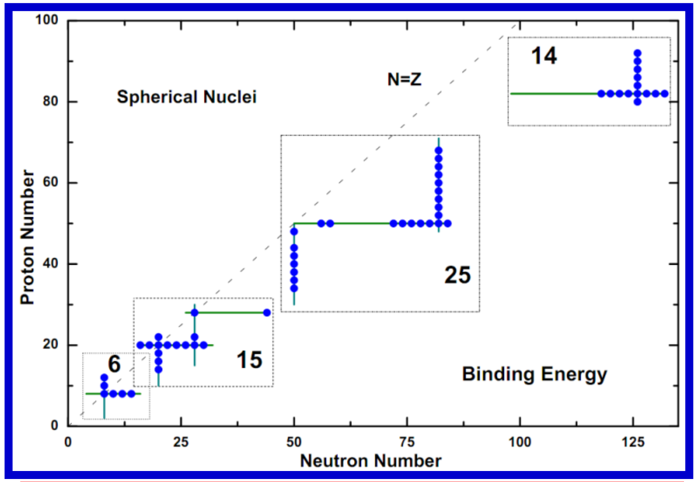
$$
\begin{aligned}
L = {} & \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi \\
& -\frac{1}{2}\alpha_S(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) - \frac{1}{2}\alpha_{TV}(\bar{\psi}\vec{\tau}\gamma_\mu\psi)(\bar{\psi}\vec{\tau}\gamma^\mu\psi) \\
& -\frac{1}{3}\beta_S(\bar{\psi}\psi)^3 - \frac{1}{4}\gamma_S(\bar{\psi}\psi)^4 - \frac{1}{4}\gamma_V[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2 \\
& -\frac{1}{2}\delta_S\partial_\nu(\bar{\psi}\psi)\partial^\nu(\bar{\psi}\psi) - \frac{1}{2}\delta_V\partial_\nu(\bar{\psi}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\gamma^\mu\psi) - \frac{1}{2}\delta_{TV}\partial_\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi) \\
& -e\frac{1-\tau_3}{2}\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}
\end{aligned}
$$

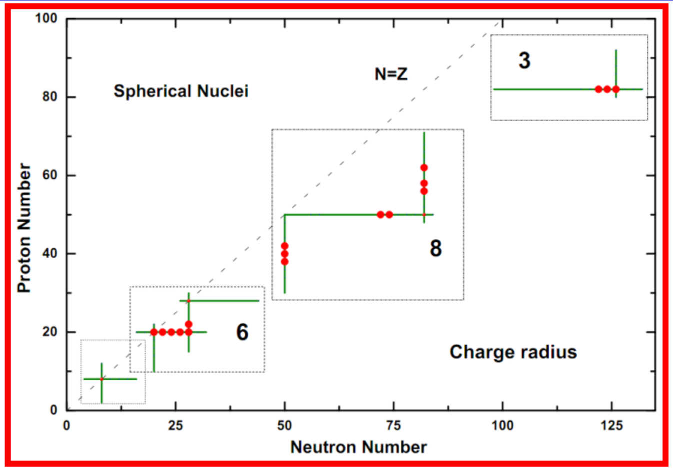
Higher order terms

Localized form of Fock terms

Parameterizations PC-PK1

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

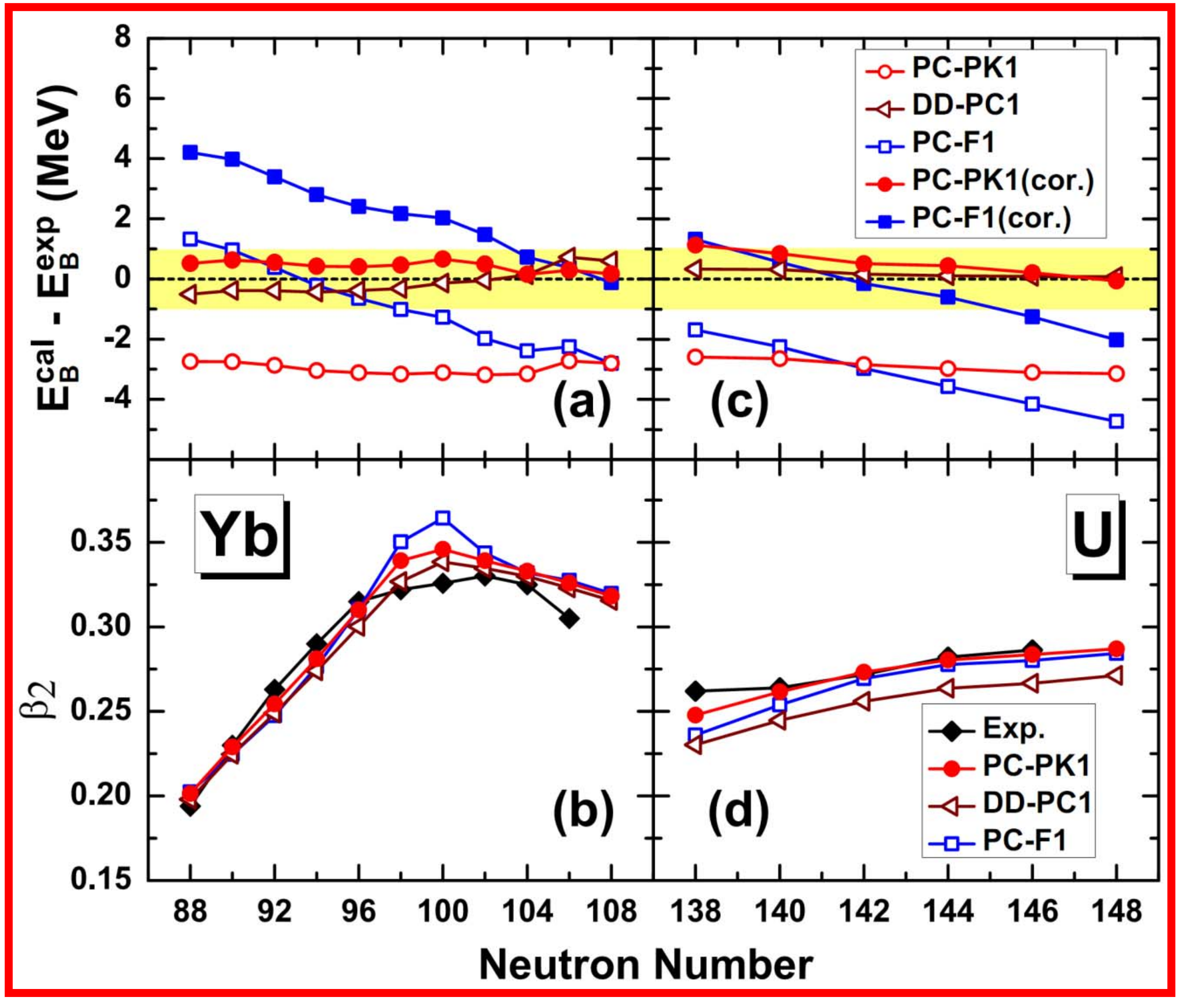




Coupl.	Cons.	PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}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

Fitting to 60 binding energies, 17 charge radii, and empirical pairing gaps of 60 selected spherical nuclei.

Deformed nuclei



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

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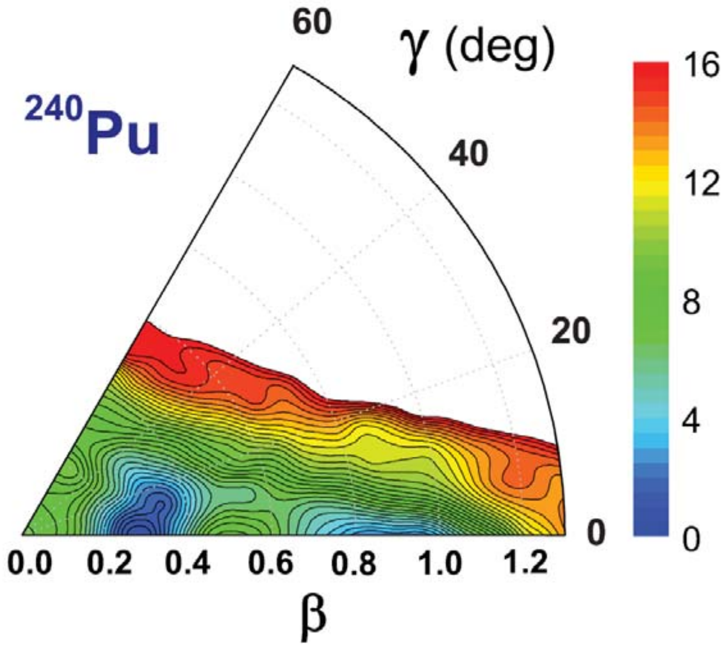
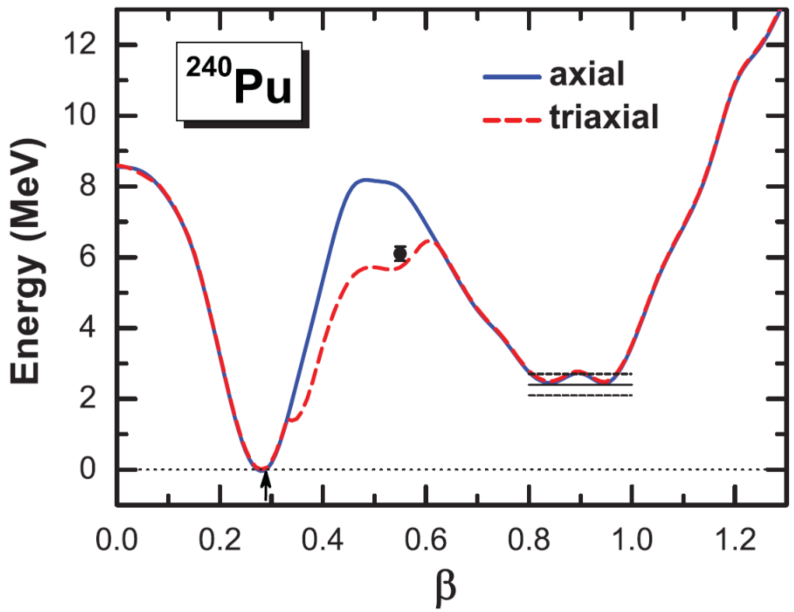
Fission barrier in actinides

The structure of ^{240}Pu and its double-humped fission barrier: a standard benchmark for self-consistent mean-field models





- ✓ The deformation of the ground state and the excited energy of the fission isomer are reproduced well;
- ✓ The inclusion of triaxial shapes lowers the inner barrier by ≈2 MeV, much closer to the available data. Li, Niksic, Vretenar, Ring, Meng, *Phys*.Rev.C**81**, 064321 (2010)

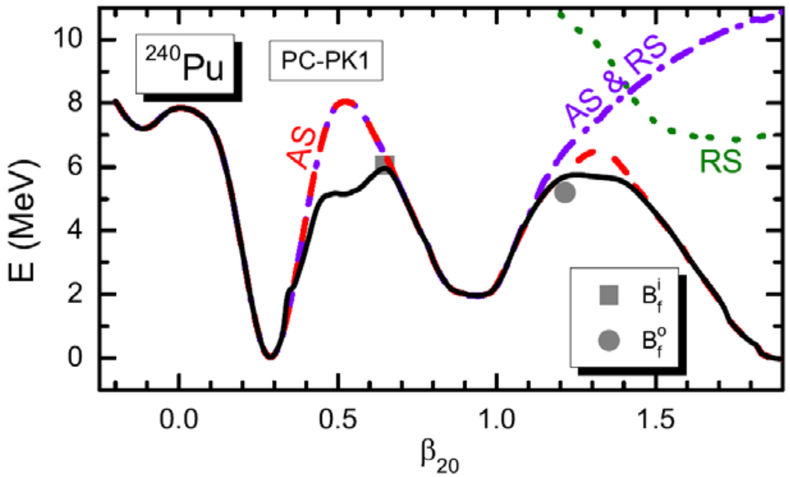
^{240}Pu: 3D PES ($\beta_{20}, \beta_{22}, \beta_{30}$) in MD constraint CDFT

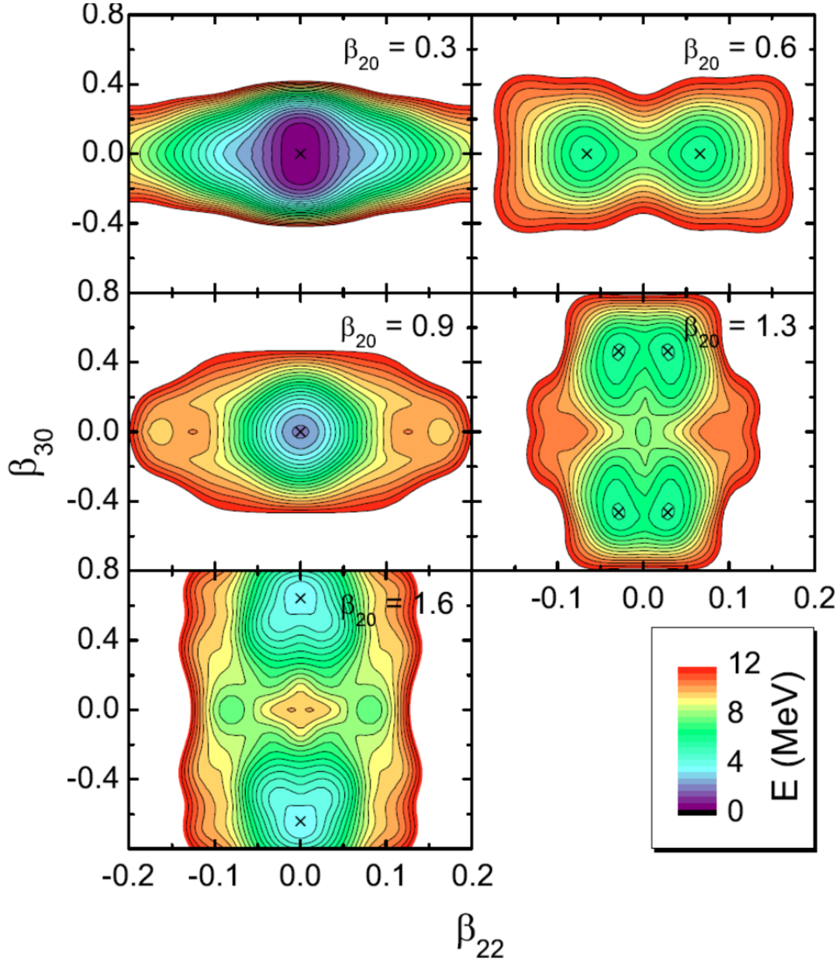
β2, β3, …: Geng, Meng, Toki, 2007, Chinese Phys. Lett. 24-1865

β2, γ, …: Meng, Peng, Zhang, Zhou, 2006, PRC 73-037303

Lu, Zhao, Zhou, PRC85 (2012) 011301R

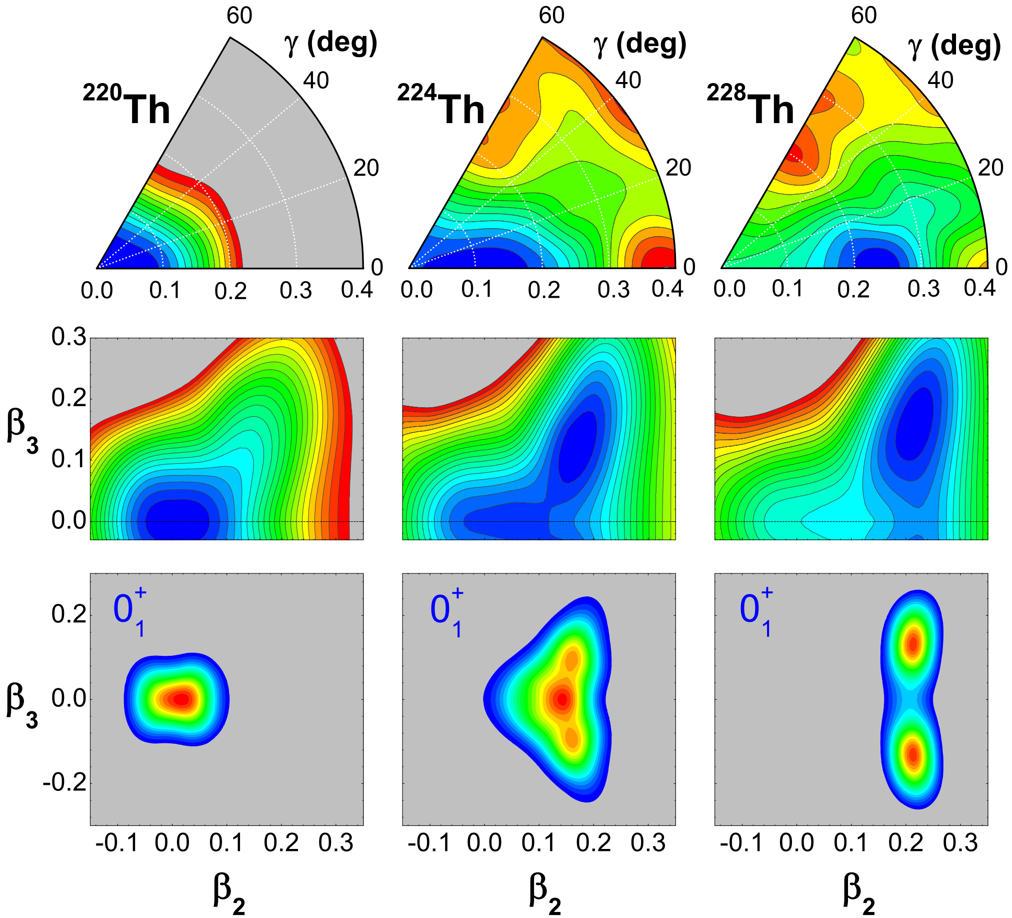
$\beta_{\lambda\mu}$ with even μ are included automatically





- Axial & reflection symmetric shapes for ground state & isomer, the latter is stiffer
- Triaxial shape around the inner barrier
- Triaxial & octupole shape around the outer barrier; this is also true for other actinide nuclei

Simultaneous quadrupole and octupole shape phase transitions in Thorium



[Z. P. Li](), [B. Y. Song](), [J. M. Yao](), [D. Vretenar](), [J. Meng]()

Simultaneous quadrupole and octupole shape phase transitions in Thorium

[arXiv:1304.3766]() [nucl-th]

Physics Letters B

In Press, *Available online 21 September 2013*

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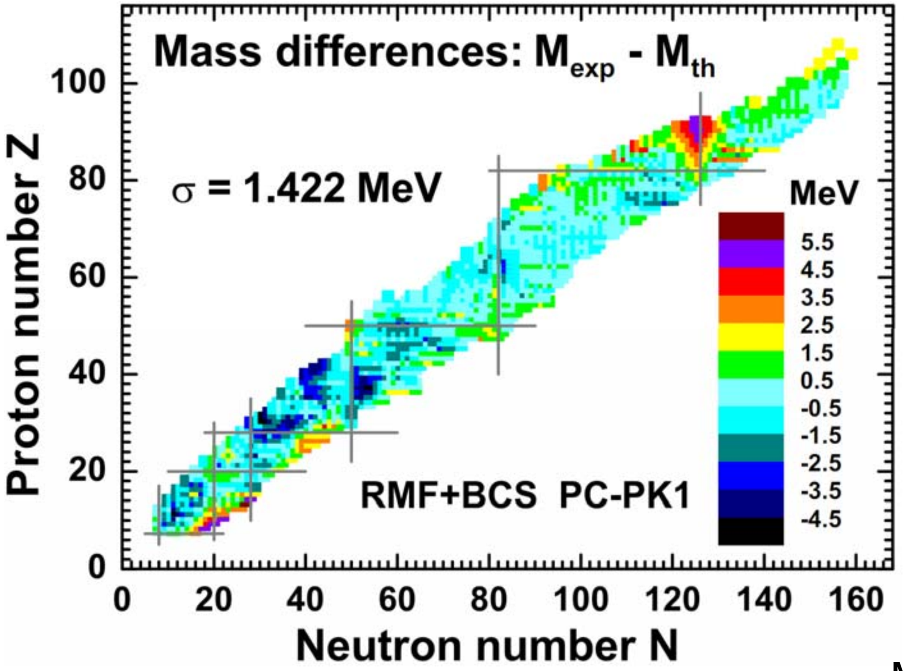
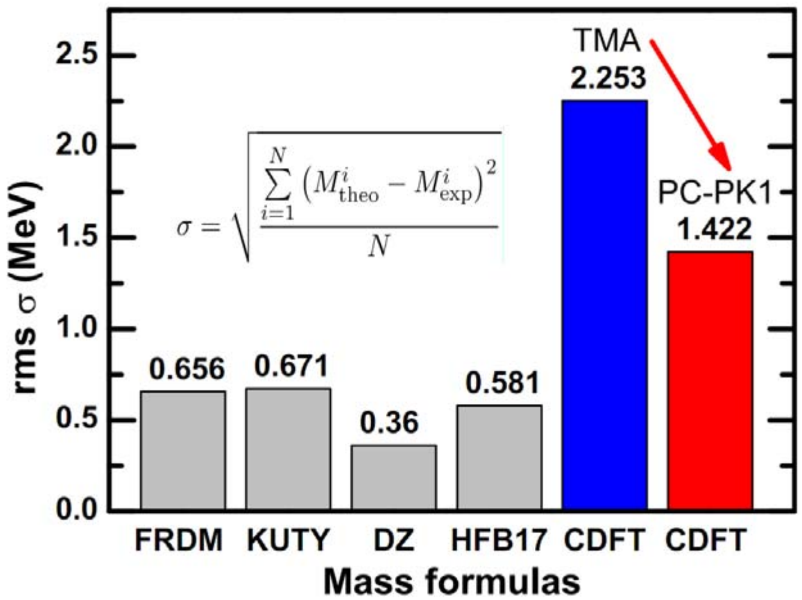
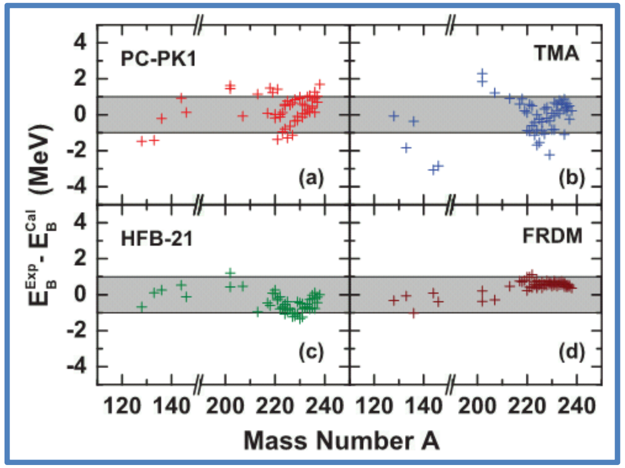
Nuclear Mass





Data for 2149 nuclei from Audi et al. NPA2003

Meng, Peng, Zhang, Zhao, Front. Phys. 8, 55 (2013)



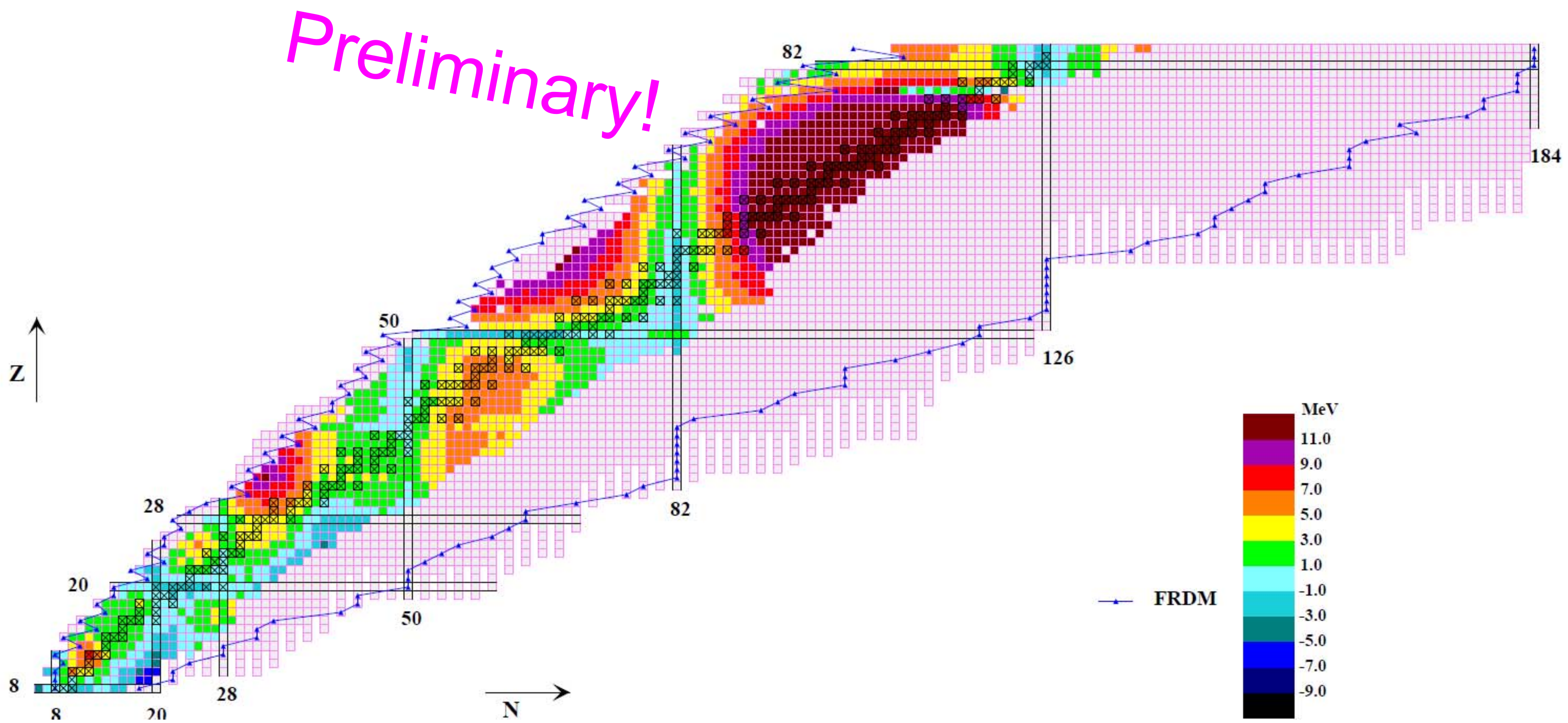
Zhao, Song, Sun. Geissel, Meng, Phys. Rev. C 86, 064324 (2012)

Crucial test for covariant density functional theory with new and accurate mass measurements from Sn to Pa

Long-term plan

Improve the mass description based on CDFT to σ ~ 0.5 MeV.

Extending the nuclear chart by continuum: from oxygen to lead

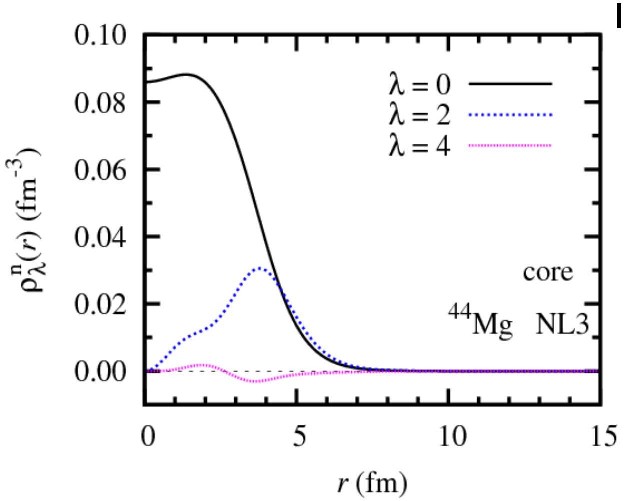


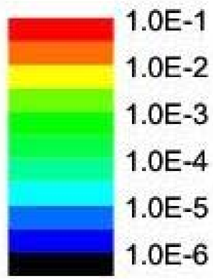
Xiaoying Qu, Ying Chen, Shuangquan Zhang, Pengwei Zhao, Ik Jae Shin, Yeunhwan Lim, Youngman Kim, Jie Meng **[arXiv:1309.3987]**

Extending the nuclear chart by continuum: from oxygen to titanium

Density of core & halo

deformed relativistic Hartree Bogoliubov in the continuum in a spherical Woods-Saxon basis

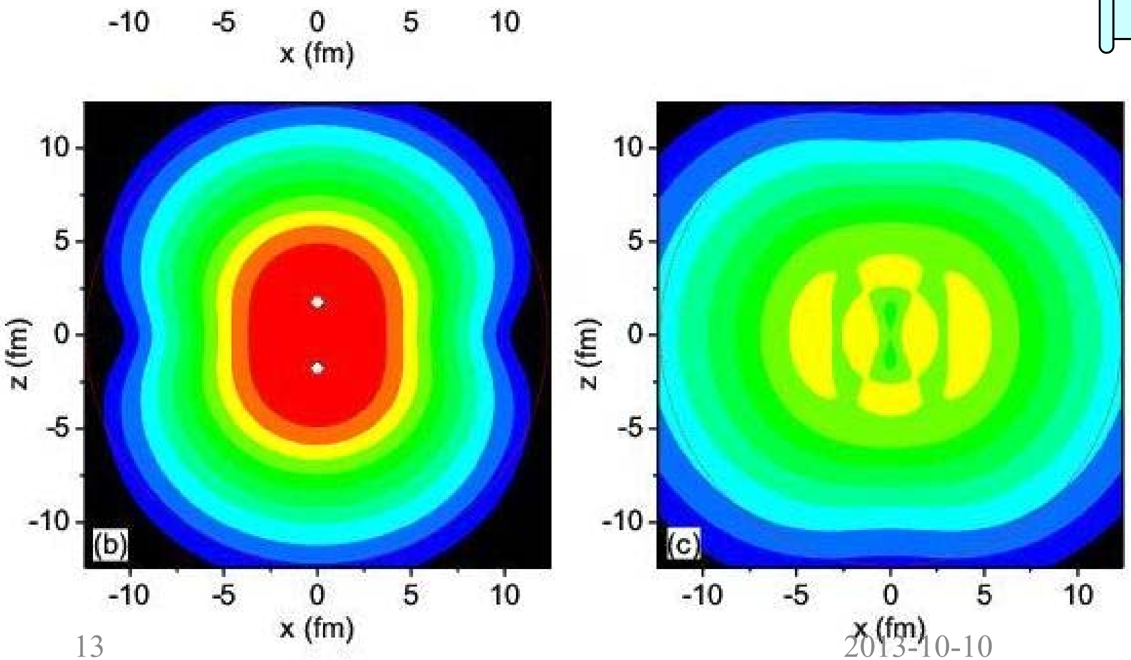


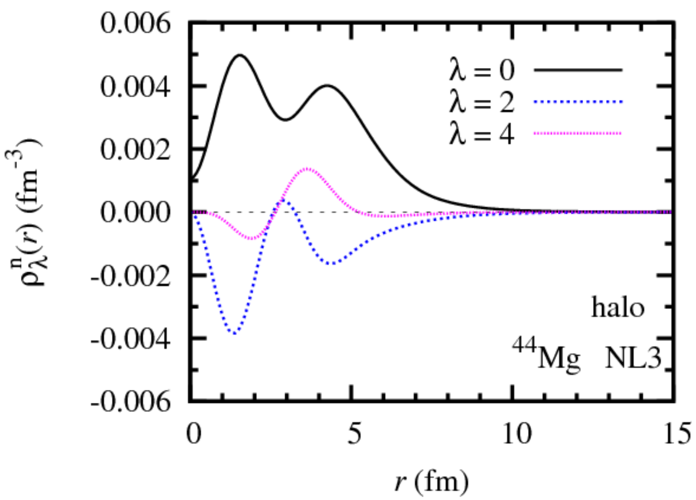


- **Prolate core, but slightly oblate halo with sizable hexadecapole component !**
- **Decoupling of deformation between core & halo**

^{44}Mg

Zhou, Meng, Ring, Zhao, Phys. Rev. C 82 (2010) 011301R



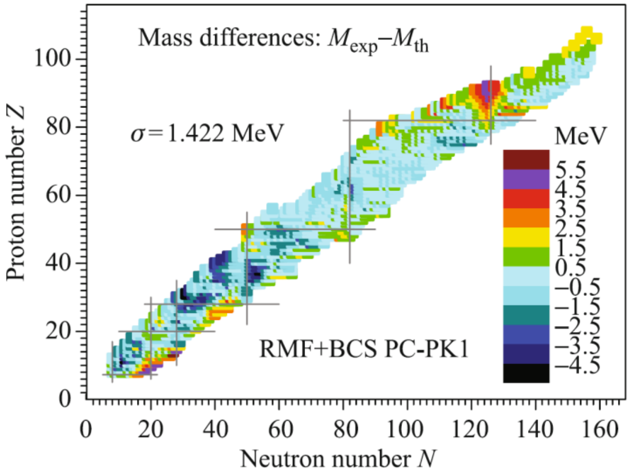


1st CDFT: RMF

Very successful in nuclear physics

Ring PPNP1996, Vretenar Phys.Rep.2005, Meng PPNP2006

- Spin-orbit splitting
- Pseudo-spin symmetry
- Nuclear saturation properties
- Exotic nuclei
- Excellent reproduction of nuclear properties
- ……



Meng, Peng, Zhang, Zhao, Front. Phys.2013

The relativistic Hartree-Fock theory

Bouyssy PRC 1987 Bernardos PRC 1993 Marcos JPG 2004 Bürvenich PRC 2002

In addition of the RMF advantages

- Pion contribution included
- Nuclear effective mass
- Fully self-consistent description for spin-isospin excitation
- ……

Long PLB2006, Long PRC2007, Liang PRL2008, Liang PRC2009

DDRHF(B): pion and Exchange term

Long, Giai, Meng, Physics letters B640 (2006) 150
Long, Ring. Giai, Meng, PHYSICAL REVIEW C81 (2012) 024308
Long, Ring. Giai, Bertulani, Meng, PHYSICAL REVIEWC **81**(2010) 031302

- RHFB equation

$$\int dr' \begin{pmatrix} h(\mathbf{r},\mathbf{r}') - \lambda & \Delta(\mathbf{r},\mathbf{r}') \\ \Delta(\mathbf{r},\mathbf{r}') & -h(\mathbf{r},\mathbf{r}') + \lambda \end{pmatrix} \begin{pmatrix} \psi_U(\mathbf{r}') \\ \psi_V(\mathbf{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\mathbf{r}) \\ \psi_V(\mathbf{r}) \end{pmatrix}$$

- Single particle Hamiltonian: $h = h^{\mathrm{kin}} + h^{\mathrm{D}} + h^{\mathrm{E}}$

Kinetic energy: $h^{\mathrm{kin}}(\mathbf{r},\mathbf{r}') = [\alpha\cdot\mathbf{p} + \beta M]\,\delta(\mathbf{r},\mathbf{r}'),$

Local potentials: $h^{\mathrm{D}}(\mathbf{r},\mathbf{r}') = [\Sigma_T(\mathbf{r})\gamma_5 + \Sigma_0(\mathbf{r}) + \beta\Sigma_S(\mathbf{r})]\,\delta(\mathbf{r},\mathbf{r}'),$

Non-local Potentials: $h^{\mathrm{E}}(\mathbf{r},\mathbf{r}') = \begin{pmatrix} Y_G(\mathbf{r},\mathbf{r}') & Y_F(\mathbf{r},\mathbf{r}') \\ X_G(\mathbf{r},\mathbf{r}') & X_F(\mathbf{r},\mathbf{r}') \end{pmatrix}$

- Pairing Force: Gogny D1S

$$V(\mathbf{r},\mathbf{r}') = \sum_{i=1,2} e^{((r-r')/\mu_i)^2}\,(W_i + B_iP^\sigma - H_iP^\tau - M_iP^\sigma P^\tau)$$

- Dirac Woods-Saxon Basis: solve the integro-differential RHFB equation

Charge-exchange excitation modes

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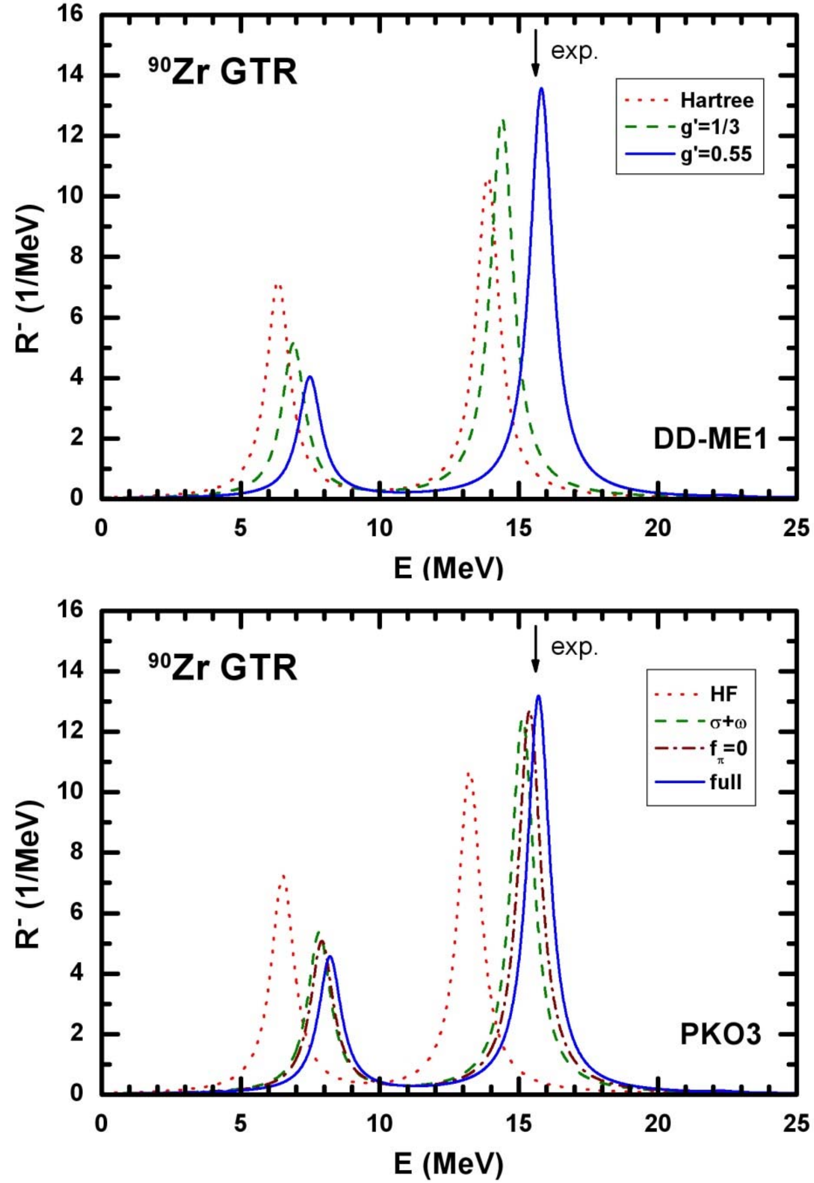
RH + RPA

- ✧ No contribution from isoscalar mesons (σ,ω), because exchange terms are missing.
- ✧ π-meson is dominant in this resonance.
- ✧ zero-range pionic counter-term g' has to be refitted to reproduce the data.

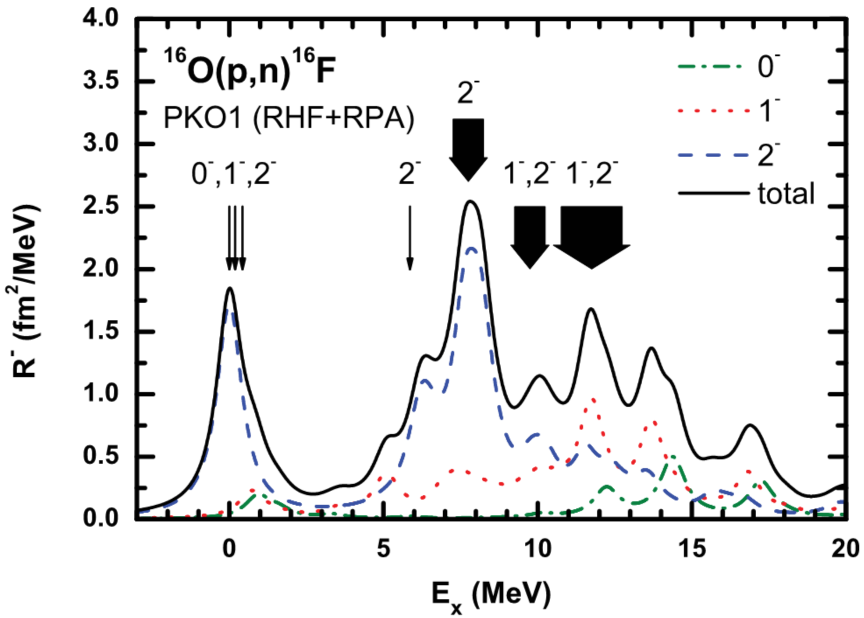
RHF + RPA

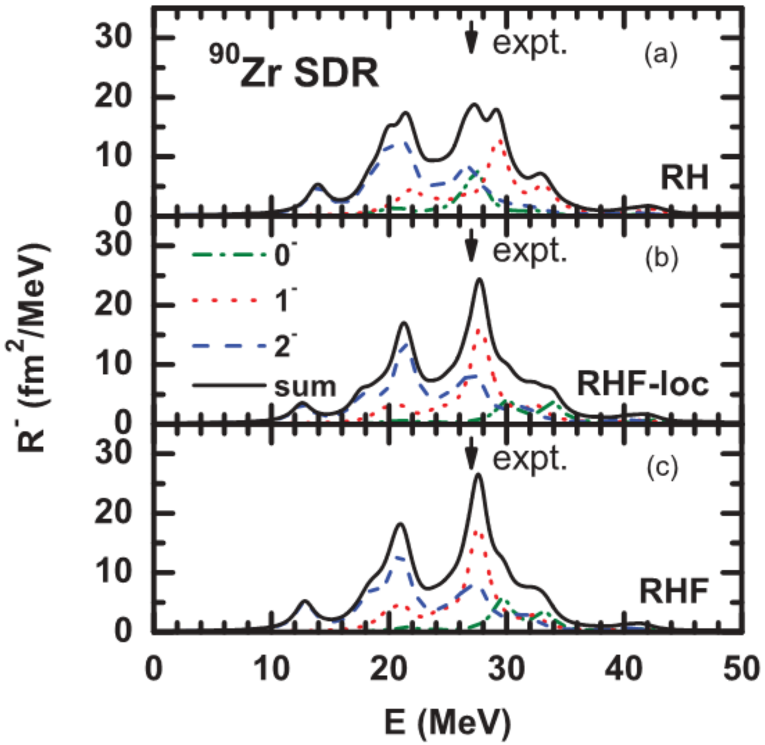
- ✧ Isoscalar mesons (σ,ω) play an essential role via the exchange terms.
- ✧ While, π-meson plays a minor role.
- ✧ g' = 1/3 is kept for self-consistency.

Liang, Giai, Meng, PRL 101, 122502 (2008)



Lcalized form of Fock terms





The fine structure of spin-dipole excitations in O-16 is reproduced quite well in a fully self-consistent RPA calculation based on the RHF theory

Liang, Giai, Meng PRL 101, 122502 (2008)
Liang, Zhao, Meng Phys. Rev. C 85, 064302 (2012)

- **A localized form of Fock terms** is proposed with considerable simplicity as compared to the conventional Fock terms.
- Based on this localized RHF theory, the spin-dipole excitation in Zr-90 is well reproduced with a RPA calculation.

Liang, Zhao, Ring, Roca-Maza, Meng Phys. Rev. C 86, 021302 (2012)

New generation CDFT: *ab initio* calculation

ab initio calculation in nuclear physics

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

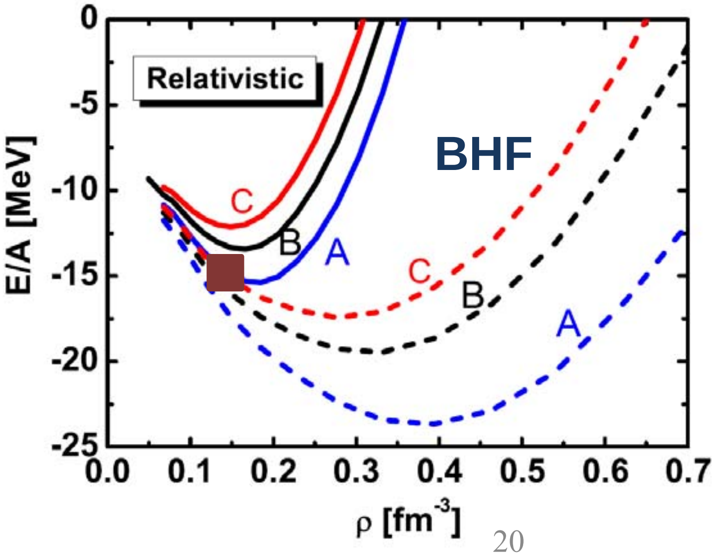
- without additional assumptions
- without additional parameters

ab initio in nuclear physics

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

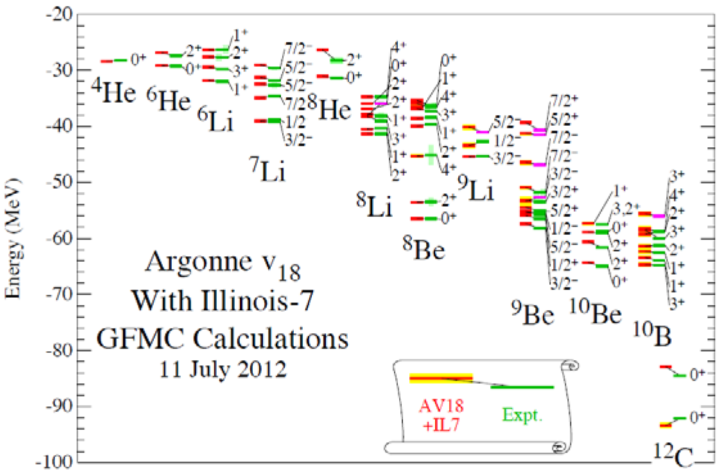
ab initio in nuclear matter

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



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

Relativistic Brueckner Hartree-Fock: nuclear matter

- Nuclear matter Anastasio PRep 1978 Brockmann PLB 1984 ter Haar PRep. 1987
- Defining an effective medium dependent meson-exchange interaction based upon the nuclear matter G matrix Brockmann PRC1990 Brockmann PRL 1992 Fritz PRL 1993

ab initio calculation CDFT attempt for finite nucleus: extracted interaction from the *ab initio* calculation for nuclear matter

- Density-dependent relativistic mean field theory Brockmann PRL1992
- Density-dependent relativistic Hartree-Fock theory Fritz PRL1993

Full *ab initio* CDFT

Relativistic Brueckner Hartree-Fock calculation for finite nucleus

- ***ab initio*** **CDFT / Full Relativistic Brueckner Hartree-Fock calculation for finite nucleus with expansion in Harmonics Oscillator (HO) basis**
- **Effective NN interaction: Brueckner G-matrix in HO basis**
- **Solve relativistic Hartree-Fock (RHF) equation in HO basis with the G-matrix in HO basis**

T-Matrix and G-Matrix

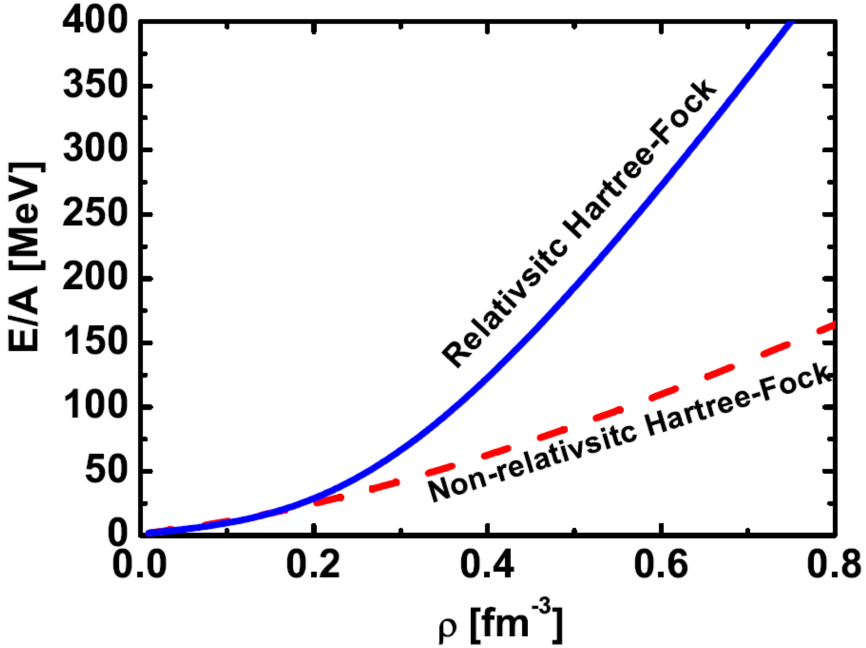
Lippmann-Schwinger Equation

Lippmann Phys. Rev 1950

$$T = V + V\frac{1}{E - H_0}T$$

- V is the realistic NN interaction
- E is the incident energy
- T-matrix is for two-body scattering

The corresponding EOS in HF



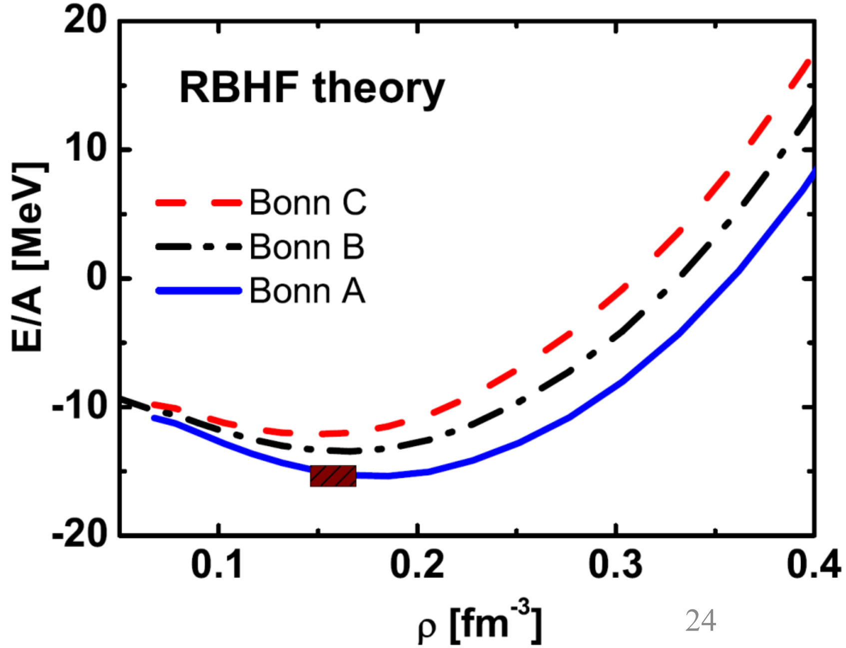
Bethe-Goldstone Equation

Brueckner Phys. Rev 1955

$$G = V + V\frac{Q}{E - H_0}G$$

- E is the starting energy
- Q is the Pauli operator
- G-matrix is for many-body problem

The corresponding EOS in HF



Bethe-Goldstone equation in basis space

$$\langle nm|G(\omega)|n'm'\rangle = \langle nm|V|n'm'\rangle + \sum_{\varepsilon_i,\varepsilon_j>\varepsilon_F} \frac{\langle nm|V|ij\rangle\langle ij|G(\omega)|n'm'\rangle}{\omega-(\varepsilon_i+\varepsilon_j)}$$

where ε_F is the Fermi energy, $\omega=\varepsilon_m+\varepsilon_n$ is the starting energy and i, j are intermediate states.

Bethe-Goldstone equation in plane wave basis

$$G_{ll'}^{\alpha}(kk'K\omega) = V_{ll'}^{\alpha}(kk') + \sum_{ll'} \frac{d^3q}{(2\pi)^3} V_{ll'}^{\alpha}(kq) \frac{Q(q,K)}{\omega-H_0} G_{ll'}^{\alpha}(qk'K\omega)$$

where α is a shorthand notation for J, S, L and T.

Matrix inversion method

$$G = \left(1-\frac{V}{\omega-H_0}\right)^{-1} V$$

Relativistic Hartree-Fock theory

Long, Giai and Meng, Phys. Lett. B 640, 150 (2006)
Long, Ring, Giai and Meng, Phys. Rev. C81, 024308 (2010)

Relativistic Hartree-Fock (RHF) equation

$$\sum_{n'} \left(\alpha\cdot p+\beta M+\beta\,\Gamma^{HF}\right)_{nn'}\psi_{n'}=\varepsilon_n\psi_n$$

where $\Gamma^{HF}_{nn'}$ is related with the density matrix $\rho_{nn'}$

$$\Gamma^{HF}_{nn'}=V_{nmn'm'}\rho_{mm'}-V_{nmm'n'}\rho_{mm'}$$

$$\psi_a=\begin{pmatrix}\sum\limits_{n=1}^{n_{\max}} f_n^{(a)}R_{nl_a}(r)\\ \sum\limits_{\tilde n=1}^{\tilde n_{\max}} g_{\tilde n}^{(a)}R_{\tilde n\tilde l_a}(r)\end{pmatrix}$$

RHF equation in HO basis

$$\begin{pmatrix}A^{RHF}_{nn'} & B^{RHF}_{n\tilde n'}\\ B^{RHF}_{\tilde n' n} & C^{RHF}_{\tilde n\tilde n'}\end{pmatrix}\begin{pmatrix}f_{n'}^{(a)}\\ g_{\tilde n'}^{(a)}\end{pmatrix}=\varepsilon_a\begin{pmatrix}f_n^{(a)}\\ g_{\tilde n}^{(a)}\end{pmatrix}$$

where

$$A^{RHF}_{nn'}=(\alpha\cdot p+\beta M)_{nn'}+\sum_b\sum_{m,m'} f_m^{(b)}f_{m'}^{(b)}(v_{nmn'm'}-v_{nmm'n'})$$

$$B^{RHF}_{n\tilde n'}=(\alpha\cdot p+\beta M)_{n\tilde n'}+\sum_b\sum_{m,\tilde m'} f_m^{(b)}g_{\tilde m'}^{(b)}(v_{nm\tilde n'\tilde m'}-v_{nm\tilde m'\tilde n'})$$

$$C^{RHF}_{\tilde n\tilde n'}=(\alpha\cdot p+\beta M)_{\tilde n\tilde n'}+\sum_b\sum_{\tilde m,\tilde m'} g_{\tilde m}^{(b)}g_{\tilde m'}^{(b)}(v_{\tilde n\tilde m\tilde n'\tilde m'}-v_{\tilde n\tilde m\tilde m'\tilde n'})$$

Relativistic Brueckner Hartree-Fock (RBHF) equation

$$\sum_{n'}\left(\alpha\cdot p+\beta M+\beta\,\Gamma^{BHF}\right)_{nn'}\psi_{n'}=\varepsilon_n\psi_n$$

where $\Gamma^{BHF}_{nn'}$ is related with the density matrix $\rho_{nn'}$

$$\Gamma^{BHF}_{nn'}=G_{nmn'm'}\rho_{mm'}-G_{nmm'n'}\rho_{mm'}$$

RHF equation in HO basis

$$\begin{pmatrix} A^{BHF}_{nn'} & B^{BHF}_{n\tilde{n}'} \\ B^{BHF}_{\tilde{n}'n} & C^{BHF}_{\tilde{n}\tilde{n}'} \end{pmatrix}\begin{pmatrix} f^{(a)}_{n'} \\ g^{(a)}_{\tilde{n}'} \end{pmatrix}=\varepsilon_a\begin{pmatrix} f^{(a)}_{n} \\ g^{(a)}_{\tilde{n}} \end{pmatrix}$$

where

$$A^{BHF}_{nn'}=(\alpha\cdot p+\beta M)_{nn'}+\sum_b\sum_{m,m'}f^{(b)}_m f^{(b)}_{m'}(G_{nmn'm'}-G_{nmm'n'})$$

$$B^{BHF}_{n\tilde{n}'}=(\alpha\cdot p+\beta M)_{n\tilde{n}'}+\sum_b\sum_{m,\tilde{m}'}f^{(b)}_m g^{(b)}_{\tilde{m}'}(G_{nm\tilde{n}'\tilde{m}'}-G_{nm\tilde{m}'\tilde{n}'})$$

$$C^{BHF}_{\tilde{n}\tilde{n}'}=(\alpha\cdot p+\beta M)_{\tilde{n}\tilde{n}'}+\sum_b\sum_{\tilde{m},\tilde{m}'}g^{(b)}_{\tilde{m}} g^{(b)}_{\tilde{m}'}(G_{\tilde{n}\tilde{m}\tilde{n}'\tilde{m}'}-G_{\tilde{n}\tilde{m}\tilde{m}'\tilde{n}'})$$

Example

- Object: ^{16}O
- Interaction: Bouyssy C

Bouyssy PRC1987

- Basis: Harmonics Oscillator (HO) (N=12)
  Relativistic Harmonics Oscillator (RHO) (N_F=12, N_D=8)

The properties of ^{16}O

	r-space[1]	HO	RHO
E (MeV)	−49.44	−49.45	−49.45
r_c (fm)	2.91	2.90	2.91
$\varepsilon_{1p_{1/2}} - \varepsilon_{1p_{3/2}}$ (MeV)	5.5	5.5	5.5

The properties of ^{16}O with different methods with Bouyssy interaction

[1] Bouyssy PRC1987

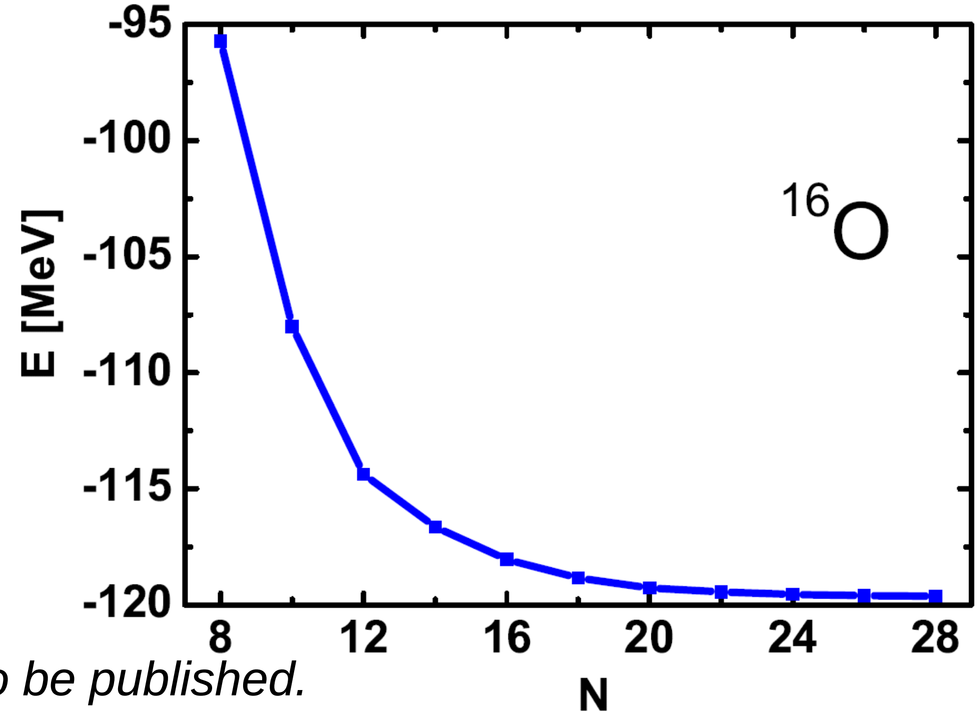
Hu, Meng, Ring, *to be published.*

Convergence of RBHF theory

Example

- Object: ^{16}O
- Interaction: Bonn A — Machleidt ANP1987
- Basis: Harmonics Oscillator (HO)

Convergence of RBHF calculation for ^{16}O



Hu, Meng, Ring, *to be published.*

Properties of ^{16}O

	EXP. [1]	RBHF (N=28)	BHF [2]	PKO1 [3]
E (MeV)	−127.62	−119.552	−104.96	−128.36
r_c (fm)	2.737	2.6357	2.291	2.679
$\varepsilon_{1p_{1/2}} - \varepsilon_{1p_{3/2}}$ (MeV)	6.3	4.1	7.5	6.3

[1] Audi NPA2003, [2] Muether PRC1990, [3]Long PLB2006

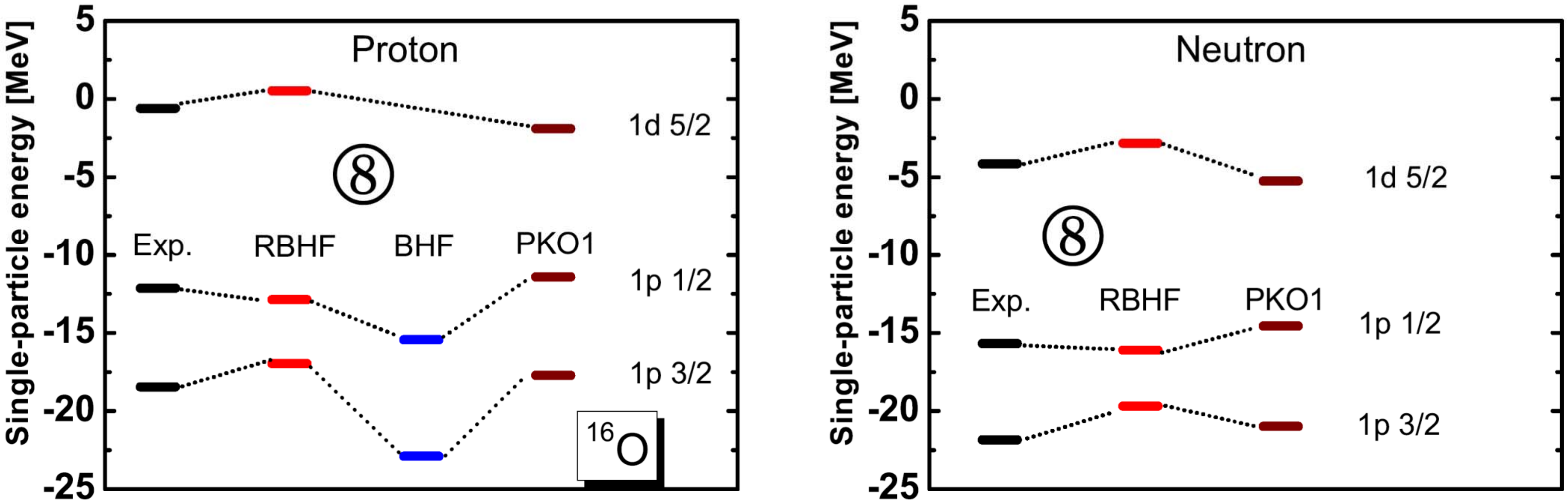
Energy components of ^{16}O in RBHF theory

Methods	$\langle T \rangle$	$\langle V_m \rangle$	E_{coul}	$E_{\mathrm{c.m.}}$	$E_{\mathrm{tot.}}$
PKO1	209.176	−340.910	13.942	−10.572	−128.364
RBHF (N=28)	235.315	−357.898	14.037	−11.006	−119.552

Hu, Meng, Ring, *to be published.*

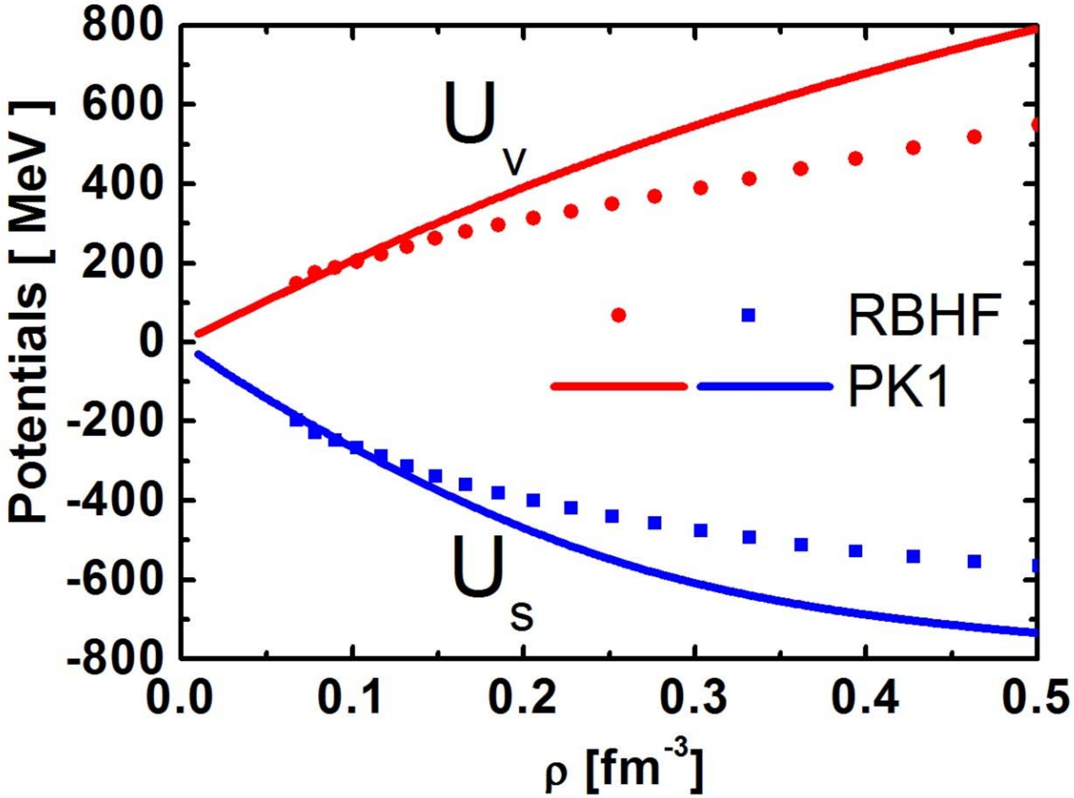
Single proton energies for ^{16}O in RBHF theory

	EXP.	RBHF (N=28)	BHF	PKO1
$\varepsilon_{1s_{1/2}}$	-40 ± 8	-34.085	-50.46	-34.682
$\varepsilon_{1p_{3/2}}$	-18.451	-16.954	-22.89	-17.719
$\varepsilon_{1p_{1/2}}$	-12.127	-12.872	-15.44	-11.417



Hu, Meng, Ring, *to be published.*

The scalar and vector potentials in RMF and RBHF theories



Spin-orbit force in RMF theory

$$\boxed{U_{S.O.} \propto (U_V - U_S)\vec{L}\cdot\vec{S}}$$

The Lagrangian of Density-dependent RH (DDRH) theory

Brockmann PRL1992

$$L = \bar{\psi}_N (i\gamma_\mu \partial^\mu - M_N - g_{\sigma N}(\rho)\sigma - g_{\omega N}(\rho)\gamma_\mu \omega^\mu - e\gamma_\mu \frac{1-\tau^3}{2} A^\mu)\psi_N$$
$$+\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$

DDRH*

$$U_S = g_{\sigma B}(\rho)\sigma$$
$$U_V = g_{\omega B}(\rho)\omega$$

The Lagrangian of Density-dependent RHF (DDRHF) theory

Fritz PRL1993

$$L = \bar{\psi}_N (i\gamma_\mu \partial^\mu - M_N - g_{\sigma N}(\rho)\sigma - g_{\omega N}(\rho)\gamma_\mu \omega^\mu - \frac{f_{\pi N}}{m_\pi}(\rho)\tau^a \gamma_5 \gamma_\mu \partial^\mu \pi^a - e\gamma_\mu \frac{1-\tau^3}{2} A^\mu)\psi_N$$
$$+\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$
$$+\frac{1}{2}\partial_\mu \pi^a \partial^\mu \pi^a - \frac{1}{2} m_\pi^2 \pi^{a2}$$

DDRHF*

$$U_S = g_{\sigma B}(\rho)\sigma$$
$$U_V = g_{\omega B}(\rho)\omega$$

Properties of ^{16}O

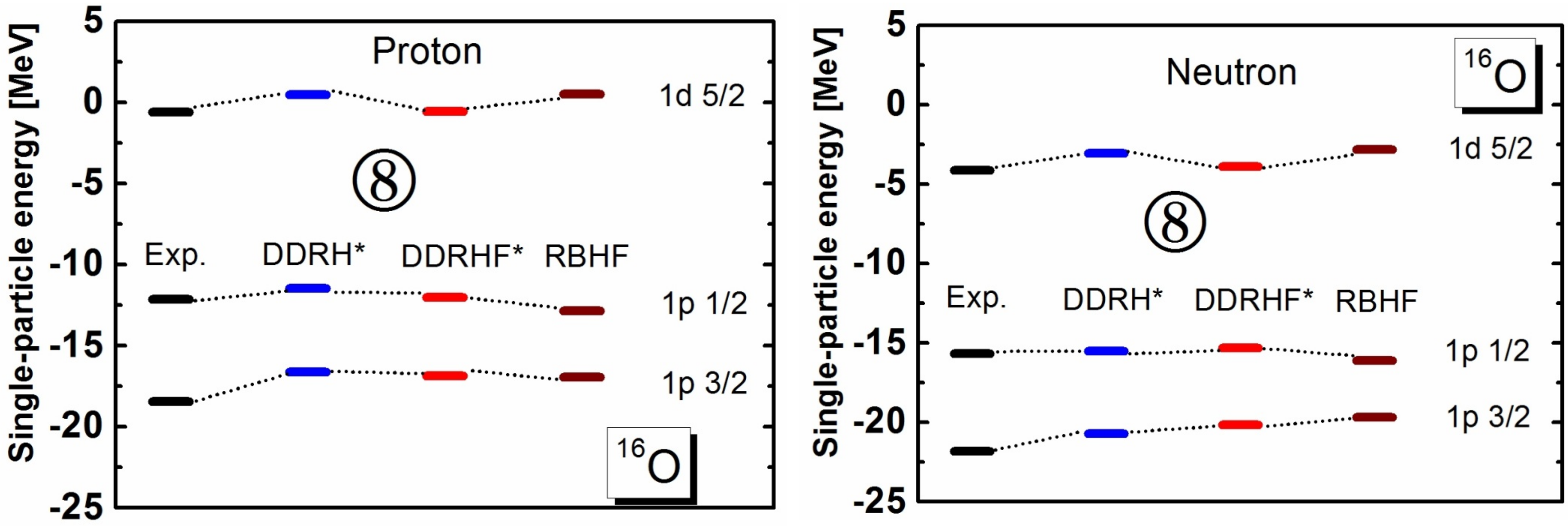
	EXP. [1]	DDRH*	DDRHF*	RBHF (N=28)
E (MeV)	−127.62	−107.72	−114.76	−119.55
r_c (fm)	2.737	2.602	2.634	2.636
$\varepsilon_{1p_{1/2}} - \varepsilon_{1p_{3/2}}$ (MeV)	6.3	5.2	4.8	4.1

[1] Audi NPA2003

* DD couplings extracted from RBHF theory at nuclear matter

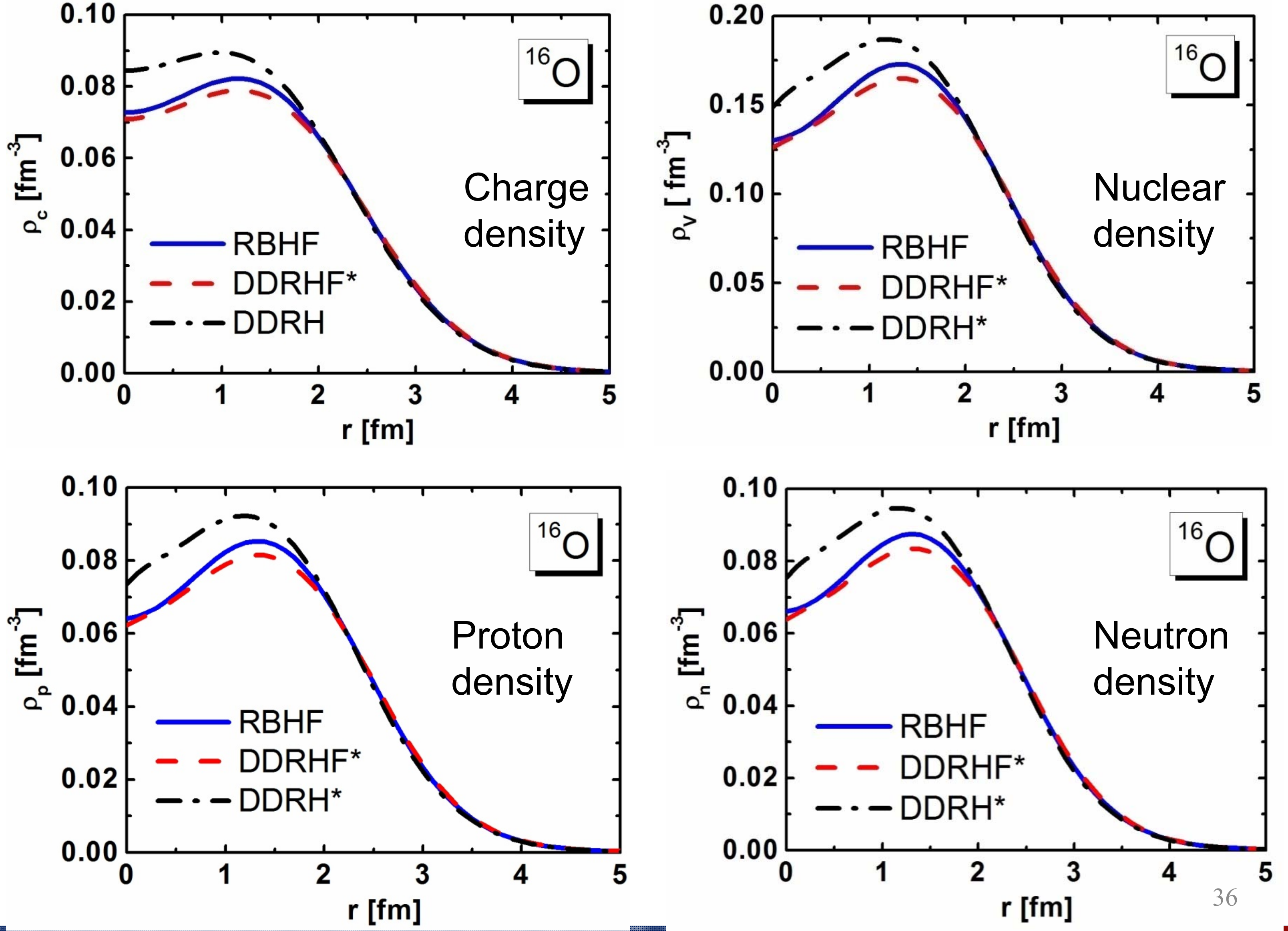
Hu, Meng, Ring, *to be published.*

Single particle levels in ^{16}O

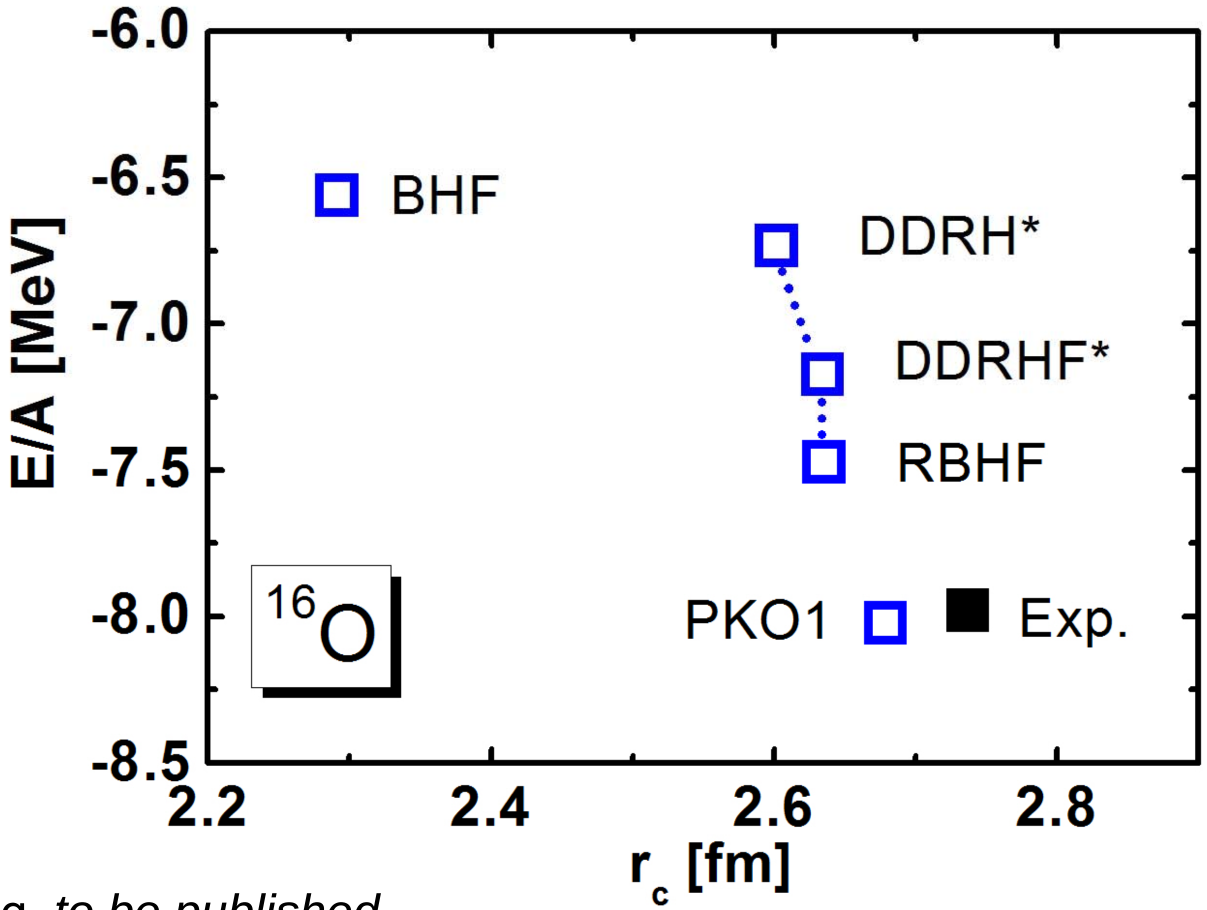


Hu, Meng, Ring, *to be published.*

Nucleon densities in ^{16}O



Relation between binding energy and radii of ^{16}O



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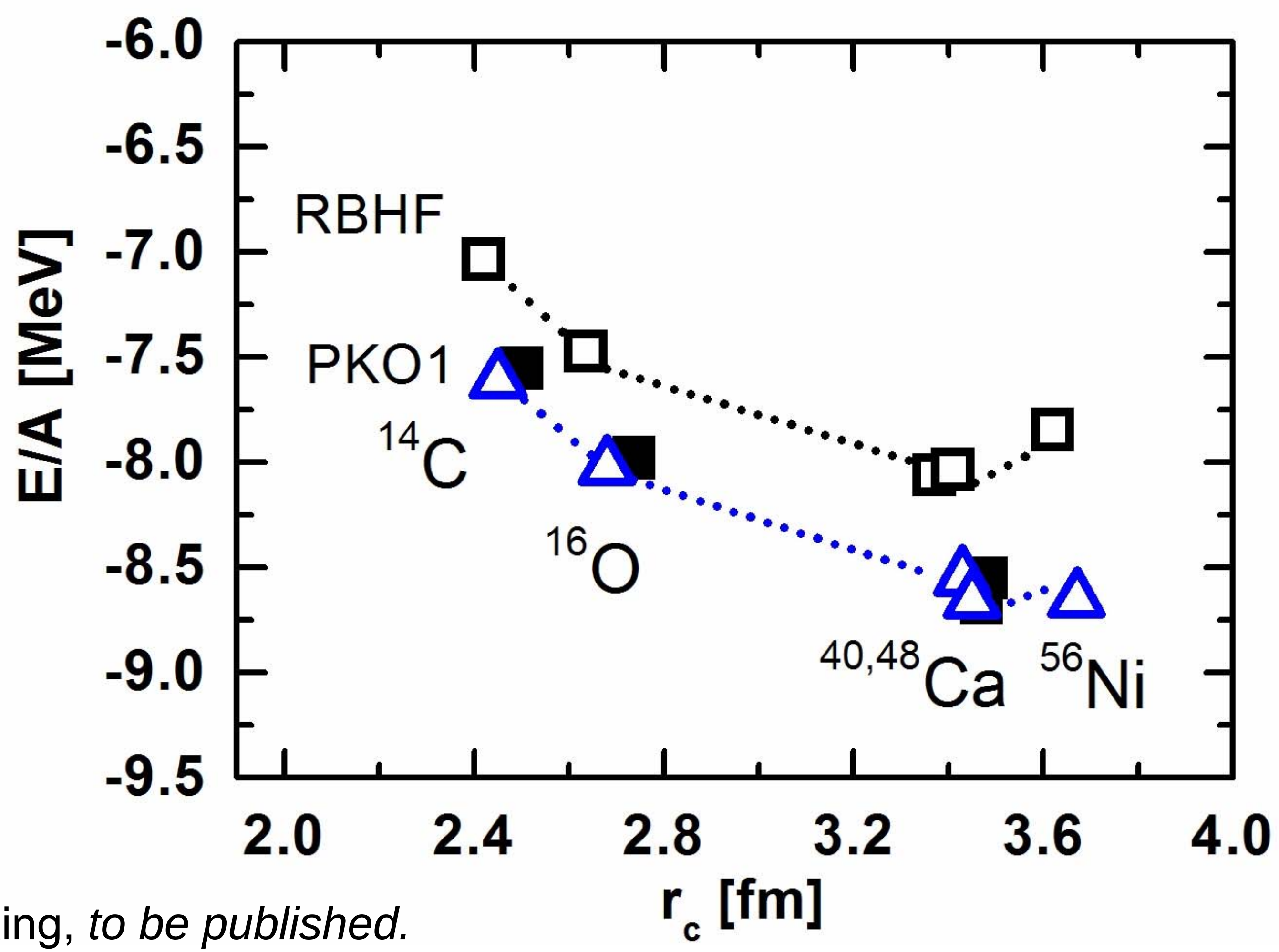
^{16}O, ^{40}Ca, ^{48}Ca and ^{56}Ni in RBHF

Relation between binding energy and radii



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Ground state properties in RBHF theory

	E (MeV)			r_c (fm)			$\varepsilon_{1p_{1/2}} - \varepsilon_{1p_{3/2}}$ (MeV)		
	Exp.	RBHF	PKO1	Exp.	RBHF	PKO1	Exp.	RBHF	PKO1
^{14}C	−105.73	−98.49	−106.66	2.50	2.42	2.45	–	4.6	6.6
^{14}O	−98.73	−91.51	−100.48	–	2.67	2.68	–	–	–
^{40}Ca	−342.05	−322.41	−341.93	3.48	3.37	3.43	7.2	5.7	6.5
^{48}Ca	−416.16	−385.62	−415.62	3.47	3.41	3.45	4.3	3.1	6.2
^{56}Ni	−483.95	−439.26	−484.61	–	3.62	3.67	–	1.2	1.8

Deviations of binding energy between data and RBHF calculation

	^{14}C	^{14}O	^{16}O	^{40}Ca	^{48}Ca	^{56}Ni
$(E_{\rm exp.} - E_{RBHF})/E_{\rm exp.}(\%)$	6.85	7.31	6.32	5.74	7.34	9.23

- The binding energy is reproduced within10% in RBHF
- The spin-orbit splitting is small

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Summary and Perspectives

- New generation of CDFT, i.e., Relativistic Brueckner-Hartree-Fock (RBHF) theory is developed for finite nuclei in HO basis.
- The code of RHF equation in HO basis is confirmed by reproduce the same results as in coordinate space.
- RBHF calculation for ^{16}O with Bonn potential has been check up to N_fermion = 28.
- The experimental binding energy, charge radii and spin-orbit splitting for ^{14}C, ^{16}O, ^{40}Ca, ^{48}Ca and ^{56}Ni are reproduced with RBHF within 10%, and RBHF results are comparable with the ones from PKO1.
- Calculation for heavier nuclei is in progress.

Thank you for your attention!