Covariant density functional theory for nuclear structure and nuclear astrophysics

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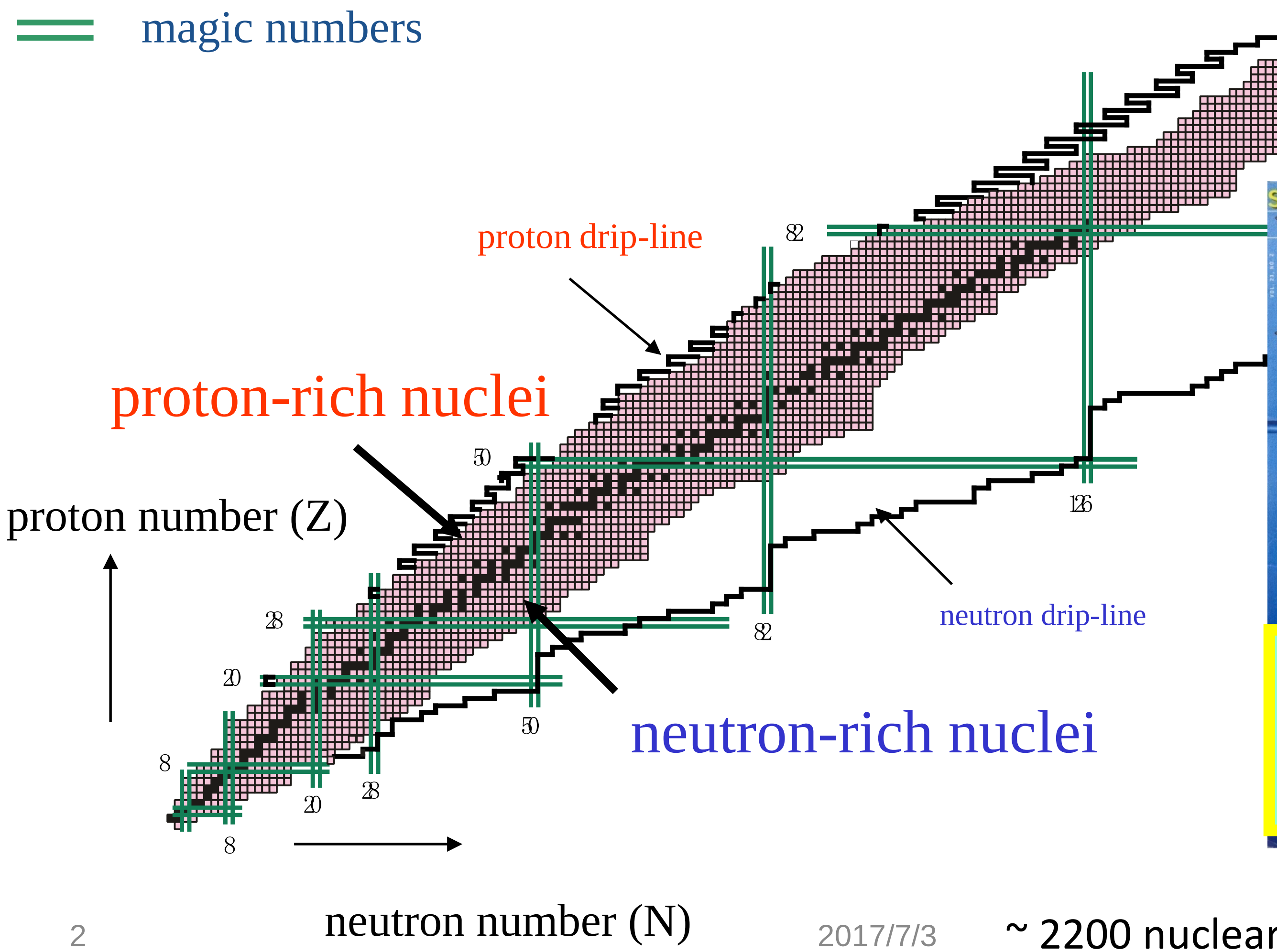
Existence Limit of nucleus

- stable nuclei ~300 nuclei
- unstable nuclei observed so far ~2700 nuclei
- drip-lines (limit of existence)（theoretical predictions) ~8000 nuclei
- magic numbers

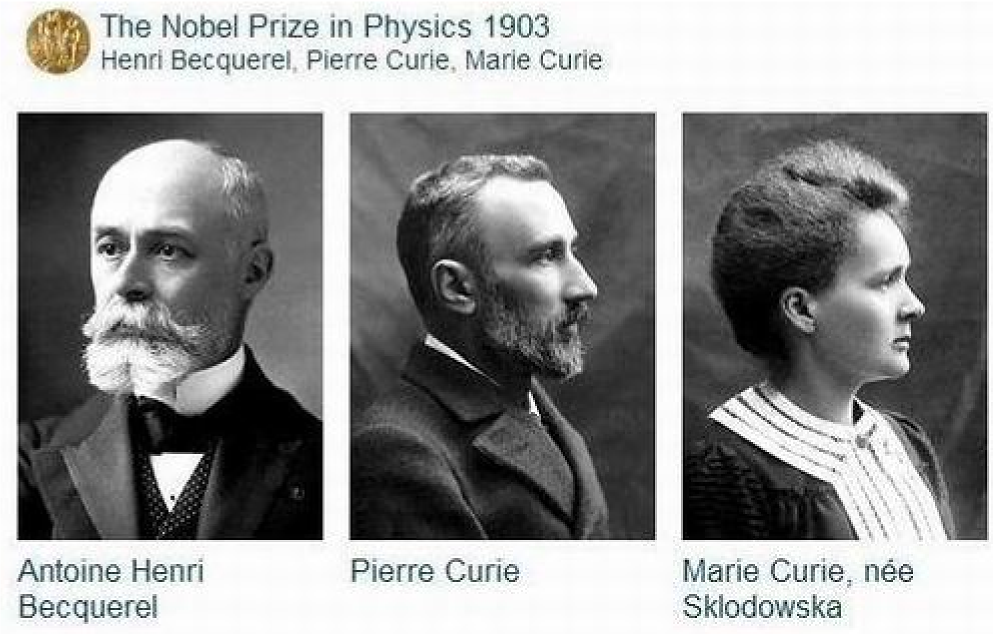


- Z=113
- Halo
- Ikeda diagram
- …

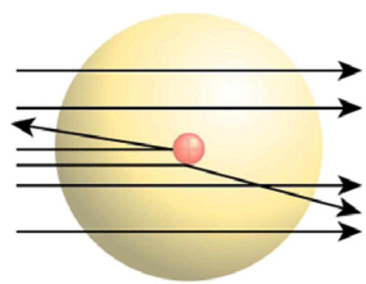
Question 3
How were the elements from iron to uranium made ?

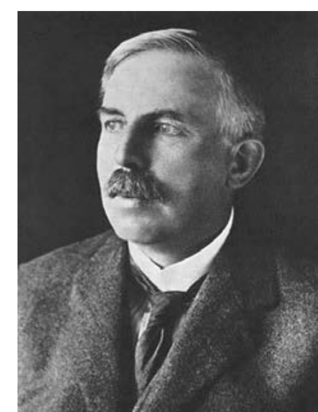
~ 2200 nuclear masses were measured

Birth of nuclear physics



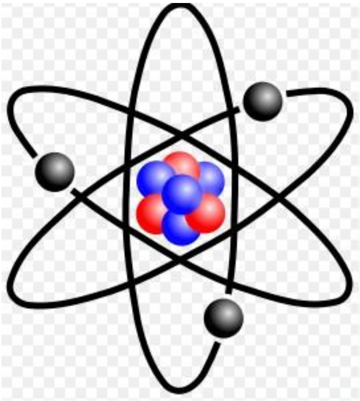
Around the turn of Nineteenth and Twentieth centuries, the discoveries of radioactivity by Becquerel and the Curies and the existence of a compact nucleus at the center of an atom by Rutherford *et al.* opened the door of nuclear science. These achievements conceived the birth of quantum mechanics, promoted the exploitation and utilization of nuclear energy and nuclear technology, and brought about a huge impact on human life.



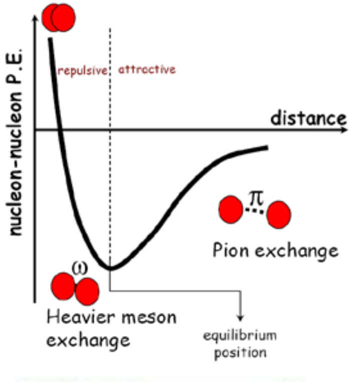


Milestone toward the nuclear model

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

Shell model & 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

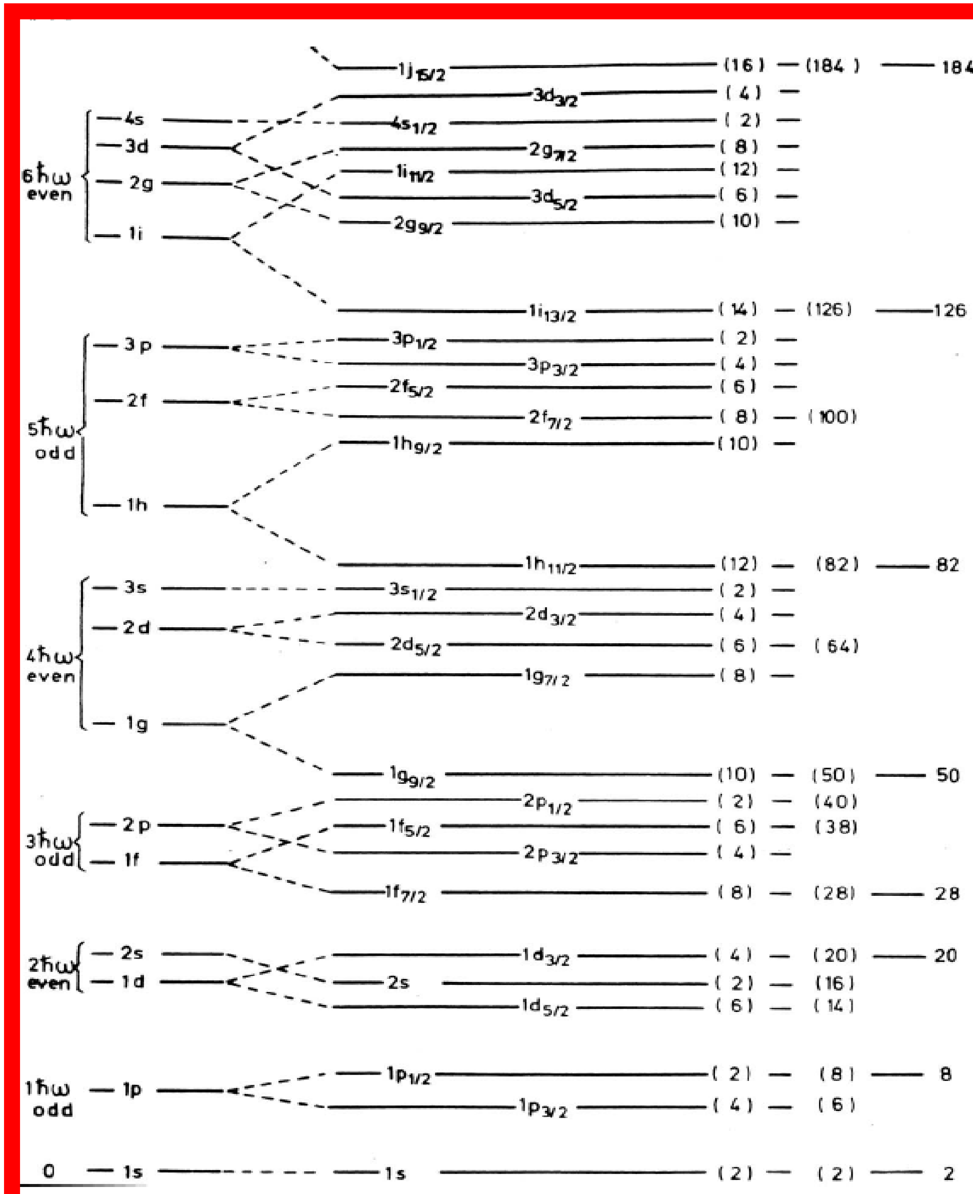

A. N. Bohr


B. R. Mottelson


J. Rainwater

Nobel Prize in Physics 1975

Shell model & Collective model



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

Strutinsky Shell correction calculation

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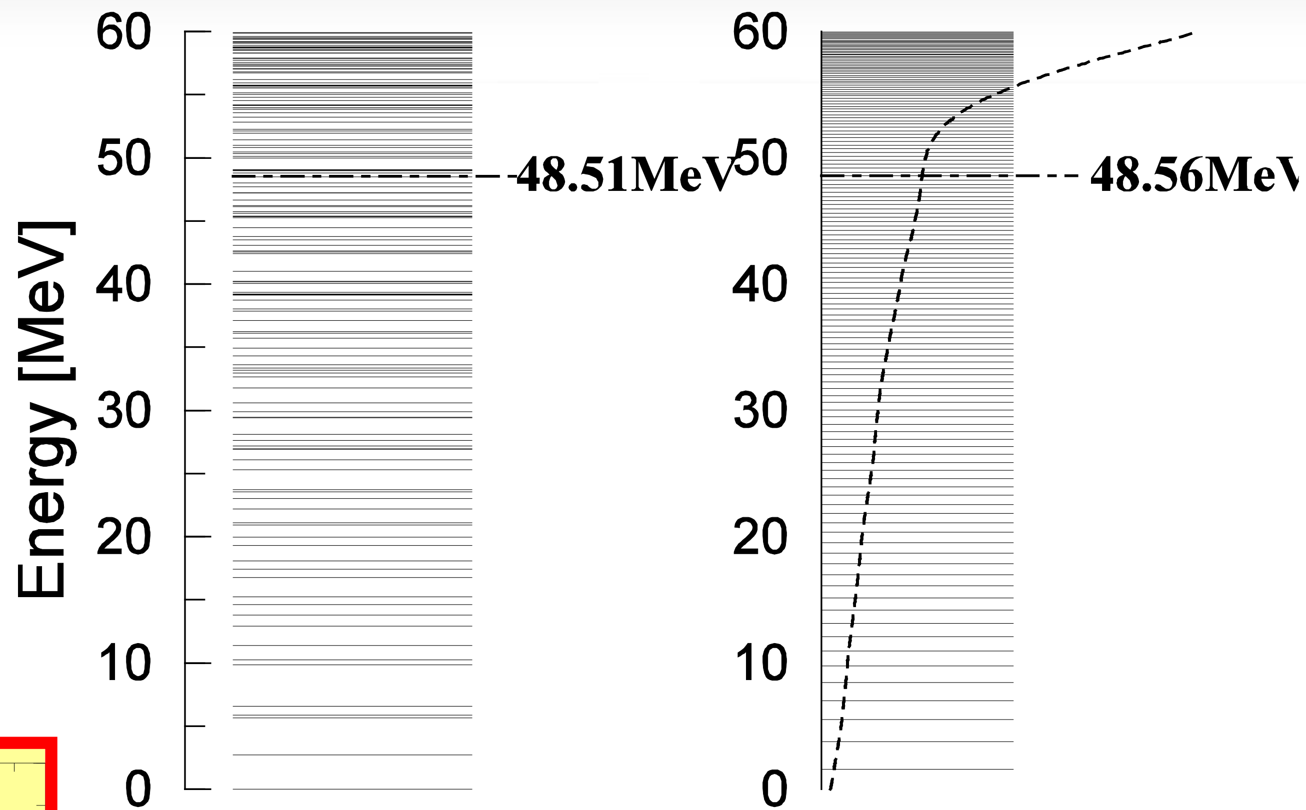
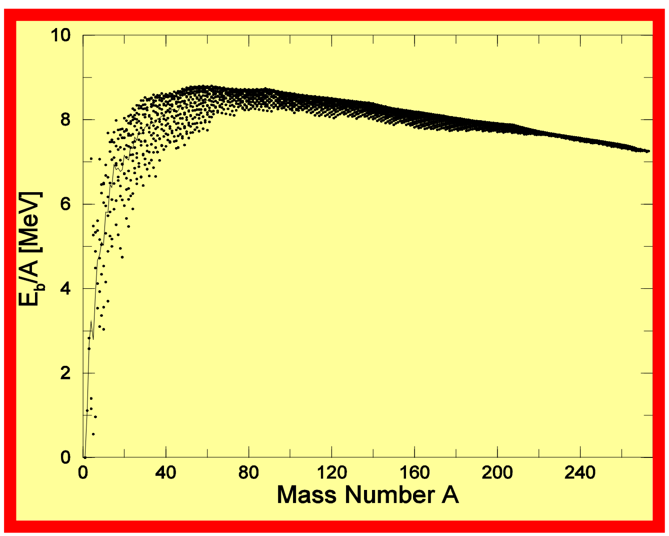
Compromise between Shell model and collective model

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

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"

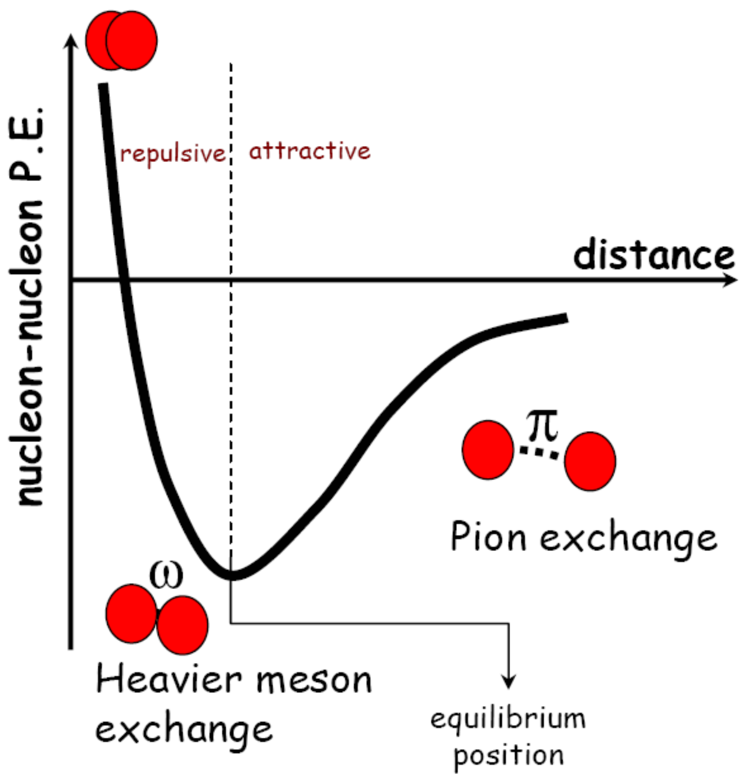
inspired by the Skyrme energy-density functional and a macroscopic-microscopic mass formula, with an rms deviation of 336 keV with respect to the 2149 measured masses in 2003 Atomic Mass Evaluation.

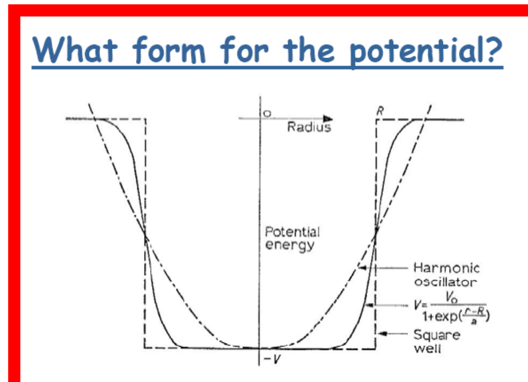
N. Wang, M. Liu and X. Z. Wu, Phys. Rev. C 81, 044322 (2010).
N. Wang, Z. Y. Liang, M. Liu and X. Z. Wu, Phys. Rev. C 82, 044304 (2010).
M. Liu, N. Wang, Y. G. Deng, and X. Z. Wu, Phys. Rev. C 84, 014333 (2011).

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).

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.





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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.

Nuclear theory

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- *Ab inito*

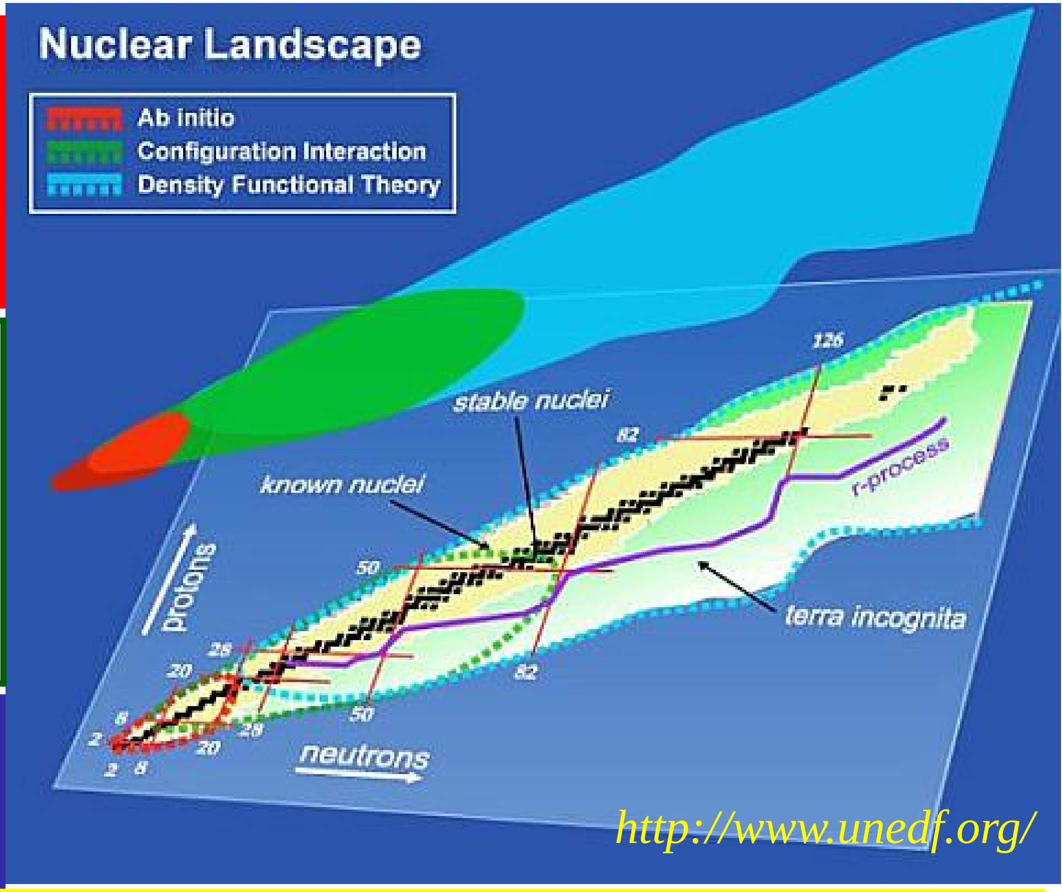
Navratil, Vary, Barrett Phys. Rev. Lett. 84 (2000) 5728
Bogner, Furnstahl, Schwenk
Prog. Part. Nucl. Phys. 65 (2010) 94
…

- 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）

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Hohenberg-Kohn theorem (1964)

The exact energy of a quantum mechanical many body system is a functional of the local density $\rho(\mathbf{r})$

$$E[\rho] = \langle\Psi|H|\Psi\rangle$$

This functional is universal. It does not depend on the system, only on the interaction.

One obtains the exact density $\rho(\mathbf{r})$ by a variation of the functional with respect to the density

note:

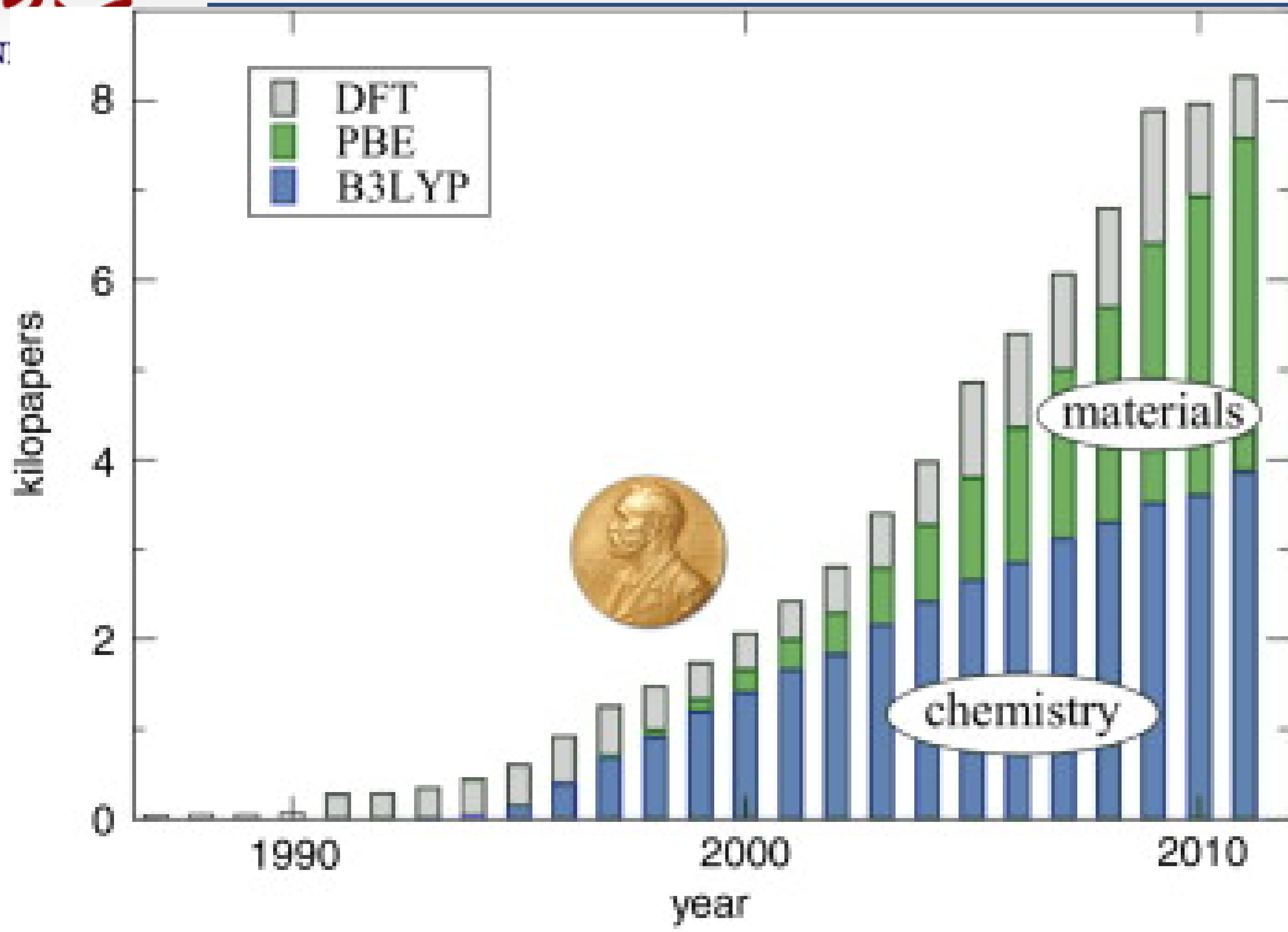
$\rho(\mathbf{r})$ is a function of 3 variables.

$\Psi(\mathbf{r}_1 \ldots \mathbf{r}_N)$ is a function of $3N$ variables.

Hohenberg

Kohn

Nobel Prize in Chemistry 1998



The numbers of papers (in kilopapers) corresponding to the search of a topic “DFT” in Web of Knowledge (grey) for different and the most popular density functional potentials: B3LYP citations (blue), and PBE citations (green, on top of blue).

K. Burke, Perspective on density functional theory, J. Chem. Phys., 136 (2012) 150901 [1-9]

Density functional theory in nuclei

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)

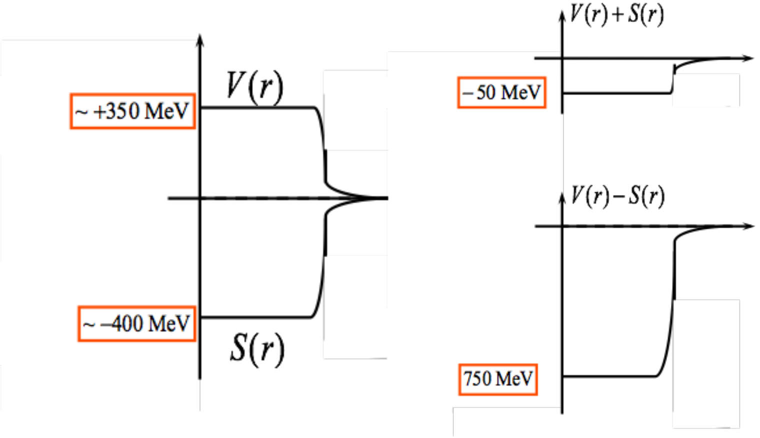
At present, the ansatz for E(ρ) is phenomenological:

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

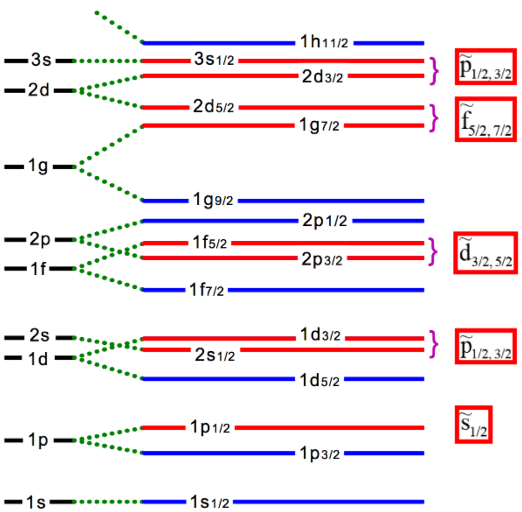
Why Covariant?

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



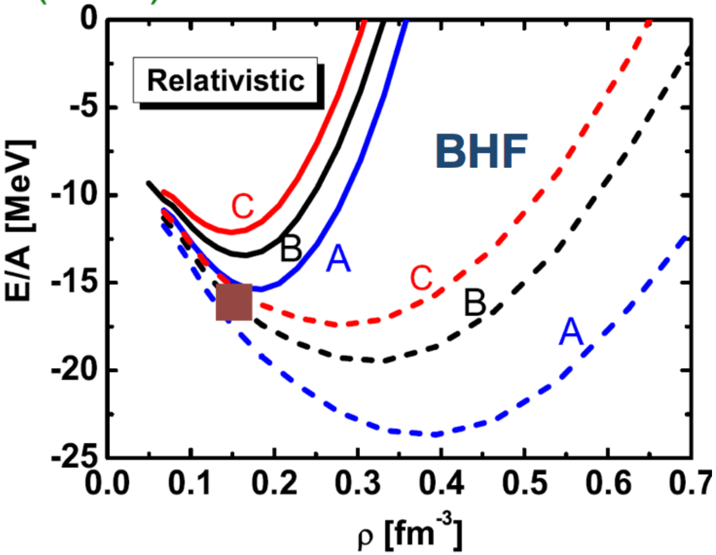
$$\begin{array}{lll} n-1, & l+2, & j=l+3/2 \\ n, & l, & j=l+1/2 \end{array}$$

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

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

Ginocchio PRL 78, 436

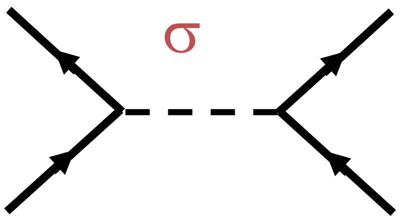


Brockmann & Machleidt, PRC42, 1965 (1990)

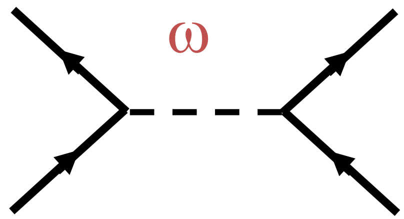
Brief introduction of CDFT

CDFT：Relativistic quantum many-body theory based on DFT and effective field theory for strong interaction

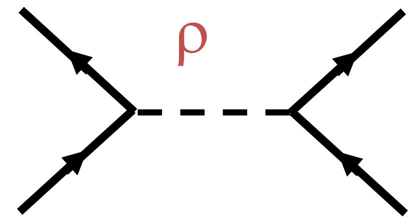
Strong force: Meson-exchange of the nuclear force



$(J^{\pi}\ T)=(0^{+}0)$



$(J^{\pi}\ T)=(1^{-}0)$



$(J^{\pi}\ T)=(1^{-}1)$

Sigma-meson:
attractive scalar field

Omega-meson:
Short-range repulsive

Rho-meson:
Isovector field

Electromagnetic force: The photon

Brief introduction of CDFT

Lagrangian:

$$L=\bar{\psi}[i\gamma^{\mu}\partial_{\mu}-M-g_{\sigma}\sigma-\gamma^{\mu}(g_{\omega}\omega_{\mu}+g_{\rho}\vec{\tau}\bullet\vec{\rho}_{\mu}+e\tfrac{1-\tau_3}{2}A_{\mu})-\tfrac{f_{\pi}}{m_{\pi}}\gamma_5\gamma^{\mu}\partial_{\mu}\vec{\pi}\bullet\vec{\tau}]\psi$$

$$+\frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma-\frac{1}{2}m_{\sigma}^2\sigma^2-\frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu}+\frac{1}{2}m_{\omega}^2\omega_{\mu}\omega^{\mu}-\frac{1}{4}\vec{R}_{\mu\nu}\bullet\vec{R}^{\mu\nu}$$

$$+\frac{1}{2}m_{\rho}^2\vec{\rho}^{\mu}\cdot\vec{\rho}_{\mu}+\frac{1}{2}\partial_{\mu}\vec{\pi}\bullet\partial^{\mu}\vec{\pi}-\frac{1}{2}m_{\pi}^2\vec{\pi}\bullet\vec{\pi}-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\Omega^{\mu\nu}=\partial^{\mu}\omega^{\nu}-\partial^{\nu}\omega^{\mu}$$

$$\vec{R}^{\mu\nu}=\partial^{\mu}\vec{\rho}^{\nu}-\partial^{\nu}\vec{\rho}^{\mu}$$

$$F^{\mu\nu}=\partial^{\mu}A^{\nu}-\partial^{\nu}A^{\mu}$$

Hamiltonian:

$$H=\bar{\psi}(-i\boldsymbol{\gamma}\bullet\nabla+M)\psi+\frac{1}{2}\int d^4y\sum_{i=\sigma,\omega,\rho,\pi,A}\bar{\psi}(x)\bar{\psi}(y)\Gamma_i D_i(x,y)\psi(y)\psi(x)$$

$$=T+V$$

$$\Gamma_{\sigma}(1,2)\equiv-g_{\sigma}(1)g_{\sigma}(2),\qquad \Gamma_{\rho}(1,2)\equiv+(g_{\rho}\gamma_{\mu}\vec{\tau})_1\cdot(g_{\rho}\gamma^{\mu}\vec{\tau})_2,$$

$$\Gamma_{\omega}(1,2)\equiv+(g_{\omega}\gamma_{\mu})_1(g_{\omega}\gamma_{\mu})_2,\ \Gamma_{\pi}(1,2)\equiv-(\tfrac{f_{\pi}}{m_{\pi}}\vec{\tau}\gamma_5\gamma_{\mu}\partial^{\mu})_1\cdot(\tfrac{f_{\pi}}{m_{\pi}}\vec{\tau}\gamma_5\gamma_{\nu}\partial^{\nu})_2$$

$$\Gamma_{\text{em}}(1,2)\equiv+\frac{e^2}{4}(\gamma_{\mu}(1-\tau_3))_1(\gamma^{\mu}(1-\tau_3))_2$$

Brief introduction of CDFT

$$H = T + \sum_{i=\sigma,\omega,\rho,\pi,A} V_i$$

$$\psi(x) = \sum_i [f_i(\mathbf{x}) e^{-i\varepsilon_i t} c_i + g_i(\mathbf{x}) e^{i\varepsilon_i' t} d_i^\dagger]$$

$$\psi^\dagger(x) = \sum_i [f_i^\dagger(\mathbf{x}) e^{i\varepsilon_i t} c_i^\dagger + g_i^\dagger(\mathbf{x}) e^{-i\varepsilon_i' t} d_i]$$

$$T = \int d\mathbf{x} \sum_{\alpha\beta} \bar{f}_\alpha (-i\gamma \cdot \nabla + M) f_\beta c_\alpha^\dagger c_\beta,$$

Hartree

$$V_i = \frac{1}{2} \int d\mathbf{x}_1 d\mathbf{x}_2 \sum_{\alpha\beta;\alpha'\beta'} c_\alpha^\dagger c_\beta^\dagger c_{\beta'} c_{\alpha'} \bar{f}_\alpha(1) \bar{f}_\beta(2) \Gamma_i(1,2) D_i(1,2) f_{\beta'}(2) f_{\alpha'}(1)$$

Fock

Energy density functional:

$$|\Phi_0\rangle = \prod_\alpha c_\alpha^\dagger |0\rangle$$

$$E = \langle \Phi_0 | H | \Phi_0 \rangle = \langle \Phi_0 | T | \Phi_0 \rangle + \sum_{i=\sigma,\omega,\rho,\pi,A} \langle \Phi_0 | V_i | \Phi_0 \rangle$$

$$= E_k + E_\sigma^D + E_\sigma^E + E_\omega^D + E_\omega^E + E_\rho^D + E_\rho^E + E_\pi + E_{\text{em}}^D + E_{\text{em}}^E$$

Equations of motion

For system with time invariance:

$$\left[\alpha\cdot\boldsymbol{p}+V(\boldsymbol{r})+\beta\left(M+S(\boldsymbol{r})\right)\right]\psi_i=\varepsilon_i\psi_i$$

$$\begin{cases} V(\boldsymbol{r})=g_\omega\omega(\boldsymbol{r})+g_\rho\tau_3\rho(\boldsymbol{r})+e\dfrac{1-\tau_3}{2}A(\boldsymbol{r}) \\ S(r)=g_\sigma\sigma(\boldsymbol{r}) \end{cases}$$

Same footing for

- Deformation
- Rotation
- Pairing (RHB,BCS,SLAP)
- …

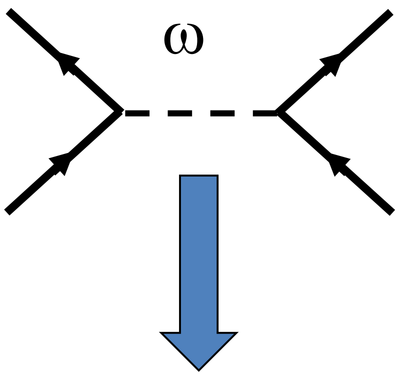
$$\left[-\Delta+m_\sigma^2\right]\sigma=-g_\sigma\rho_s-g_2\sigma^2-g_3\sigma^3$$

$$\left[-\Delta+m_\omega^2\right]\omega=g_\omega\rho_b-c_3\omega^3$$

$$\left[-\Delta+m_\rho^2\right]\rho=g_\rho\left[\rho_b^{(n)}-\rho_b^{(p)}\right]-d_3\rho^3$$

$$\begin{cases} \rho_s(\boldsymbol{r})=\sum_{i=1}^A\bar{\psi}_i(\boldsymbol{r})\psi_i(\boldsymbol{r}) \\ \rho_v(\boldsymbol{r})=\sum_{i=1}^A\psi_i^+(\boldsymbol{r})\psi_i(\boldsymbol{r}) \\ \rho_3(\boldsymbol{r})=\sum_{i=1}^A\psi_i^+(\boldsymbol{r})\tau_3\psi_i(\boldsymbol{r}) \\ \rho_c(\boldsymbol{r})=\sum_{i=1}^A\psi_i^+(\boldsymbol{r})\dfrac{1-\tau_3}{2}\psi_i(\boldsymbol{r}) \end{cases}$$

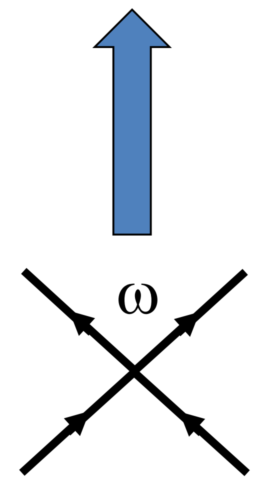
Effective Point-Coupling interaction



$$H=\bar{\psi}_i\left(-i\gamma\bullet\nabla+M\right)\psi_i+\frac{1}{4}F^{i\nu}F_{i\nu}$$
$$+\frac{1}{2}((\nabla\sigma)^2+m_\sigma^2\sigma^2)+g_\sigma\sigma\rho_s+\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma^4$$
$$+\frac{1}{2}g_\omega\omega_0\rho_v+\frac{1}{2}g_\rho\vec{\rho}_0\rho_3$$

$$g_\omega\omega=\frac{1}{1-\Delta/m_\omega^2}\frac{g_\omega^2}{m_\omega^2}\rho_v=\frac{g_\omega^2}{m_\omega^2}\rho_v+\frac{g_\omega^2}{m_\omega^4}\Delta\rho_v+\cdots\approx\alpha_v\rho_v+\delta_v\Delta\rho_v$$

$$H=\bar{\psi}_i\left(-i\gamma\cdot\nabla+M\right)\psi_i+\frac{1}{4}F^{i\nu}F_{i\nu}$$
$$+\frac{1}{2}\alpha_S\rho_S^2+\frac{1}{2}\delta_S\rho_S\Delta\rho_S+\frac{1}{3}\beta_S\rho_S^3+\frac{1}{4}\gamma_S\rho_S^4$$
$$+\frac{1}{2}\alpha_V\rho_V^2+\frac{1}{2}\delta_V\rho_V\Delta\rho_V+\frac{1}{2}\alpha_{TV}\rho_{TV}^2+\frac{1}{2}\delta_{TV}\rho_{TV}\Delta\rho_{TV}$$



Equations of motion

For system with time invariance:

$$\left[\alpha\cdot\boldsymbol{p}+V(\boldsymbol{r})+\beta\left(M+S(\boldsymbol{r})\right)\right]\psi_i=\varepsilon_i\psi_i$$

$$\begin{cases} V(\boldsymbol{r})=\alpha_V\rho_V(\boldsymbol{r})+\gamma_V\rho_V^3(\boldsymbol{r})+\delta_V\Delta\rho_V(\boldsymbol{r})+\alpha_{TV}\rho_{TV}(\boldsymbol{r})+\delta_{TV}\Delta\rho_{TV}(\boldsymbol{r})+e\dfrac{1-\tau_3}{2}A(\boldsymbol{r}) \\ S(r)=\alpha_S\rho_S+\beta_S\rho_S^2+\gamma_S\rho_S^3+\delta_S\Delta\rho_S \end{cases}$$

Without Klein-Gordon equation

$$\begin{cases} \rho_s(\boldsymbol{r})=\sum_{i=1}^{A}\bar{\psi}_i(\boldsymbol{r})\psi_i(\boldsymbol{r}) \\ \rho_v(\boldsymbol{r})=\sum_{i=1}^{A}\psi_i^{+}(\boldsymbol{r})\psi_i(\boldsymbol{r}) \\ \rho_3(\boldsymbol{r})=\sum_{i=1}^{A}\psi_i^{+}(\boldsymbol{r})\tau_3\psi_i(\boldsymbol{r}) \\ \rho_c(\boldsymbol{r})=\sum_{i=1}^{A}\psi_i^{+}(\boldsymbol{r})\dfrac{1-\tau_3}{2}\psi_i(\boldsymbol{r}) \end{cases}$$

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

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

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

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

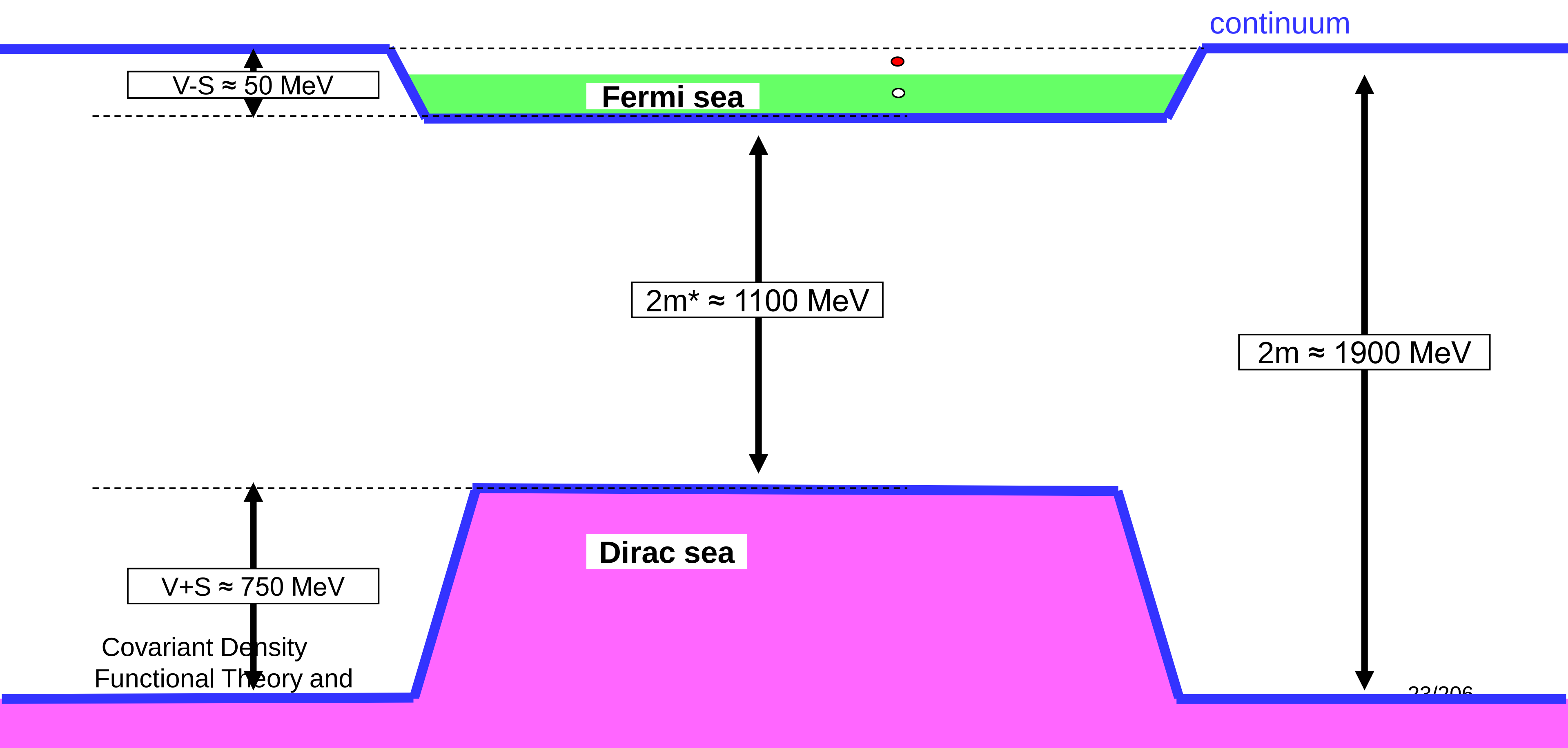
$$E_{der} = \frac{1}{2}\int (\delta_S\rho_S\triangle\rho_S + \delta_V\rho_V\triangle\rho_V + \delta_{tV}\rho_{tV}\triangle\rho_{tV})d\mathbf{r}$$

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

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

scalar potential: *S(r) ≈ -400 MeV*

vector potential: *V(r) ≈ 350 MeV*



Covariant density functional

Meson Exchange

Nonlinear parameterizations:

$$M, m_\sigma, m_\omega, m_\rho, g_\sigma, g_\omega, g_\rho, g_2, g_3, c_3, d_3$$

NL3, NLSH, TM1, TM2, PK1, …

Density dependent parameterizations:

$$M, m_\sigma, m_\omega, m_\rho, g_\sigma(\rho), g_\omega(\rho), g_\rho(\rho)$$

TW99, DD-ME1, DD-ME2, PKDD, …

Point Coupling

Nonlinear parameterizations:

$$M, \alpha_S, \alpha_V, \alpha_{TV}, \delta_S, \delta_V, \delta_{TV}, \beta_S, \gamma_S, \gamma_V$$

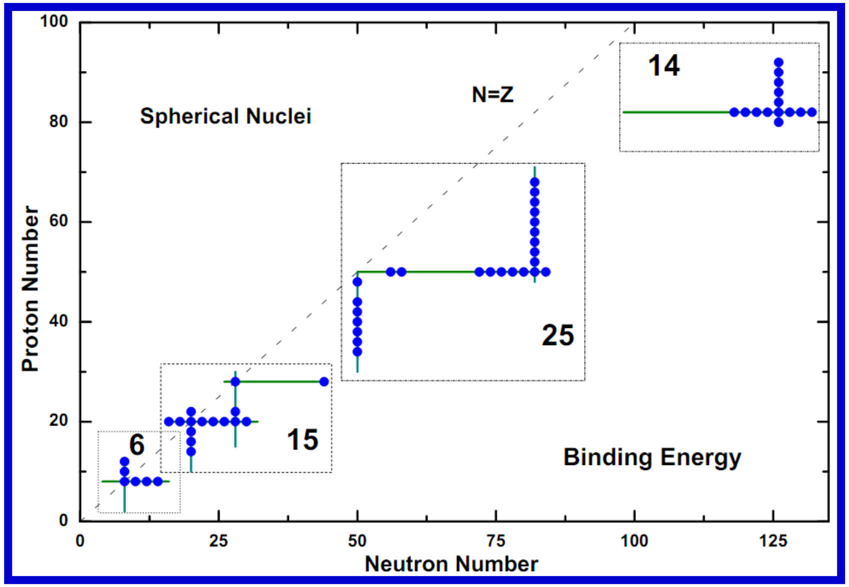
PC-LA, PC-F1, PC-PK1 …

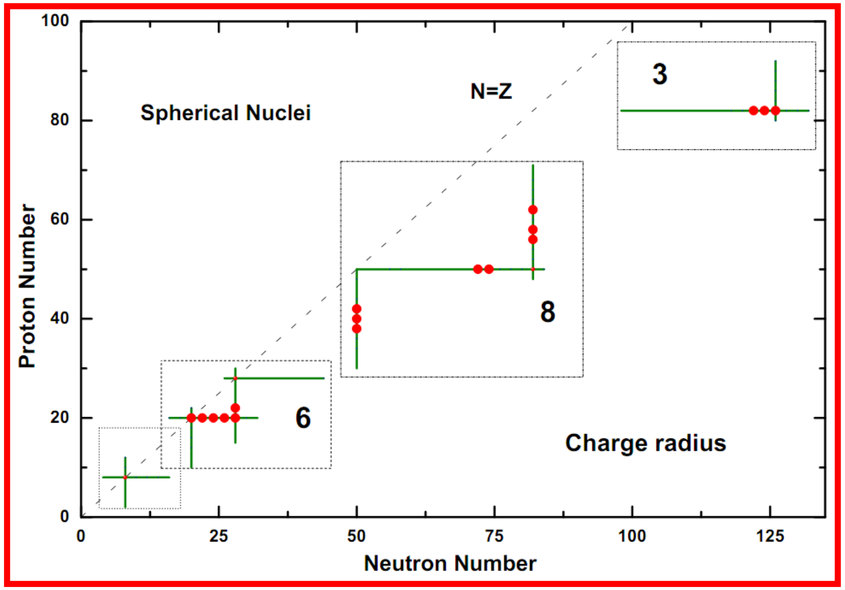
Density dependent parameterizations:

$$M, \delta_S, \alpha_S(\rho), \alpha_V(\rho), \alpha_{TV}(\rho)$$

DD-PC1, …

Covariant density functional PC-PK1





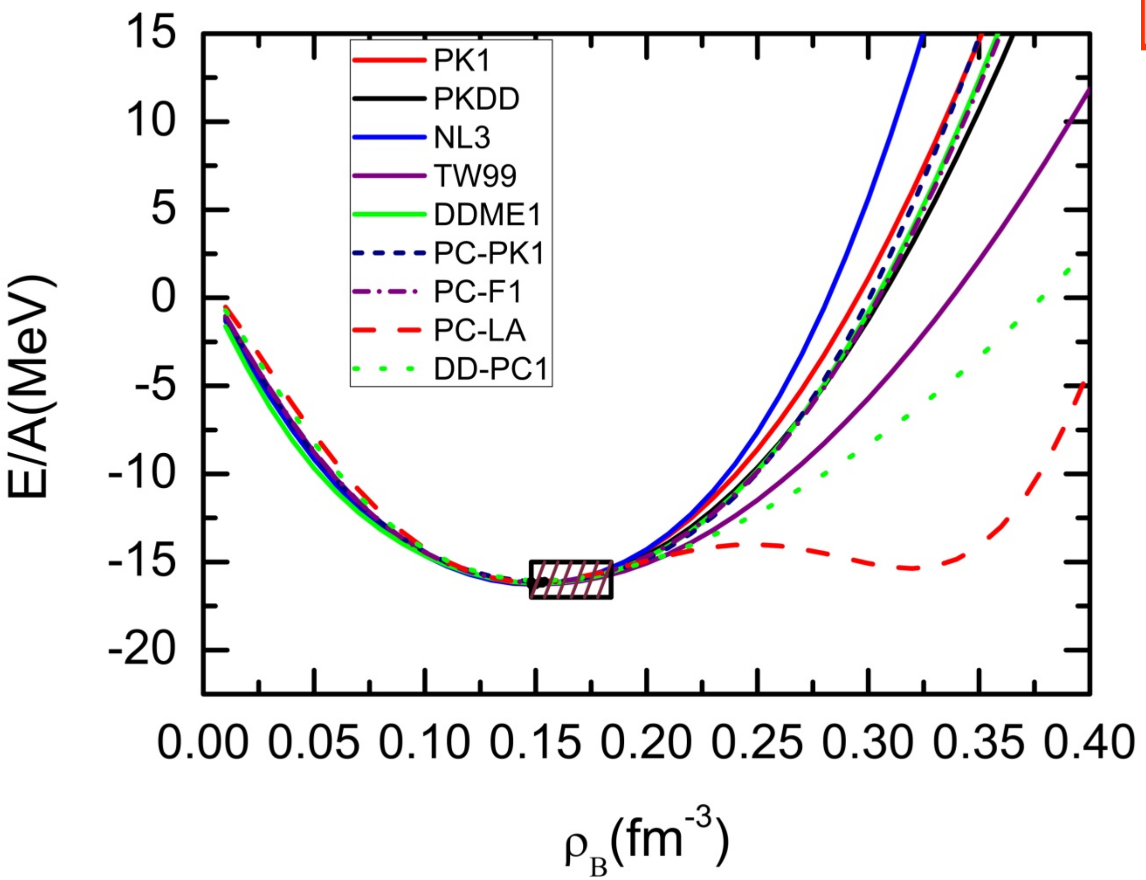
Coupl.	Cons.	PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}
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)

Nuclear matter properties

Binding energy per nucleon:

$$E / A = \varepsilon / \rho - M$$



EOS of symmetric nuclear matter

Nuclear matter properties

Saturation point: $p(\rho_0) = 0$

- **Symmetry energy**

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

$$E_{sym}(\rho) = \frac{1}{2}\left(\frac{\partial^2(\varepsilon/\rho)}{\partial t^2}\right)_{t=0}, t = \frac{\rho_n-\rho_p}{\rho_n}$$

$$L = 3\rho_0\left(\frac{\partial E_{sym}(\rho)}{\partial \rho}\right)_{\rho_0}, K_{sym} = 9\rho_0^2\left(\frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\right)_{\rho_0}$$

- **Compressibility**

$$K(\alpha) \approx K_0 + K_{asy}\alpha^2, \alpha = (\rho_n-\rho_p)/(\rho_n+\rho_p)$$

$$K_0 = 9\rho_0^2\left[\frac{\partial^2(\varepsilon/\rho)}{\partial \rho^2}\right]_{\rho_0}$$

$$K_{asy} = K_{sym} - 6L$$

- **Effective masses**

$$M_D^* = M^* = M + S$$

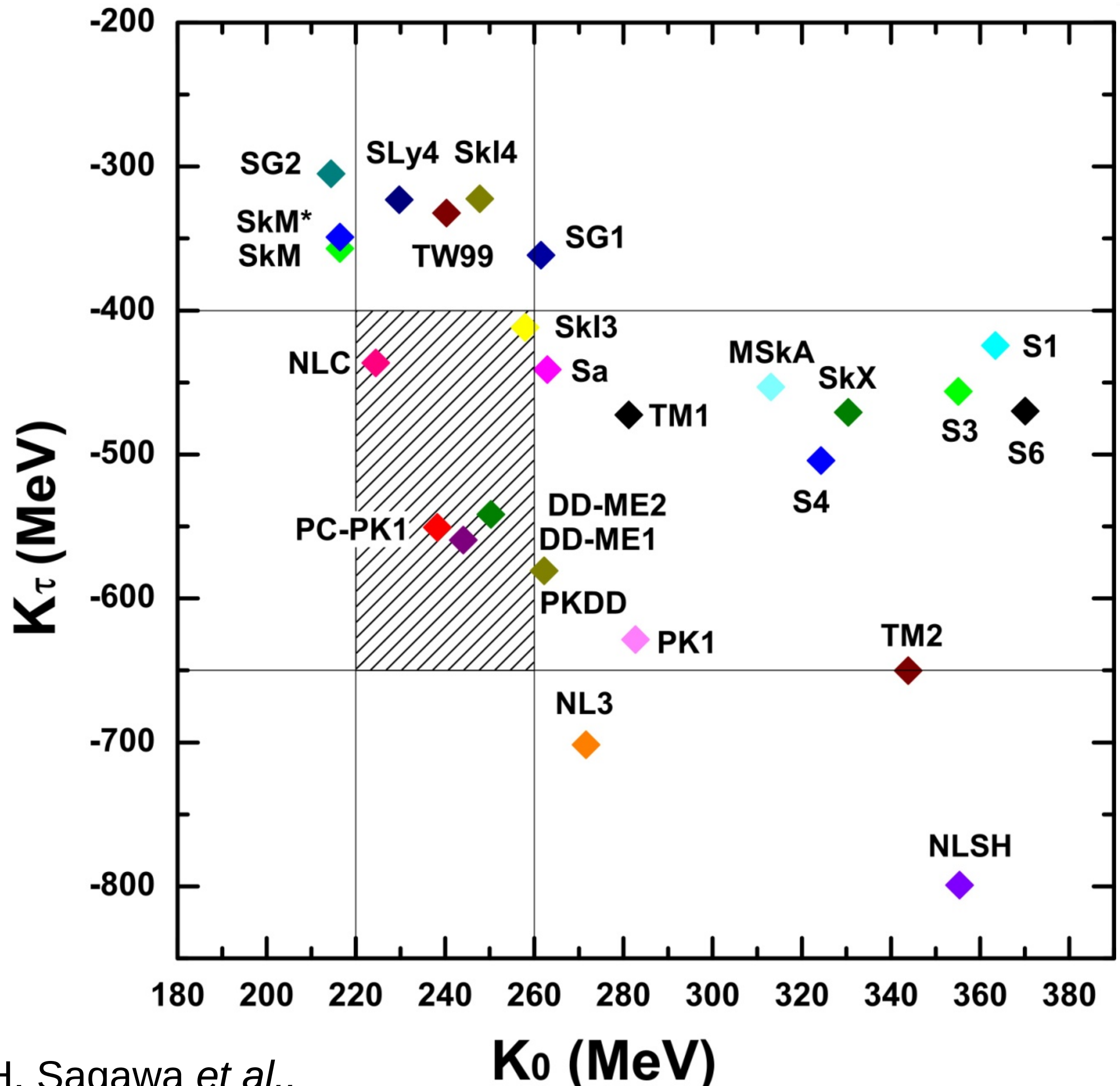
$$M_L^* = \sqrt{(M_D^*)^2 + k_F^2}$$

CDFT for Nuclear matter

Saturation properties:

Model	ρ_0 (fm^{-3})	E/A (MeV)	M_D^*/M	M_L^*/M	E_{sym} (Mev)	L (MeV)	K_{sym} (MeV)	K_0 (MeV)	K_{asy} (MeV)
Empirical	0.166	-16	$0.55-0.60$	0.8	~ 32	88		240	-550
	± 0.018	± 1		± 0.1		± 25		± 20	± 100
NL3	0.148	-16.25	0.59	0.65	37.4	119	101	272	-611
PK1	0.148	-16.27	0.61	0.66	37.6	116	55	283	-640
TW99	0.153	-16.25	0.55	0.62	32.8	55	-125	240	-457
DD-ME1	0.152	-16.2	0.58	0.64	33.1	56	-101	245	-435
PKDD	0.15	-16.27	0.57	0.63	36.8	90	-81	262	-622
PC-LA	0.148	-16.13	0.58	0.64	37.2	108	-61	264	-711
PC-F1	0.151	-16.17	0.61	0.67	37.8	117	74	255	-628
PC-PK1	0.153	-16.12	0.59	0.65	35.6	113	95	238	-582
DD-PC1	0.152	-16.06	0.58	0.64	33	70	-108	230	-529

$K_\tau = K_{\tau,v} + K_{\tau,s} A^{-1/3}$



We know K_A from E_{GMR}:

$$E_{GMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

In an approximate way, K_A may be expressed as:

$$K_A \sim K_\infty\,(1 + cA^{-1/3}) + K_\tau\,((N-Z)/A)^2 + K_{Coul}\,Z$$

Data from from Umesh Garg, also H. Sagawa *et al.*, *Phys. Rev. C* ***76, 034327 (2007)***

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Neutron star properties in CDFT

The predictions given by DDRHF with the PKO series and RMF with PK1, TM1, DD-ME1, DD-ME2, and PKDD fulfill all the *M*-*R* constraints.

Sun, Long, Meng and Lombardo, PRC **78**, 065805(2008)

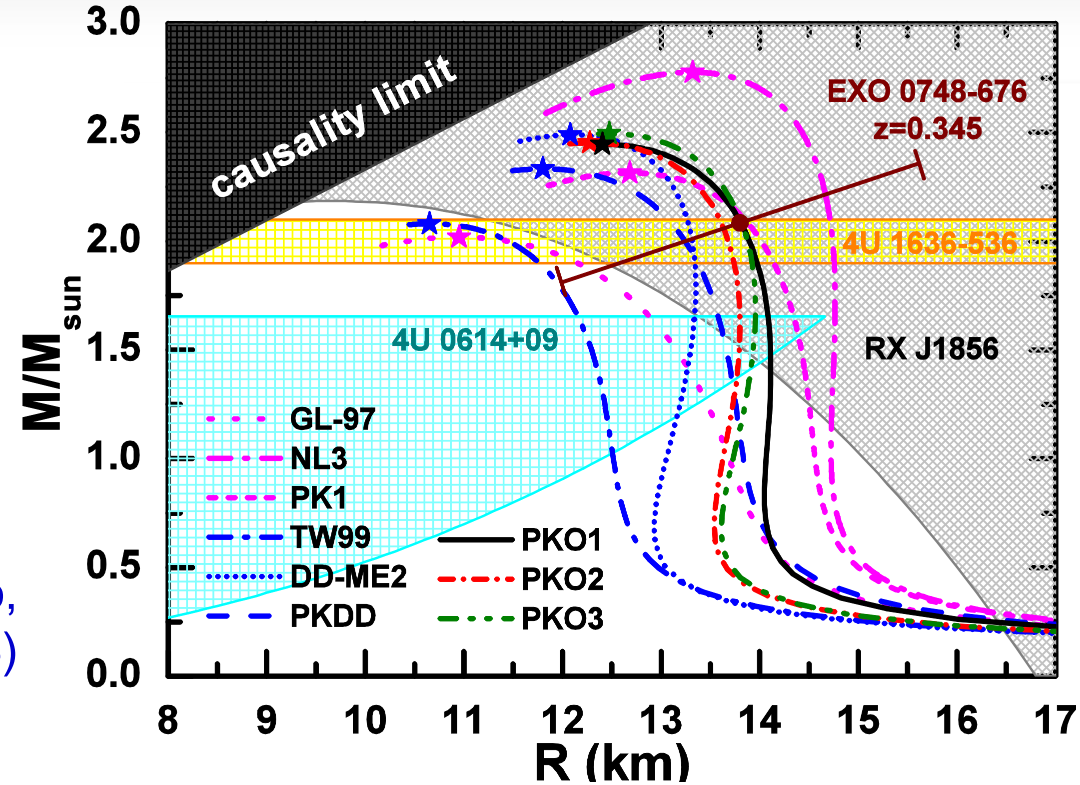


TABLE VI. The criteria of the *M*-*R* constraints: (1) the isolated neutron star RX J1856, (2) EXO 0748-676, (3) the low-mass X-ray binary 4U 0614 + 09, (4-u) 4U 1636-536 with its upper mass limits, and (4-l) 4U 1636-536 with its lower mass limits. Fulfillment (violation) of a constraint is indicated with + (−) and the marginal cover is marked with δ. See the text for details.

	PKO1	PKO2	PKO3	GL-97	NL1	NL3	NLSH	TM1	PK1	TW99	DD-ME1	DD-ME2	PKDD
1	+	+	+	−	+	+	+	+	+	−	+	+	+
2	+	+	+	+	+	+	+	+	+	Δ	+	+	+
3	+	+	+	+	Δ	Δ	−	+	+	+	+	+	+
4-u	+	+	+	−	+	+	+	+	+	Δ	+	+	+
4-l	+	+	+	+	+	+	+	+	+	+	+	+	+

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

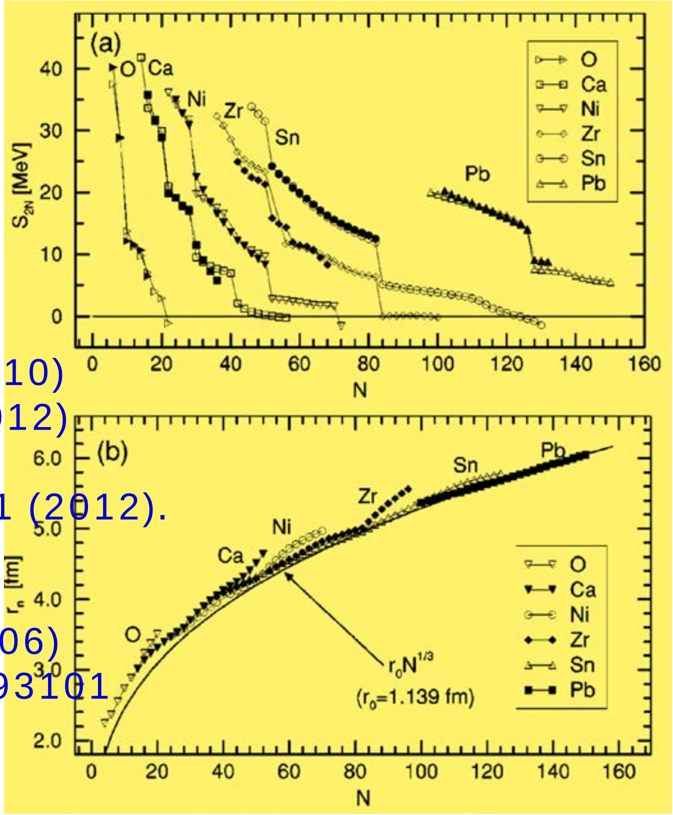
Relativistic Continuum Hartree-Bogoliubov theory

Spherical nucleus: continuum & pairing
Meng & Ring, PRL77,3963 (96)
Meng & Ring, PRL80,460 (1998)
Meng, NPA 635, 3-42 (1998) Meng, Tanihata, & Yamaji, PLB 419, 1(1998)
Meng, Toki, Zeng, Zhang & Zhou, PRC65, 041302R

Spherical nucleus but in DDRHFB: Fock term
Long, Ring, Meng & Van Giai, PRC81 , 031302
Wang, Dong, Long, PRC 87, 047301(2013).
Lu, Sun, Long, PRC 87, 034311 (2013).

Deformed nucleus: deformation & blocking
Zhou, Meng, Ring & Zhao, Phys. Rev. C 82, 011301 (R)(2010)
Li, Meng, Ring, Zhao & Zhou, Phys. Rev. C 85, 024312 (2012)
Chen, Li, Liang & Meng, Phys. Rev. C 85, 067301 (2012)
Li, Meng, Ring, Zhao & Zhou, Chin. Phys. Lett. 29, 042101 (2012).

Reviews:
Meng,Toki, Zhou, Zhang, Long & Geng, PPNP 57. 460 (2006)
Meng and Zhou, J. Phys. G: Nucl. Part. Phys. 42 (2015) 093101



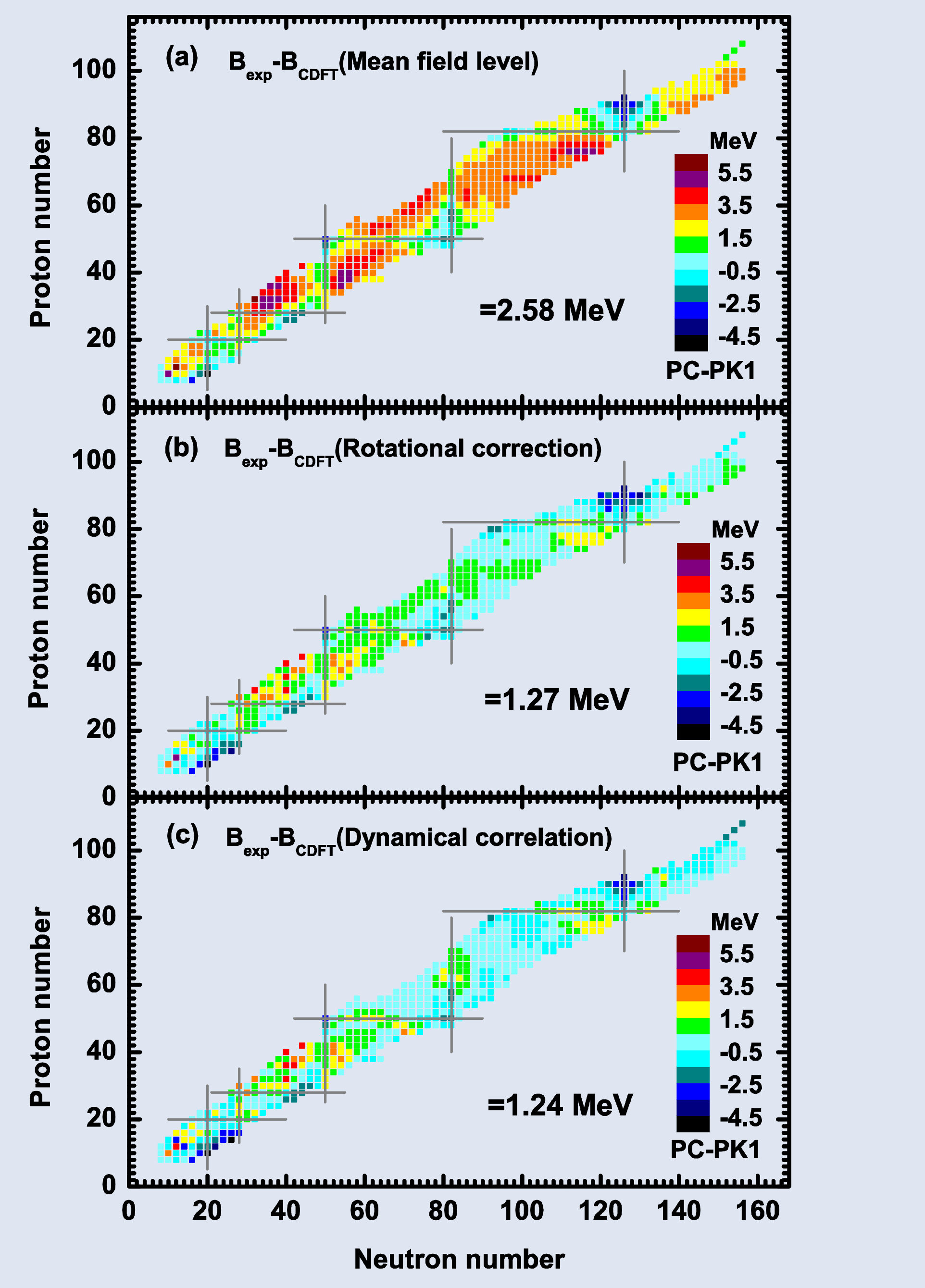
CDFT calculated binding energies by PC-PK1 with the data for 575 even–even nuclei:

(a) the binding energies of the lowest mean-field states;

(b) including the rotational correction energies;

(c) the full dynamical correlation Energies.

Zhang, Niu, Li, Yao, Meng, Front. Phys. 9(2014) 529



PC-PK1

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

Drip-lines in variant models

The number of bound nuclides with between 2 and 120 protons is around 7,000 28JUNE2012|VOL486|NATURE|509

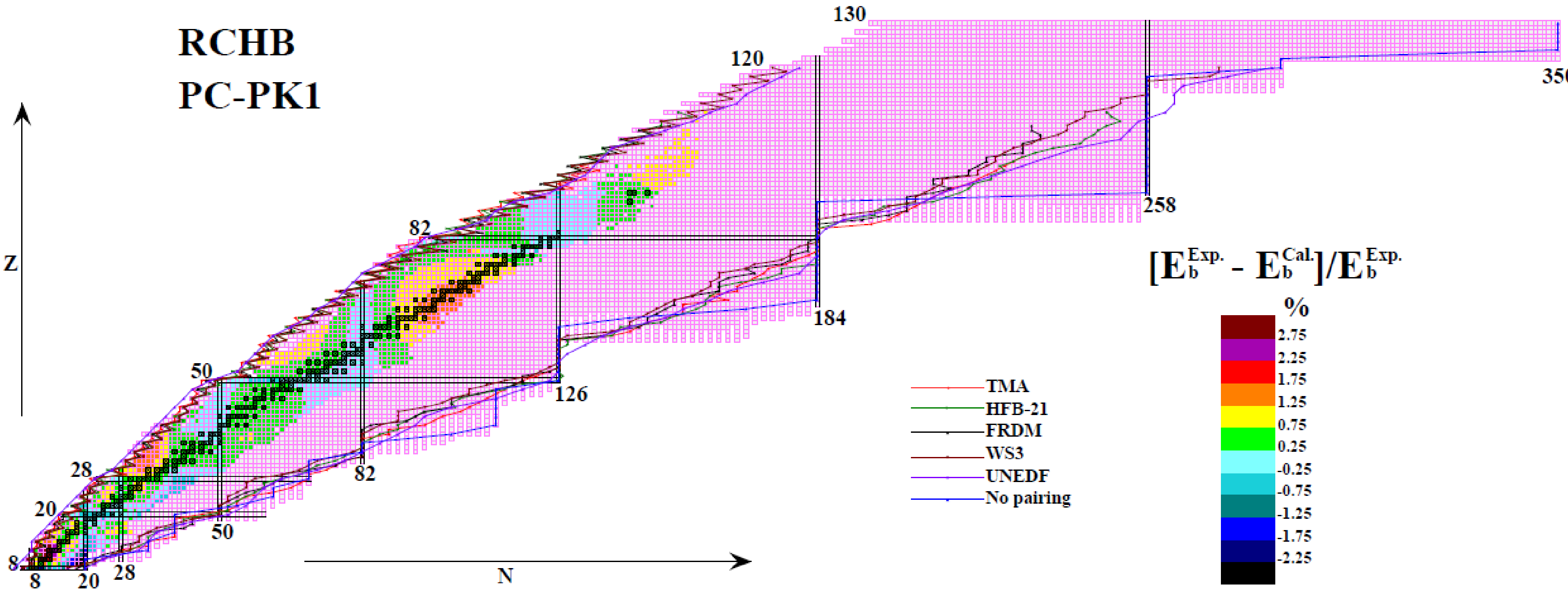
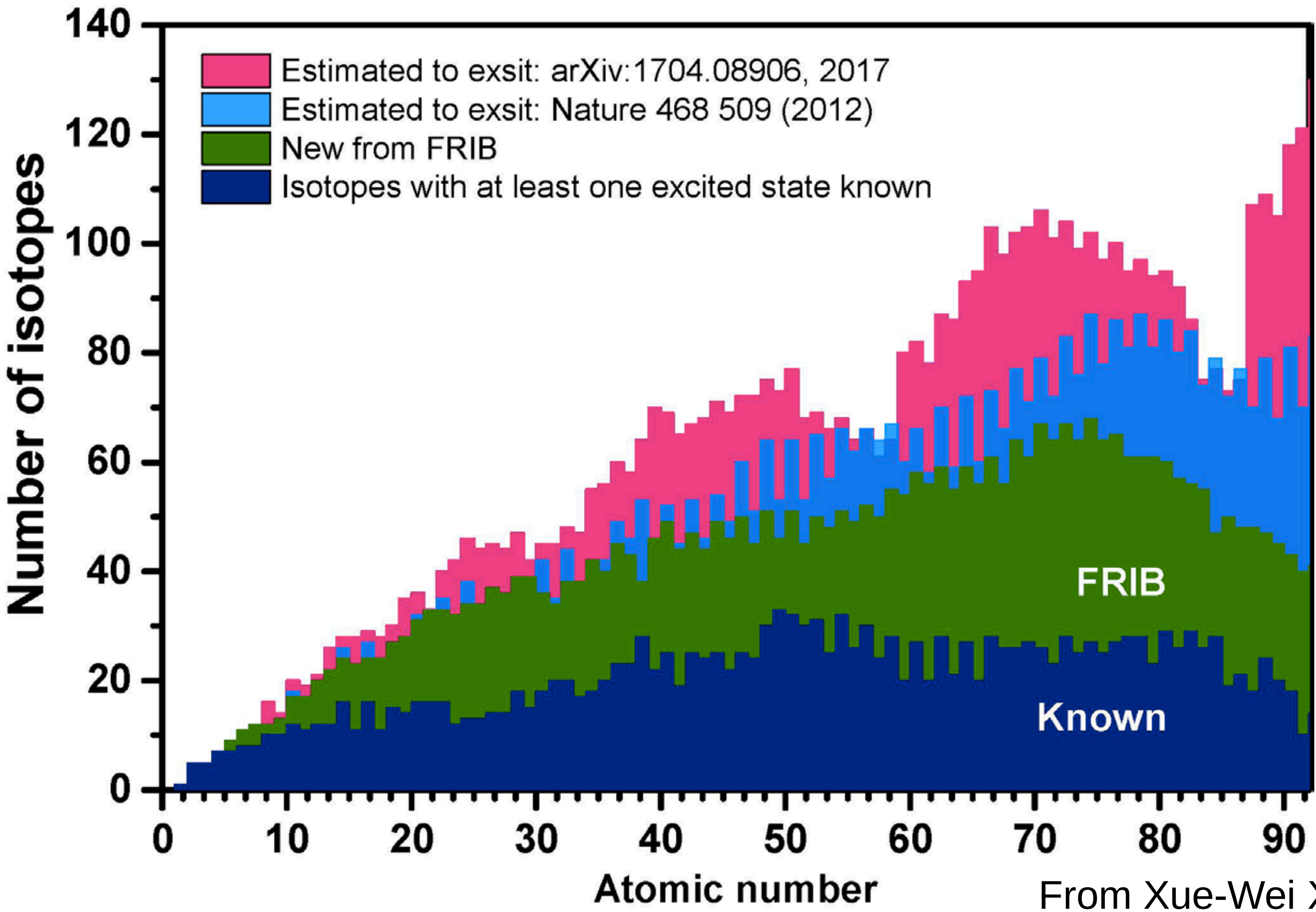


Figure: 10532 bound nuclei from Z=8 to Z=130 predicted by RCHB theory with PC-PK1. For 2227 nuclei with data, binding energy differences between data and calculated results are shown in different color. The nucleon drip-lines predicted TMA, HFB-21, WS3, FRDM , UNEDF and without pairing correlation are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

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

Rare Isotope Beams Facilities



From Xue-Wei Xia

FRIB will be able to make most of all possible isotopes

CDFT in a static external field

CDFT in a static external field includes:

- Constrained CDFT is a powerful tool to investigate the shape evolution, shape isomers, shape-coexistence, and fission landscapes.
- Cranking CDFT obtained by transforming from the laboratory to the intrinsic frame is widely used to describe rotational spectra in near spherical, deformed, superdeformed, and triaxial nuclei.

Review on cranking CDFT:

1. Vretenar, Afanasjev, Lalazissis, Ring, Physics Reports 409 (2005)101-260
2. Meng, Peng, Zhang, Zhao, Front. Phys. 8 (2013) 55-79

Multidimentionally constrained CDFT

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

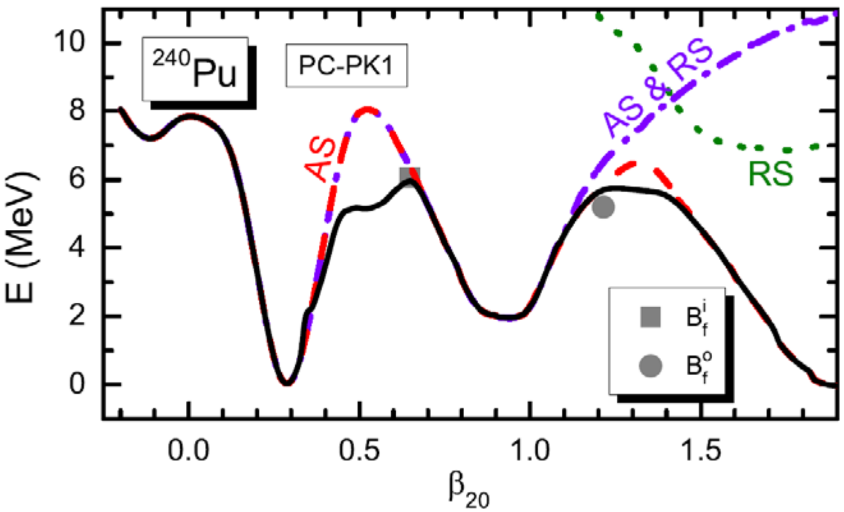


Figure: Potential energy curve of ^{240}Pu

1. Lu, Zhao, Zhou, PRC 85, 011301 (2012)
2. Zhao, Lu, Zhao, Zhou, PRC 86, 057304 (2012)
3. Lu, Zhao, Zhao, Zhou, PRC 89, 014323 (2014)
4. Zhao, Lu, Vretenar, Zhao, Zhou, arXiv:1404.5466 (2014)

Abusara, Afanasjev, and Ring, PRC 85, 024314 (2012)

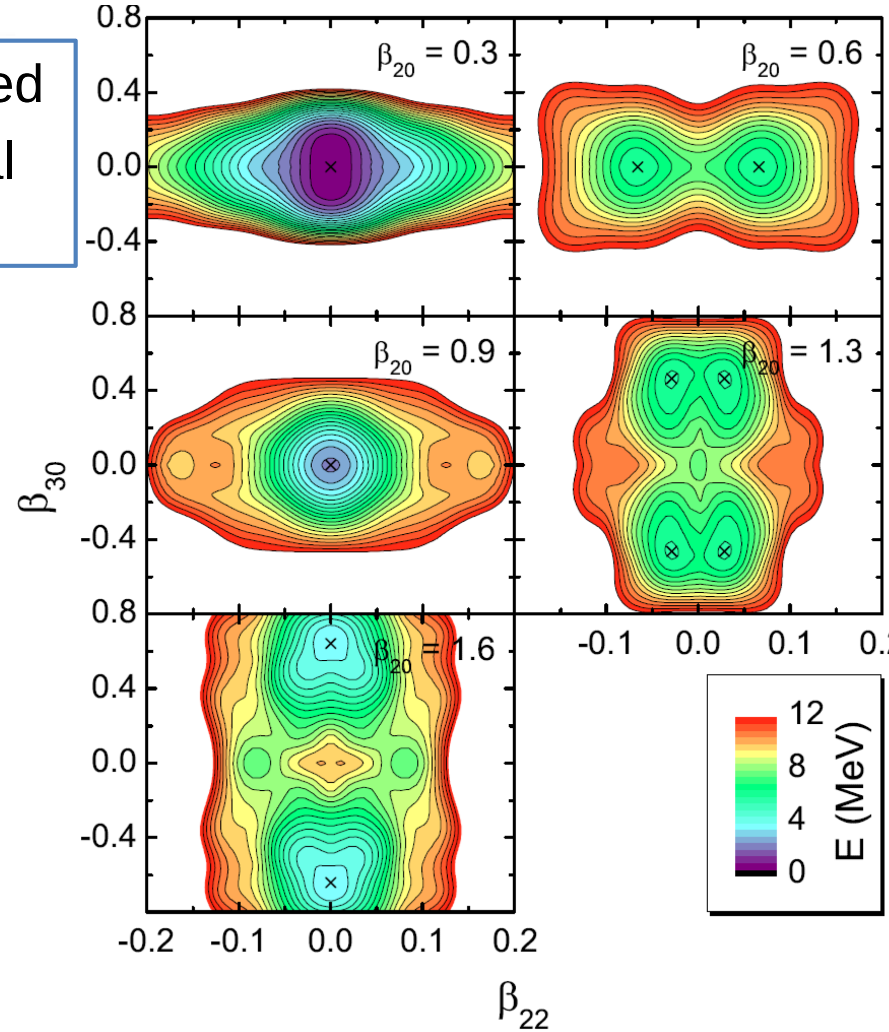


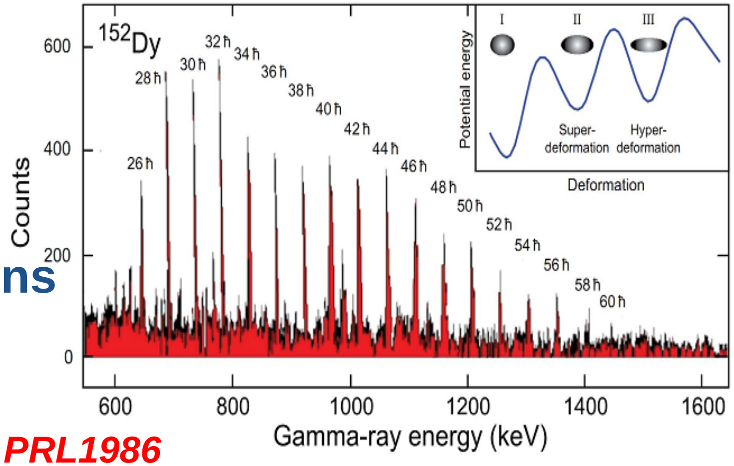
Figure: 3D PES of ^{240}Pu

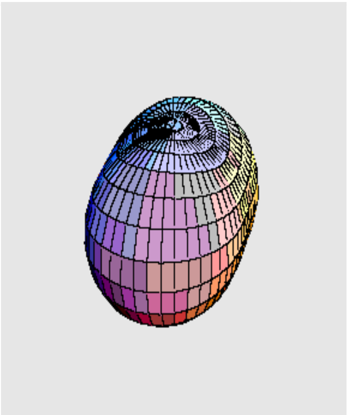
courtesy of B.N. LU

Electric and Magnetic Rotation

ΔI = 2

E2 Transitions



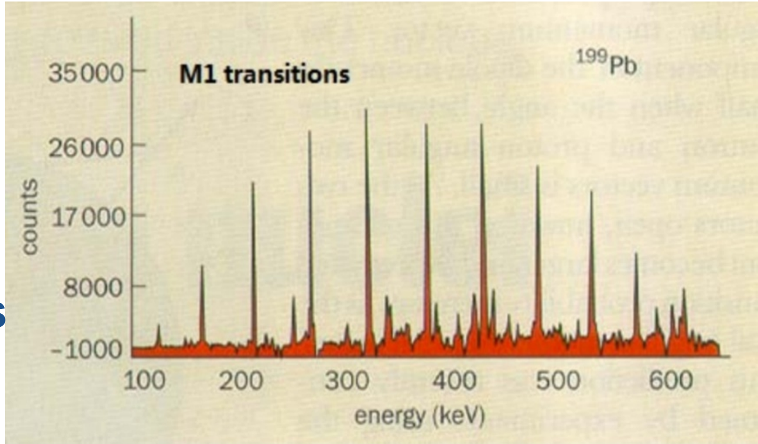


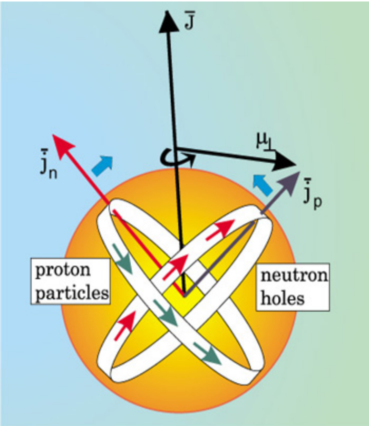
Twin PRL1986

Vretenar, Afanasjev, Lalazissis, Ring, Physics Reports 409 (2005)101

ΔI = 1

M1 Transitions



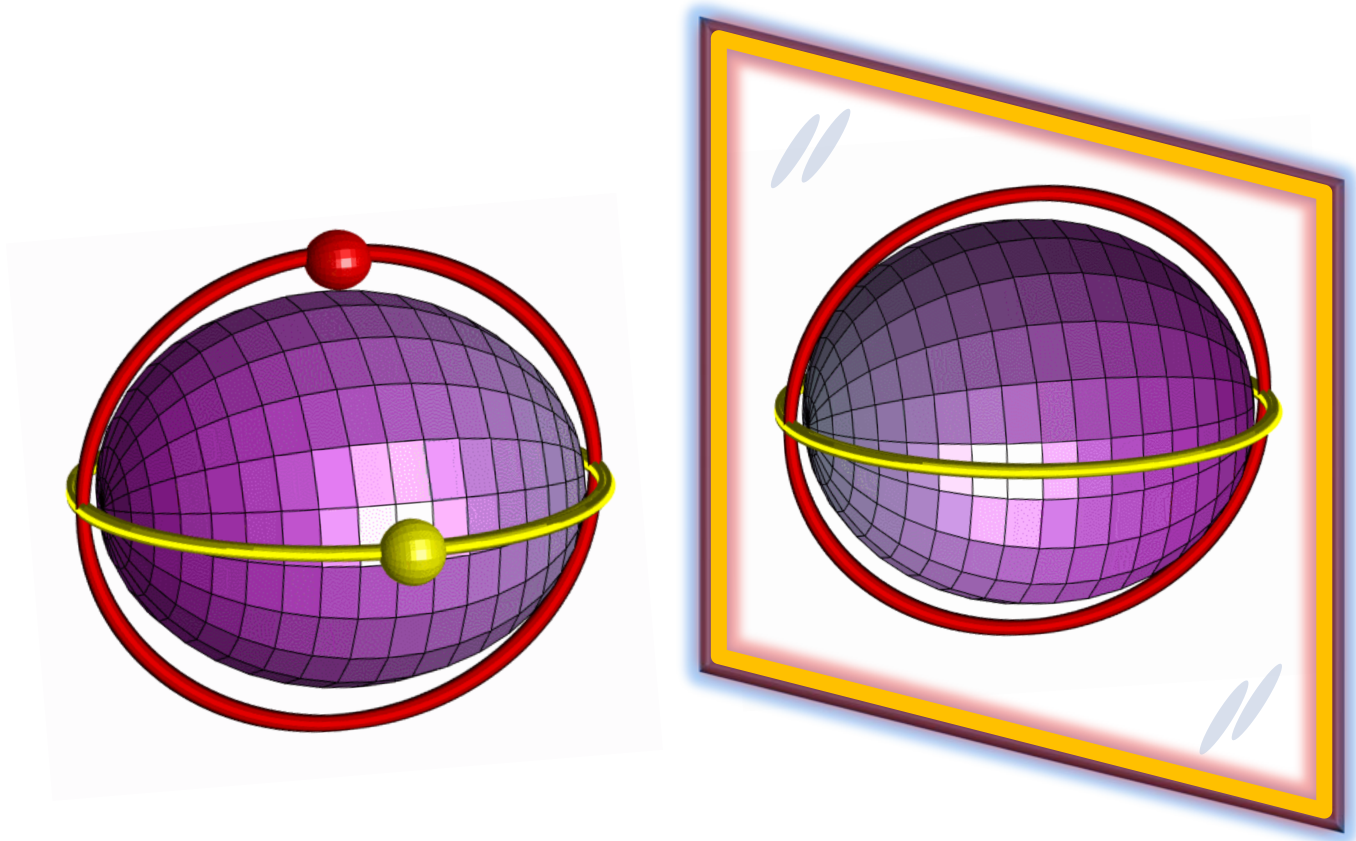


Frauendorf RMP2001   Hübel PPNP2005

Meng, Peng, Zhang, Zhao, Front. Phys. 8 (2013) 55-79

Zhao, Peng, Liang, Ring, Meng, PRL 107, 122501 (2011) - Anti-magnetic

Chiral Rotation



courtesy of X.H. Wu

Chiral symmetry breaking in intrinsic frame

Chiral symmetry in atomic nuclei

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ELSEVIER

Nuclear Physics A 617 (1997) 131–147

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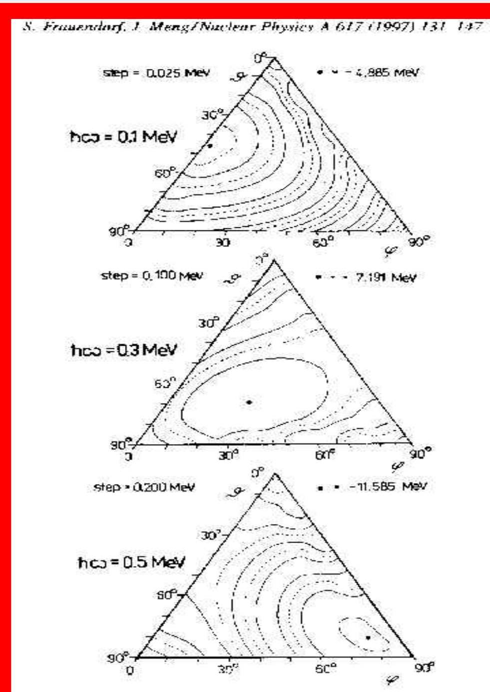
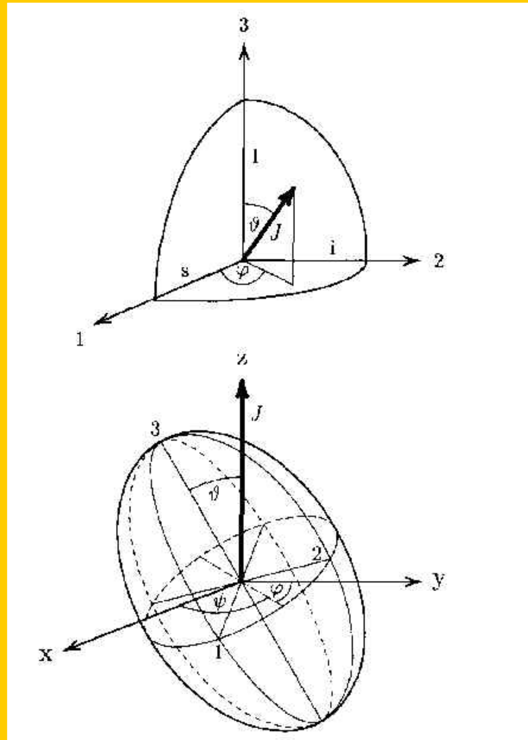


Tilted rotation of triaxial nuclei

S. Frauendorf, Jie Meng [1]

Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf e.V., PF 510119, 01314 Dresden, Germany



Abstract

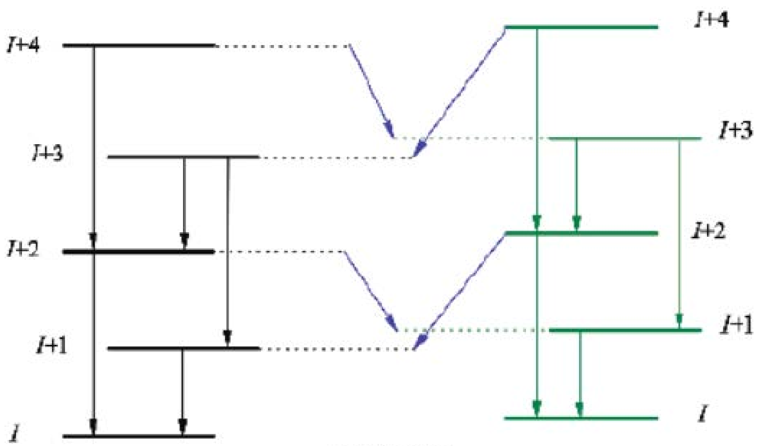
The Tilted Axis Cranking theory is applied to the model of two particles coupled to a triaxial rotor. Comparing with the exact quantal solutions, the interpretation and quality of the mean field approximation is studied. Conditions are discussed when the axis of rotation lies inside or outside the principal planes of the triaxial density distribution. The planar solutions represent $\Delta I = 1$ bands, whereas the aplanar solutions represent pairs of identical $\Delta I = 1$ bands with the same parity. The two bands differ by the chirality of the principal axes with respect to the angular momentum vector. The transition from planar to chiral solutions is evident in both the quantal and the mean field calculations. Its physical origin is discussed.

PACS: ...
Keywords: Tilted axis cranking; Triaxiality; Chirality

[1] Also at Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, PR China. Present address: Alexander von Humboldt fellow, Physik-Department der Technischen Universität München, D-85747 Garching, Germany.

Nuclear Chirality：Based on the geometry for one particle and one hole coupled to a triaxial rotor with gamma=30^0

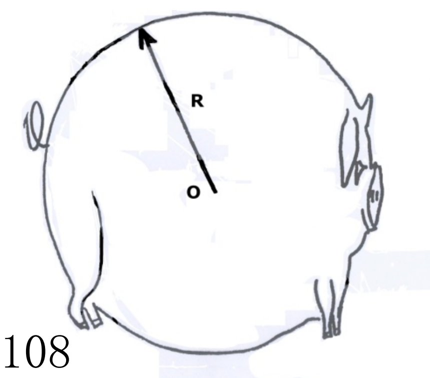
1. nearly degenerate doublet bands
2. S(I) independent of spin
3. identical spin alignments
4. identical B(M1), B(E2) values
5. staggering of B(M1)/B(E2) ratios
6. interband B(E2)=0 at high spin



手征双重带

$|I+\rangle = 1/2^{1/2}(|IL\rangle + |IR\rangle)$, $|I-\rangle = i/2^{1/2}(|IL\rangle - |IR\rangle)$

图2　原子核手性的实验信号之一：实验上观测到宇称相同的和在一定自旋范围内近简并的两条 $\Delta I = 1$ 的转动带（L 和 R 分别表示左手性和右手性的量子数）



S.Y. Wang, S.Q. Zhang, B. Qi, and J. Meng, Chinese Physics Letters 24 (2007) 664

孟杰 物理 38（2009）108

First Observations of the Chiral doublets bands

Observed in 2001

VOLUME 86, NUMBER 6 PHYSICAL REVIEW LETTERS 5 FEBRUARY 2001

Chiral Doublet Structures in Odd-Odd $N = 75$ Isotones: Chiral Vibrations

K. Starosta,[1,*] T. Koike,[1] C. J. Chiara,[1] D. B. Fossan,[1] D. R. LaFosse,[1] A. A. Hecht,[2] C. W. Beausang,[2] M. A. Caprio,[2] J. R. Cooper,[2] R. Krücken,[2] J. R. Novak,[2] N. V. Zamfir,[2,†] K. E. Zyromski,[2] D. J. Hartley,[3] D. L. Balabanski,[3,‡] Jing-ye Zhang,[3] S. Frauendorf,[4] and V. I. Dimitrov[4,‡]

[1]*Department of Physics and Astronomy, SUNY at Stony Brook, Stony Brook, New York 11794*
[2]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
and Institute for Nuclear and Hadronic Physics, Research Center Rossendorf, 01314 Dresden, Germany

(Received 24 July 2000)

New sideband partners of the yrast bands built on the $\pi h_{11/2} \nu h_{11/2}$ configuration were identified in $_{55}$Cs, $_{57}$La, and $_{61}$Pm $N = 75$ isotones of ^{134}Pr. These bands form with ^{134}Pr unique doublet-band systematics suggesting a common basis. Aplanar solutions of 3D tilted axis cranking calculations for triaxial shapes define left- and right-handed chiral systems out of the three angular momenta provided by the valence particles and the core rotation, which leads to spontaneous chiral symmetry breaking and the doublet bands. Small energy differences between the doublet bands suggest collective chiral vibrations.

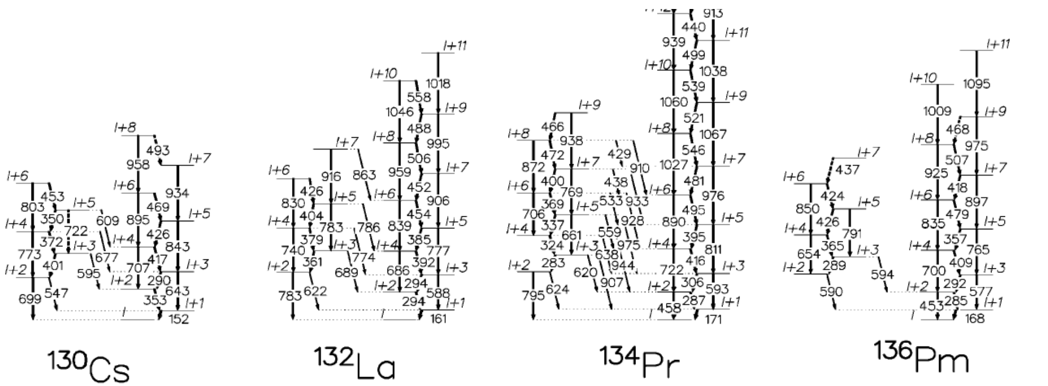


FIG. 2. Partial level schemes presenting the $\pi h_{11/2} \nu h_{11/2}$ bands and newly identified sidebands of ^{130}Cs, ^{132}La, and ^{136}Pm from the current study, and for ^{134}Pr from Ref. [3]. For each $N = 75$ isotone, the yrast $\Delta I = 1$ $\pi h_{11/2} \nu h_{11/2}$ band is shown on the right while the $\Delta I = 1$ sideband is shown on the left side of each level scheme.

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MχD proposed in 2006

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

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

J. Meng,[1,2,3,*] J. Peng,[1] S. Q. Zhang,[1] and S.-G. Zhou[2,3]

[1]*School of Physics, Peking University, Beijing 100871, China*

[2]*Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, China*

[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

(Received 30 March 2005; published 15 March 2006)

Adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches are developed for the first time. A new phenomenon, the existence of multiple chiral doublets (MχD), i.e., more than one pair of chiral doublet bands in one single nucleus, is suggested for ^{106}Rh based on the triaxial defor corresponding proton and neutron configurations.

DOI: 10.1103/PhysRevC.73.037303 PACS number(s): 21.10.Re, 21.60.Jz, 21

The investigation followed by:

- ***Prediction for other odd-odd Rh isotopes:*** **J. Peng et al., PRC77, 024309 (2008)**
- ***Confirmed with time-odd fields included:*** **J. M. Yao et al., PRC79, 067302 (2009)**
- ***Prediction for the odd-A Rh isotopes:*** **J. Li et al., PRC83, 037301 (2011)**

First observation of the MχD bands

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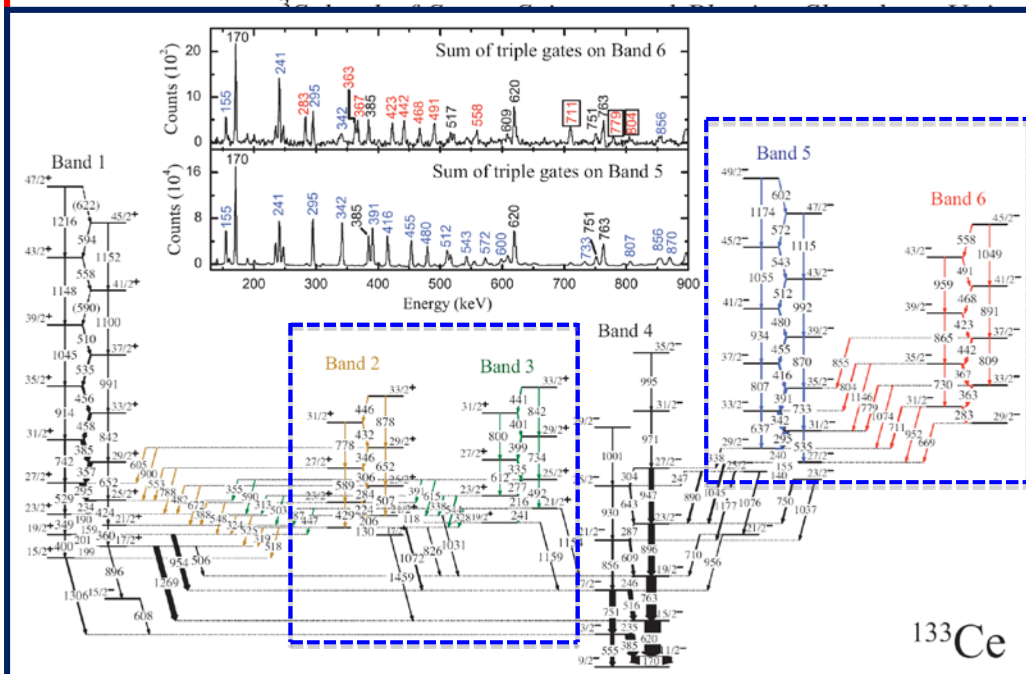
PRL **110**, 172504 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

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

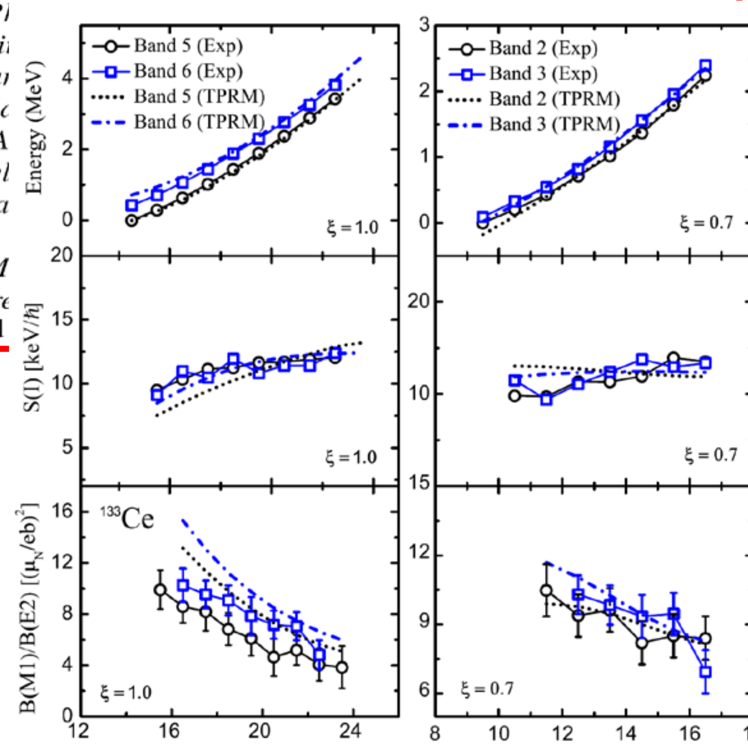
A. D. Ayangeakaa,[1] U. Garg,[1] M. D. Anthony,[1] S. Frauendorf,[1] J. T. Matta,[1] B. K. Nayak,[1,*] D. Patel,[1] Q. B. Chen (陈启博),[2] S. Q. Zhang (张双全),[2] P. W. Zhao (赵鹏巍),[2] B. Qi (亓斌),[3] J. Meng (孟杰),[2,4,5] R. V. F. Janssens,[6] M. P. Carpenter,[6] C. J. Chiara,[6,7] F. G. Kondev,[8] T. Lauritsen,[6]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

Spontaneous chiral and reflection symmetry breaking

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

Evidence for Octupole Correlations in Multiple Chiral Doublet Bands

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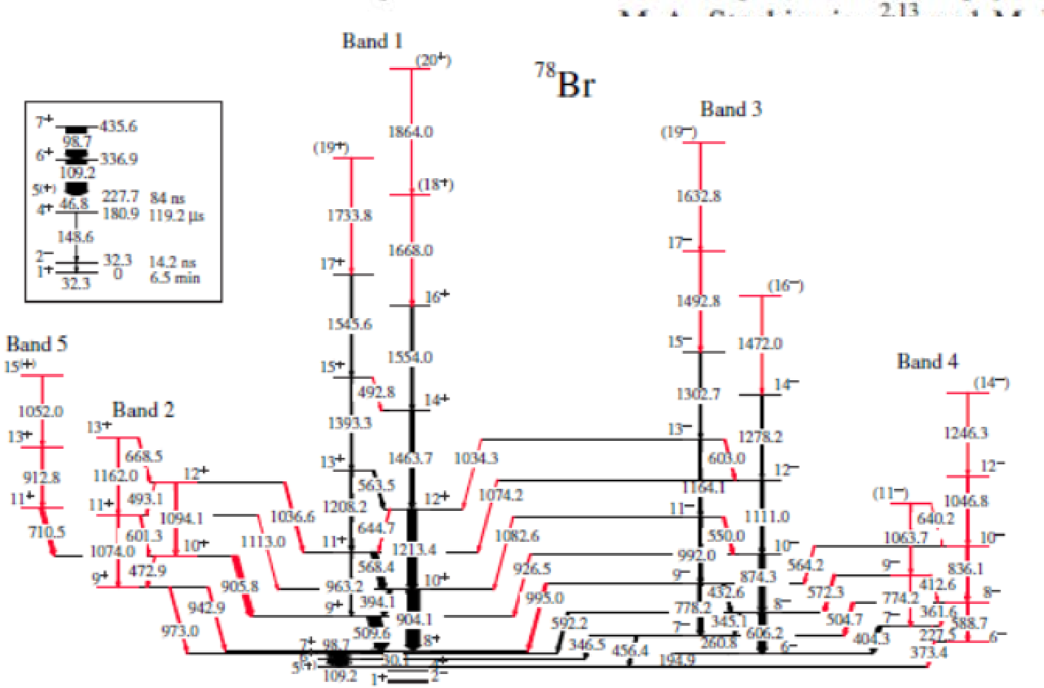
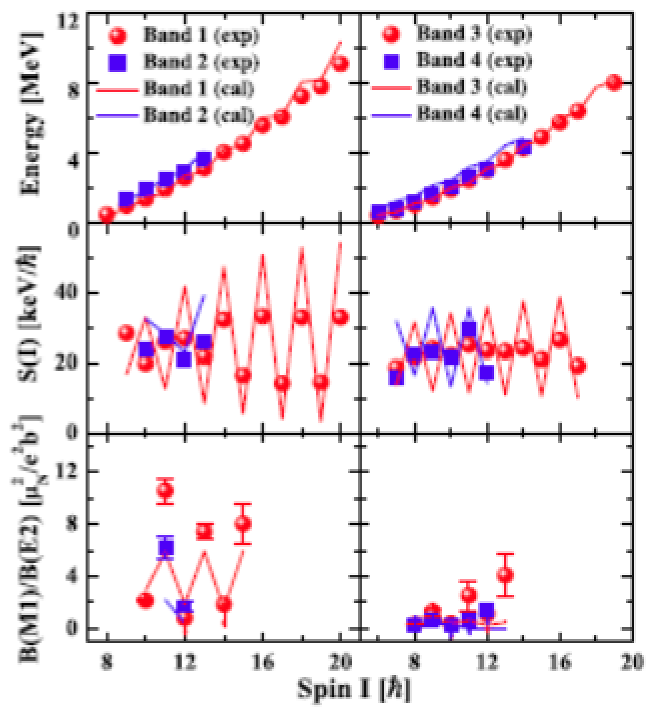




Time-dependent CDFT

- For excited states, a proper method is time-dependent CDFT.
- In analogy to the Hohenberg-Kohn theorem, there exists the Runge-Gross theorem.
- Runge-Gross theorem provides an exact mapping of the full time-dependent many-body problem onto a time-dependent single-particle problem.
- The corresponding single-particle field is not only time-dependent, but also depends on the single-particle density with its full time dependence, i.e., it includes memory effects.

Time-dependent CDFT

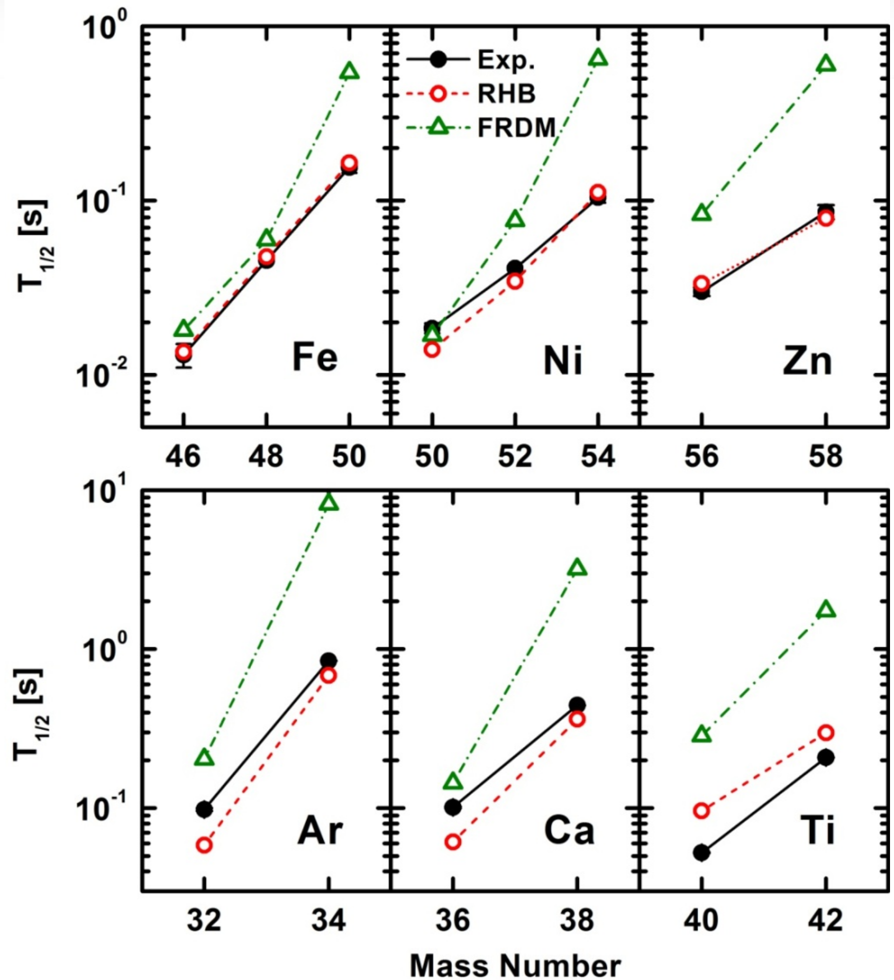
- For vibrations with small amplitude, it can be expanded in the vicinity of the ground state and a connection to the static energy density functional can be found.
- In the adiabatic approximation, i.e. by neglecting the memory effects and the energy dependence in Fourier space, one ends up with the RPA with a residual interaction derived as the second derivative of the static energy functional with the density.
- RPA provides a successful description of the mean energies of giant resonances in nuclei, but not able to reproduce the decay width of these excitations.
- For the decay width and the fragmentation of single-particle states, one has to go beyond mean field and to consider the energy dependence of the self-energy. This can be done within the particle-vibrational coupling (PVC) model.

Paar, Vretenar, Khan, Colo, Rep. Prog. Phys. 70, 691 (2007).

RHB+QRPA: Nuclear β⁺/EC-decay half-lives

▸ RHB+QRPA: well reproduces the experimental half-lives for neutron-deficient Ar, Ca, Ti, Fe, Ni, and Zn isotopes by a universal T=0 pairing strength.

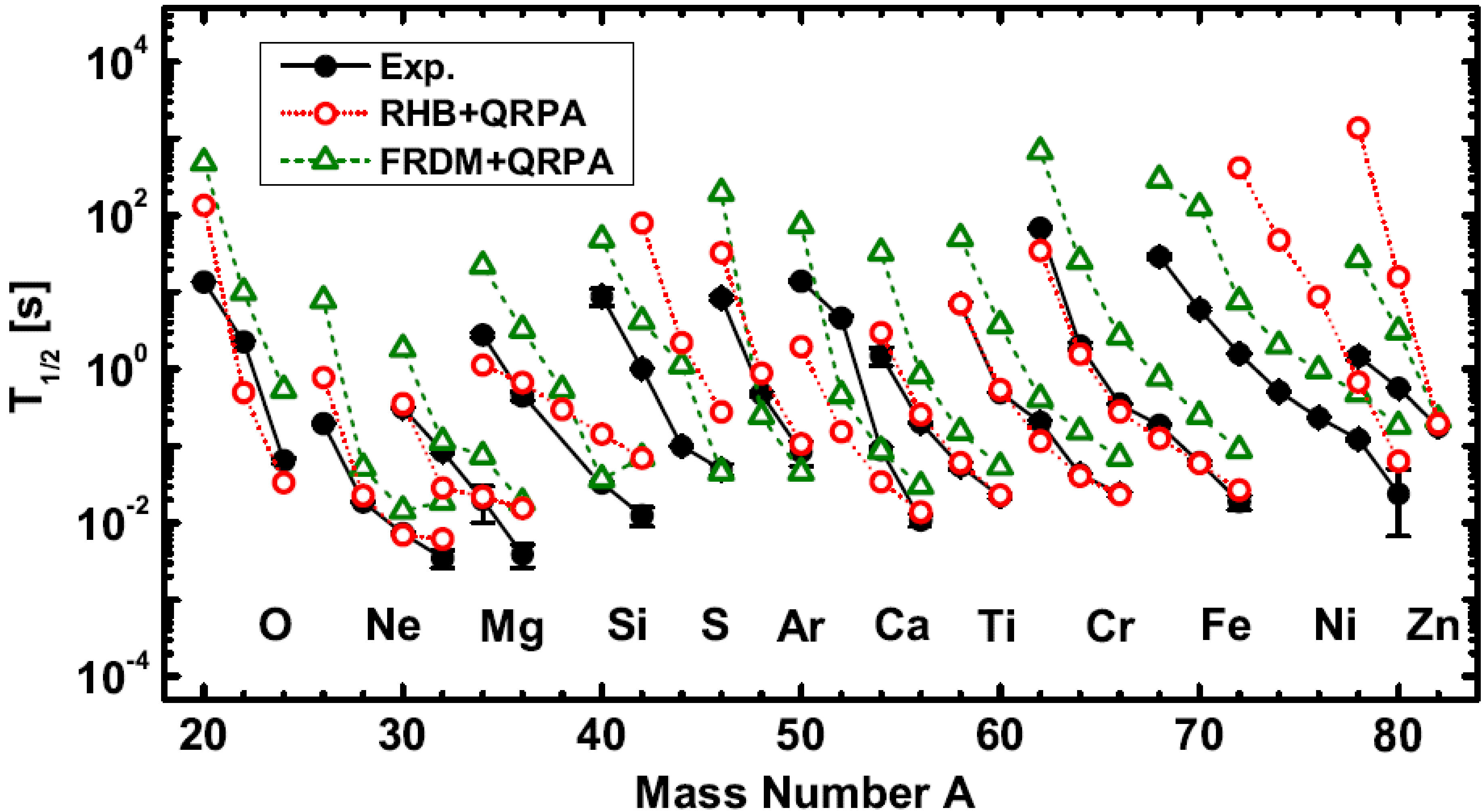
▸ FRDM+QRPA: systematically overestimates the nuclear half-lives 🡐 the pp residual interactions in the T=0 channel are not considered.



Nuclear β⁺/EC-decay half-lives calculated in RHB+QRPA model with the PC-PK1 parameter set.

Niu et al., PRC 87, 051303(R) (2013)

RHB+QRPA/PC-**PK1: Nuclear β**-decay half-lives



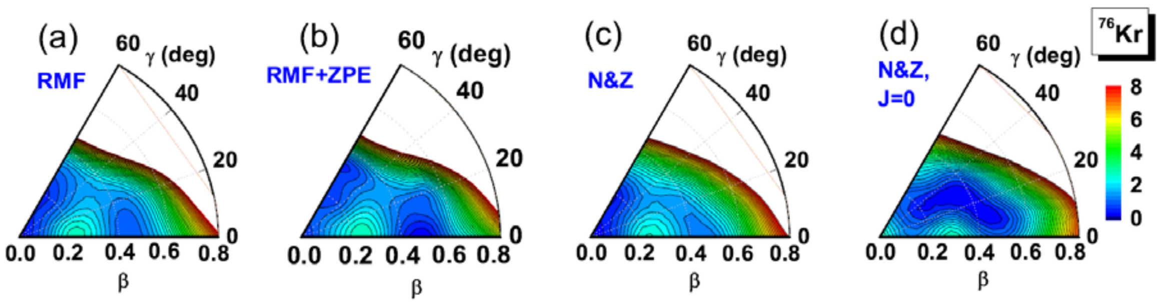
Z. Y. Wang, Z. M. Niu, Y. F. Niu, J. Y. Guo [arXiv:1503.01222]
Nuclear $β$-decay half-lives in the relativistic point-coupling model

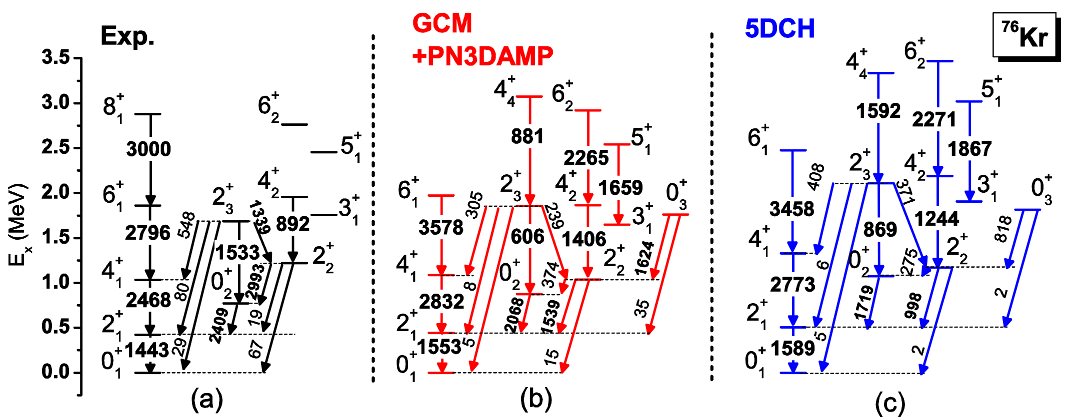
Symmetry restoration and fluctuations

- Many-body energy takes the form of a functional of all transition density matrices between the various Slater determinants of different deformation and orientation. Mixing of these different configurations allows the restoration of symmetries and to take into account fluctuations around the mean-field equilibrium solution.
- In full space and with deformation degrees of freedom, such calculations require considerable numerical efforts, at the limit of present computer capabilities.
- A considerable simplification is by using the constraint calculations for the derivation of a **collective Hamiltonian** in these degrees of freedom.

Nuclear low-lying states: CDFT+GCM+PN3DAMP

7D GCM: two deformation parameters + projection 3DAM and 2PN





◈ The low-energy spectrum in ^{76}Kr are well reproduced after including triaxiality in the full microscopic GCM+ PN3DAMP calculation based on the CDFT using PC-PK1.

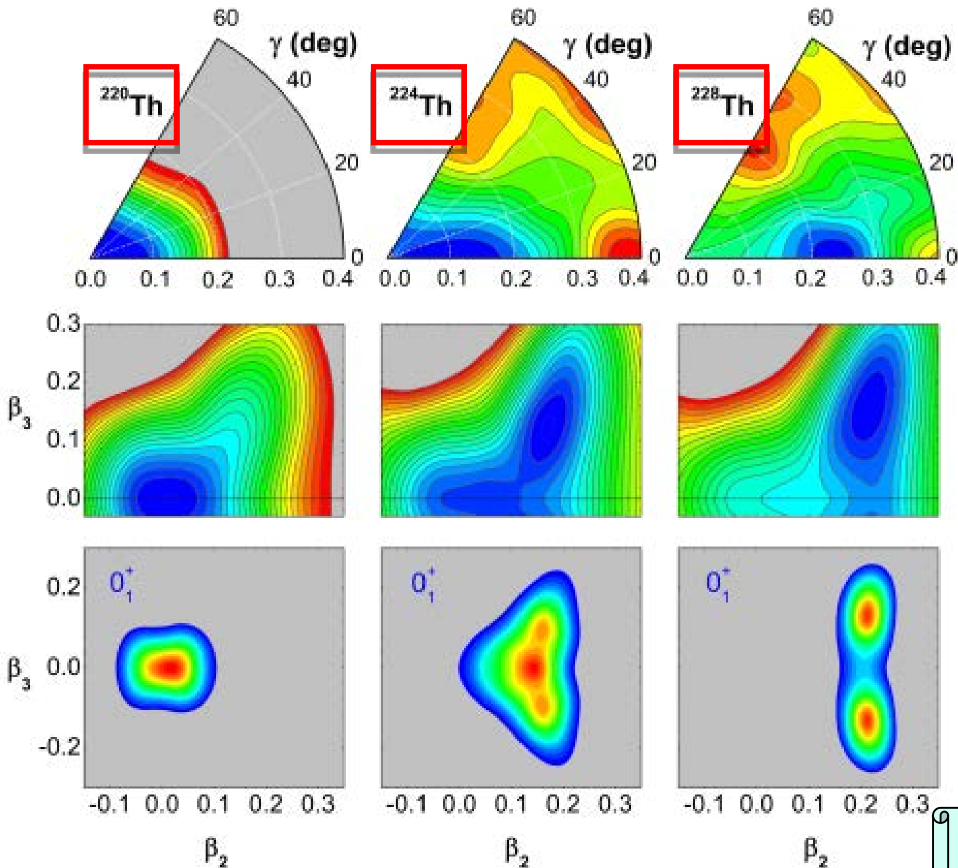
◈ This study answers the important question of dynamic correlations and triaxiality in shape-coexistence nucleus ^{76}Kr and provides the first benchmark for the EDF based collective Hamiltonian method.

Yao, Hagino, Li, Meng, Ring, Phys. Rev. C 89, 054306 (2014)

Benchmark for the collective Hamiltonian in five dimensions

Simultaneous shape phase transition

5DCH Calculations based on CDFT PC-PK1 indicate a simultaneous quantum shape phase transition from spherical to prolate shapes, and from reflection symmetric to octupole shapes.



triaxial quadrupole energy surfaces

axially-symmetric quadrupole–octupole energy surfaces

probability density distributions for the ground states

Li, Song, Yao, Vretenar, and Meng, Phys. Lett. B 726 (2013) 866

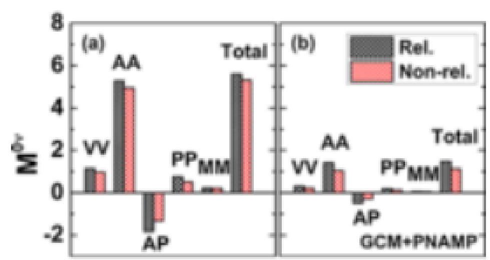
Relativistic description of nuclear matrix elements in neutrinoless double-β decay

Phys. Rev. C 90, 054309 – Published 10 November 2014
Song, Yao, Ring, and Meng

Editors' Suggestion

Relativistic description of nuclear matrix elements in neutrinoless double-β decay

L. S. Song, J. M. Yao, P. Ring, and J. Meng
Phys. Rev. C **90**, 054309 (2014) – Published 10 November 2014



Phys. Rev. C 91, 024316 (2015)
Yao, Song, Hagino, Ring, and Meng

TABLE II. The calculated NME $M^{0\nu}$ of the $0\nu\beta\beta$ decay with the REDF (PC-PK1), in comparison with those by the NREDF (D1S), RQRPA, PHFB, ISM, and IBM2. Only the results considering the short-range correlation (SRC) effect by UCOM, except for the IBM2 where CCM is used and using the parameter $R = 1.2A^{1/3}$ fm are adopted for comparison. The values in the parentheses are the results with additional pairing fluctuations.

Models $g_A(0)$	REDF(PC-PK1) 1.254	NREDF(D1S) 1.25	RQRPA (Tübingen) 1.254	PHFB 1.254	ISM 1.25	IBM2 1.269
$^{48}Ca \to {}^{48}Ti$	2.94	2.37 (2.23)			0.85	2.38
$^{76}Ge \to {}^{76}Se$	6.13	4.60 (5.55)	5.17		2.81	6.16
$^{82}Se \to {}^{82}Kr$	5.40	4.22 (4.67)	5.32		2.64	4.99
$^{96}Zr \to {}^{96}Mo$	6.47	5.65 (6.50)	1.77	3.32		3.00
$^{100}Mo \to {}^{100}Ru$	6.58	5.08 (6.59)	3.88	7.22		4.50
$^{116}Cd \to {}^{116}Sn$	5.52	4.72 (5.35)	3.21			3.29
$^{124}Sn \to {}^{124}Te$	4.33	4.81 (5.79)			2.62	4.02
$^{130}Te \to {}^{130}Xe$	4.98	5.13 (6.40)	4.07	4.66	2.65	4.61
$^{136}Xe \to {}^{136}Ba$	4.32	4.20 (4.77)	2.54		2.19	3.79
$^{150}Nd \to {}^{150}Sm$	5.60	1.71 (2.19)		3.24		2.88

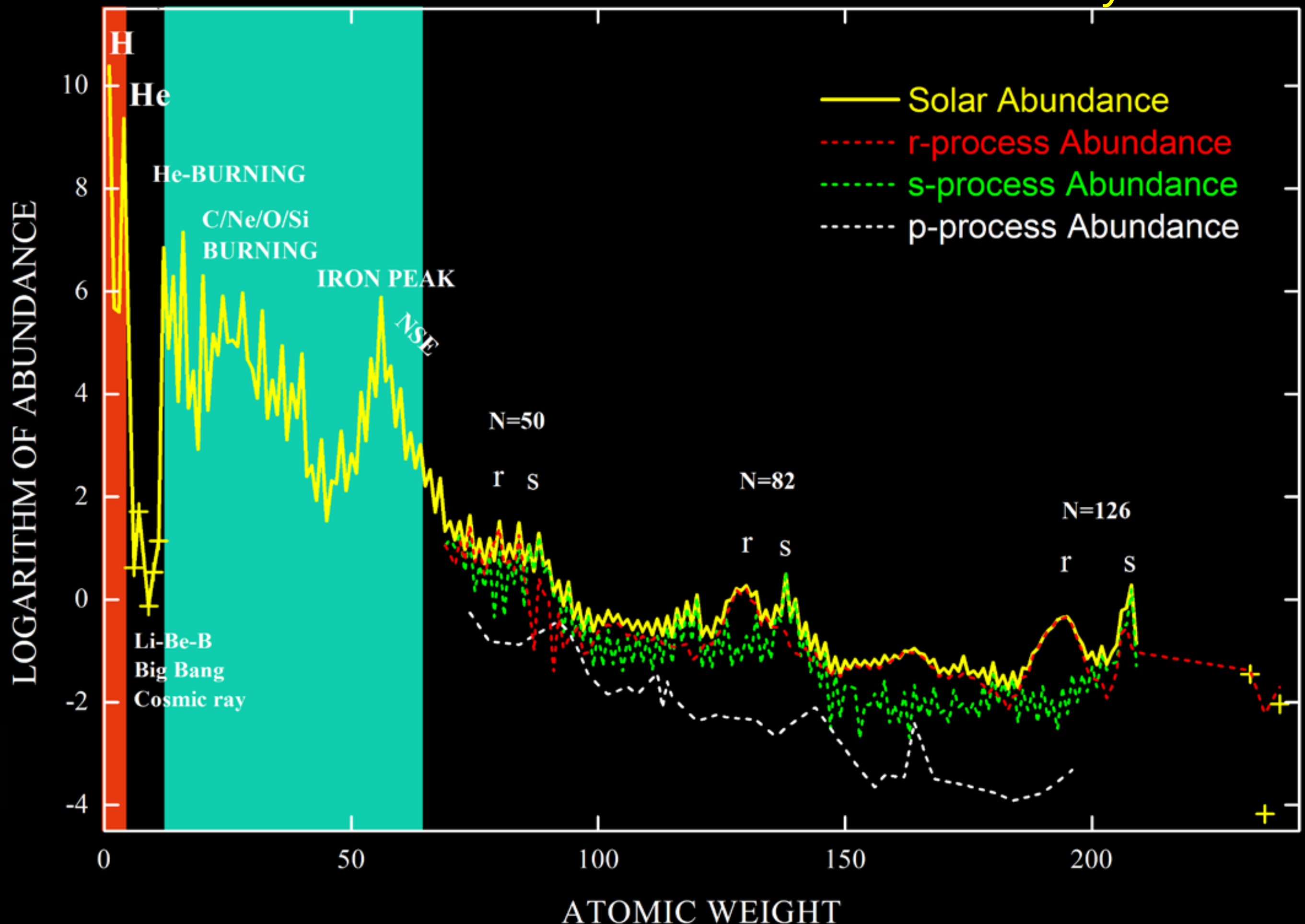
The authors report a fully relativistic des
based on a state-of-the-art nuclear struc
and electric quadrupole transitions in bo
double-β decay experiments.

Application of CDFT in Nuclear astrophysics

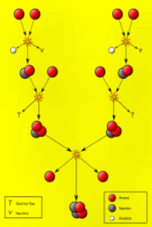
THE EVOLUTION OF ELEMENTS

Follow the Footprint of Nucleosynthesis

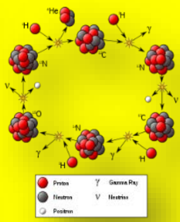
Courtesy of Zhu Lee



Hydrogen Burning

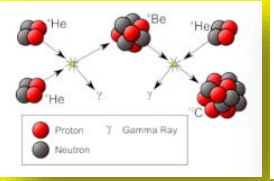


pp-chain

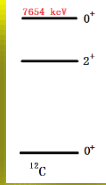


CNO Cycle

Helium Burning

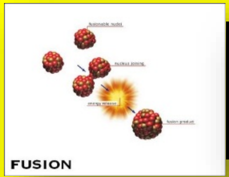


Triple-alpha

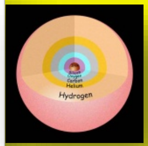


Hoyle State

C/Ne/O/Si Burning

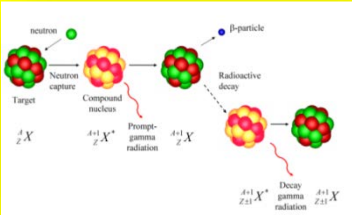


Fusion

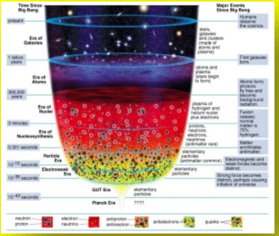


Massive Star

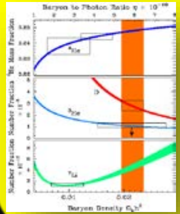
Neutron Capture

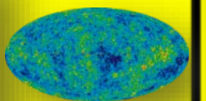


3 Mins After Big Bang



Big Bang Nucleosynthesis

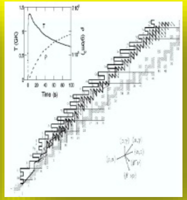




CMB

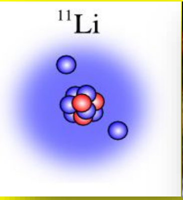
Stellar Nucleosynthesis

Type I X-ray Burst



Explosive H-He Burning

From nucleus to star



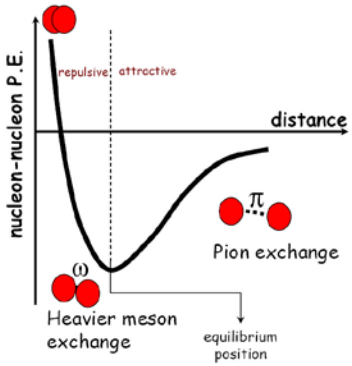
Exotic Nuclei

Stellar Evolution

Nuclear covariant density functional theory tomorrow

The effective interaction in current CDFT is not derived from the basic theory of the strong interaction --- QCD. As indicated by the successes achieved by the covariant density functional, the feasibility of a unified self-consistent description of nuclear ground state and excitation properties starting from an effective nucleon-nucleon interaction is anticipated.

In future, one needs to obtain properly the nucleon-nucleon interaction in nuclear medium starting from the quantum chromo-dynamics, eventually to build the standard model of nuclear structure that can implement the ab initio exploration for all nuclei in the nuclear chart.



Thank you for your attention!

北京大學 PEKING UNIVERSITY

ab initio covariant investigations of heavy nuclei

CHIN. PHYS. LETT. Vol. 33, No. 10 (2016) 102103

Express Letter

Relativistic Brueckner–Hartree–Fock Theory for Finite Nuclei *

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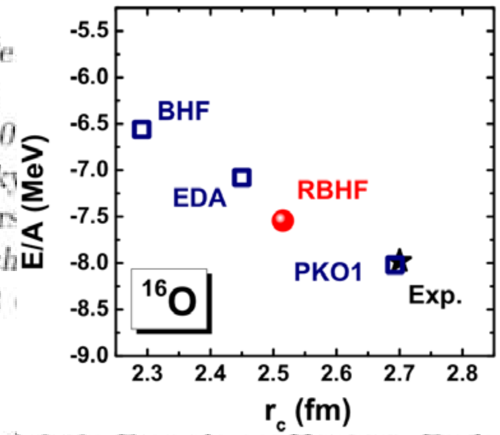

(Received 17 September 2016)

Starting with a bare nucleon-nucleon interaction, for the first time the full relativistic Brueckner–Hartree–Fock equations are solved for finite nuclei in a Dirac–Woods–Saxon basis. No free parameters are introduced to calculate the ground-state properties of finite nuclei. The nucleus ^{16}O is investigated as an example. The resulting ground-state properties, such as binding energy and charge radius, are considerably improved as compared with the non-relativistic Brueckner–Hartree–Fock results and much closer to the experimental data. This opens the door for ab initio covariant investigations of heavy nuclei.