北京大學

GSI - FAIR Colloquium

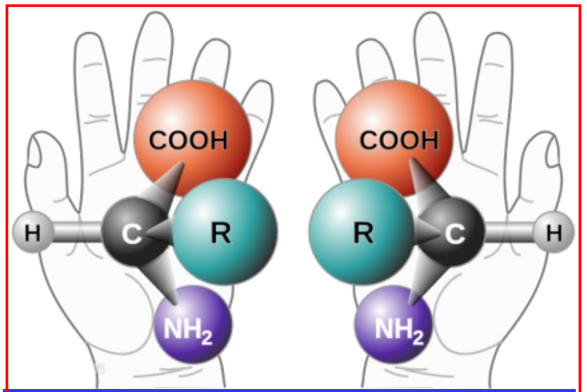
GSI, Main Lecture Hall, Tuesday, July 11, 2023

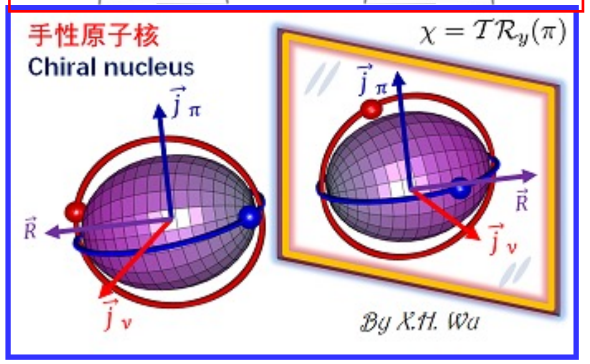
Mass and shape of the exotic nuclei

Jie MENG （孟 杰）

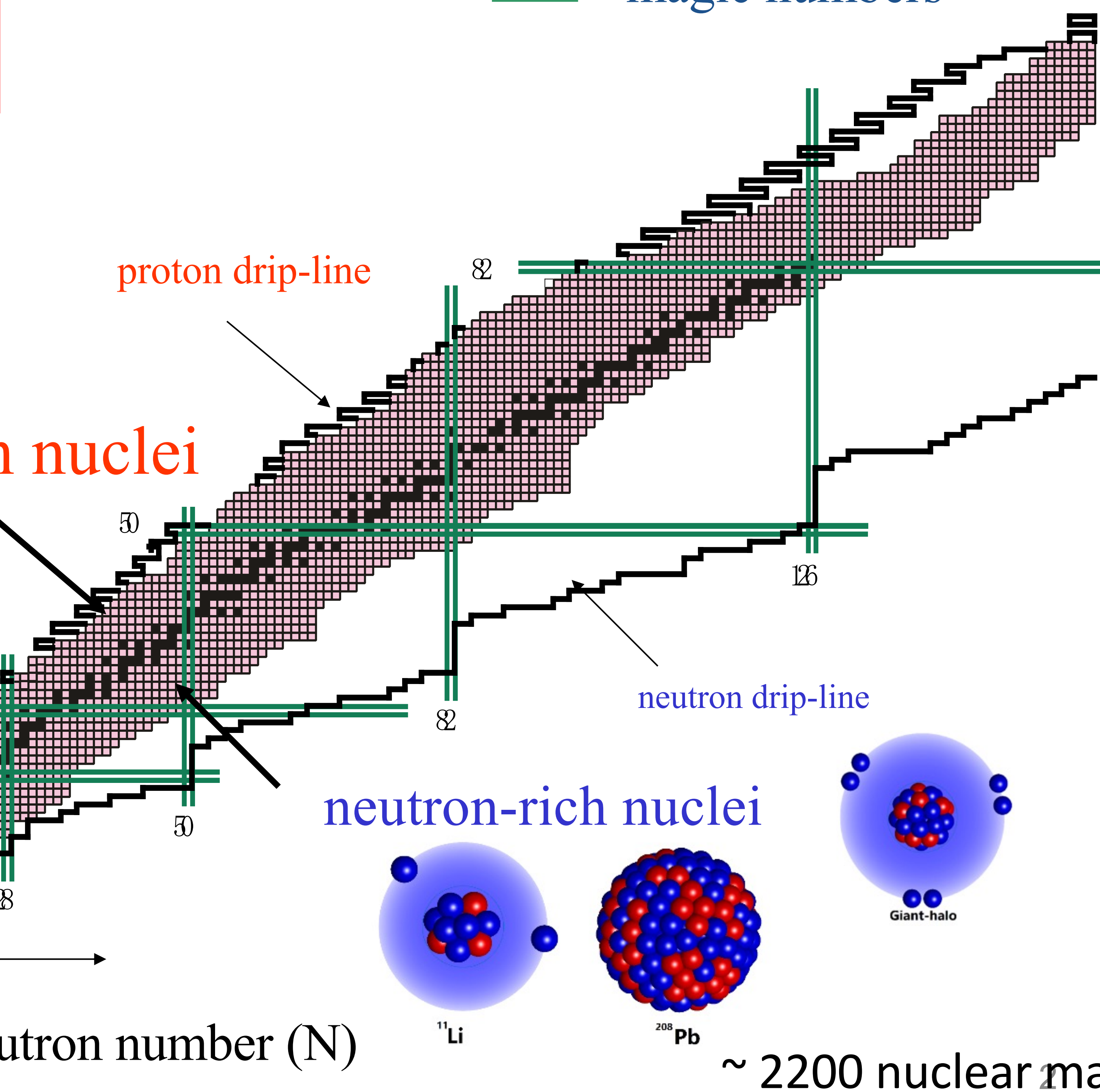
School of Physics， Peking University（北京大学物理学院）

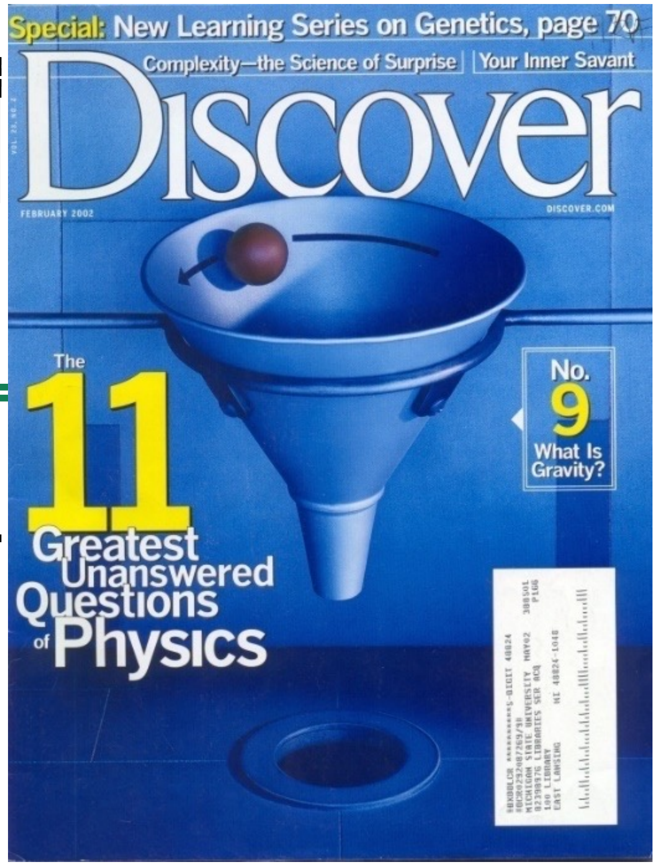
Existence Limit of nucleus





■	stable nuclei	~300 nuclei
□	unstable nuclei observed	~2700 nuclei
—	drip-lines（predictions)	~8000 nuclei
=	magic numbers	

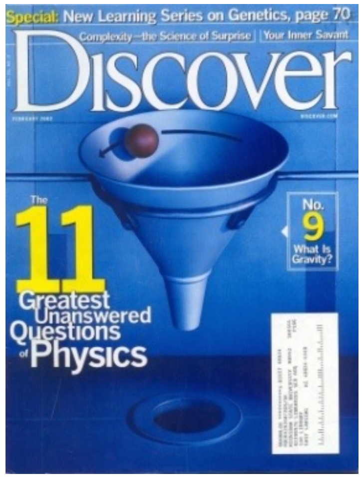




~ 2200 nuclear masses were measured

How were the heavy elements from iron to Uranium made?

Discovery: "11 greatest unanswered questions of Physics"

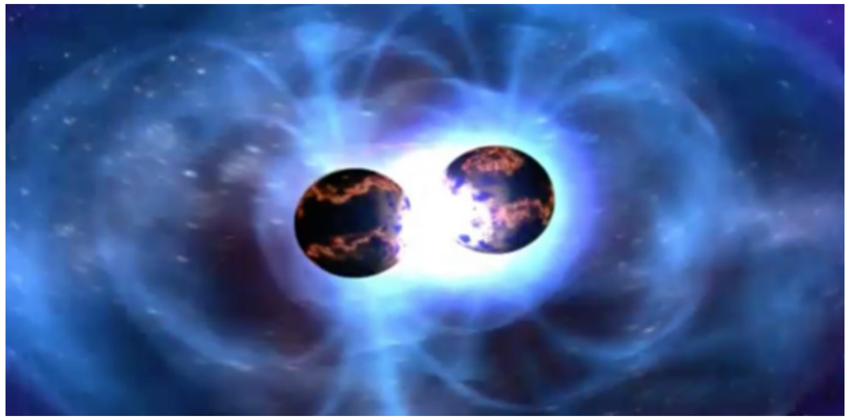


Key mechanism: rapid neutron capture process (r-process)

r-process sites

GW170817 neutron-star-merger event shows that neutron star merger is one of the r-process sites

ApJL 848, L12 (2017)

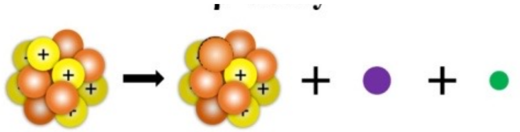


big process in nucleosynthesis study

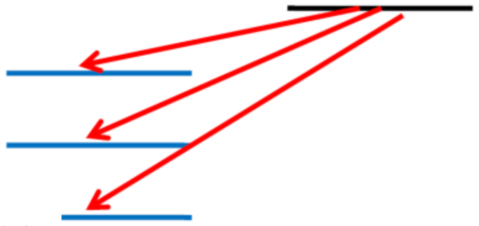
Systematic nuclear physics knowledge: mass, β-decay half-lives, reaction rates …

Accurate description: difficult problem in nuclear physics

β decay



Gamow-Teller transition



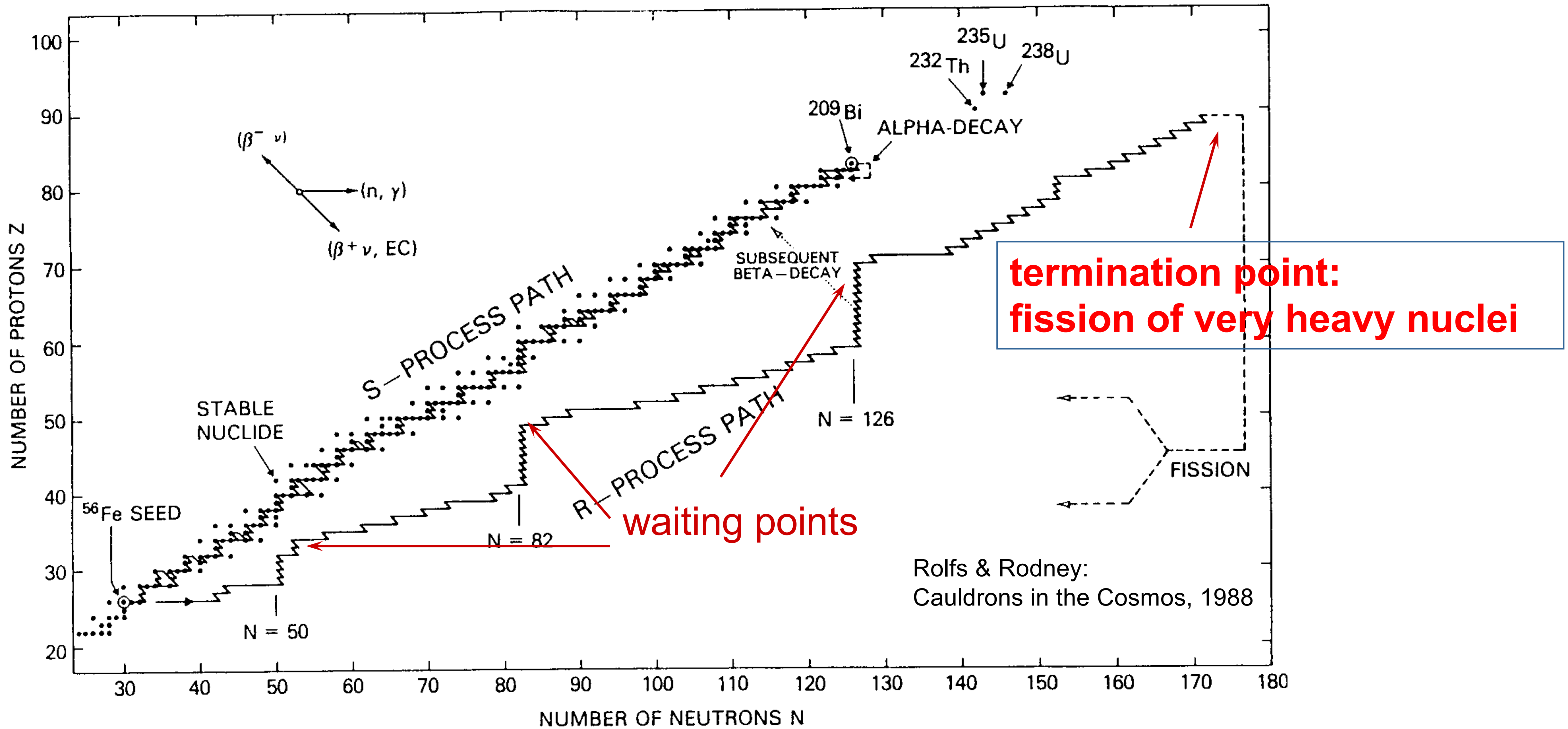
key: difficulties in experiments

Large-scale accurate theoretical calculations nuclear are demanded

r–process

r-process (r = rapid neutron capture process) ⇔ **n capture time: $\tau_n << \tau_\beta$**

unstable nucleus reacts before capturing decay



typical lifetimes for unstable nuclei far from the valley of β stability: $10^{-4} – 10^{-2}$ s

requiring n capture time: $\tau_n \sim 10^{-4}$ s ⇔ $n_n \sim 10^{20}$ n/cm^3

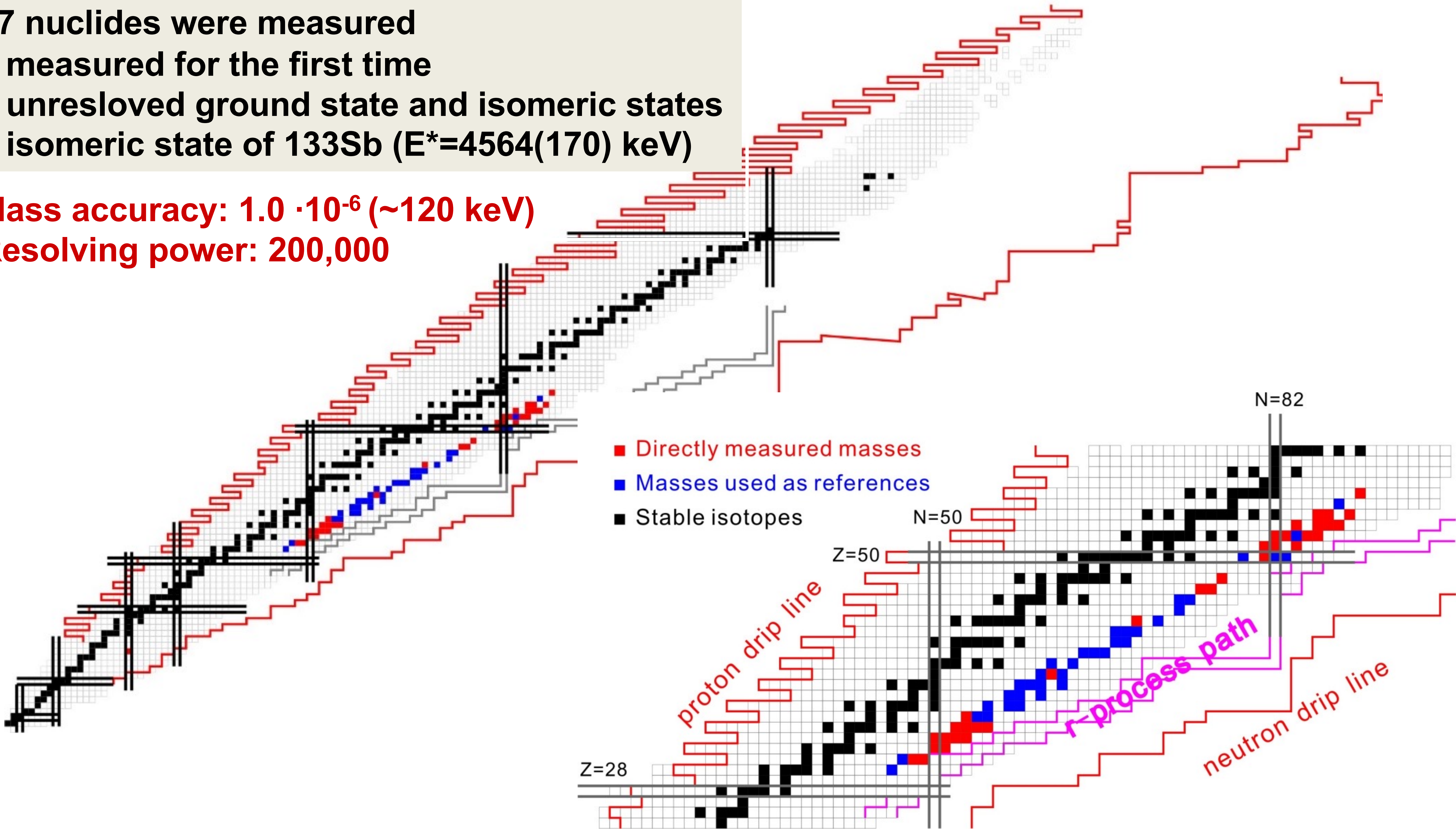
explosive scenarios needed to account for such high neutron fluxes

Mass measurement

Short-Lived Neutron-Rich Nuclei with the Novel Large-Scale Isochronous Mass Spectrometry at the FRS-ESR Facility Sun et al. NPA 812 (2008) 1-12

71 nuclides covered
27 nuclides were measured
8 measured for the first time
8 unresloved ground state and isomeric states
1 isomeric state of 133Sb (E*=4564(170) keV)

Mass accuracy: 1.0 $\cdot 10^{-6}$ (~120 keV)
Resolving power: 200,000

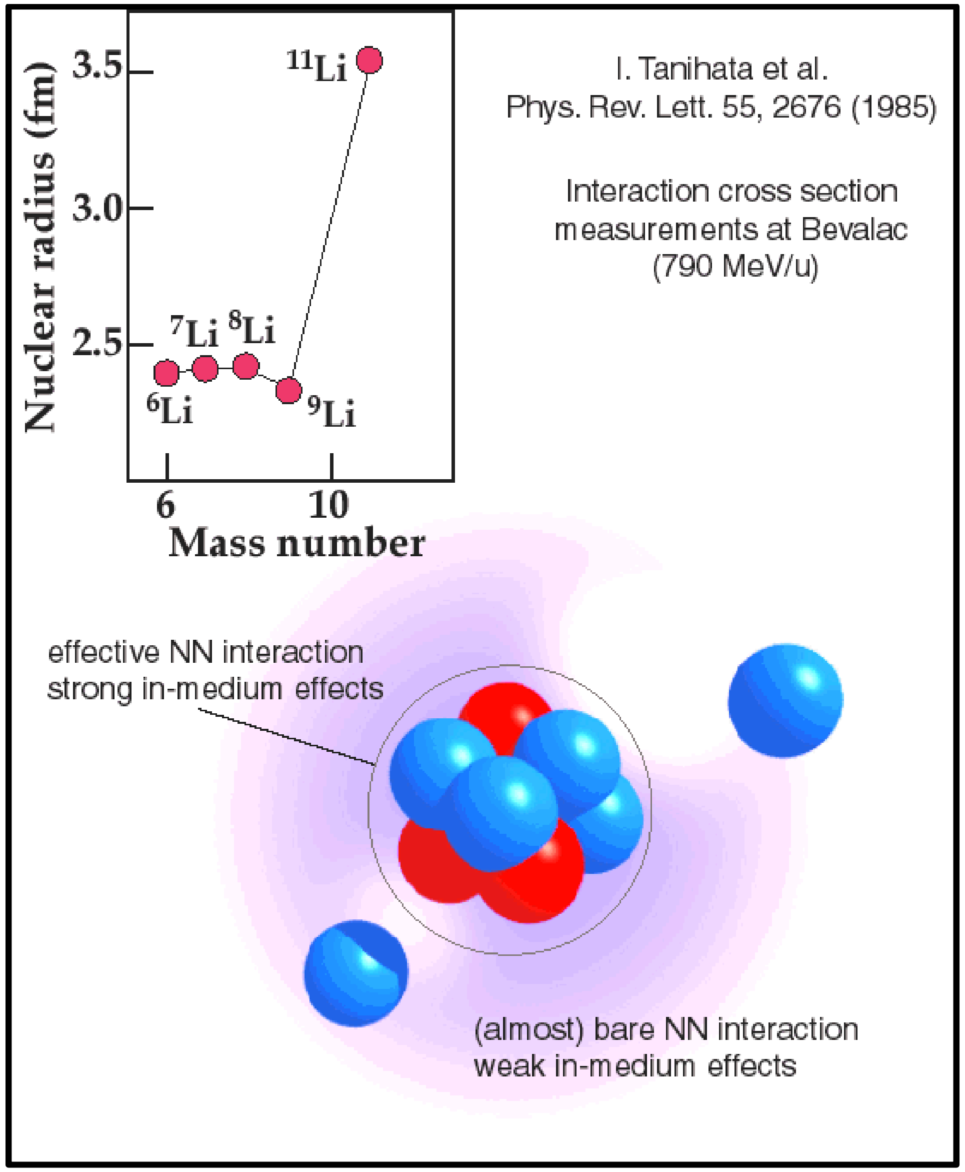


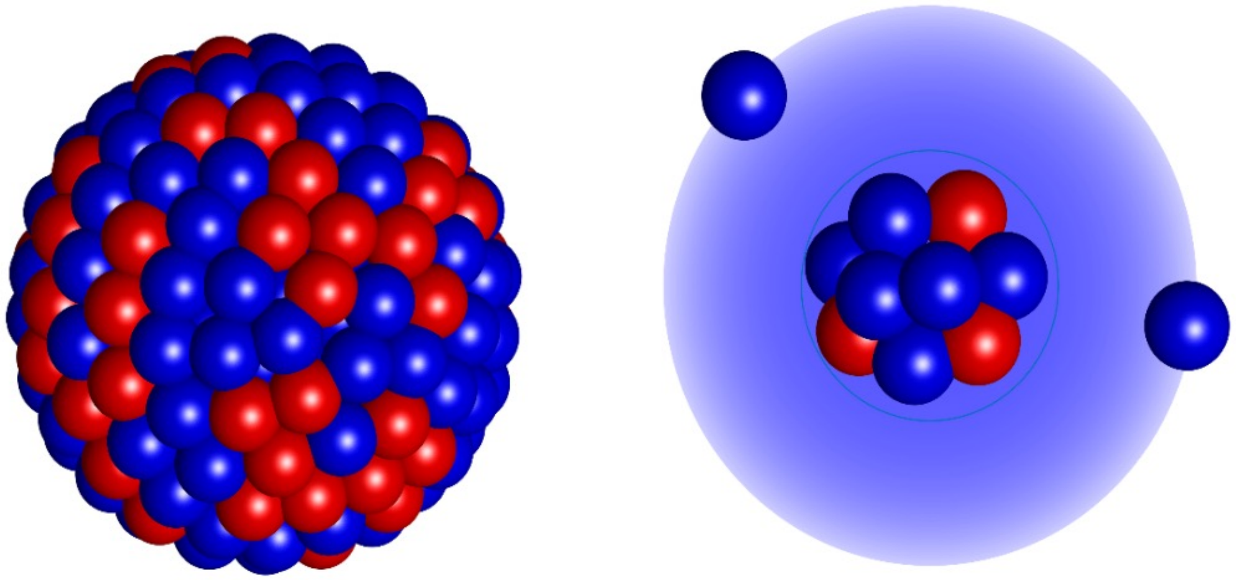
Facility for Antiproton and Heavy Ion Research (FAIR)

Darmstadt

New phenomena in exotic nucleus

I. Tanihata, et al Phys. Rev. Lett. 55 (1985) 2676





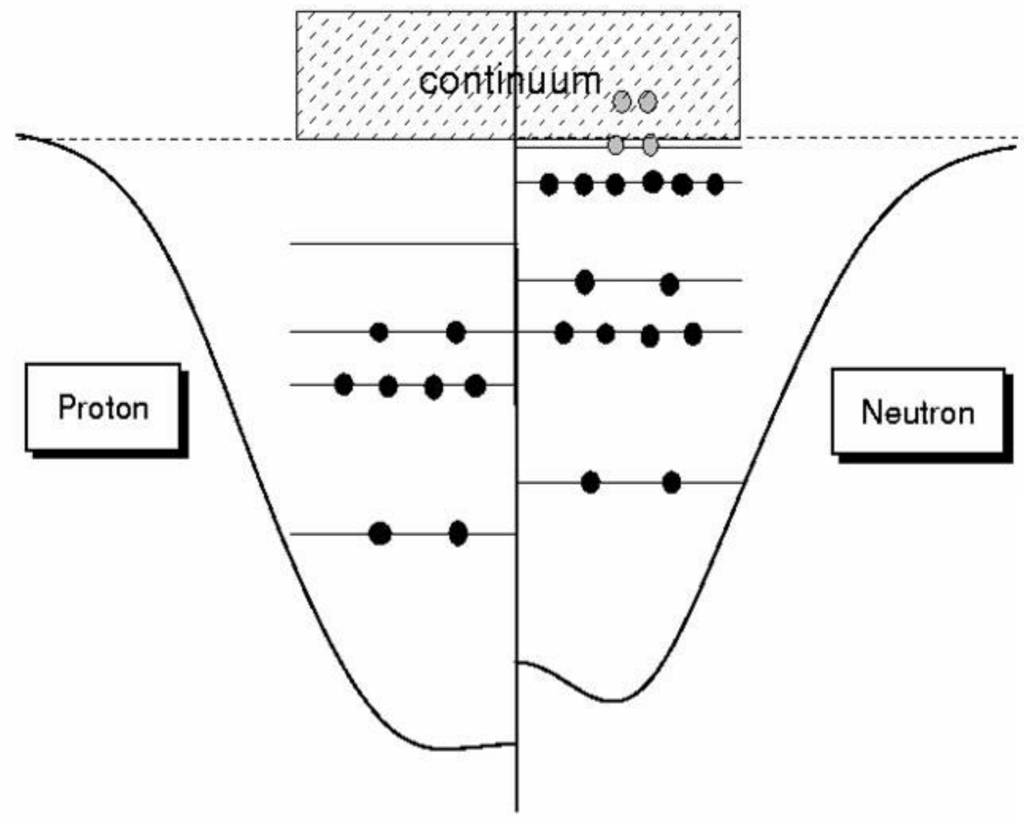
Meng and Ring, Phys. Rev. Lett. 77 (1996) 3963
Meng and Ring, Phys. Rev. Lett. 80 (1998) 460

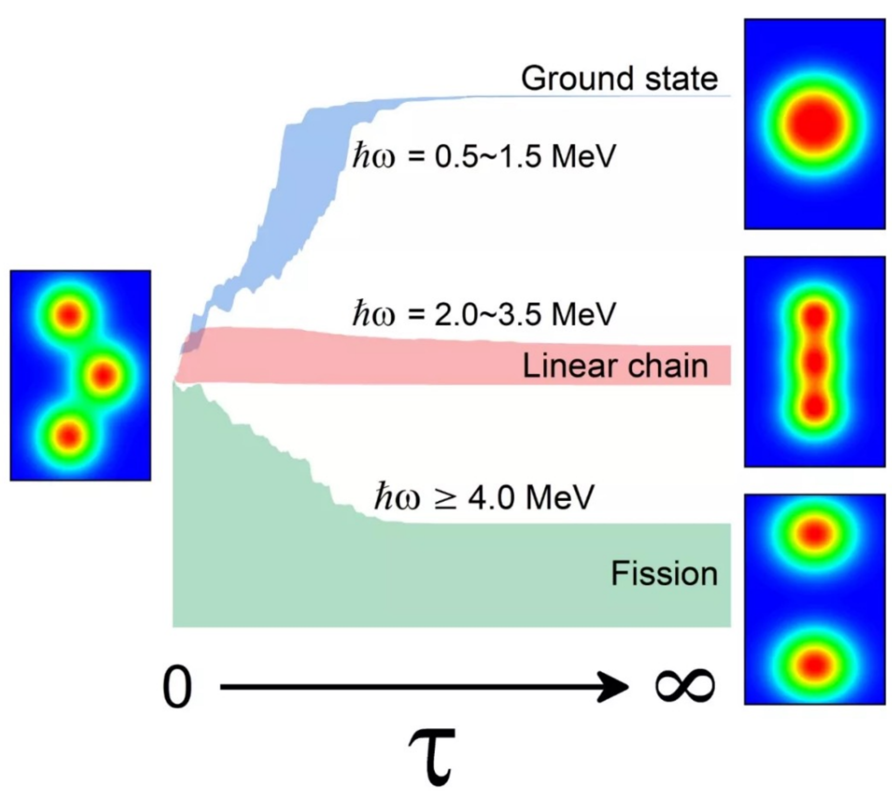
Shell structure, low density， continuum ， bound state, spatial distribution, pairing correlation, coupling between bound state and continuum…

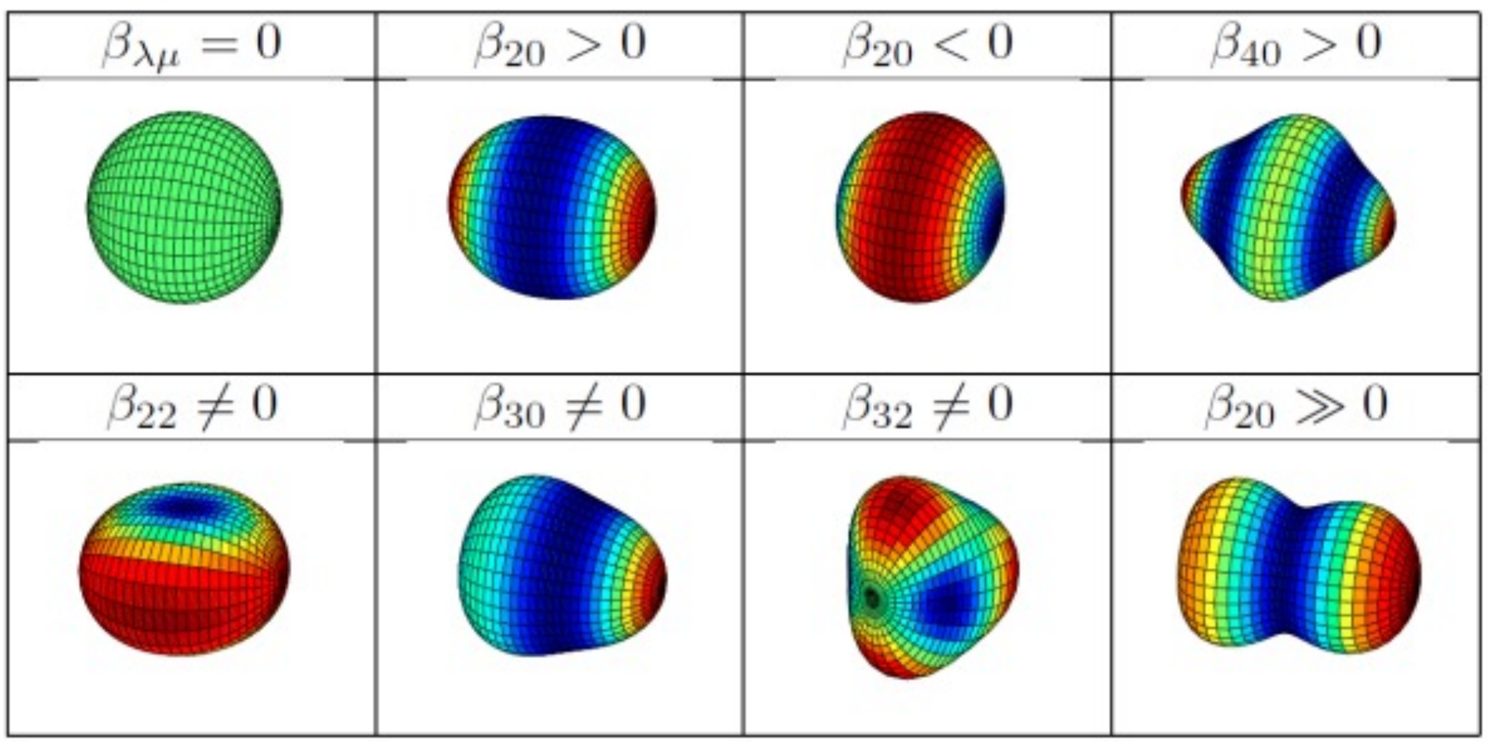
- Meng, Toki, Zhou, Zhang, Long & Geng, Prog. Part. Nucl. Phys. 57 (2006) 470
- Meng and Zhou, J. Phys. G: 42 (2015) 093101

From Xin-Hui Wu

Continuum, deformation, clustering, …







By Bing-Nan Lu

Ren, Zhang, Zhao, Itagaki, Maruhn, Meng, SCPMA 62, 112062 (2019)
Ren, Zhao, Meng, Physics Letters B 801 (2020) 135194

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Toward Relativistic *ab initio DFT*

Progress in Particle and Nuclear Physics 109 (2019) 103713

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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Review

Towards an *ab initio* covariant density functional theory for nuclear structure

Shihang Shen [a,b,c], Haozhao Liang [d,e], Wen Hui Long [f,g], Jie Meng [a,h,i,*], Peter Ring [a,j]

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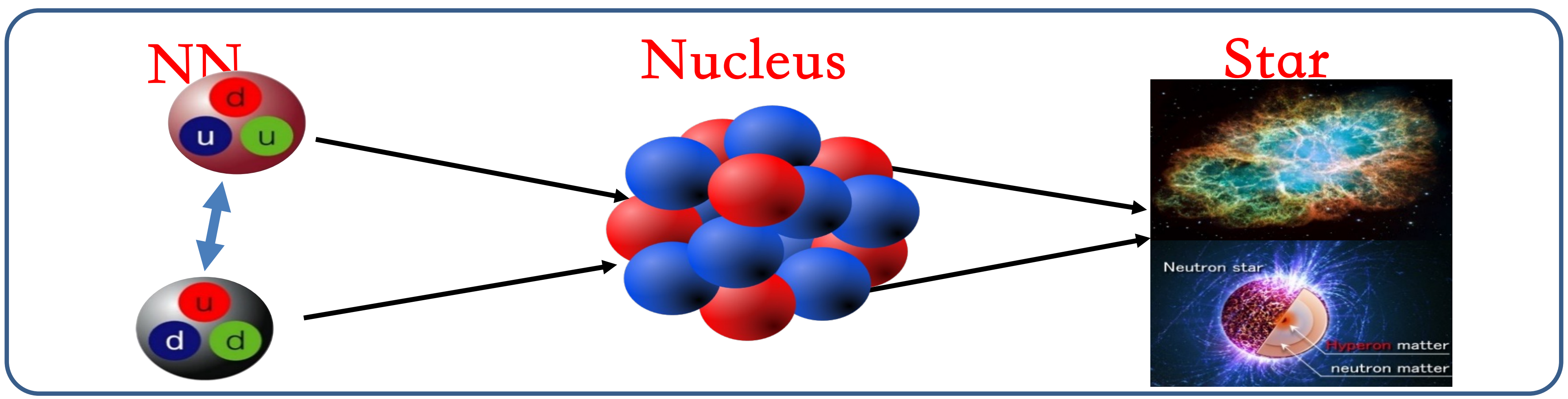
[b] Dipartimento di Fisica, Università degli Studi di Milano, Italy
[c] INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy
[d] RIKEN Nishina Center, Wako 351-0198, Japan



QCD/EFT → Relativistic *ab initio* → Relativistic DFT

Relativistic NN interaction

□ Chiral Nucleon-Nucleon Interaction

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Accurate Relativistic Chiral Nucleon-Nucleon Interaction up to Next-to-Next-to-Leading Order

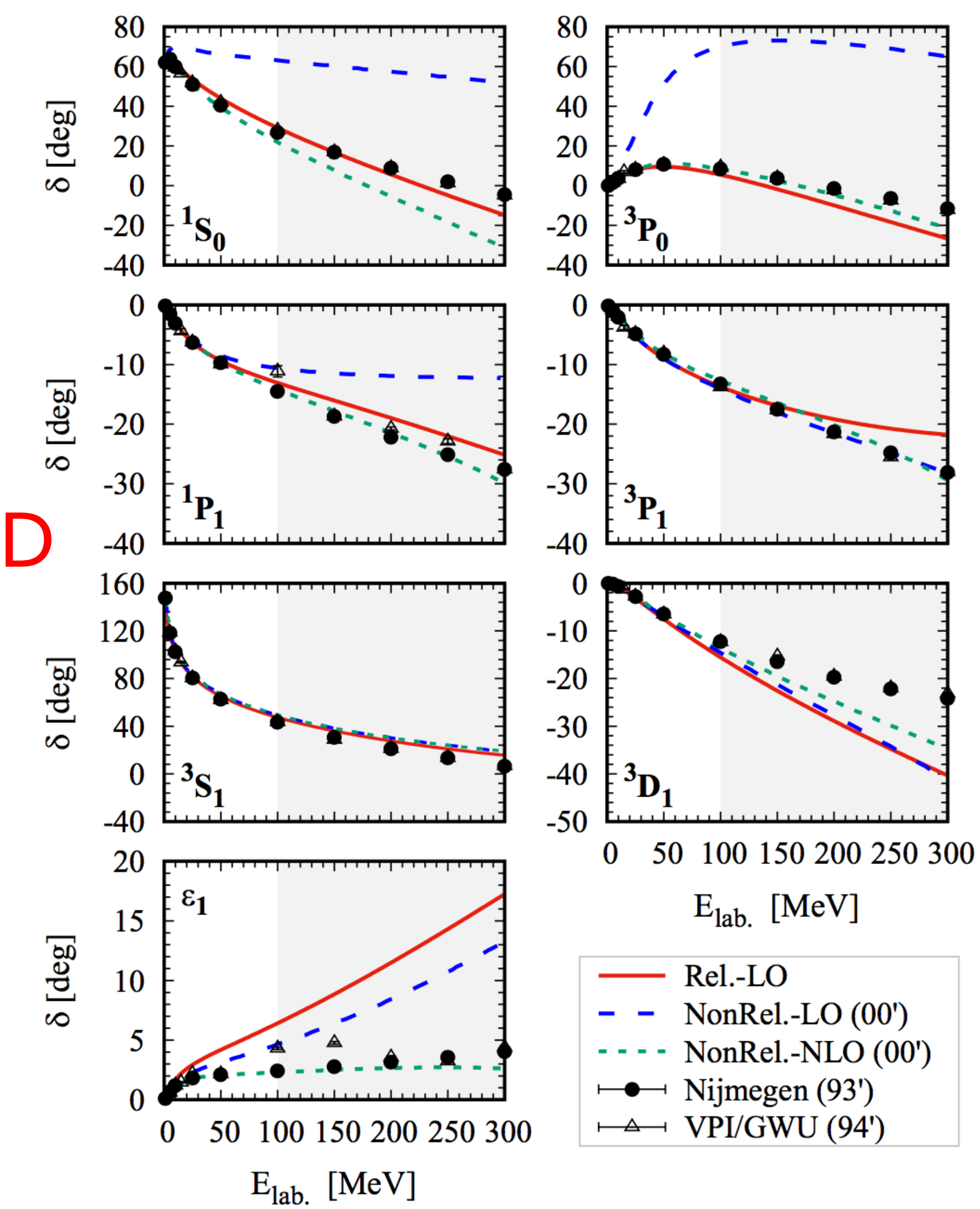
Jun-Xu Lu, Chun-Xuan Wang, Yang Xiao, Li-Sheng Geng, Jie Meng, and Peter Ring

Phys. Rev. Lett. **128**, 142002 – Published 6 April 2022

X. L. Ren, K. W. Li, L. S. Geng, B. W. Long, P. Ring, and J. Meng,

Leading order relativistic chiral nucleon-nucleon interaction,

Chin. Phys. C 42, 014103(2018) J



□ Baryon Interaction by lattice QCD

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Accepted Paper

Dibaryon with highest charm number near unitarity from lattice QCD

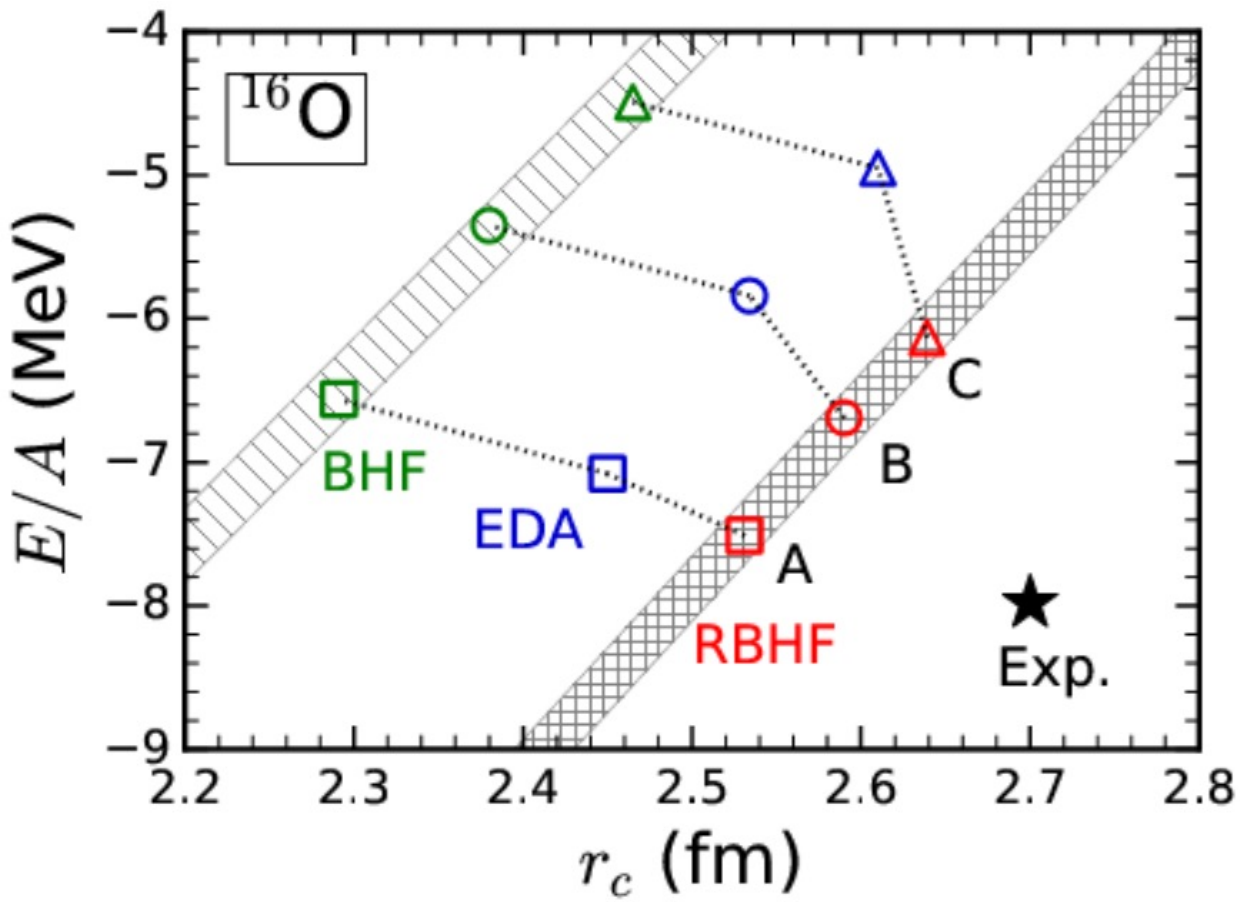
Phys. Rev. Lett.

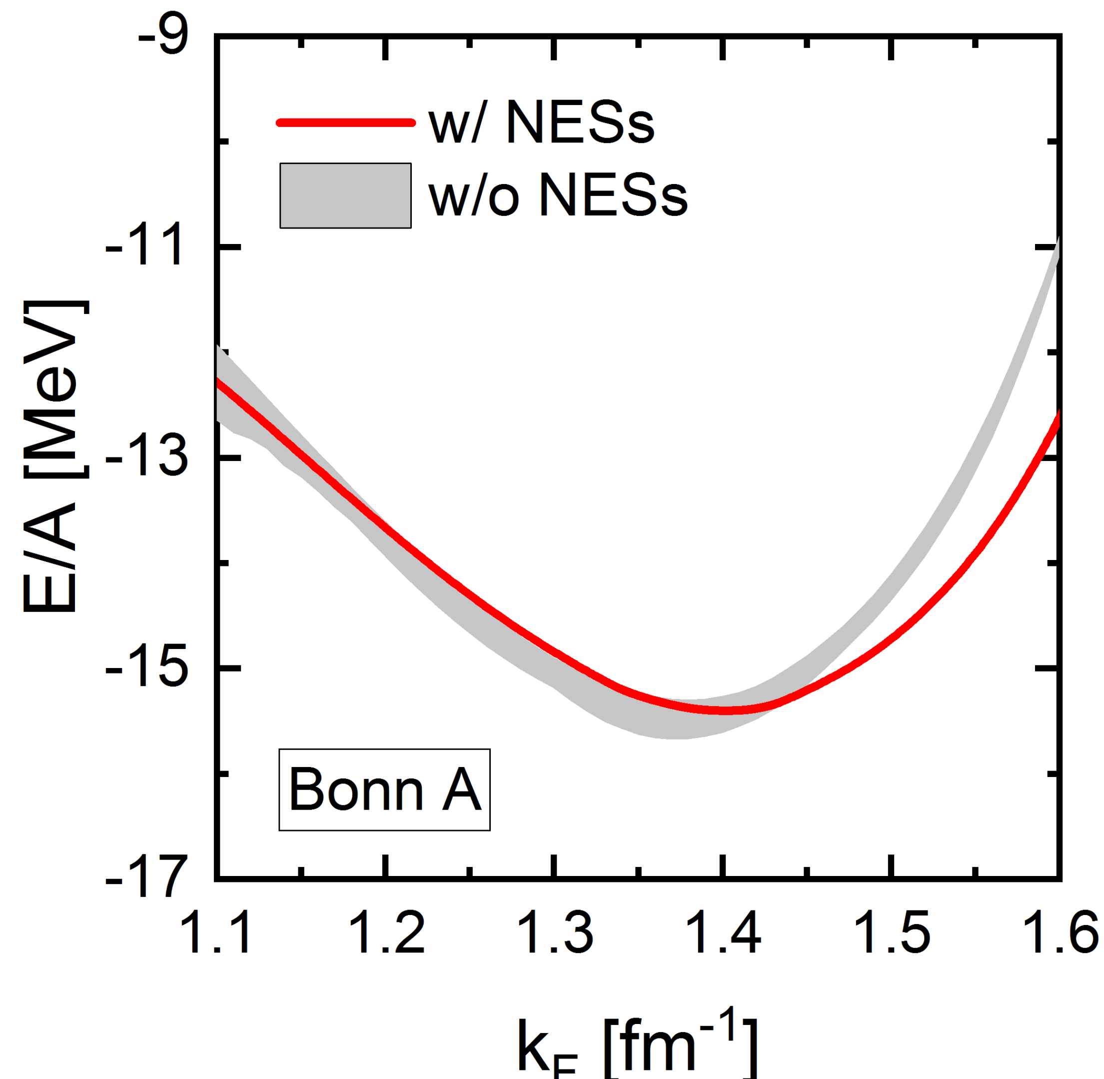
Yan Lyu, Hui Tong, Takuya Sugiura, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Jie Meng, and Takaya Miyamoto

Accepted 2 July 2021

ab initio calculation

Relativistic Brueckner Hartree-Fock Theory





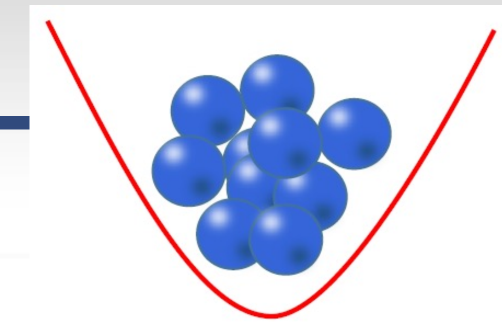
Energies and **charge radii** of ^{16}O in RBHF in comparison with EDA and BHF

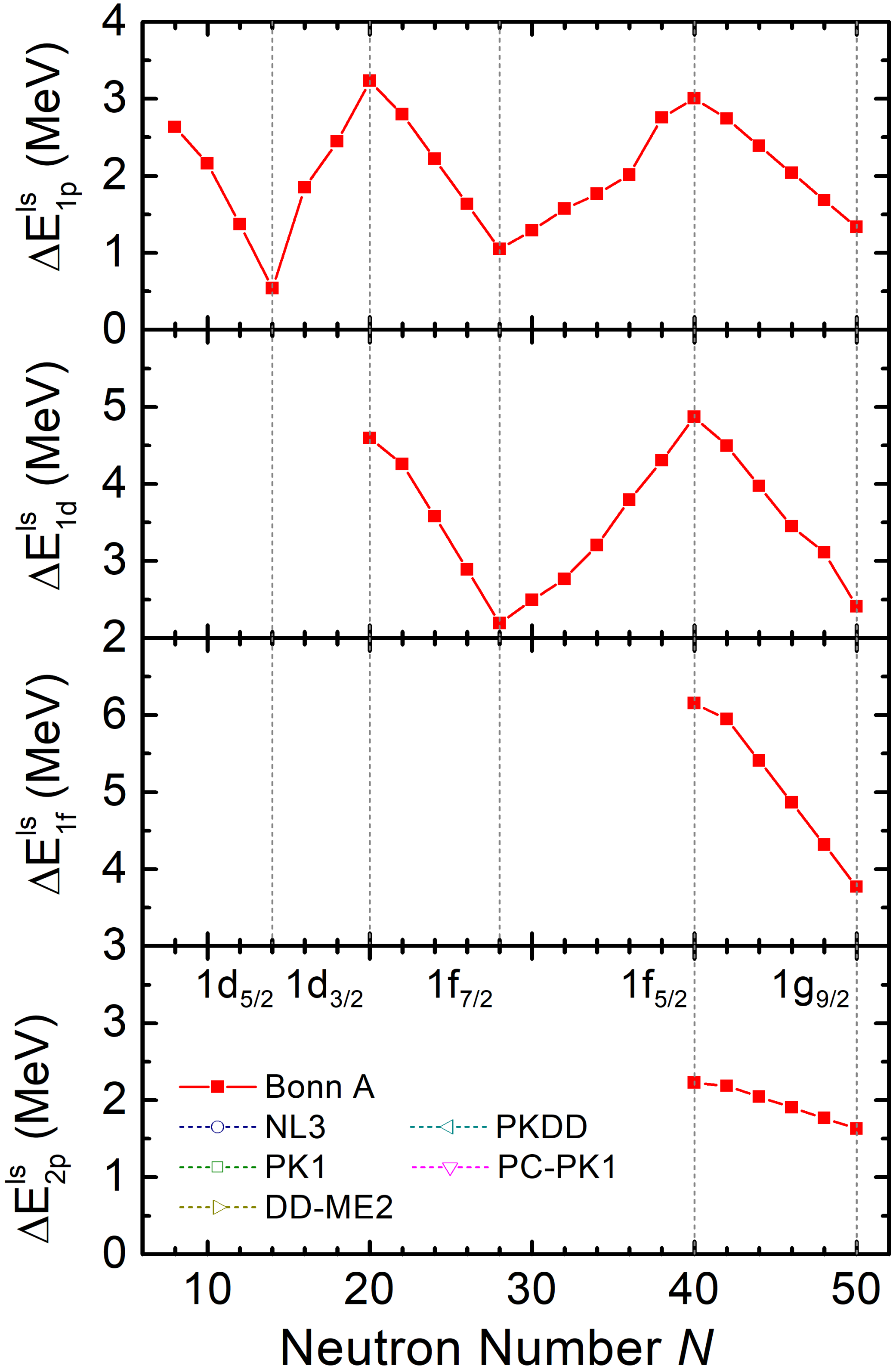
Binding energy per nucleon for symmetric nuclear matter by RBHF theory in full Dirac space

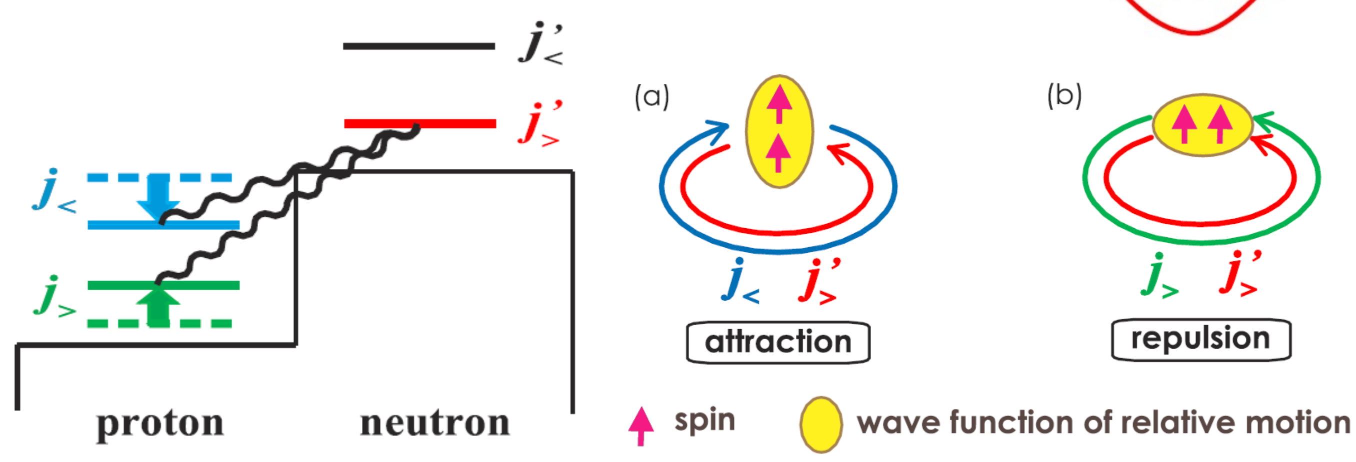
Shen, Hu, Liang, Meng, Ring, Zhang,
Relativistic Brueckner–Hartree–Fock Theory for Finite Nuclei .
Chin. Phys. Lett. 33 (2016) 102103

Wang, Zhao, Ring , Meng,
Nuclear matter in RBHF theory with Bonn potential in the full Dirac
Phys. Rev. C103(2021)054319

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)

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Fully self-consistent relativistic Brueckner theory

Progress in Particle and Nuclear Physics 109 (2019) 103713

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Review

Towards an *ab initio* covariant density functional theory for nuclear structure

Check for updates

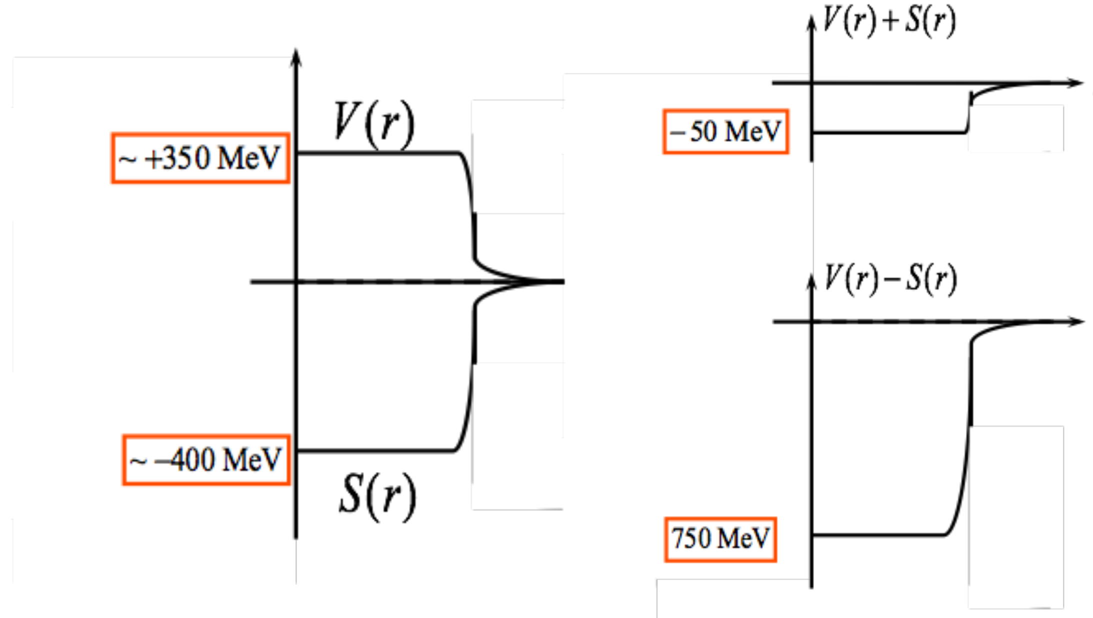
Shihang Shen [a,b,c], Haozhao Liang [d,e], Wen Hui Long [f,g], Jie Meng [a,h,i,*], Peter Ring [a,j]

[a] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[b] *Dipartimento di Fisica, Università degli Studi di Milano, Italy*
[c] *INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*
[d] *RIKEN Nishina Center, Wako 351-0198, Japan*

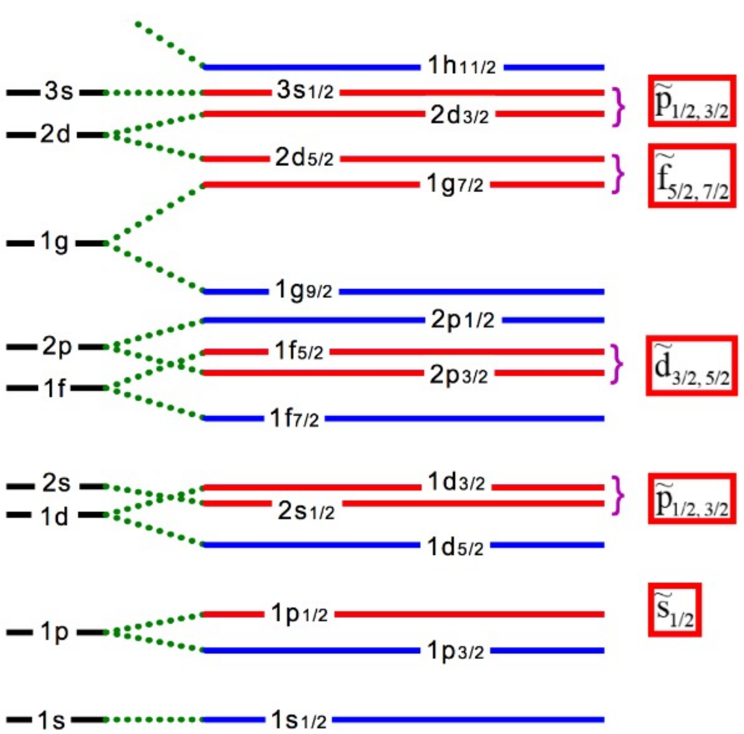
Why Covariant?

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



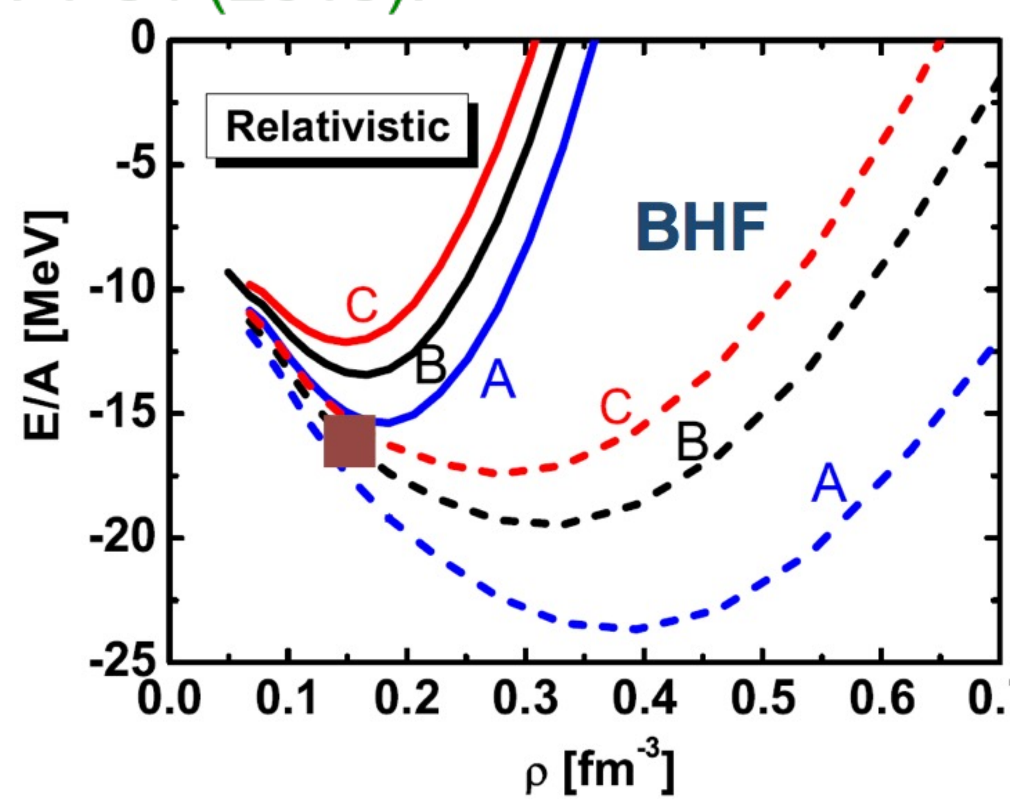
$$n-1, \quad l+2, \quad j=l+3/2$$
$$n, \quad l, \quad j=l+1/2$$

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

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

Ginocchio PRL 78, 436

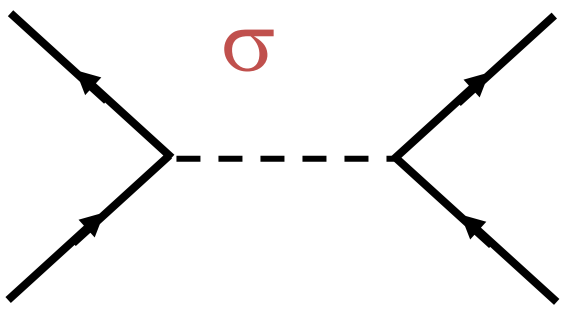


Brockmann & Machleidt, PRC42, 1965 (1990)

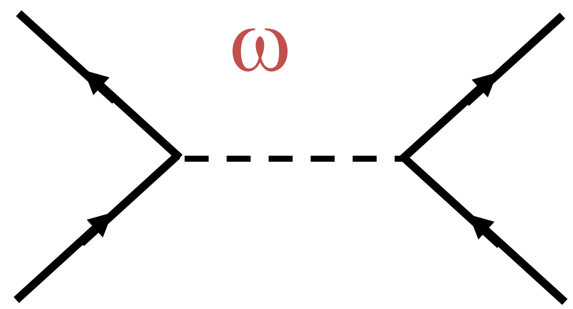
Brief introduction of CDFT

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

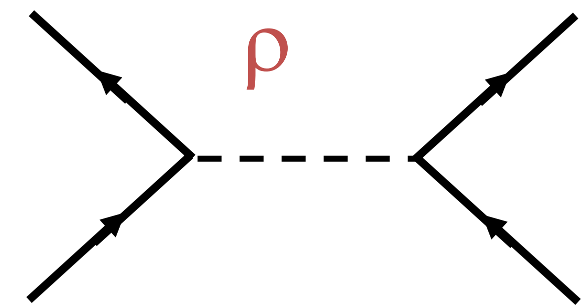
Strong force: Meson-exchange of the nuclear force



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



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



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

Sigma-meson:
attractive scalar field

Omega-meson:
Short-range repulsive

Rho-meson:
Isovector field

Electromagnetic force: The photon

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

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

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

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

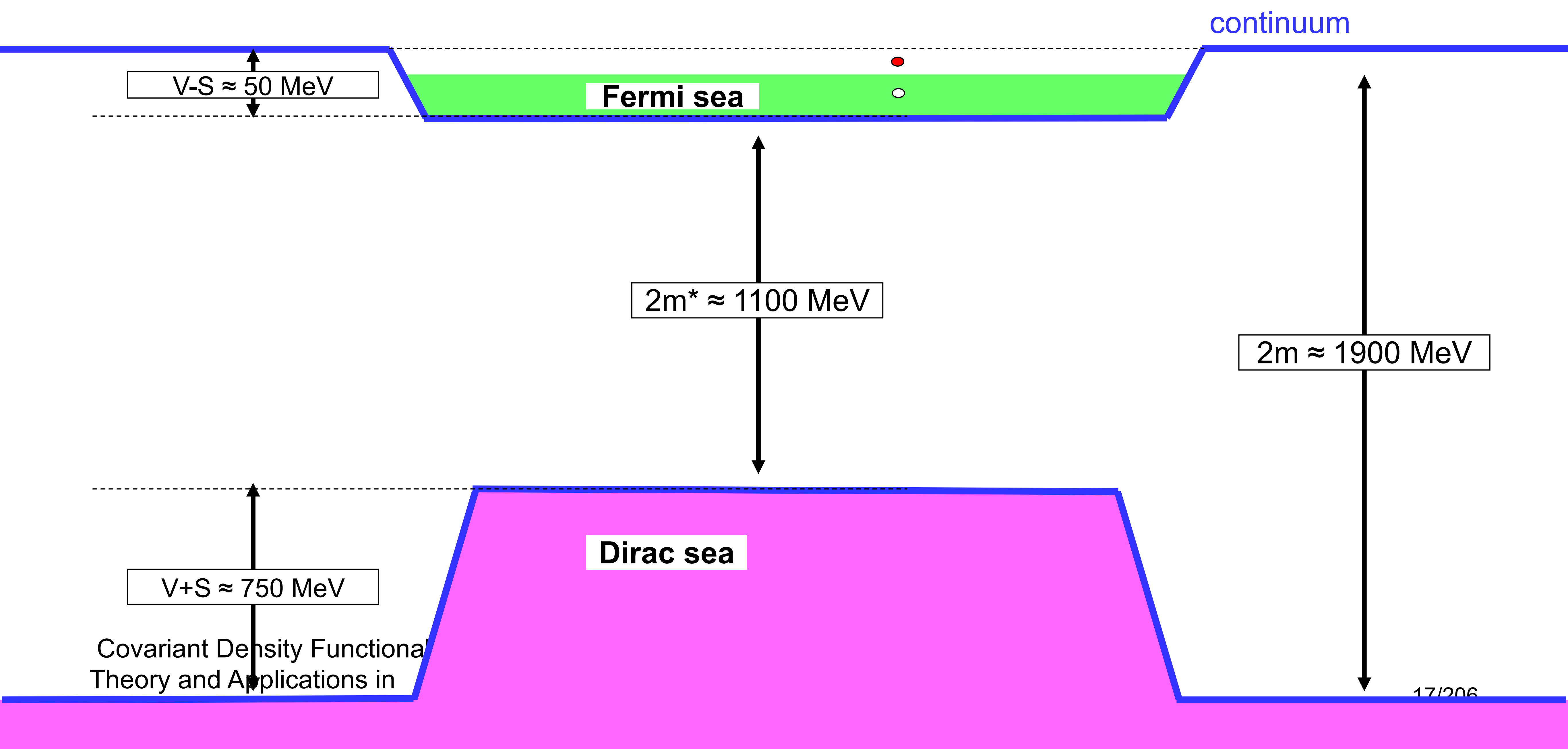
$$E_{der} = \frac{1}{2}\int (\delta_S\rho_S\triangle\rho_S + \delta_V\rho_V\triangle\rho_V + \delta_{tV}\rho_{tV}\triangle\rho_{tV}) d\mathbf{r}$$

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

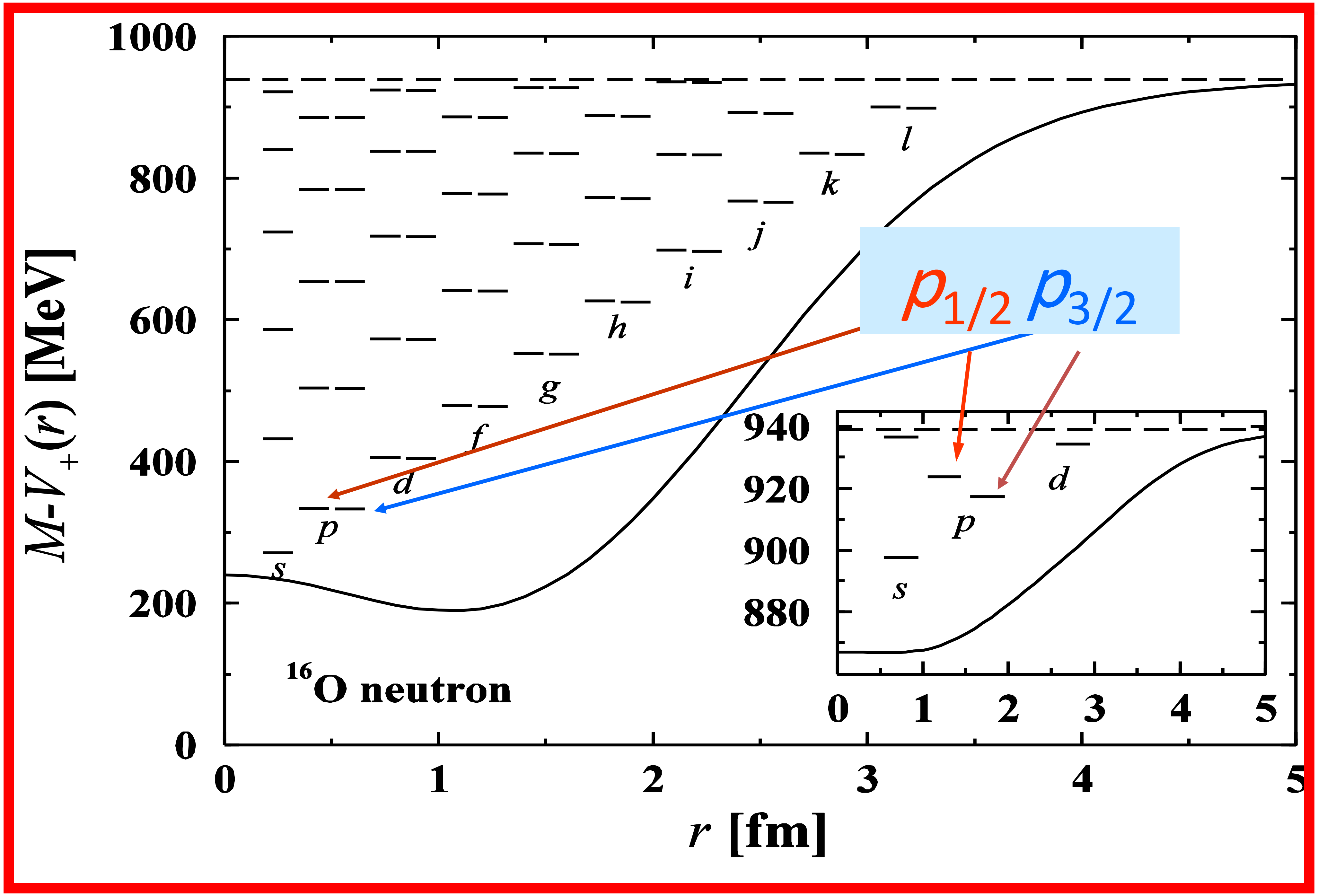
$$\begin{pmatrix} m+S+V & \boldsymbol{\sigma}(\boldsymbol{p}-V) \\ \boldsymbol{\sigma}(\boldsymbol{p}-V) & -m-S+V \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix} = \varepsilon \begin{pmatrix} f \\ g \end{pmatrix}$$

scalar potential: $S(r) \approx -400$ MeV

vector potential: $V(r) \approx 350$ MeV



Spin symmetry - Anti-nucleons



Zhou, Meng, Ring, PRL92(03)262501

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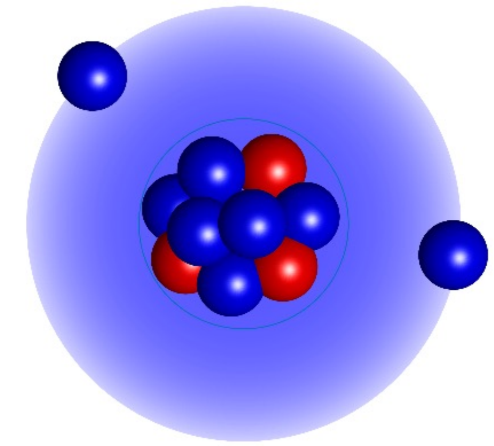
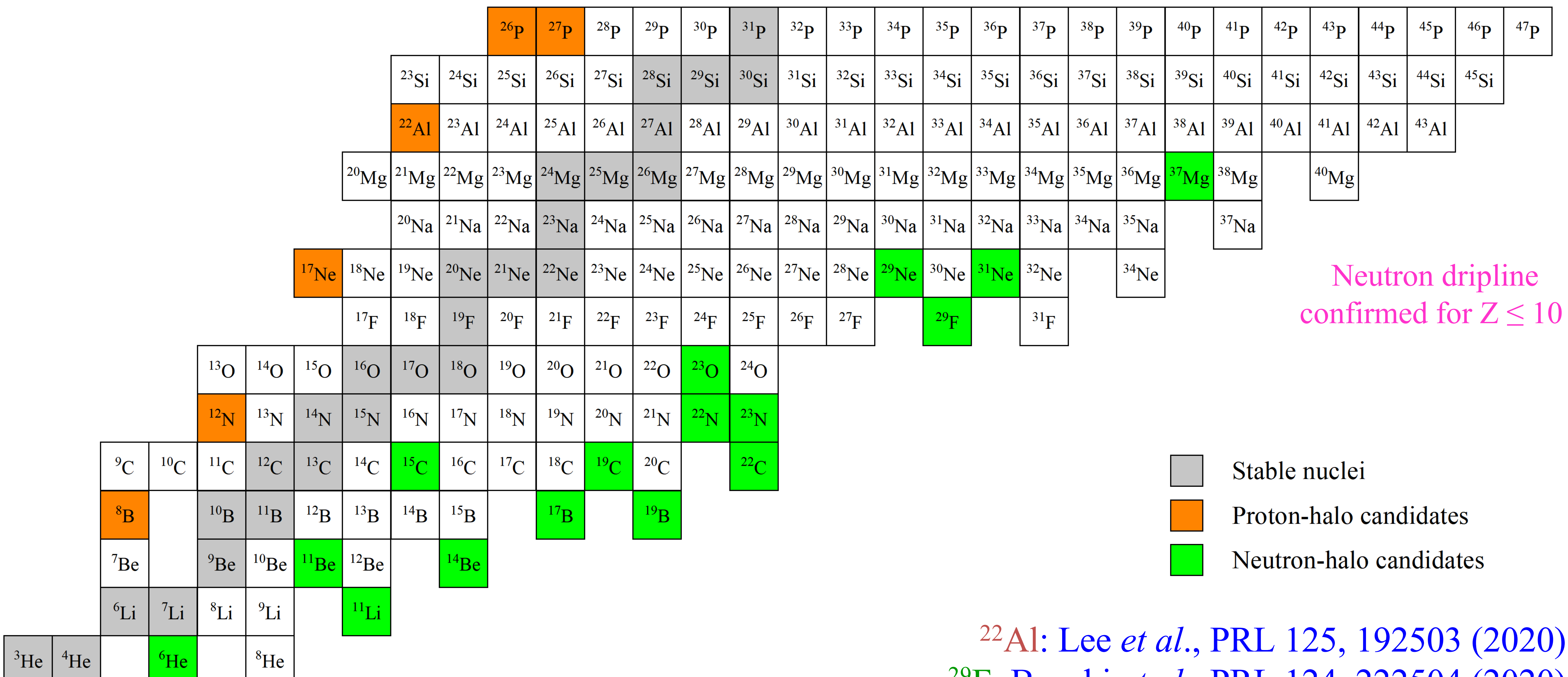
Halo nuclei



^{11}Li

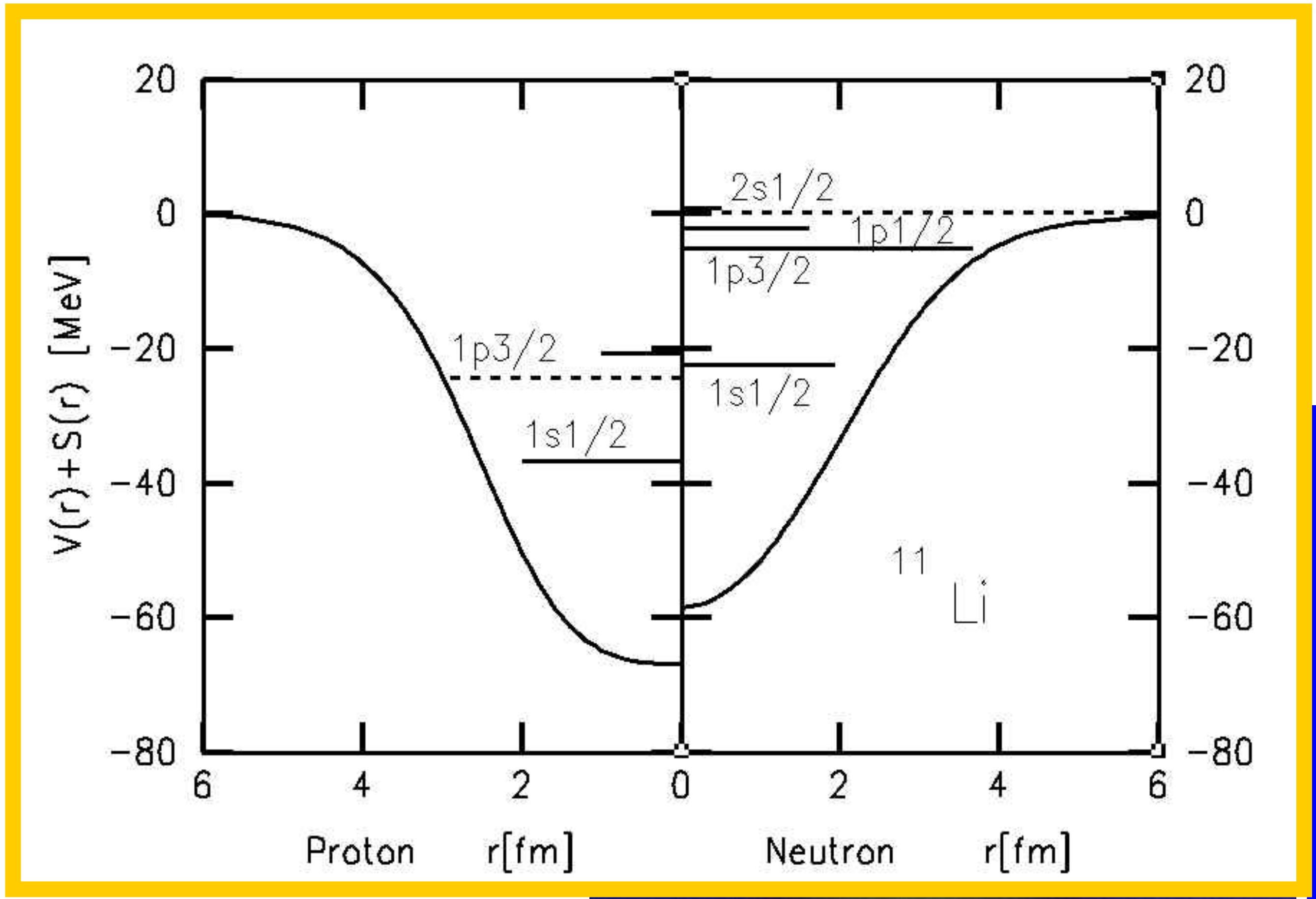
- Halo nuclei have attracted lots of attention since the discovery of the halo phenomenon in ^{11}Li.

Tanihata *et al.*, PRL 55, 2676 (1985)
Tanihata *et al.*, PPNP 68, 215 (2013)



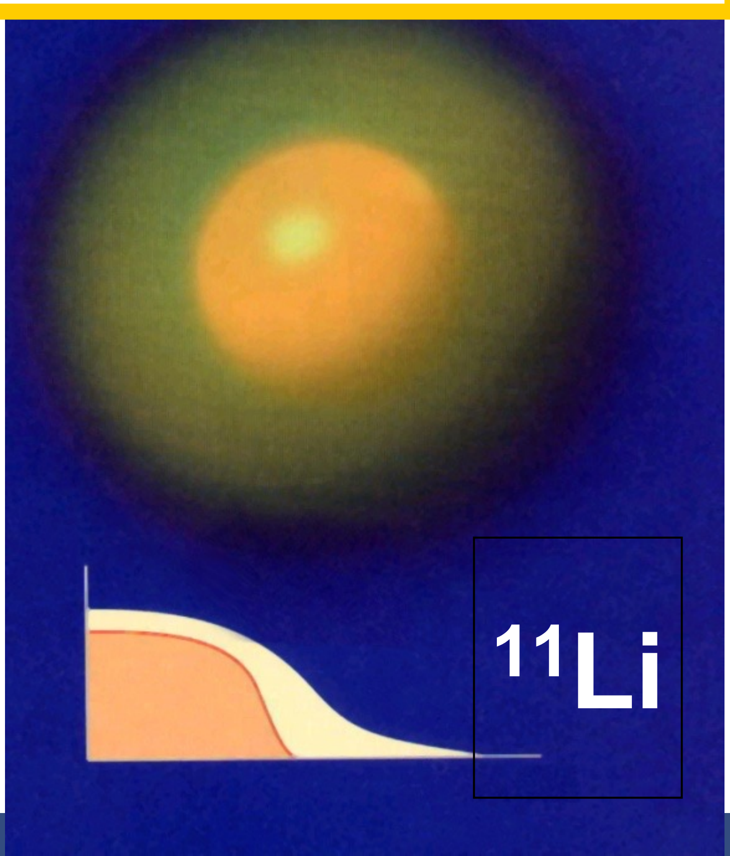
^{22}Al: Lee *et al.*, PRL 125, 192503 (2020)
^{29}F: Bagchi *et al.*, PRL 124, 222504 (2020)
^{37}Mg: Kobayashi *et al.*, PRL 112, 242501 (2014)

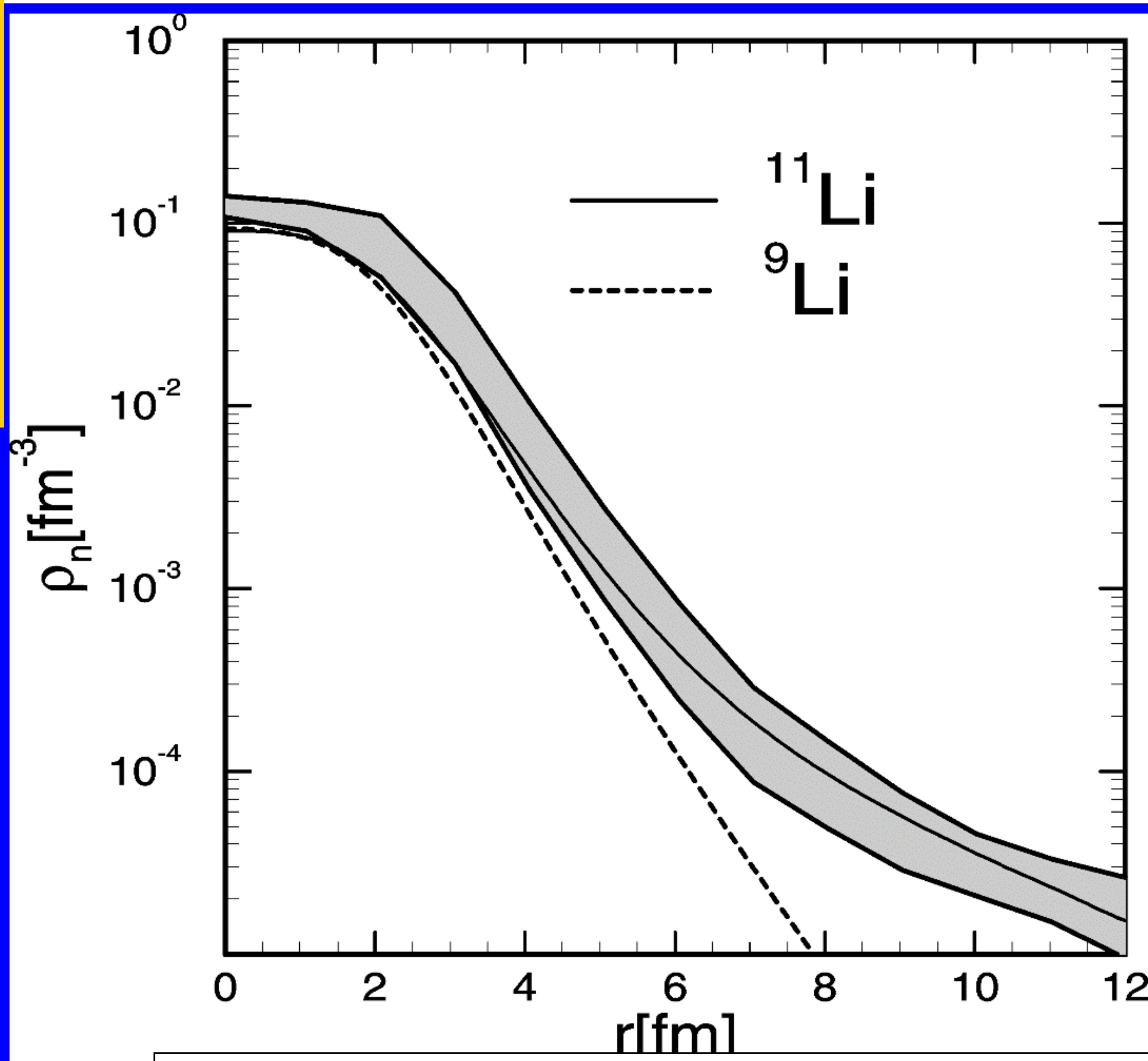
Density in 11-Li



Relativist. Continuum Hartree-Bogoliubov theory with

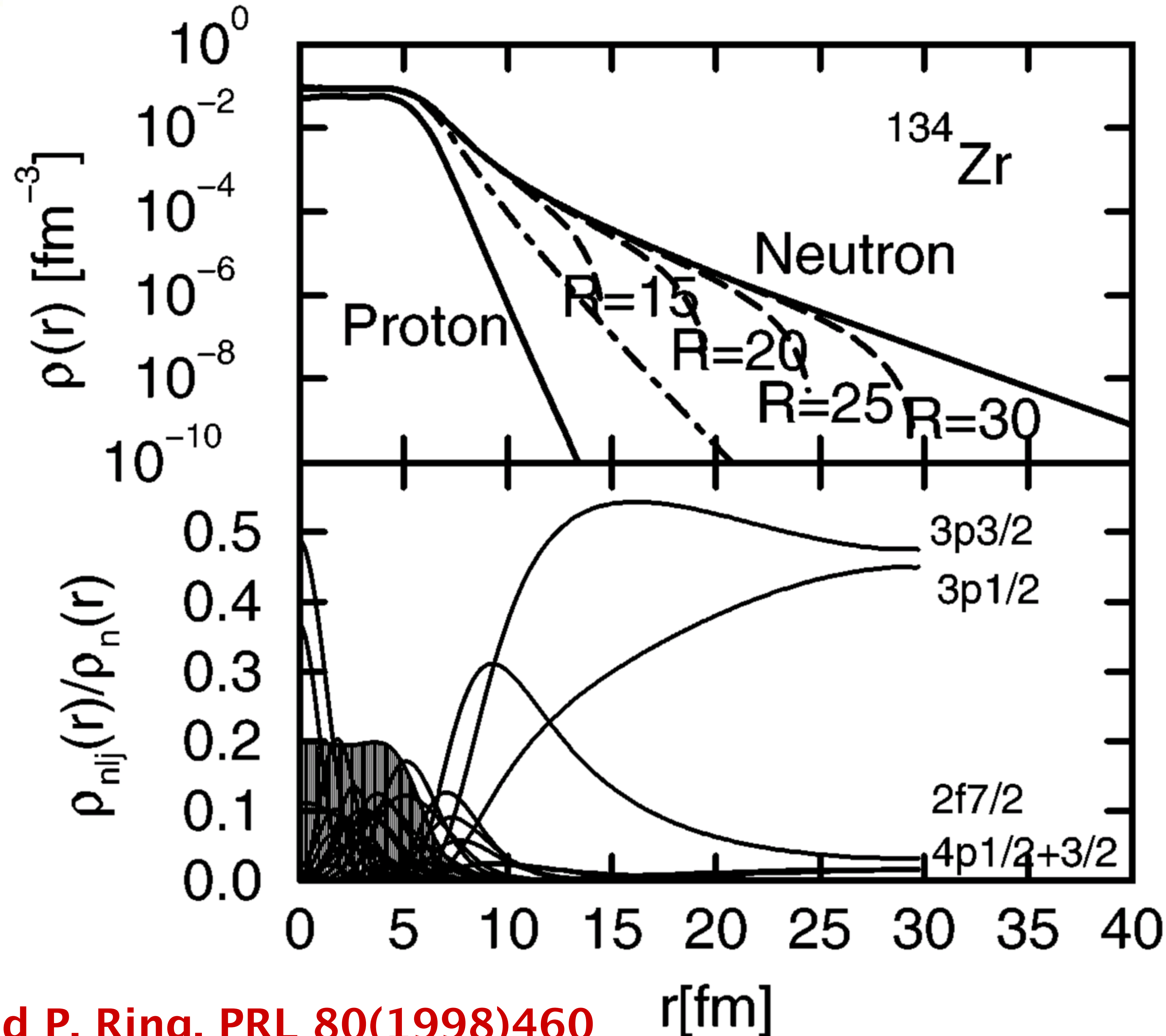
densitiy dependent pairing force





J. Meng and P. Ring, PRL 77, 3963 (1996),

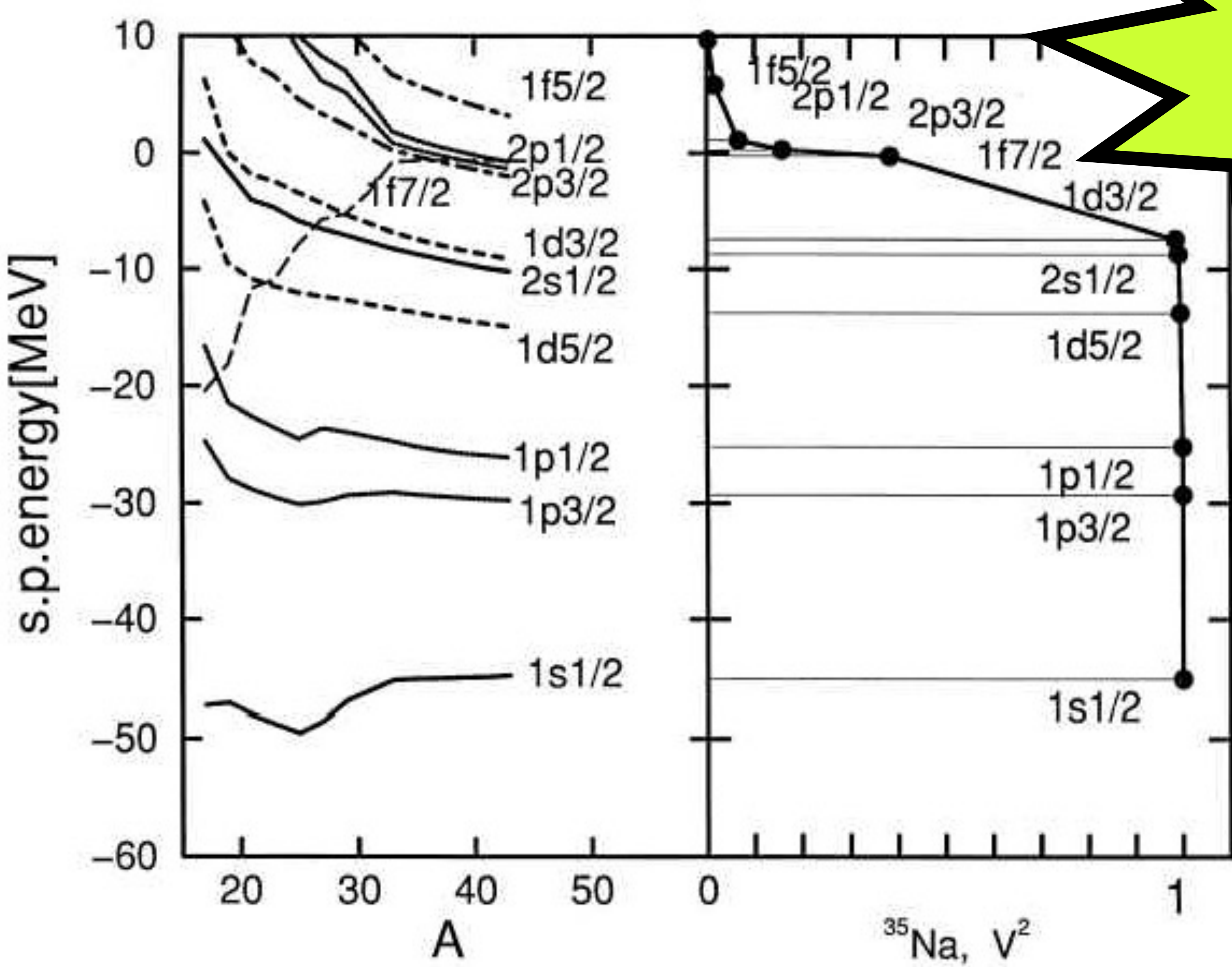
Giant halos



J. Meng and P. Ring, PRL 80(1998)460

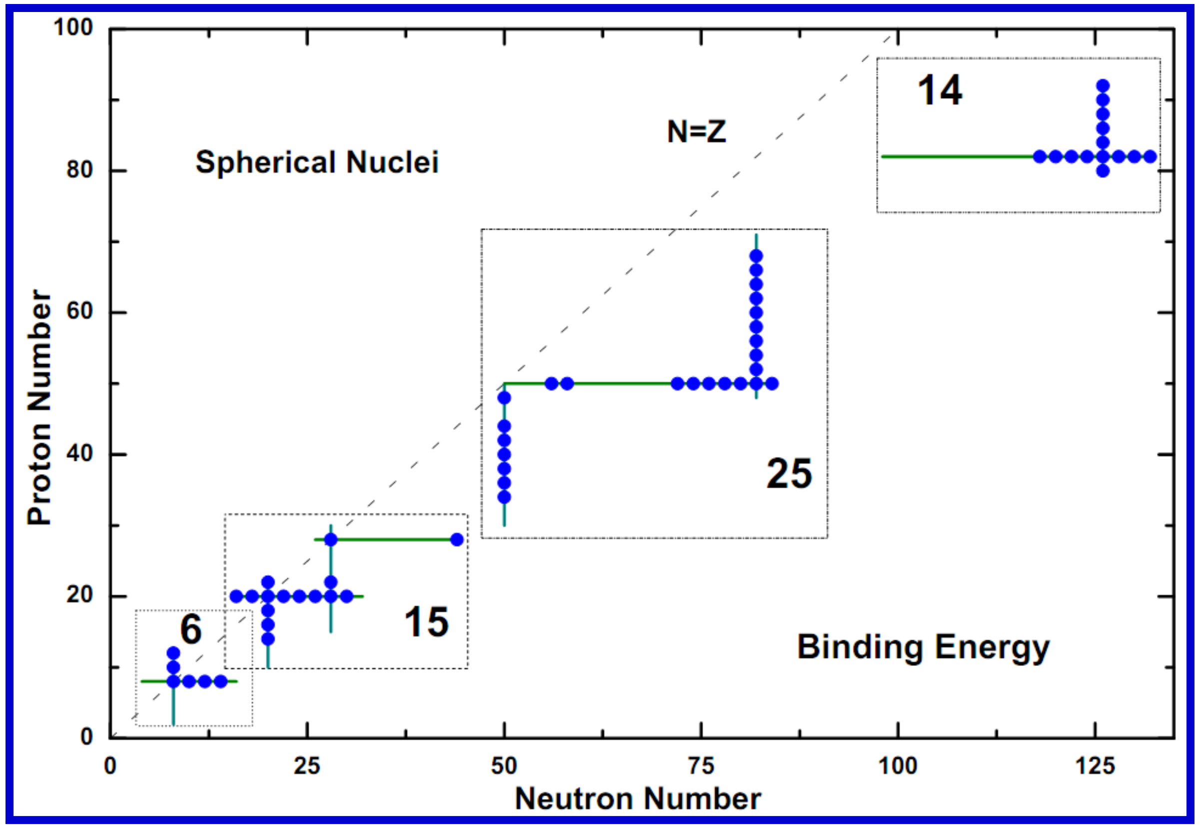
Exotic Phenomena

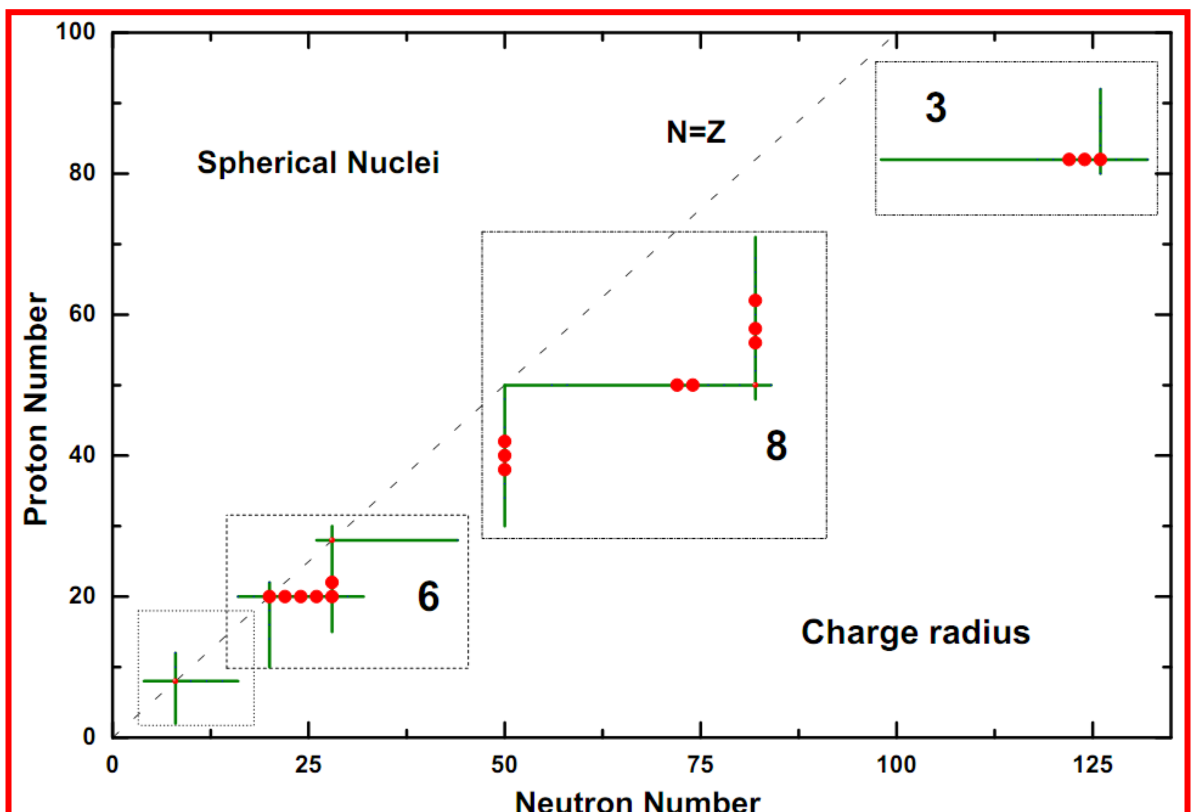
Meng, Tanihata & Yamaji, PLB419, 1(1998)



Earlier prediction on giant halos in Na isotopes

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)

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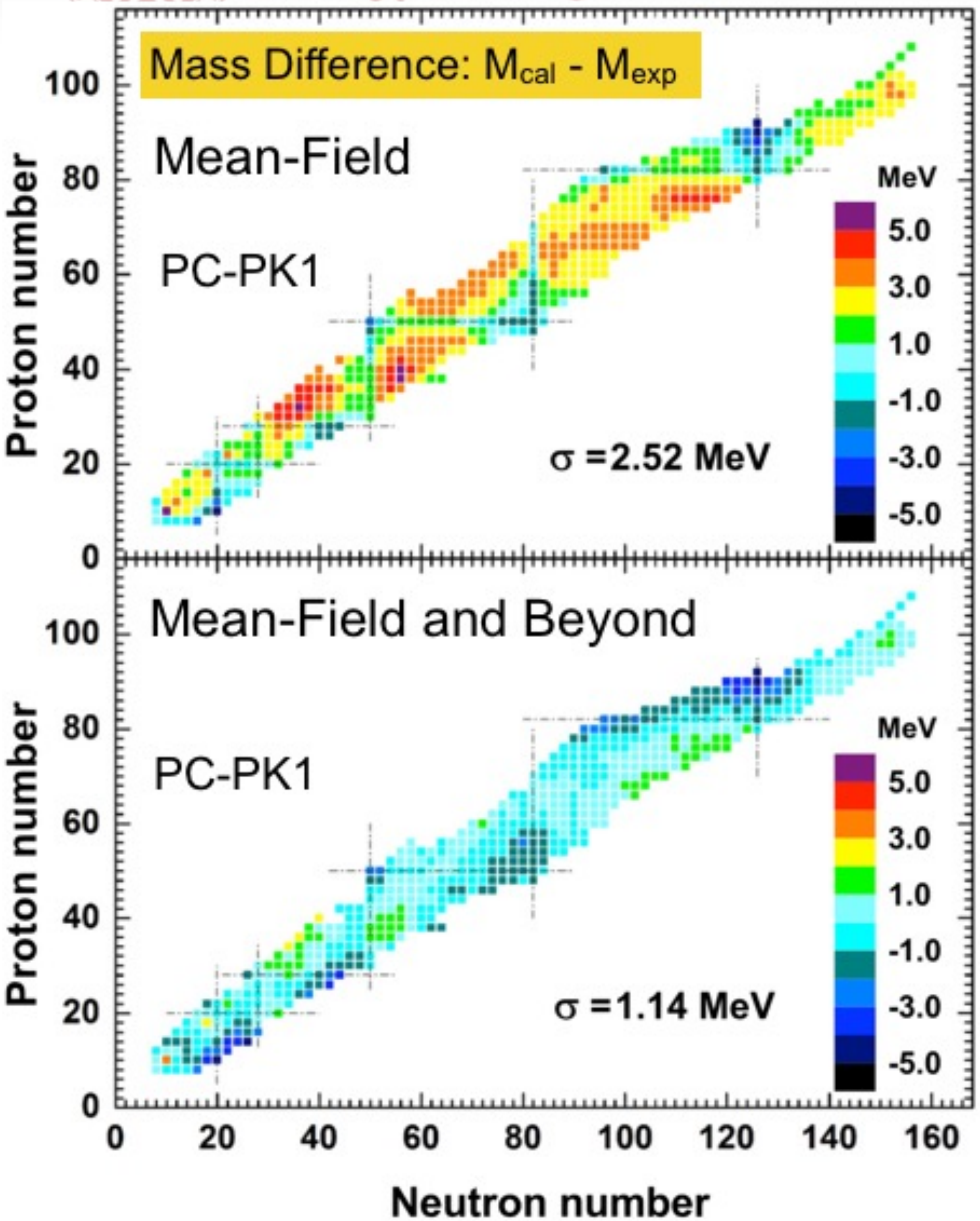
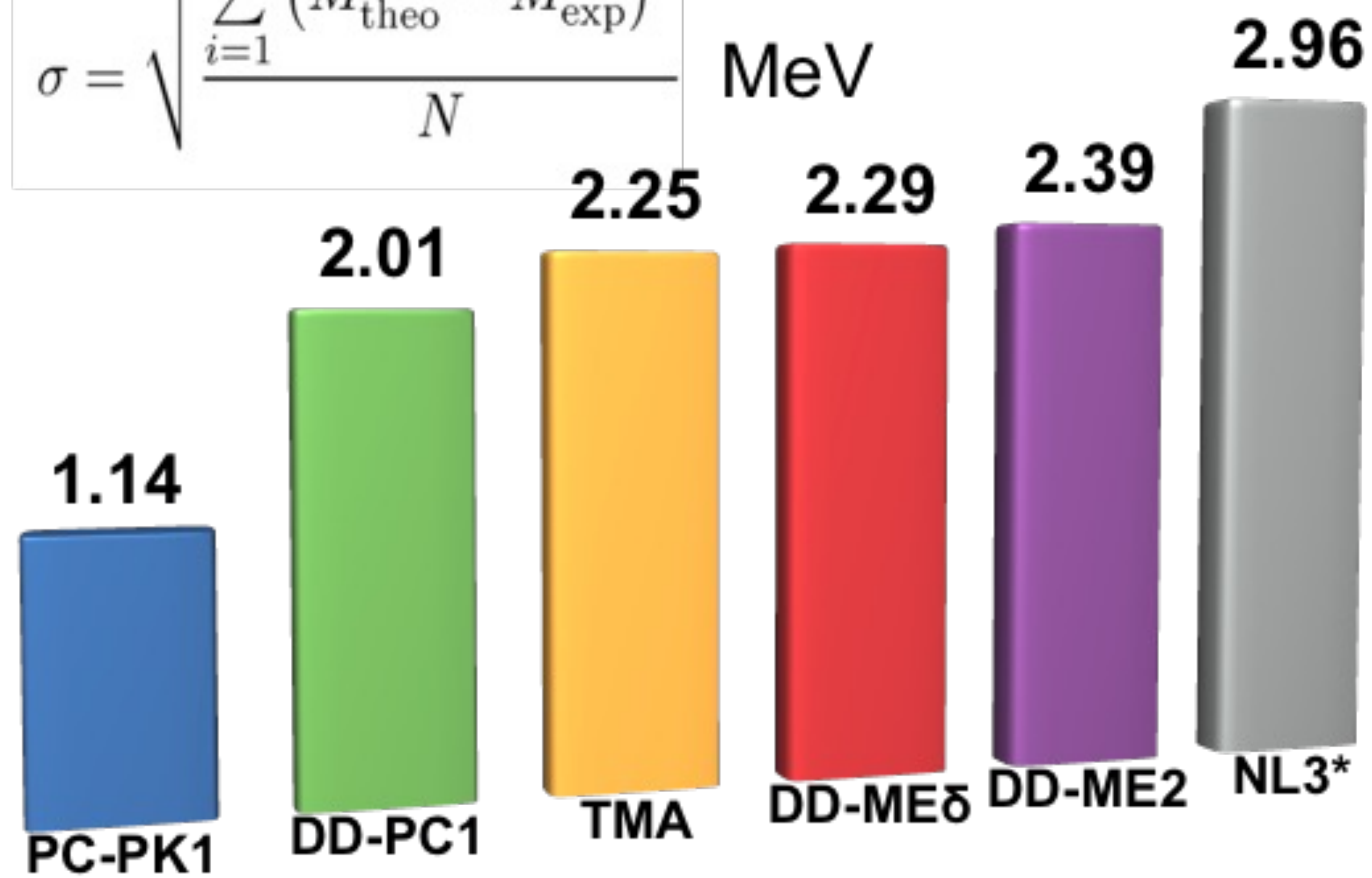
Excellent functional PC-PK1



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

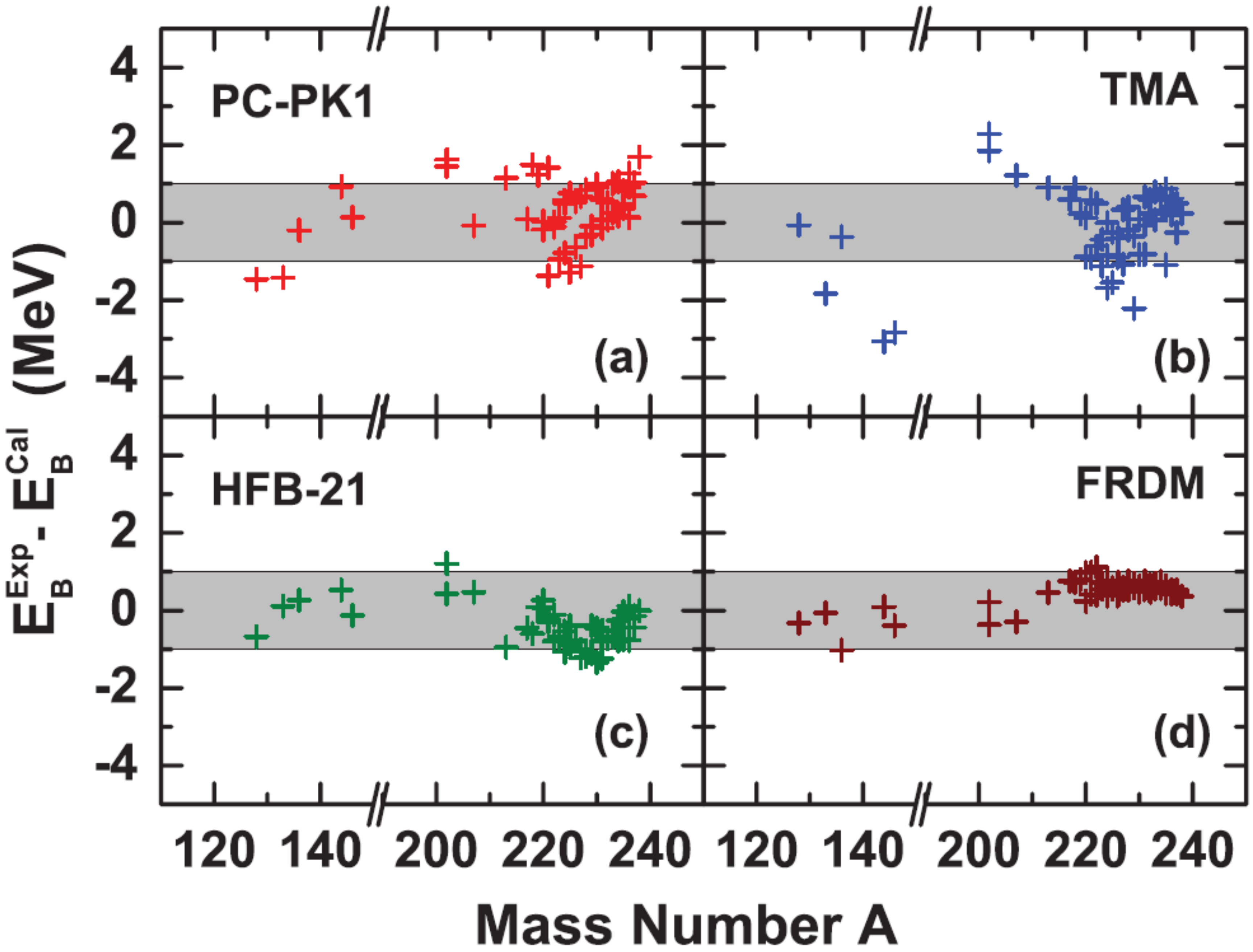


Agbemava PRC 2014
Geng PTP 2005

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

Best density functional for nuclear masses so far!

Predictive power



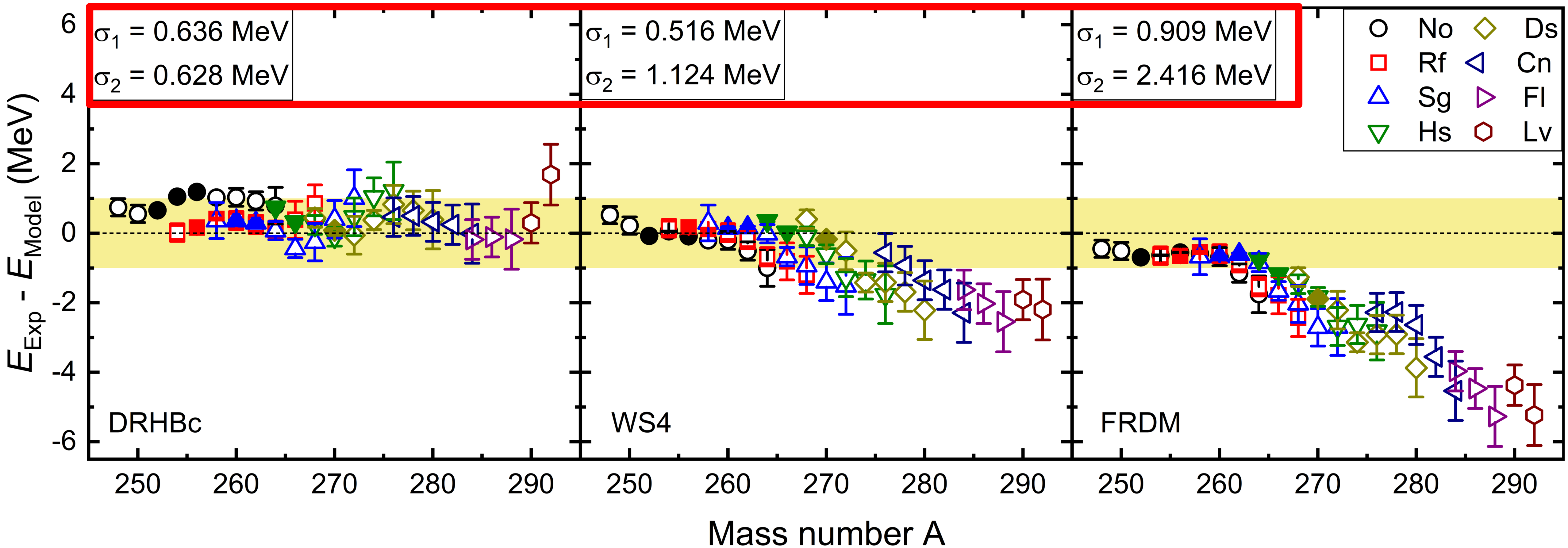
P. W. Zhao, *et al*. Phys. Rev. C, 86 024324 (2012)

Data from L. Chen, *et al*. Nucl. Phys. A 882 71 (2012)

- ✓ 53 new mass measured at GSI are reproduced well by PC-PK1 (only 11 parameters) with a rms deviation of 0.859 MeV.

Predictive power

Z = 102–116



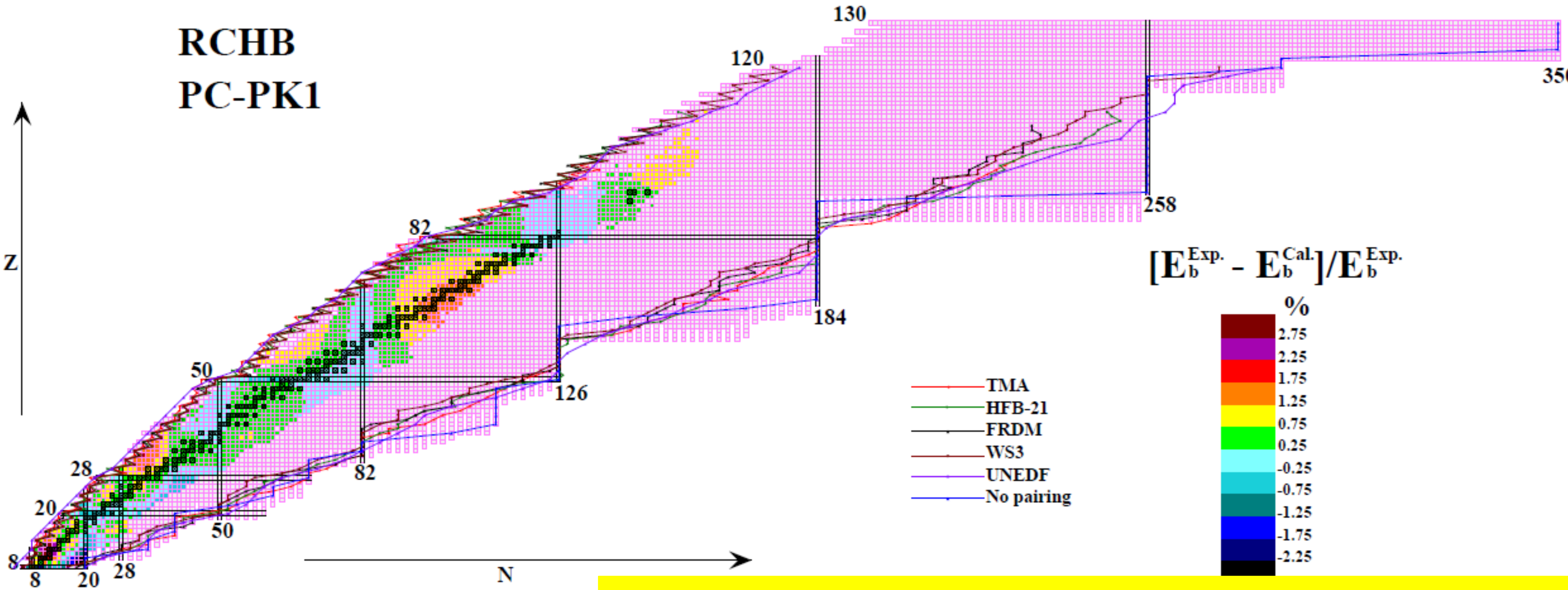
Kaiyuan Zhang, et al

Phys. Rev. C104 (2021) L021301

Predictive power for superheavy nuclear mass and possible stability beyond the neutron drip line in deformed relativistic Hartree-Bogoliubov theory in continuum

Drip-lines in variant models

The number of bound nuclides with between 2 and 120 protons is around 7,000 2 8 J U N E 2 0 1 2 | V O L 4 8 6 | N AT U R E | 5 0 9



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

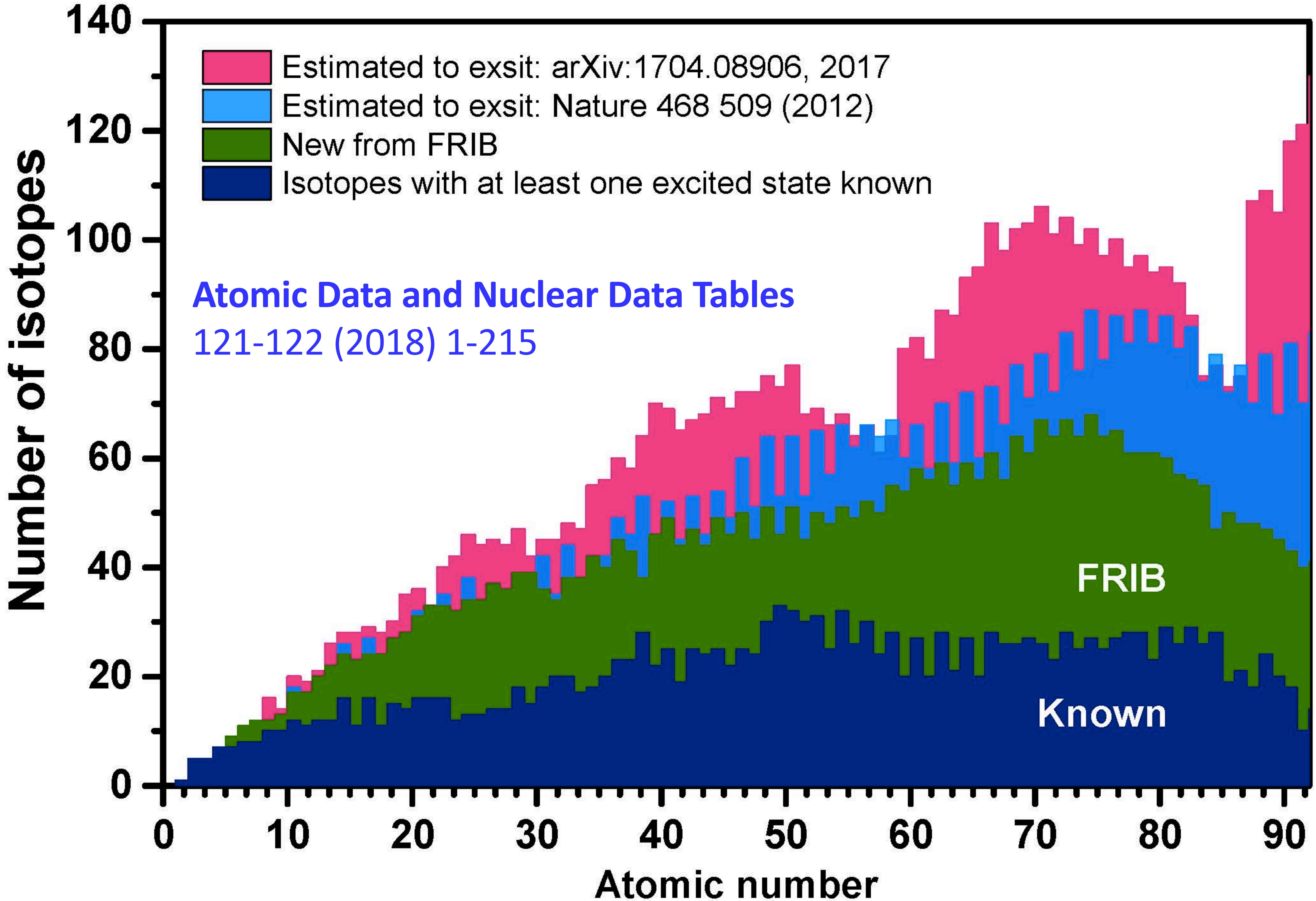
Atomic Data and Nuclear Data Tables 121-122 (2018) 1-215

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



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RCHB mass table

First nuclear mass table including continuum effects

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

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journal homepage: www.elsevier.com/locate/adt

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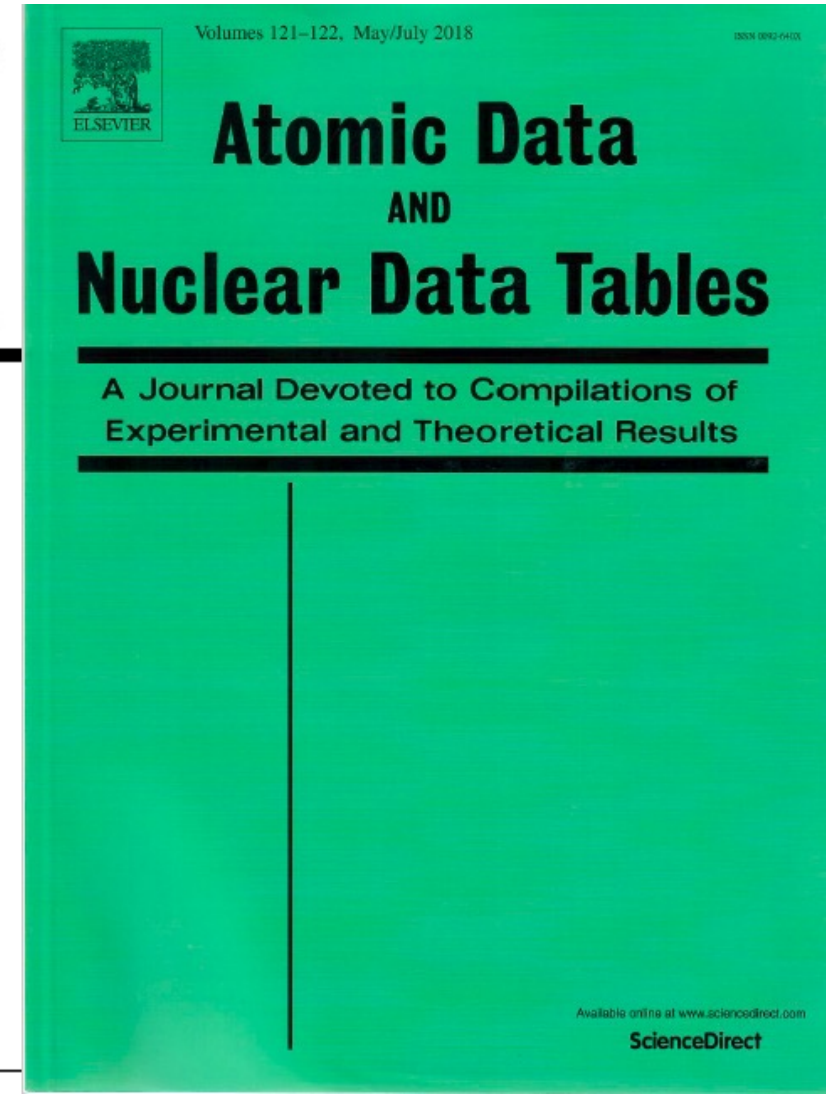

The limits of the nuclear landscape explored by the relativistic continuum Hartree–Bogoliubov theory

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,*]

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[d] State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China
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[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
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ARTICLE INFO

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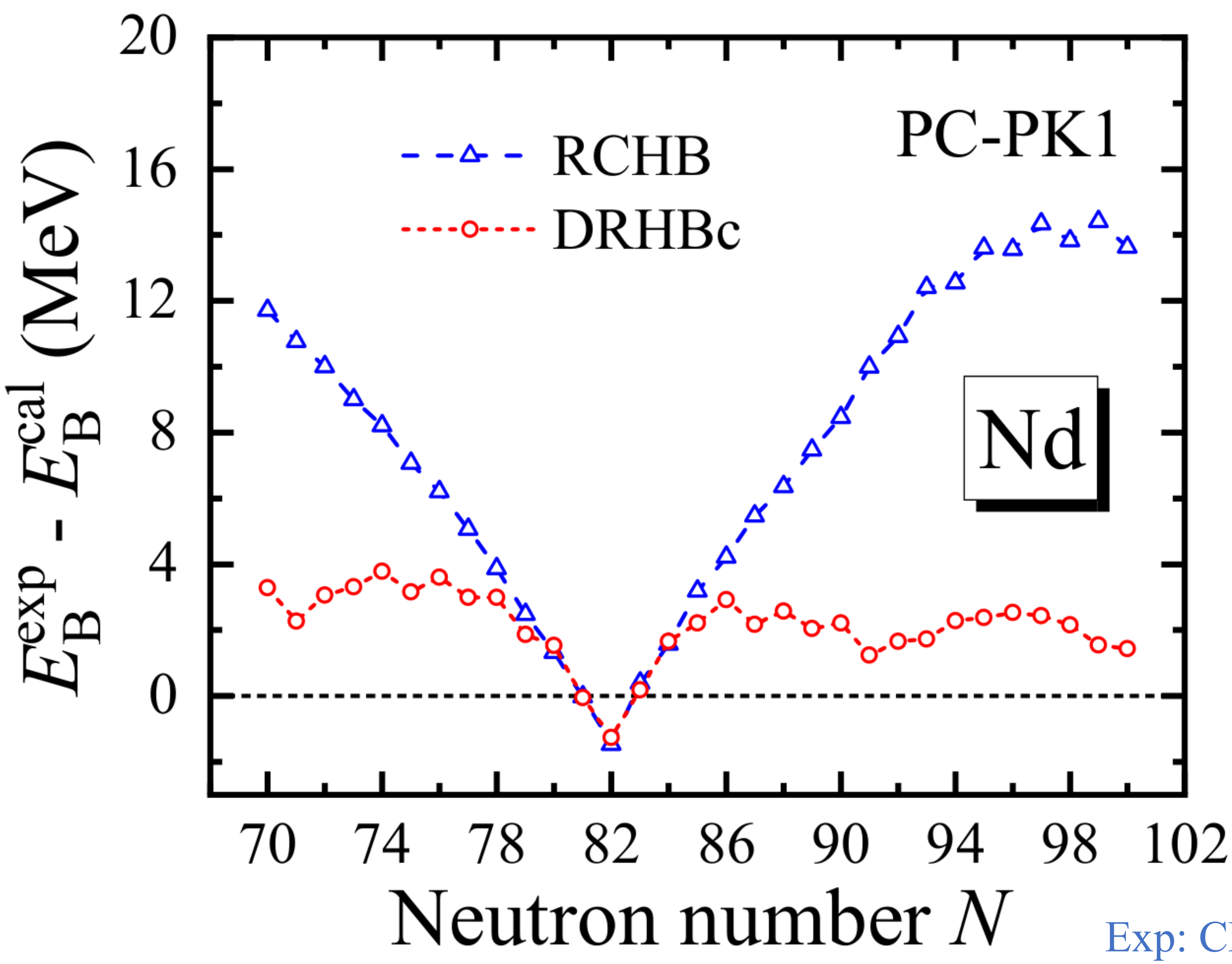
ABSTRACT

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,

Deformation improve the accuracy



Exp: CPC 45, 030003 (2021)
Even-even: PRC 102, 024314 (2020)

- ✓ Root-mean-square (rms) deviations:
  - DRHBc 2.38 MeV RCHB 9.08 MeV
- ✓ With deformation effect included, the data can be better reproduced.
- ✓ The rotational correction energy is expected to further improve the results for odd nuclei.

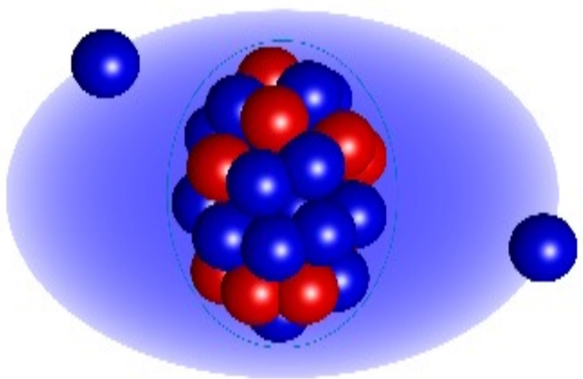
Deformed halos

✓There has been controversy over the existence of deformed halo nuclei.

Otsuka, Muta, Yokoyama, Fukunishi, and Suzuki, NPA 588, 113c (1995)
Misu, Nazarewicz, and Aberg, NPA 614, 44 (1997)
Tanihata, Hirata, and Toki, NPA 583, 769 (1995)
Nunes, NPA 757, 349 (2005)

✓Considering deformation, pairing, and continuum effects, the deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) predicts deformed halo nuclei.

Zhou, Meng, Ring, and Zhao, PRC 82, 011301(R) (2010)
Li, Meng, Ring, Zhao, and Zhou, PRC 85, 024312 (2012)



✓Recently, candidates of deformed halo nuclei have been suggested in experiment, ^{31}Ne and ^{37}Mg.

Nakamura *et al*., PRL 112, 142501 (2014)
Kobayashi *et al*., PRL 112, 242501 (2014)

✓DRHBc theory has been applied for halo and other exotic phenomena.

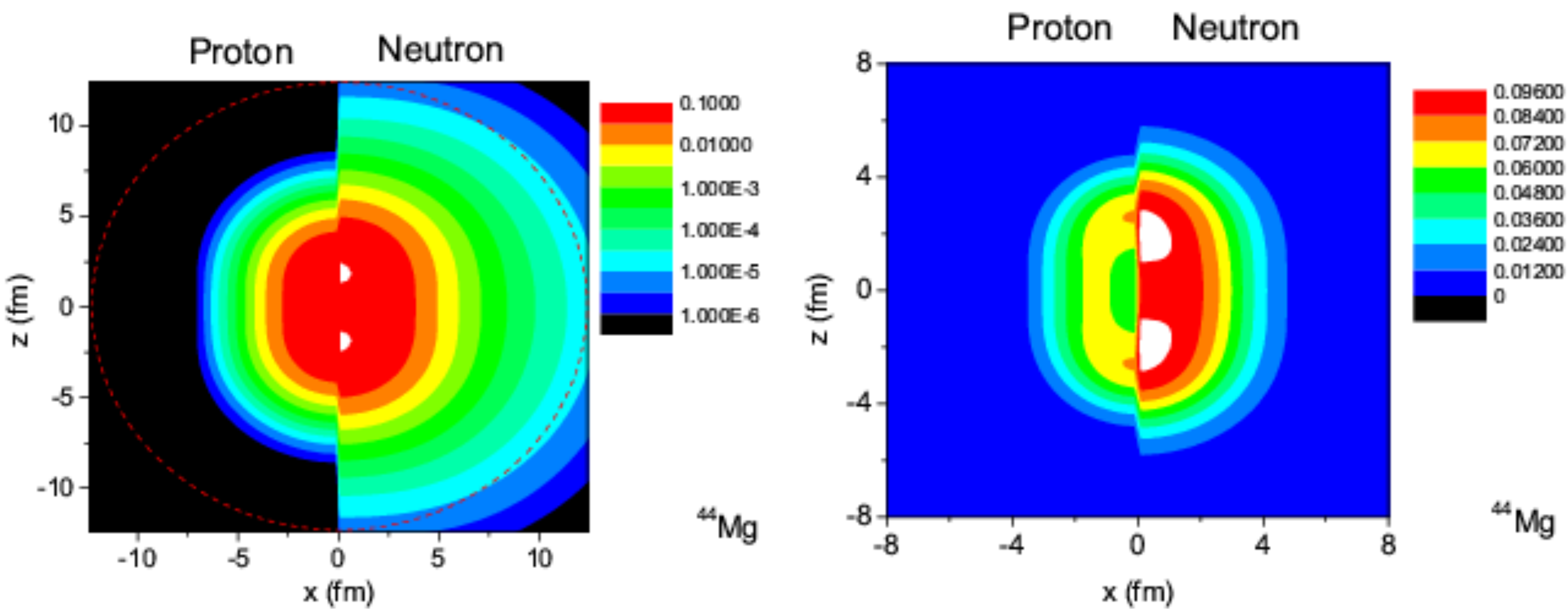
Sun, Zhao, and Zhou, PLB 785, 530 (2018)
Zhang, Wang, and Zhang PRC 100, 034312 (2019)
Sun, Zhao, and Zhou, NPA 1003, 122011 (2020)
Yang *et al*., PRL 126, 082501 (2021)

Sun, PRC 103, 054315 (2021)
Zhang *et al*., PRC 104, L021301 (2021)
Pan *et al*., PRC 104, 024331 (2021)
He *et al*., CPC 45, 101001 (2021)

^{44}Mg: Density distributions

Zhou_Meng_Ring_Zhao2010_PRC82-011301R
Zhou_Meng_Ring_Zhao2011_JPConfProc312-092067
Li_Meng_Ring_Zhao_Zhou2012_PRC85-024312

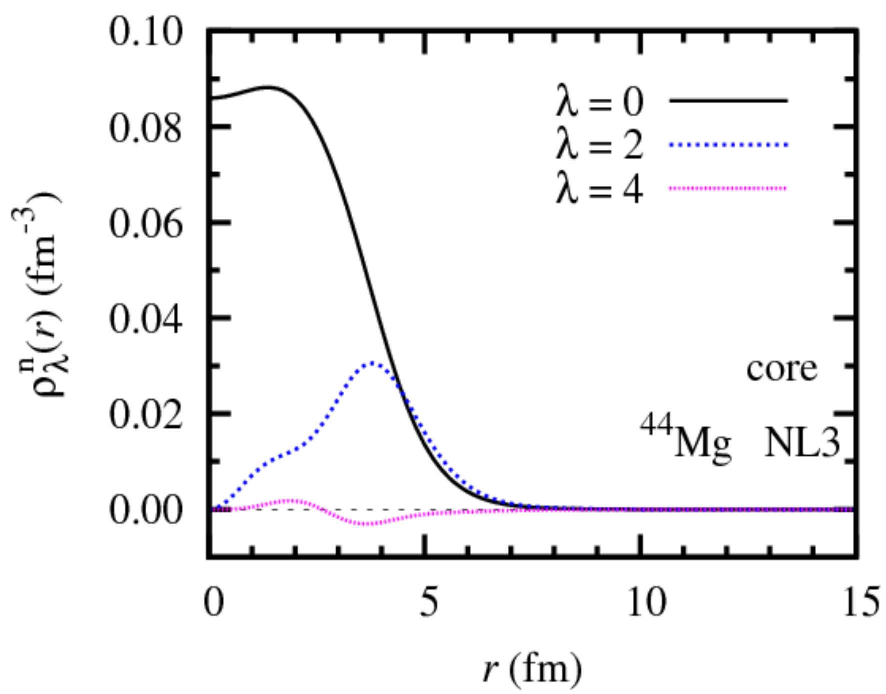
- Prolate deformation
- Large spatial extension in neutron density distribution

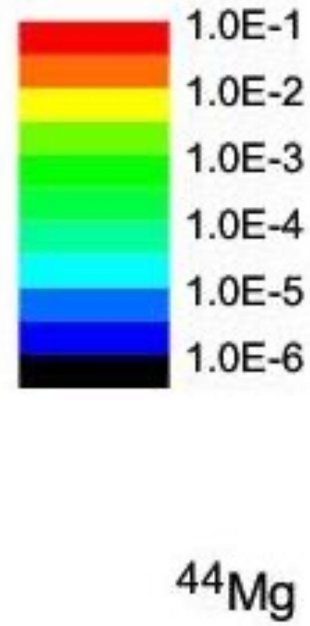


Viewpoint: A Walk Along the Dripline by Paul Cottle and Kirby Kemper
http://link.aps.org/doi/10.1103/Physics.5.49

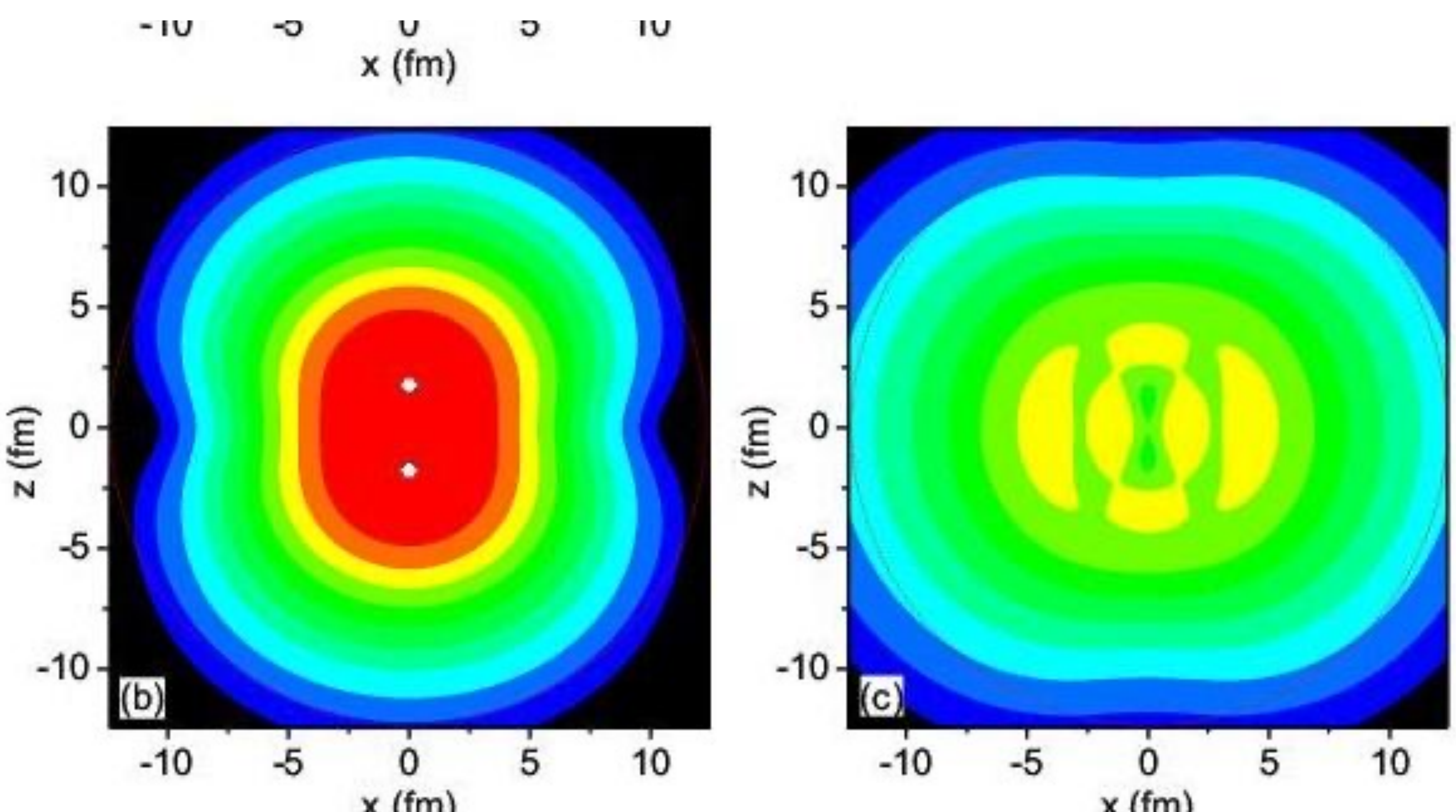
Prolate core & oblate halo

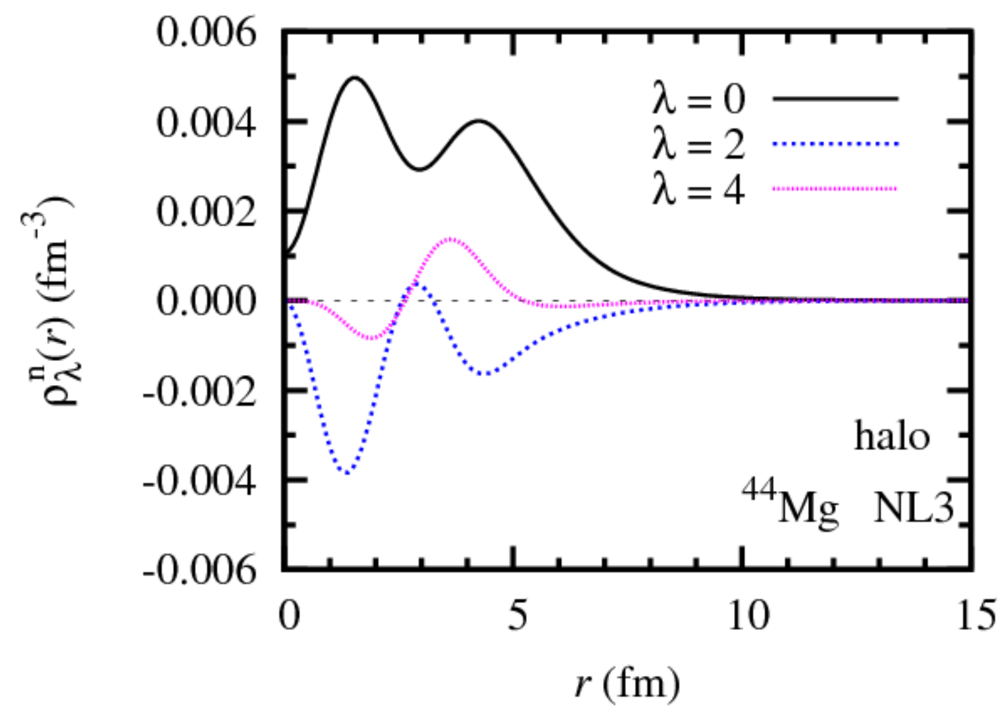
Zhou, Meng, Ring & Zhao, Phys. Rev. C 82, 011301 (2010)





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





Viewpoint: A Walk Along the Dripline by Paul Cottle and Kirby Kemper

http://link.aps.org/doi/10.1103/Physics.5.49

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DRHBc mass table collaboration

PC-PK1 + DRHBc

I. Even–even nuclei

II. Even Z–Odd N nuclei

III. Odd-Z nuclei

1st Paper by DRHBc Collaboration

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Deformed relativistic Hartree-Bogoliubov theory in continuum with a point-coupling functional: Examples of even-even Nd isotopes

Kaiyuan Zhang (张开元) *et al.* (DRHBc Mass Table Collaboration)

Phys. Rev. C **102**, 024314 – Published 12 August 2020

PHYSICAL REVIEW C **102**, 024314 (2020)

Deformed relativistic Hartree-Bogoliubov theory in continuum with a point-coupling functional: Examples of even-even Nd isotopes

Kaiyuan Zhang (张开元),[1] Myung-Ki Cheoun,[2] Yong-Beom Choi,[3] Pooi Seong Chong,[4] Jianmin Dong (董建敏),[5,6] Lisheng Geng (耿立升),[7] Eunja Ha,[2] Xiaotao He (贺晓涛),[8] Chan Heo,[4] Meng Chit Ho,[4] Eun Jin In,[9] Seonghyun Kim,[2] Youngman Kim,[10] Chang-Hwan Lee,[3] Jenny Lee,[4] Zhipan Li (李志攀),[11] Tianpeng Luo (骆天鹏),[1] Jie Meng (孟杰),[1,*] Myeong-Hwan Mun,[12] Zhongming Niu (牛中明),[13,14] Cong Pan (潘琮),[1] Panagiota Papakonstantinou,[15] Xinle Shang (尚新乐),[5,6] Caiwan Shen (沈彩万),[16] Guofang Shen (申国防),[7] Wei Sun (孙玮),[11] Xiang-Xiang Sun (孙向向),[17,18] Chi Kin Tam,[4] Thaivayongnou ,[7] Chen Wang (王晨),[8] Sau Hei Wong,[4] Xuewei Xia (夏学伟),[19] Yijun Yan (晏一珺),[5,6] Ryan Wai-Yen Yeung,[4] To Chung Yiu,[4] Shuangquan Zhang (张双全),[1] Wei Zhang (张炜),[20] and Shan-Gui Zhou (周善贵)[17,18,21,22]
(DRHBc Mass Table Collaboration)

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2]*Department of Physics and Origin of Matter and Evolution of Galaxy (OMEG) Institute, Soongsil University, Seoul 156-743, Korea*
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[4]*Department of Physics, The University of Hong Kong, Pokfulam 999077, Hong Kong*
[5]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
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DRHBc Mass Table Collaboration

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Deformed relativisti
with a point-couplin

Cong Pan (潘琮) *et al.* (DRHBc M
Phys. Rev. C **106**, 014316 – Publi

Article

PHYSICAL REVIEW C **106**, 014316 (2022)

Deformed relativistic Hartree-Bogoliubov theory in continuum with a point-coupling functional. II. Examples of odd Nd isotopes

Cong Pan (潘琮),[1] Myung-Ki Cheoun,[2] Yong-Beom Choi,[3] Jianmin Dong (董建敏),[4,5] Xiaokai Du (杜晓凯),[1] Xiao-Hua Fan (范小华),[6] Wei Gao (高威),[7] Lisheng Geng (耿立升),[8,7] Eunja Ha,[9] Xiao-Tao He (贺晓涛),[10] Jinke Huang (黄靳苛),[7] Kun Huang (黄坤),[10] Seonghyun Kim,[2] Youngman Kim,[11] Chang-Hwan Lee,[3] Jenny Lee,[12] Zhipan Li (李志攀),[6] Zhi-Rui Liu (刘治瑞),[10] Yiming Ma (马艺铭),[13] Jie Meng (孟杰),[1,*] Myeong-Hwan Mun,[2,14] Zhongming Niu (牛中明),[15] Panagiota Papakonstantinou,[11] Xinle Shang (尚新乐),[4,5] Caiwan Shen (沈彩万),[16] Guofang Shen (申国防),[8] Wei Sun (孙玮),[6] Xiang-Xiang Sun (孙向向),[17,18] Jiawei Wu (吴佳威),[10] Xinhui Wu (吴鑫辉),[1] Xuewei Xia (夏学伟),[19] Yijun Yan (晏一珺),[4,5] To Chung Yiu,[12] Kaiyuan Zhang (张开元),[1,20] Shuangquan Zhang (张双全),[1] Wei Zhang (张炜),[7] Xiaoyan Zhang (张晓燕),[15] Qiang Zhao (赵强),[21,1] Ruyou Zheng (郑茹尤),[8] and Shan-Gui Zhou (周善贵)[18,22,23,24]
(DRHBc Mass Table Collaboration)

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2]*Department of Physics and Origin of Matter and Evolution of Galaxy Institute, Soongsil University, Seoul 156-743, Korea*
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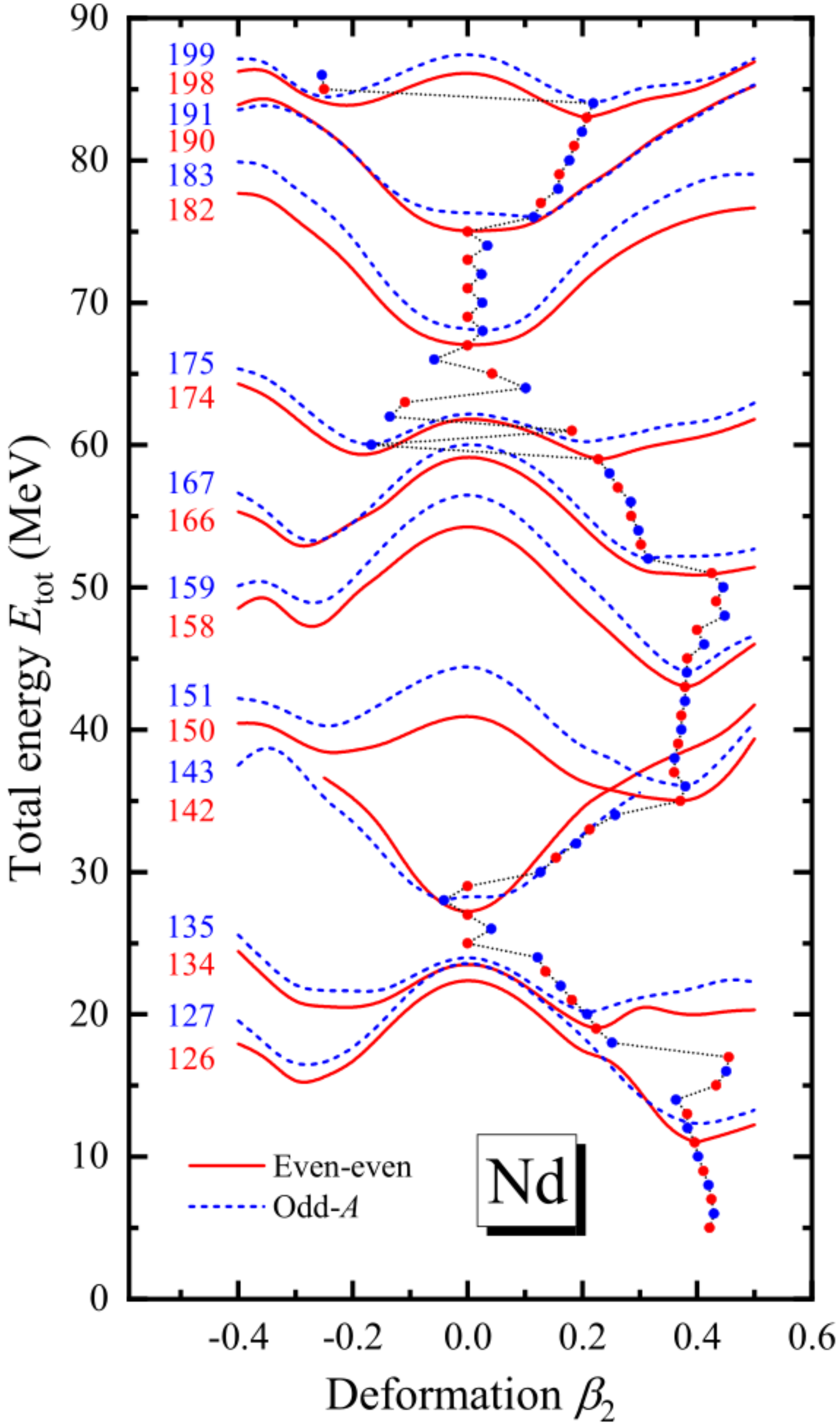
[7]*School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, China*

Potential energy curve (PEC)

- ✓ Ground state for odd-A nuclei are double checked by different blocking.
- ✓ The PEC of odd-A nuclei are similar to their even-even neighbors.
- ✓ Sudden change of β_2 corresponds to possible shape coexistence.



CDFT for nuclear masses

Atomic Data and Nuclear Data Tables 144 (2022) 101488

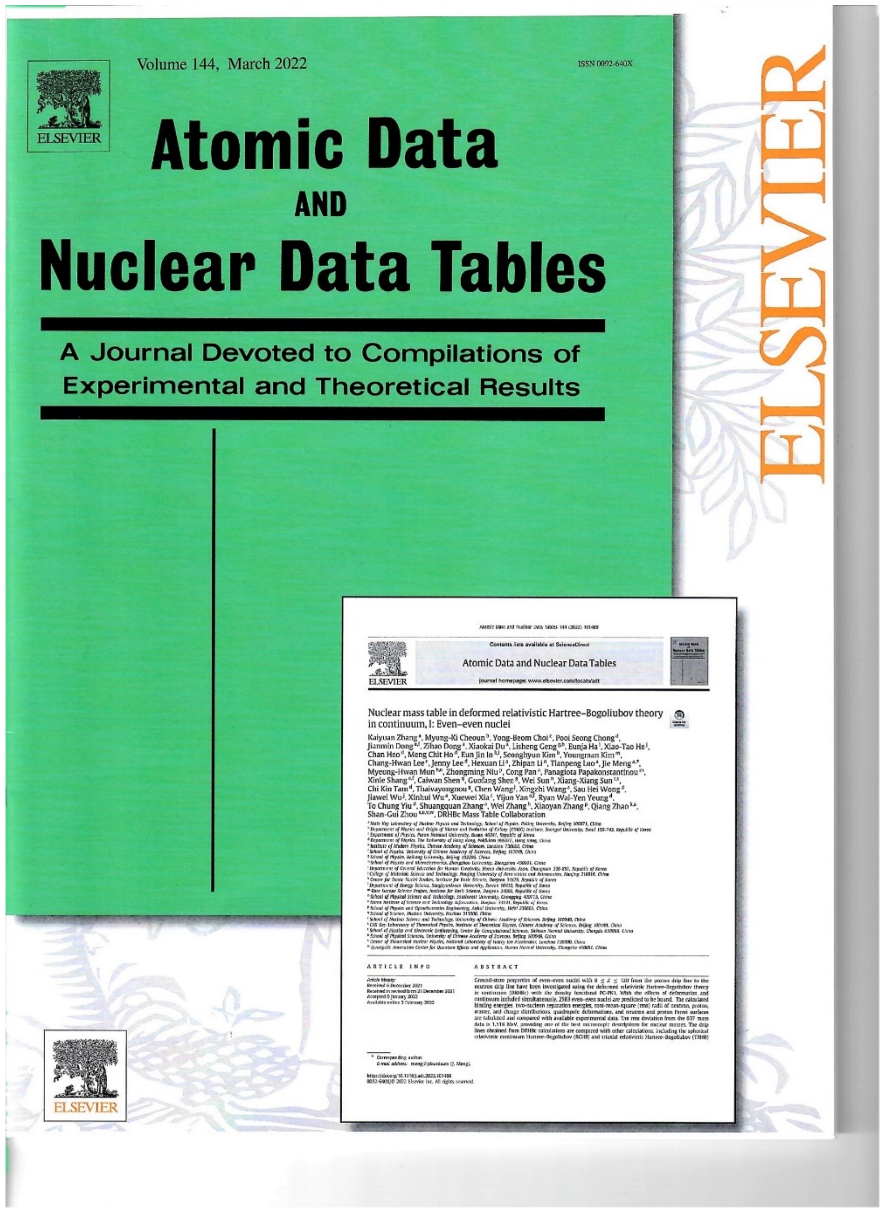
Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

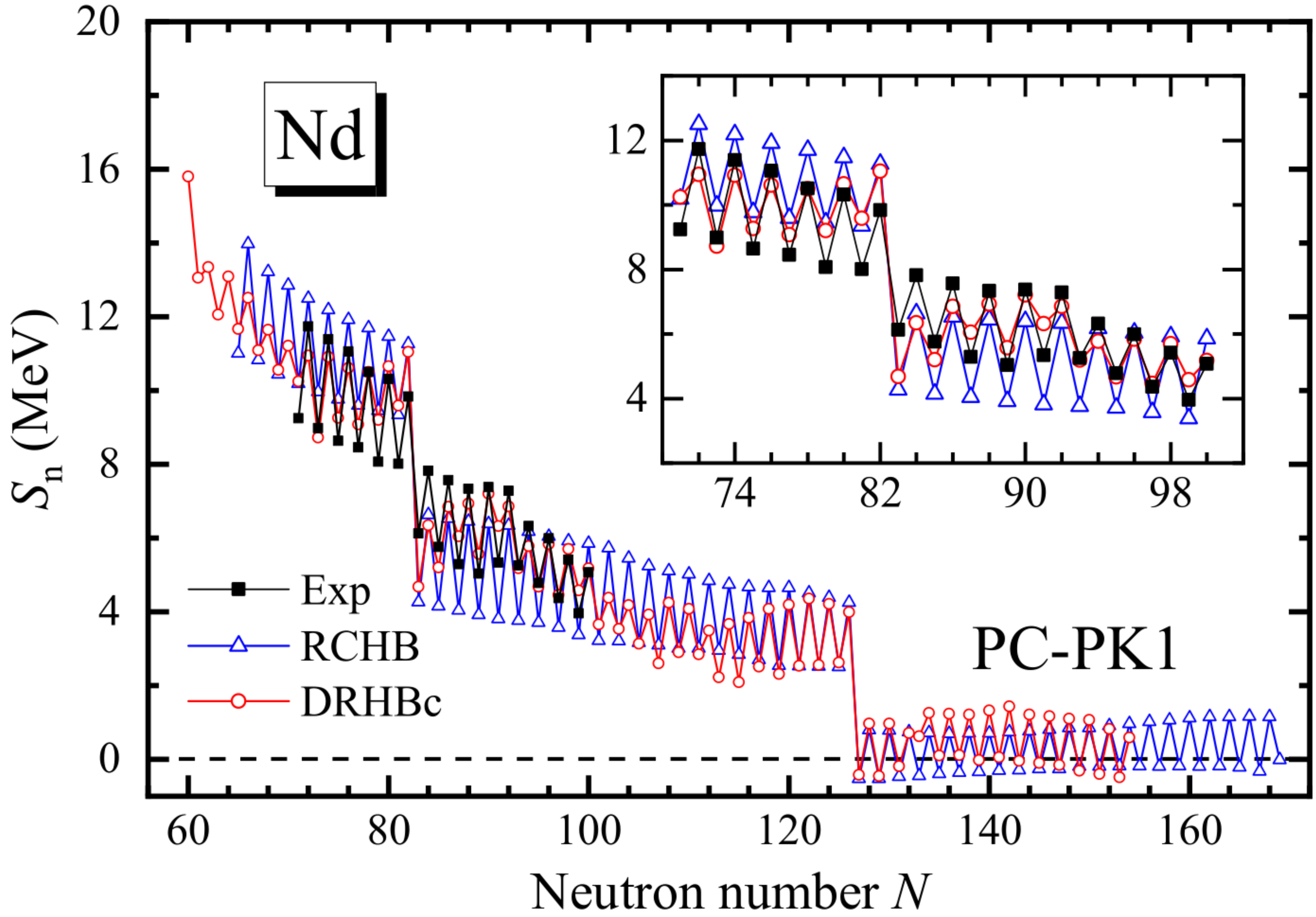
journal homepage: www.elsevier.com/locate/adt

Nuclear mass table in deformed relativistic Hartree–Bogoliubov theory in continuum, I: Even–even nuclei

Kaiyuan Zhang [a], Myung-Ki Cheoun [b], Yong-Beom Choi [c], Pooi Seong Chong [d], Jianmin Dong [e,f], Zihao Dong [a], Xiaokai Du [a], Lisheng Geng [g,h], Eunja Ha [i], Xiao-Tao He [j], Chan Heo [d], Meng Chit Ho [d], Eun Jin In [k,l], Seonghyun Kim [b], Youngman Kim [m], Chang-Hwan Lee [c], Jenny Lee [d], Hexuan Li [a], Zhipan Li [n], Tianpeng Luo [a], Jie Meng [a,*], Myeong-Hwan Mun [b,o], Zhongming Niu [p], Cong Pan [a], Panagiota Papakonstantinou [m], Xinle Shang [e,f], Caiwan Shen [q], Guofang Shen [g], Wei Sun [n], Xiang-Xiang Sun [r,s], Chi Kin Tam [d], Thaivayongnou [g], Chen Wang [j], Xingzhi Wang [a], Sau Hei Wong [d], Jiawei Wu [j], Xinhui Wu [a], Xuewei Xia [t], Yijun Yan [e,f], Ryan Wai-Yen Yeung [d], To Chung Yiu [d], Shuangquan Zhang [a], Wei Zhang [h], Xiaoyan Zhang [p], Qiang Zhao [k,a], Shan-Gui Zhou [s,u,v,w], DRHBc Mass Table Collaboration

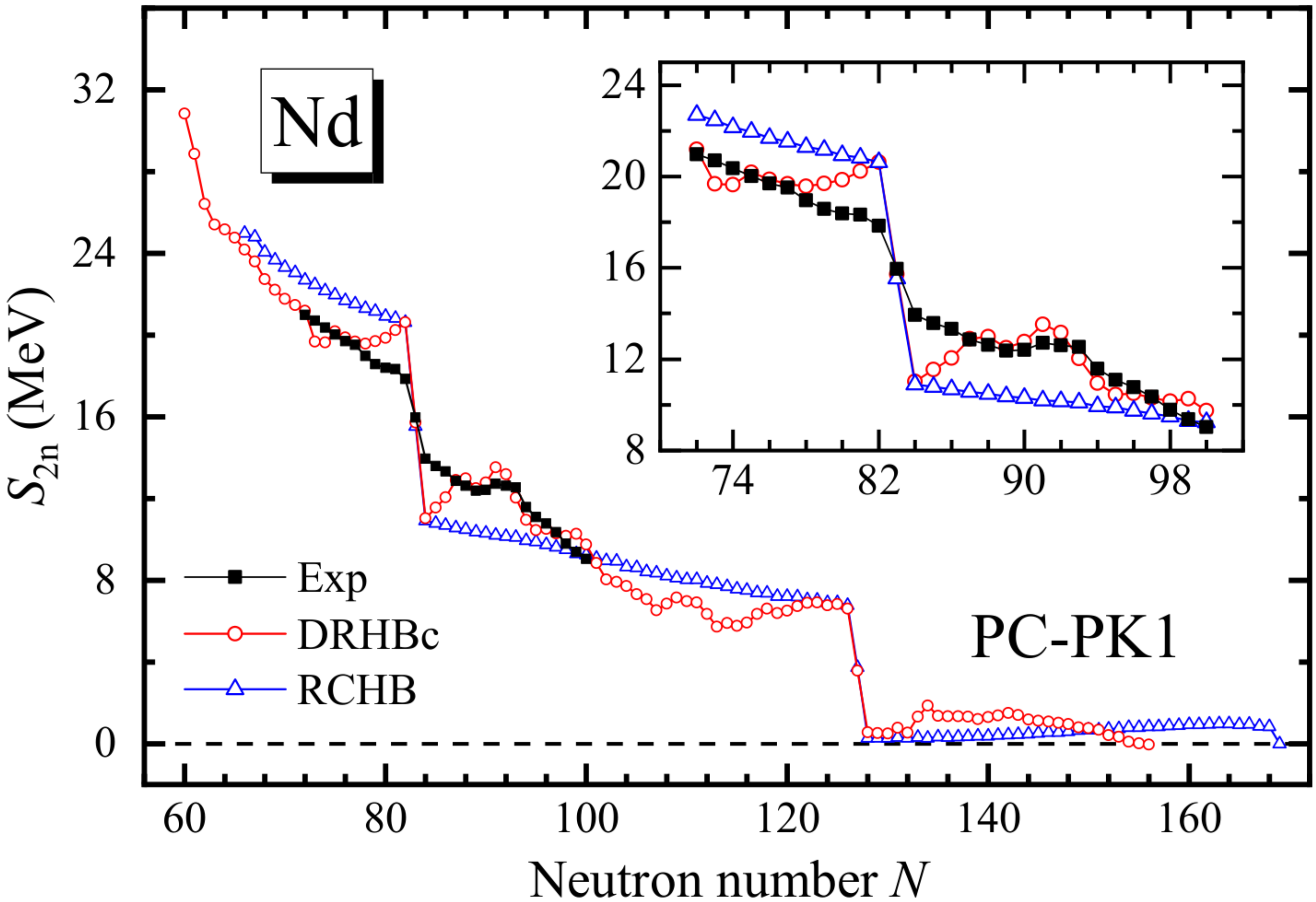


One-neutron separation energy



- ✓ Rms deviations: DRHBc: 0.74 MeV RCHB: 1.10 MeV
- ✓ One-neutron drip line: DRHBc: $N = 126$ RCHB: $N = 126$

Two-neutron separation energy



- ✓ Rms deviations: DRHBc: 1.10 MeV RCHB: 2.04 MeV
- ✓ Two-neutron drip line: DRHBc: $N = 154$ RCHB: $N = 168$

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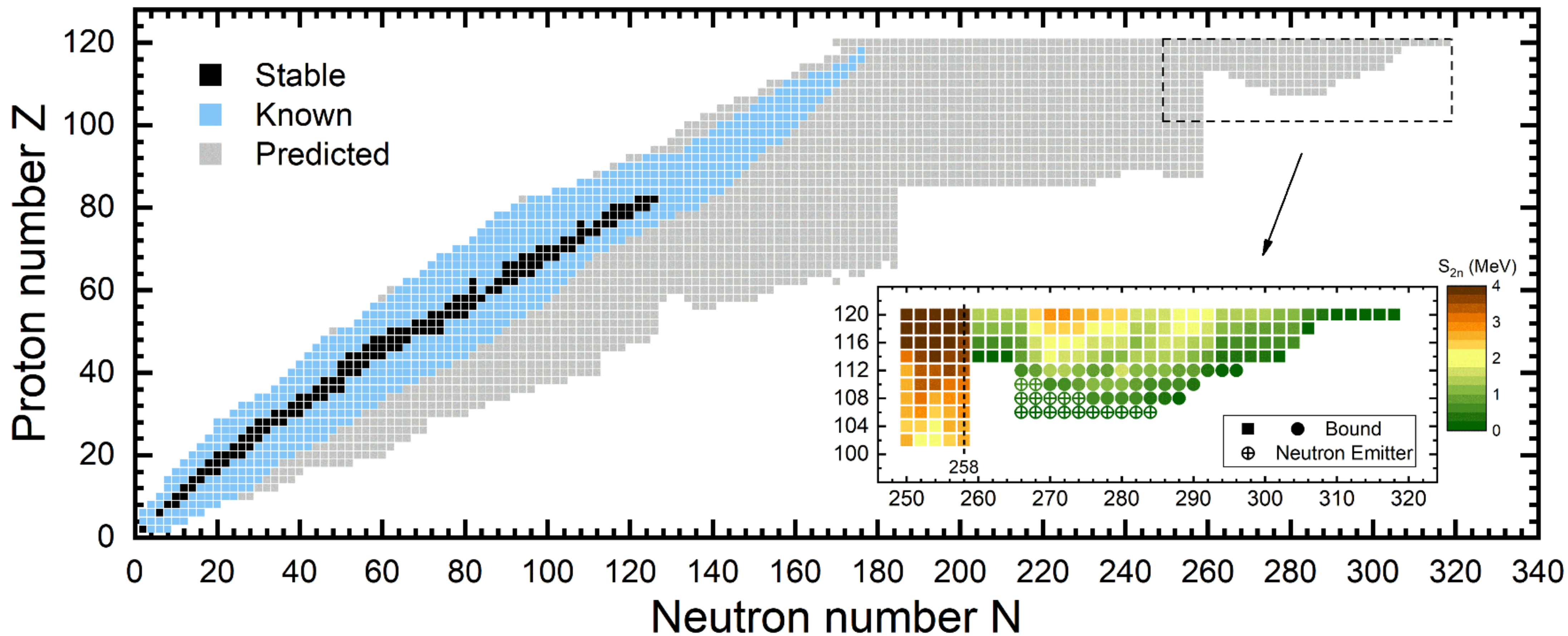
DRHBc Mass Table

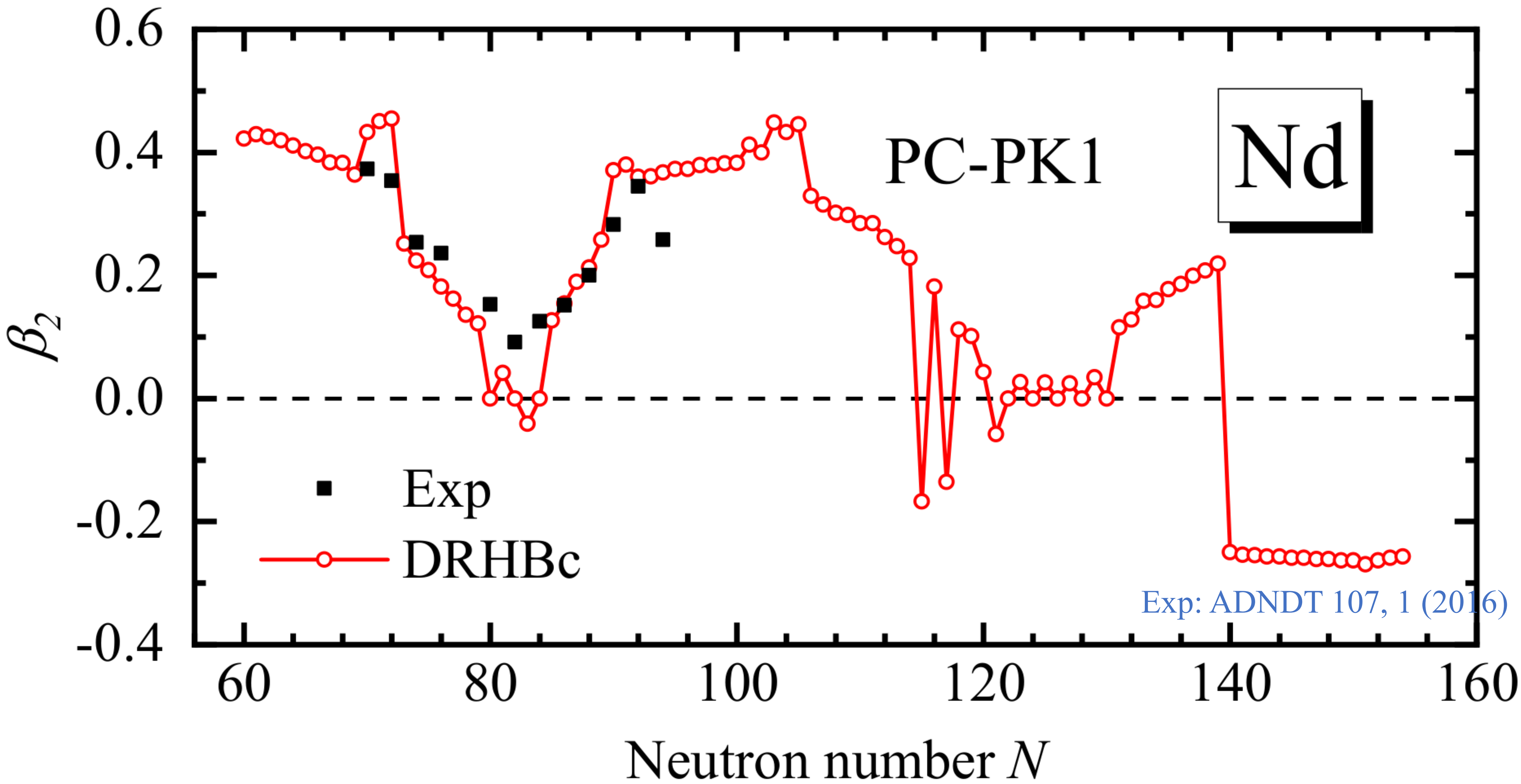
- ➢ **PC-PK1 + DRHBc, 2583 even-even nuclei with 8 ≤ Z ≤ 120, first mass table including both deformation and continuum, σ = 1.5 MeV**

K. Y. Zhang *et al*. (DRHBc Collaboration), Nuclear mass table in deformed relativistic Hartree–Bogoliubov theory in continuum, I: Even–even nuclei, **At. Data Nucl. Data Tables** 144, 101488 (2022)



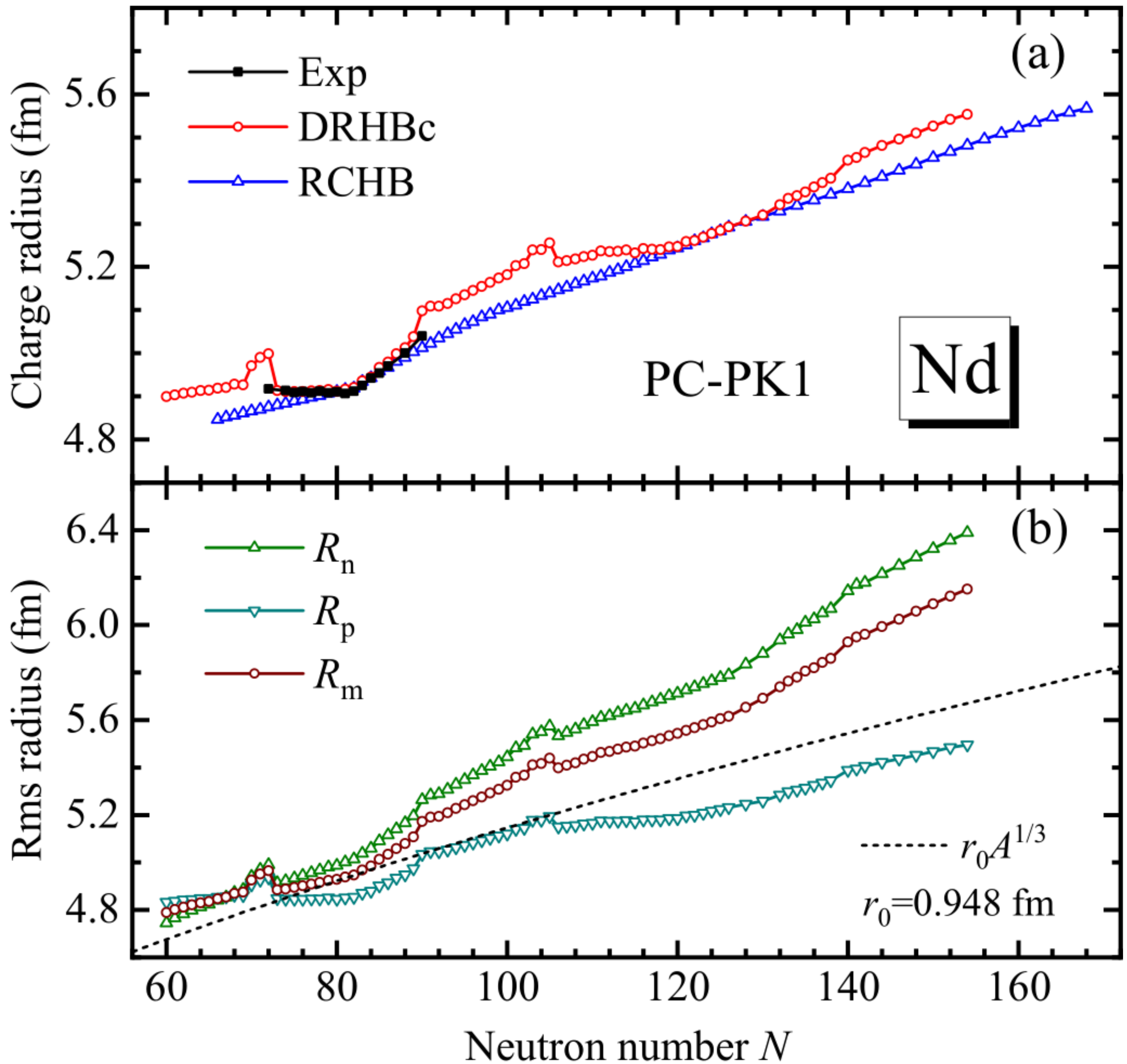
✓DRHBc mass table for even-even nuclei has been constructed’

Quadrupole deformation



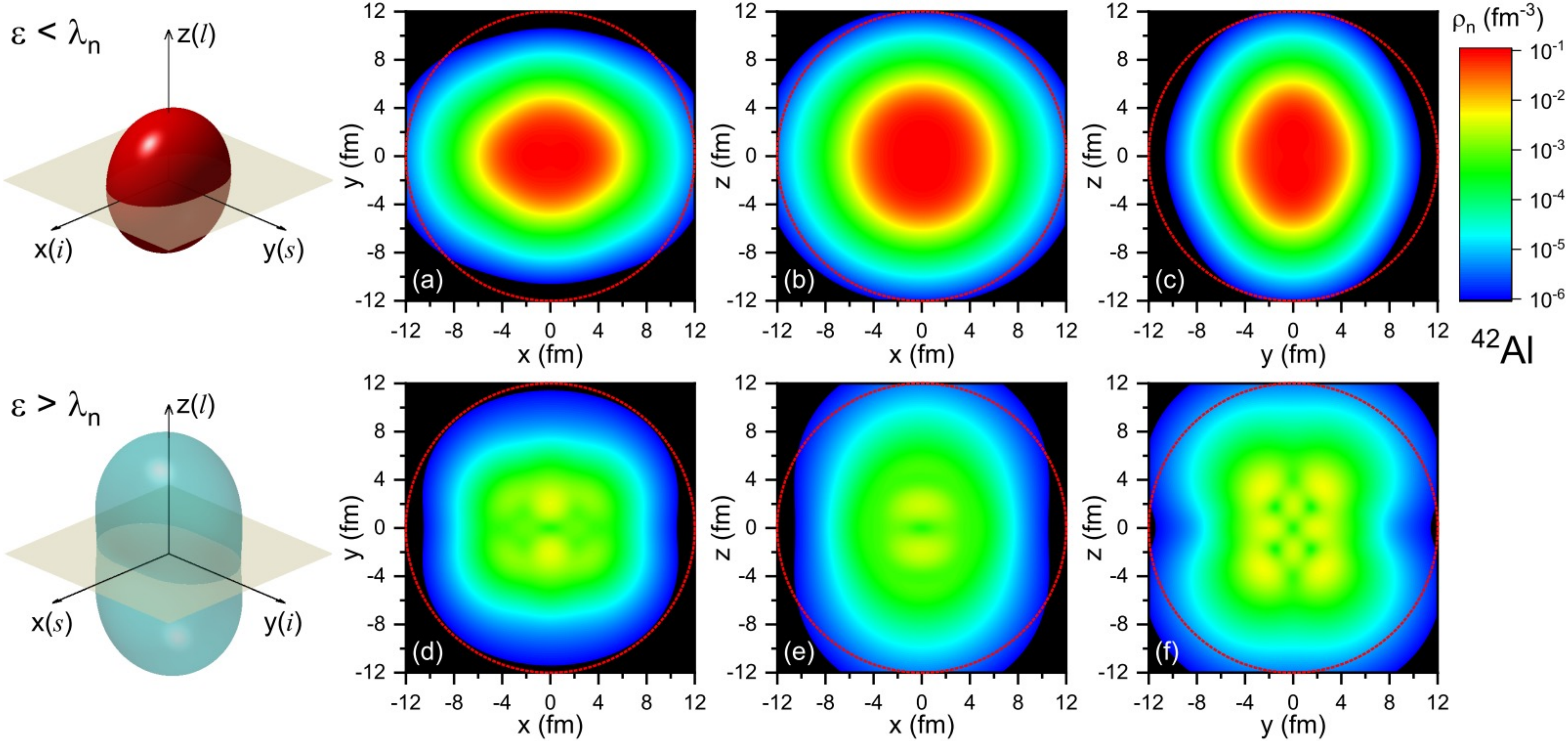
- ✓ Calculation for even-even nuclei reproduce with the data and the odd-*A* nuclei follow the trend.

Rms radii



✓ DRHBc theory reproduced the observed rms radii well

Halo in triaxial nucleus ^{42}Al



- ✓ Core: $r = 3.85$ fm, $\beta = 0.38$, $\gamma = 50°$, $z > x > y$
- ✓ Halo: $r = 5.26$ fm, $\beta = 0.79$, $\gamma = -23°$, $z > y > x$

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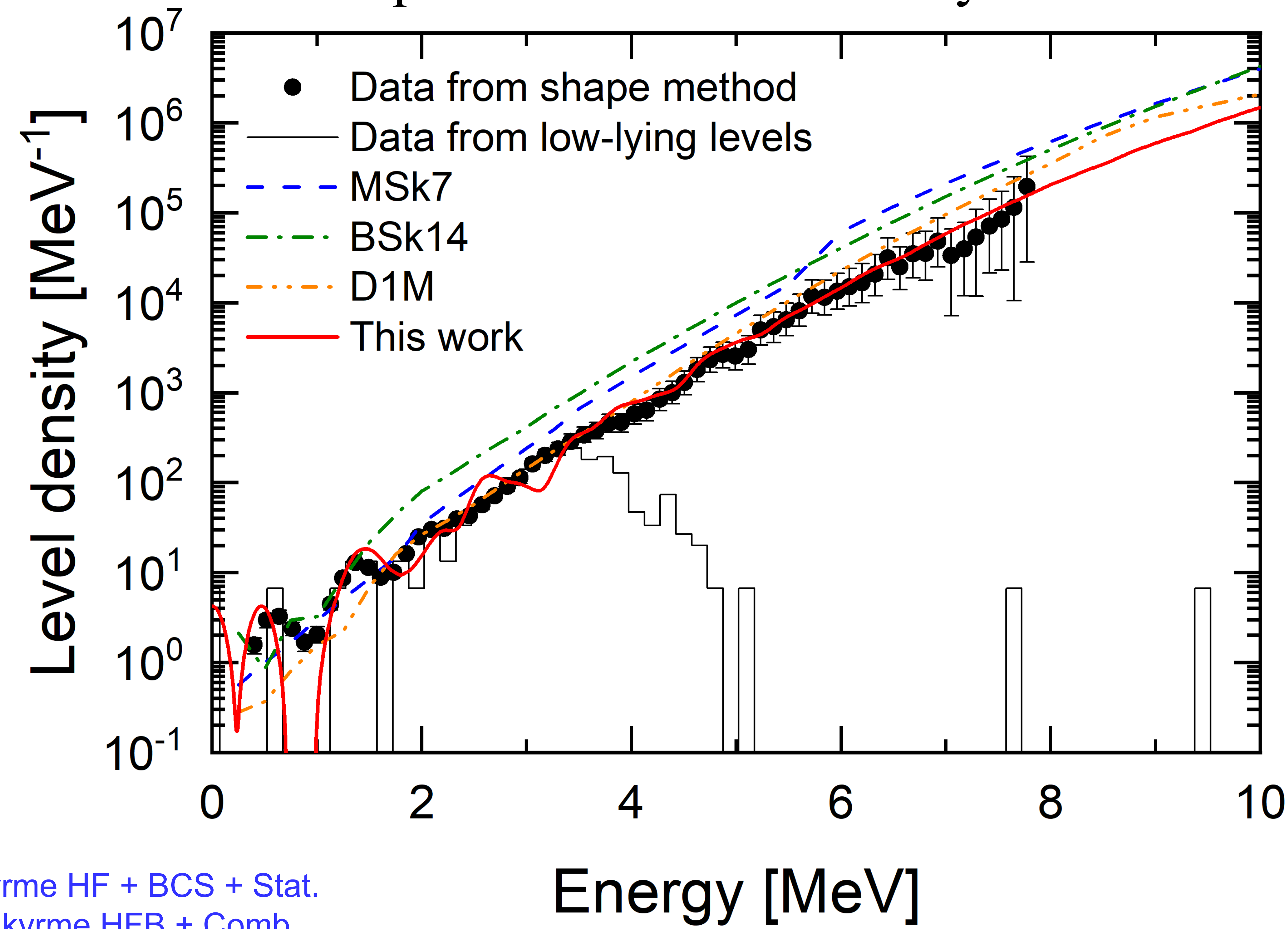
Nuclear level density

CDFT + combination + Strutinski well reproduce the level density in ^{112}Cd

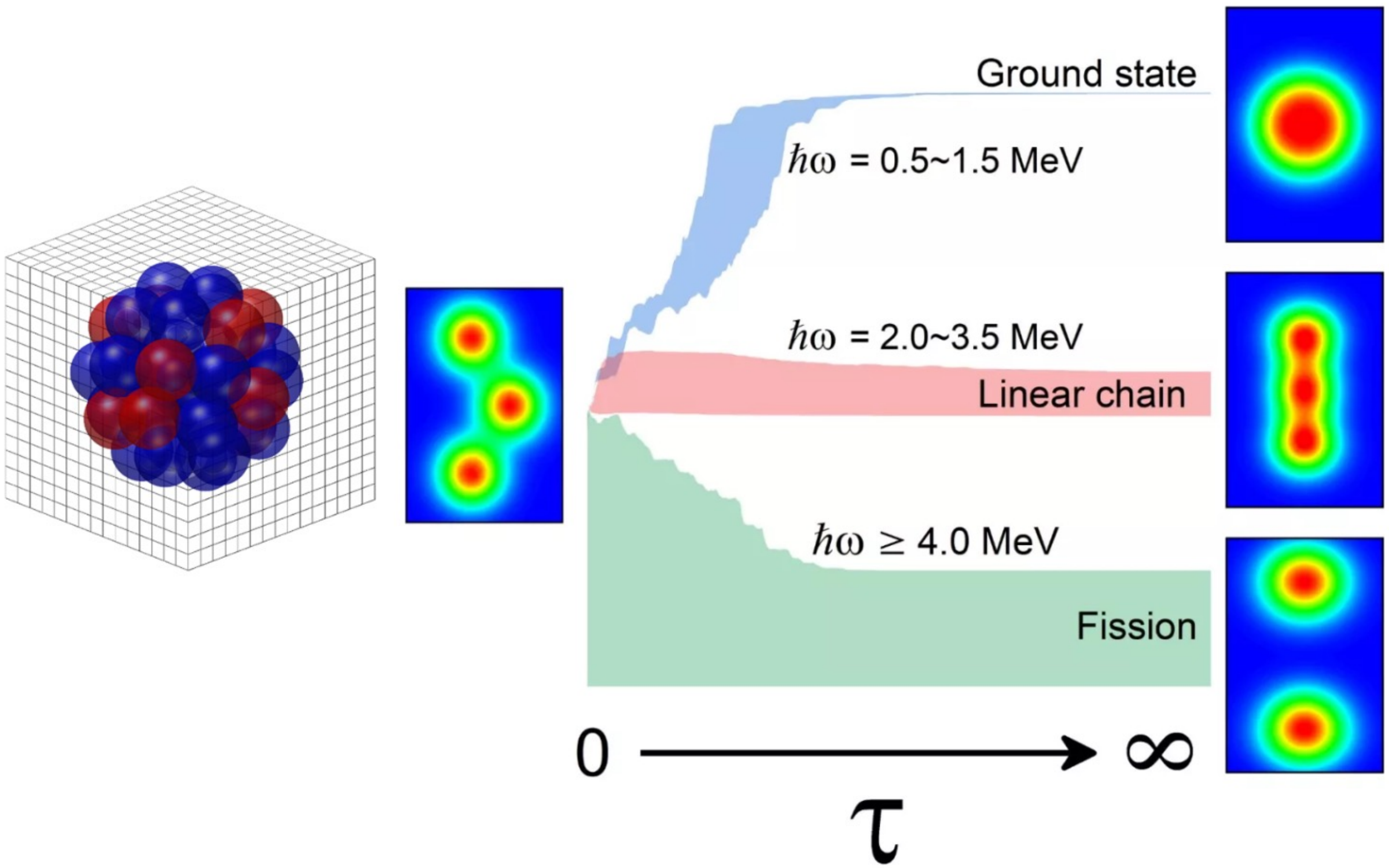


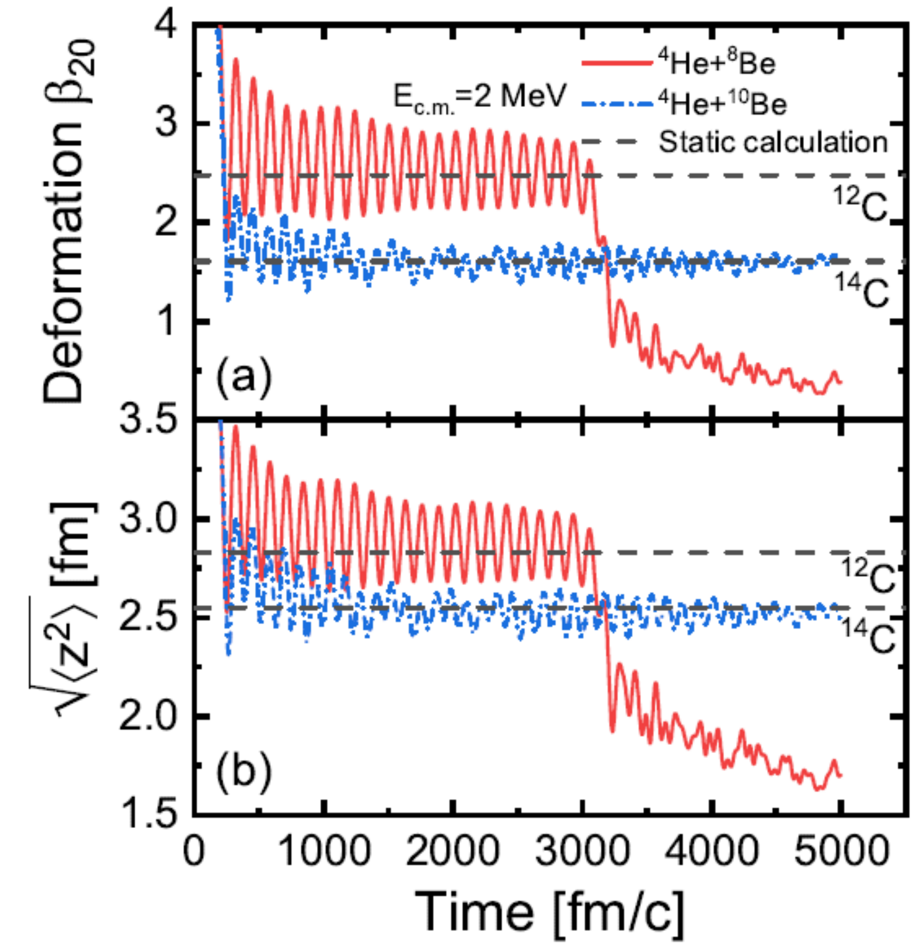
MSk7: Skyrme HF + BCS + Stat.
BSk14: Skyrme HFB + Comb.
D1M: Gogny THFB + Comb.

(Time-depend) CDFT in 3D lattice

EoM on 3D lattice with the inverse Hamiltonian and Fourier spectral methods.

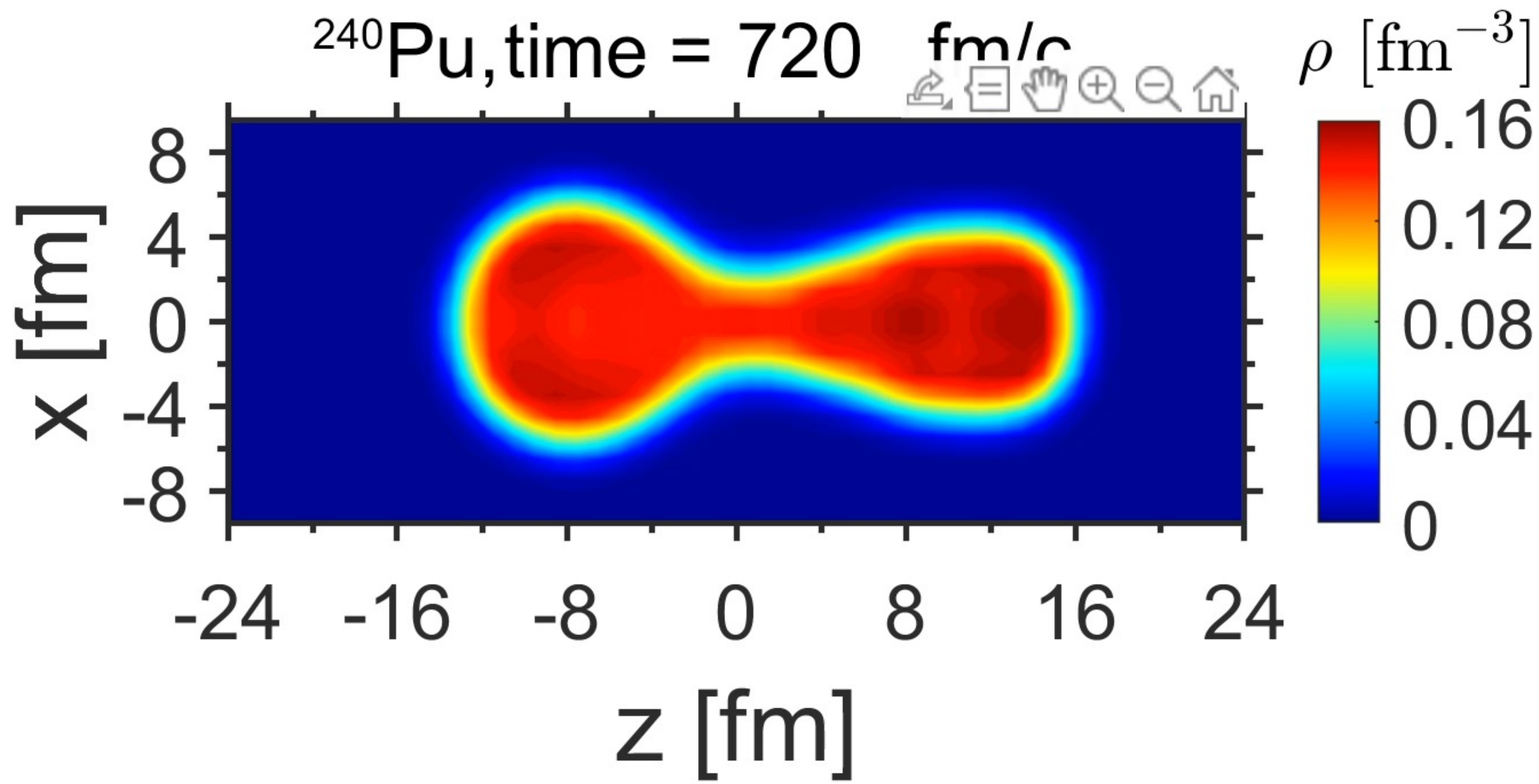
Linear 3α clusters chain structure for ^{12}C against the bending and fission in **cranking CDFT** and **TD CDFT** on a 3D lattice





Ren, Zhang, Zhao, Itagaki, Maruhn, Meng, SCPMA 62, 112062 (2019)
Ren, Zhao, Meng, Physics Letters B 801 (2020) 135194

^{240}Pu: Nuclear density



Ren, Vretenar, Nikšić, PWZ, Zhao, Meng, PRL 128, 172501 (2022)

(Time-depend) CDFT in 3D lattice

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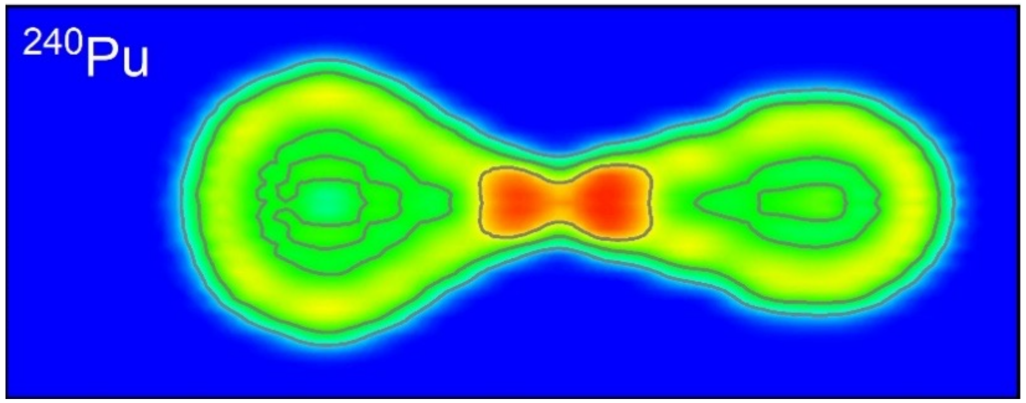
PHYSICAL REVIEW LETTERS **128,** 172501 (2022)

Dynamical Synthesis of ^{4}He in the Scission Phase of Nuclear Fission

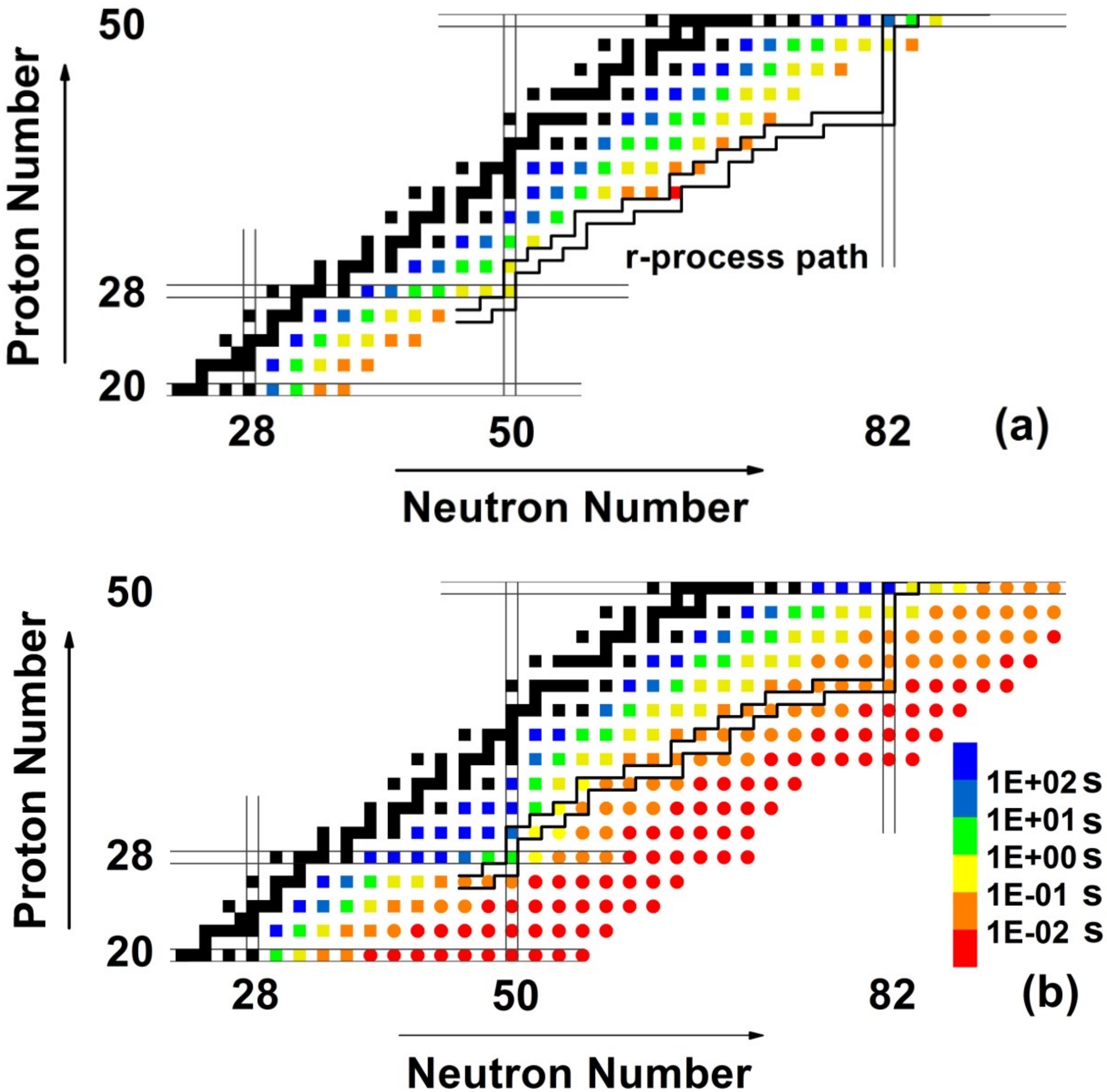
Z. X. Ren,[1] D. Vretenar,[2,1,*] T. Nikšić,[2,1] P. W. Zhao,[1,†] J. Zhao,[3] and J. Meng[1,‡]
[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2]*Physics Department, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia*
[3]*Center for Circuits and Systems, Peng Cheng Laboratory, Shenzhen 518055, China*



Localization functions in the x-z coordinate near the scission

- Z. X. Ren, J. Zhao, D. Vretenar, T. Nikšić, P. W. Zhao, and J. Meng, Microscopic analysis of induced nuclear fission dynamics, **Phys. Rev. C** 105, 044313 (2022)
- Z. X. Ren, D. Vretenar, T. Nikšić, P. W. Zhao, J. Zhao, and J. Meng, Dynamical synthesis of ^{4}He in the scission phase of nuclear fission, **Phys. Rev. Lett.** 128, 172501 (2022)

RHFB+QRPA: Nuclear β⁻-decay half-lives



- Available data are well reproduced by including an isospin-dependent proton-neutron pairing interaction in the isoscalar channel of the RHFB+QRPA model.

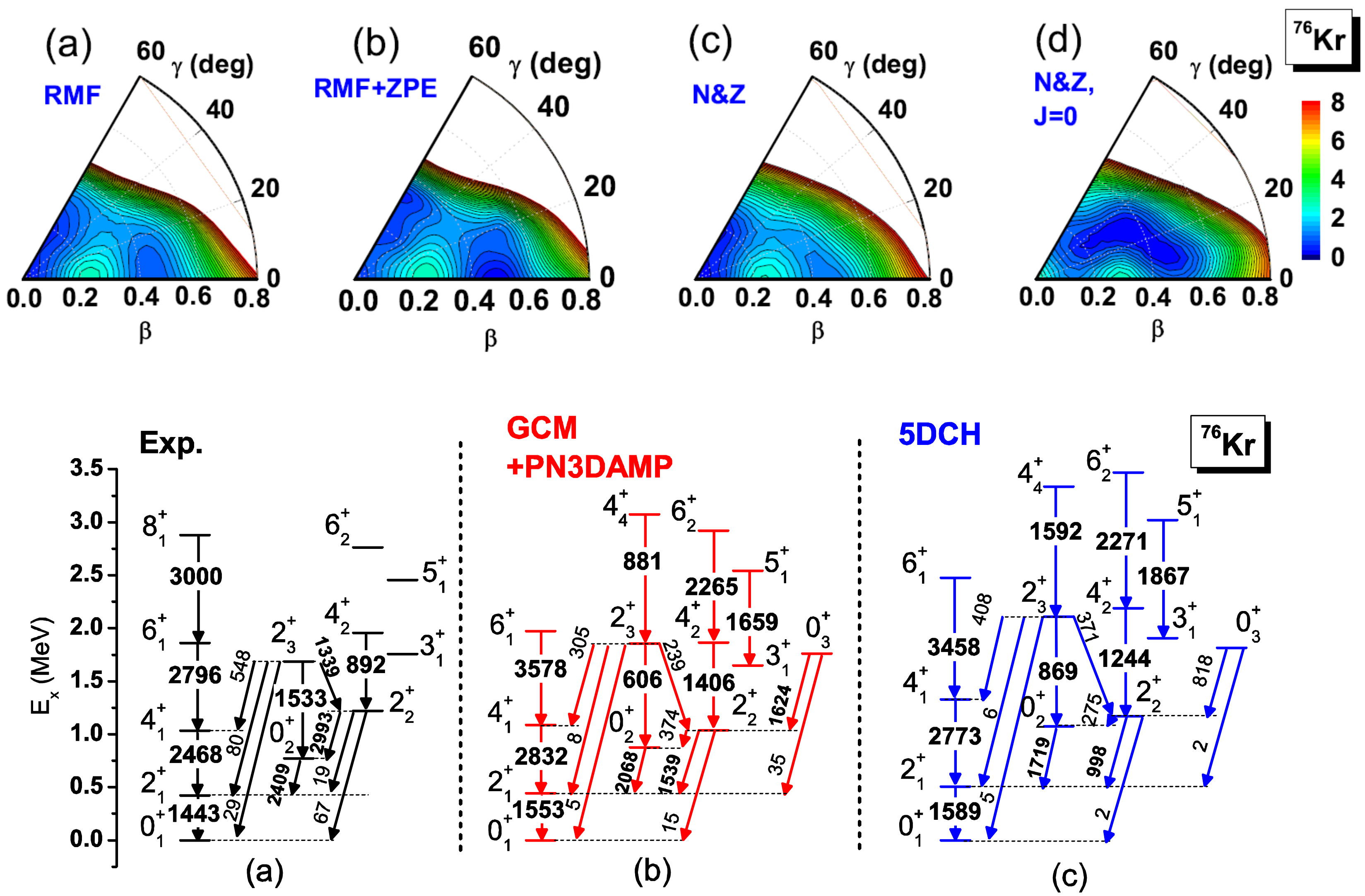
$$V_{T=0}(1,2) = -V_0 \sum_{j=1}^{2} g_j e^{-r_{12}^2/\mu_j^2} \hat{\Pi}_{S=1,T=0},$$

$$V_0 = V_1 + \frac{V_2}{1+e^{a+b(N-Z)}},$$

Niu et al., PLB 723, 172 (2013)

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

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Summary

- ✓ Origin of the heavy elements is one of the fundamental problems in modern science.
- ✓ Stragedy to build Relativistic density functional based on QCD-spirited NN interaction and *ab inito* calculation is proposed.
- ✓ Predictive power of the functional PC-PK1 is shown for both nuclear ground and excited states.
- ✓ DRHBc mass table calculations are completed for even Z nuclei and will be started for odd Z nuclei .
- ➢ Experimental data are reproduced well with continuum and deformation effects. Interesting topics including the bound states beyond the neutron drip line, and the tensor force manifestations are discussed.

Thank you for your attention!

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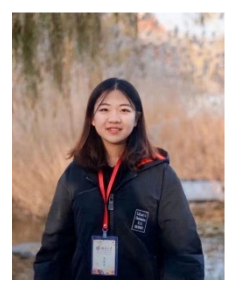
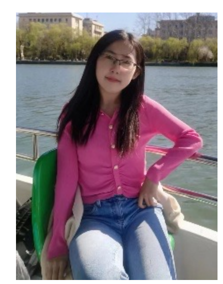

Yanyu Chen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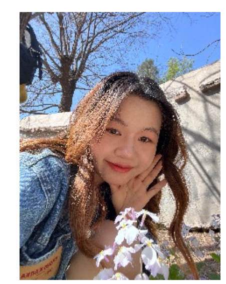
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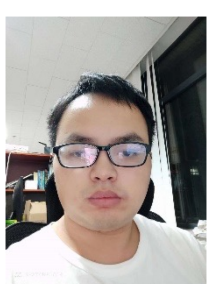
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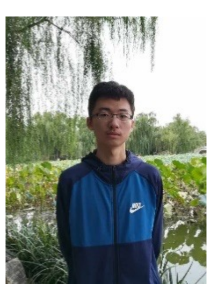
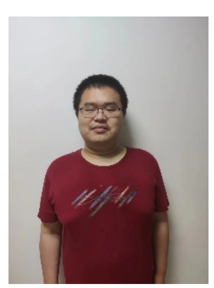
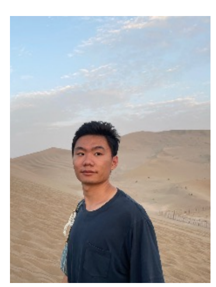

Xiaofei Jiang


Bo Li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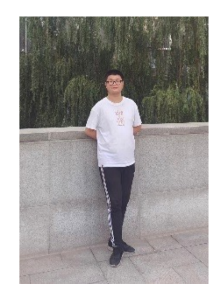
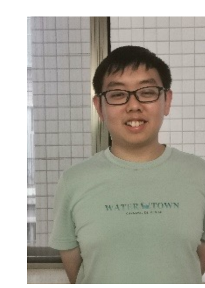
Lingyi Dai


Teng Qu

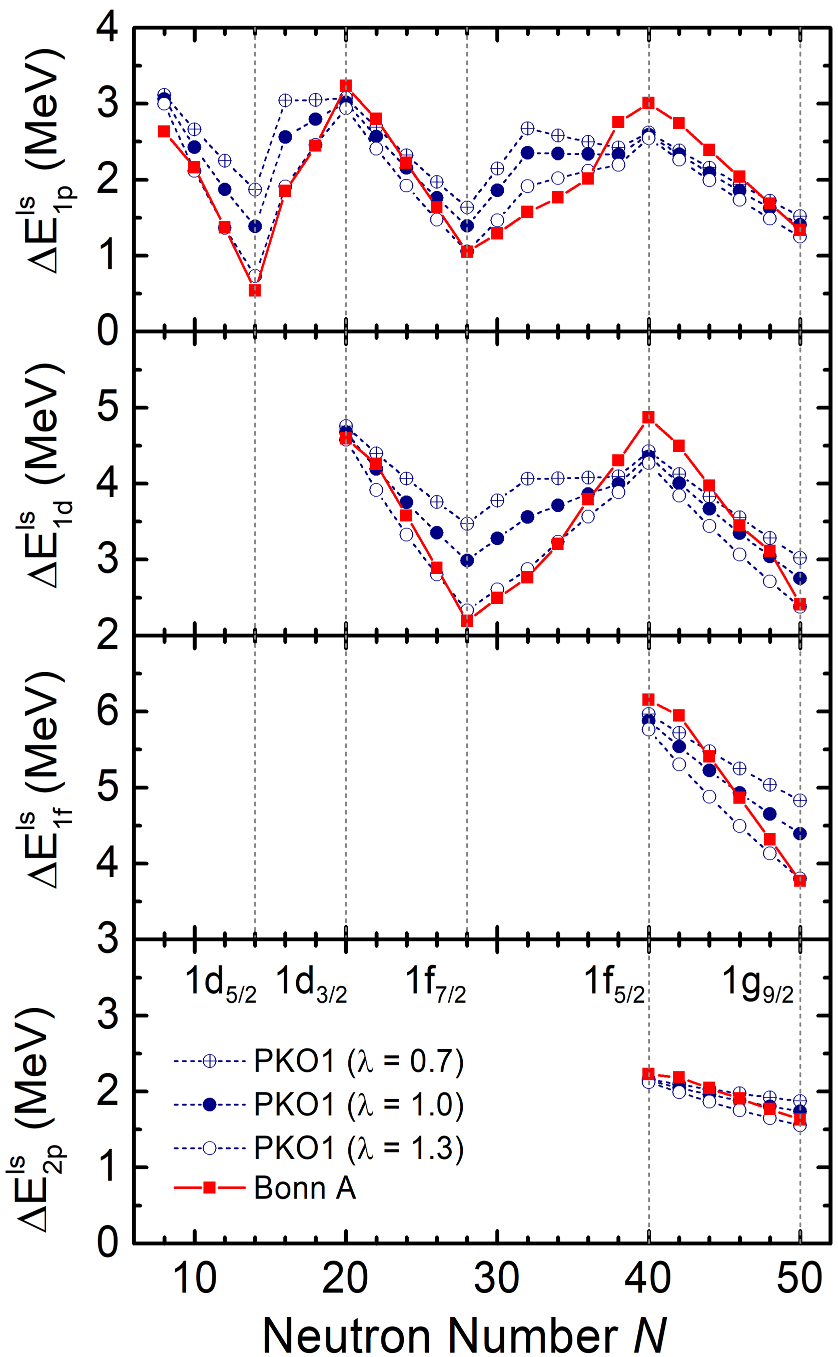

Chang Zhou


Tianxing Huang


Peng Guo

The origin of the heavy elements is one of the fundamental problems in modern science. To solve this problem, the knowledge of nuclear properties is essential. Before the new generation of nuclear facilities can provide the missing data, the reliable and accurate theoretical predictions are indispensable. In this presentation, approaches based on the relativistic density functional with continuum and deformation effects are introduced. Related physics applications are discussed, including masses and shapes of exotic nuclei, bound states beyond the neutron drip line, and the tensor force manifestations.

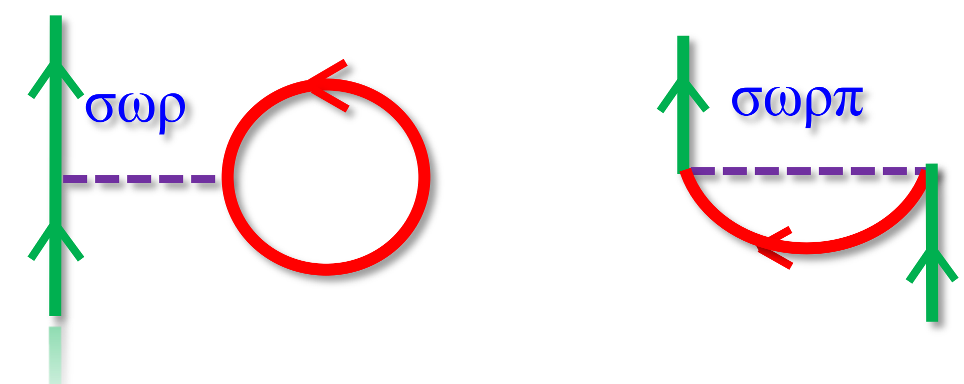
Tensor effects on spin-Orbit Splitting



- **Neutron drop is a neutron system confined in an external field.**

……

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



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)

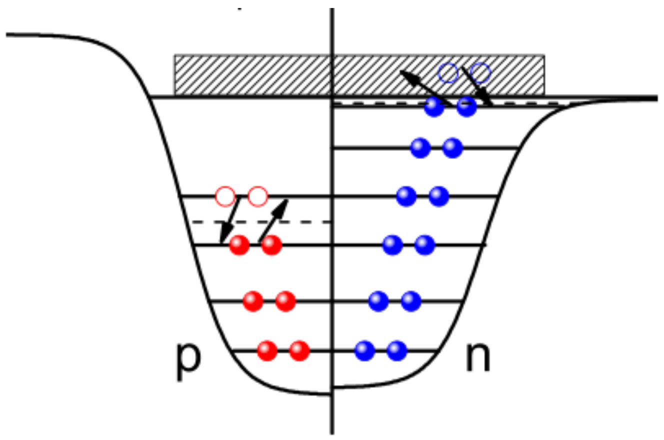
- **RHF** shows similar pattern, mainly contributed by ***π*****NN tensor interaction**.
- Neither RBHF nor CDFT includes **beyond-mean-field effects** ➔ **a fair comparison!**

Spherical halo nuclei & Giant halos

✓Self-consistent description of the neutron halo in ^{11}Li is achieved by the relativistic continuum Hartree-Bogoliubov (RCHB) theory.

Meng and Ring, PRL 77, 3963 (1996)

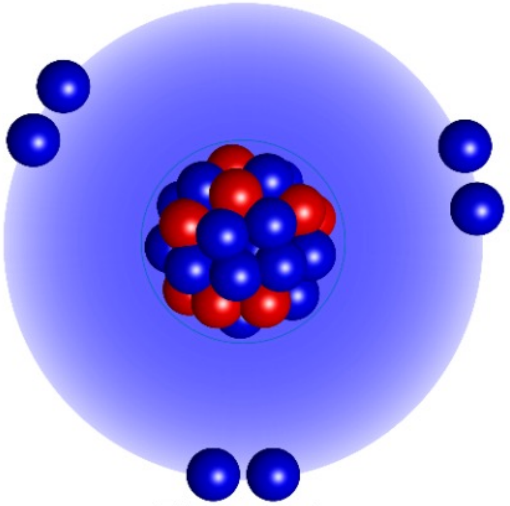
✓Pairing correlations and continuum effects are very important for the description of halos.



Meng and Ring, PRL 77, 3963 (1996)
Meng *et al*., PPNP 57, 470 (2006)

✓The RCHB theory also predicts giant halos in Zr isotopes.

Meng and Ring, PRL 80, 460 (1998)



✓Later studies support the prediction of giant halos in Zr and Ca isotopes.

Meng, Toki, Zeng, Zhang, and Zhou, PRC 65, 041302(R) (2002)
Sandulescu, Geng, and Hillhouse, PRC 68, 054323 (2003)
Terasaki, Zhang, Zhou, Meng, PRC 74, 054318 (2006)
Grasso, Yoshida, Sandulescu, and Van Giai, PRC 74, 064317 (2006)

Multidimentionally constrained CDFT

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

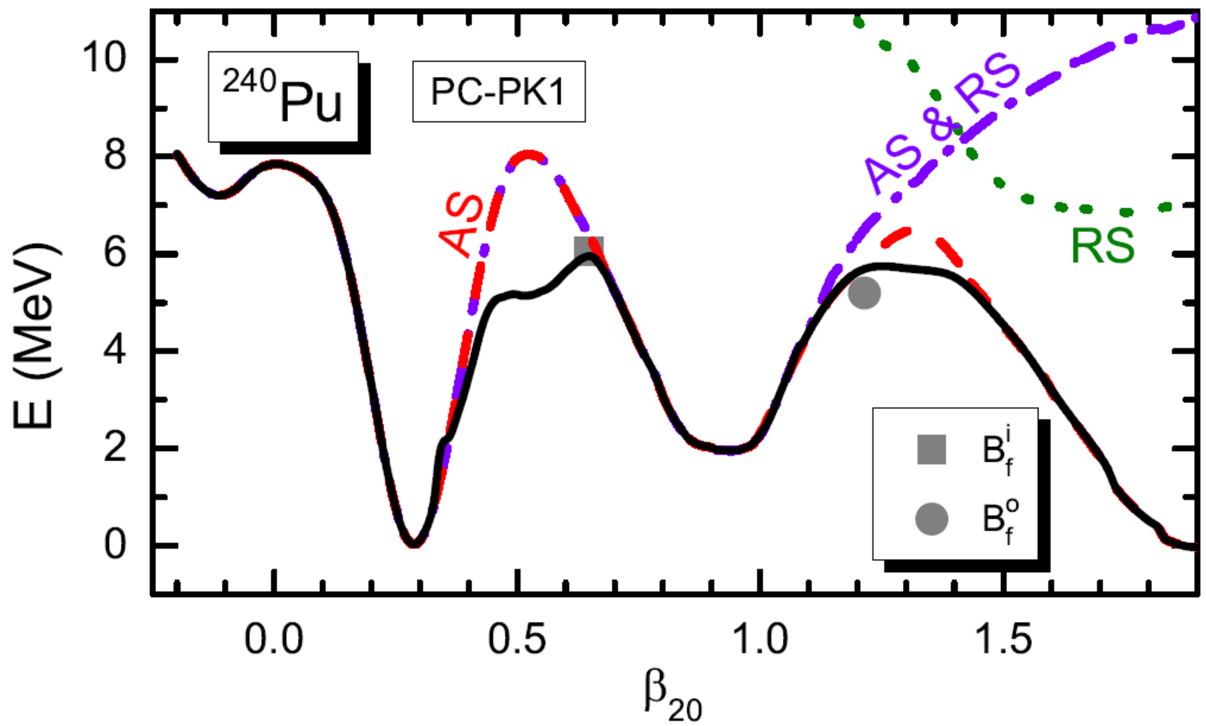


Figure: Potential energy curve of ^{240}Pu

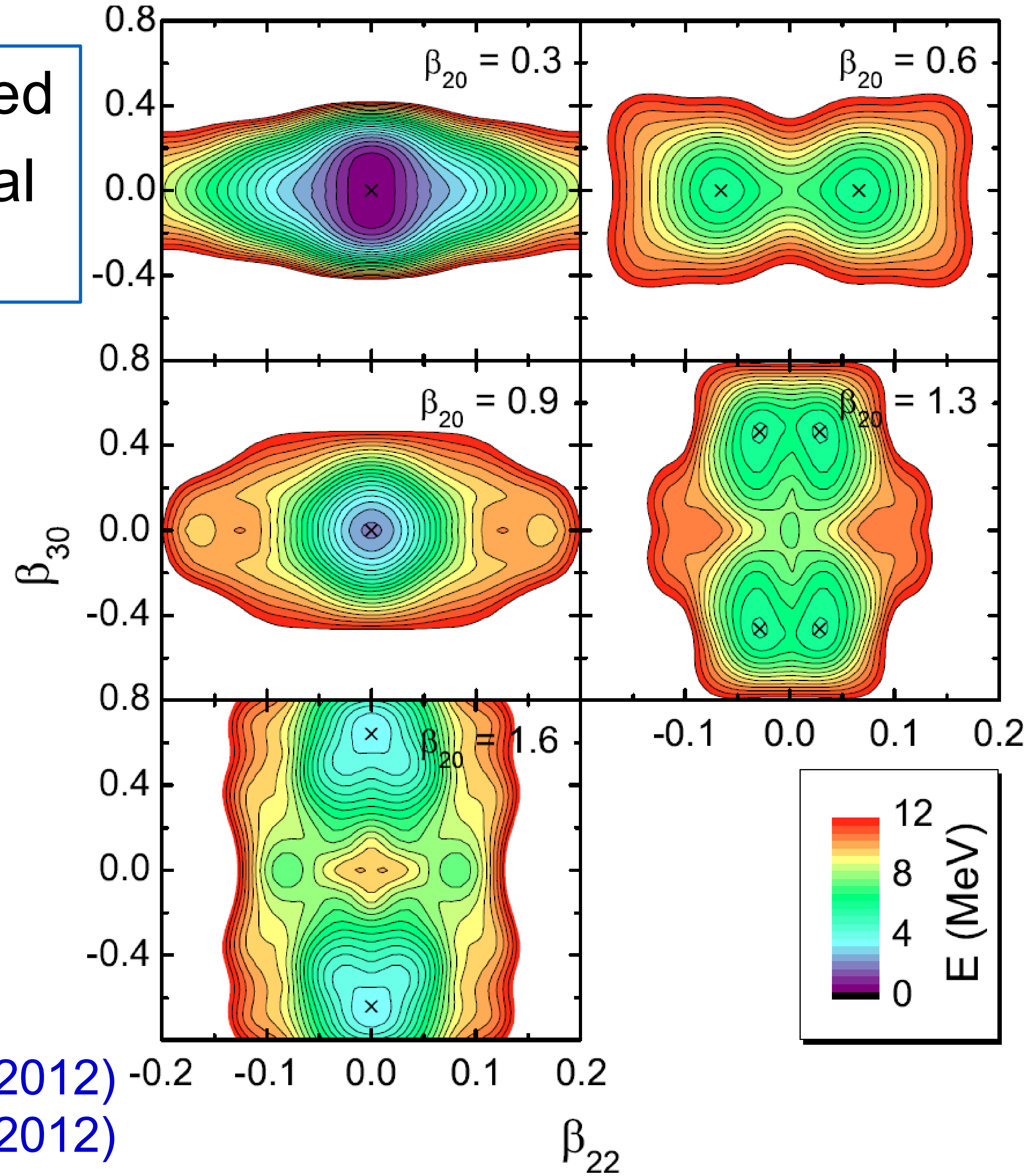
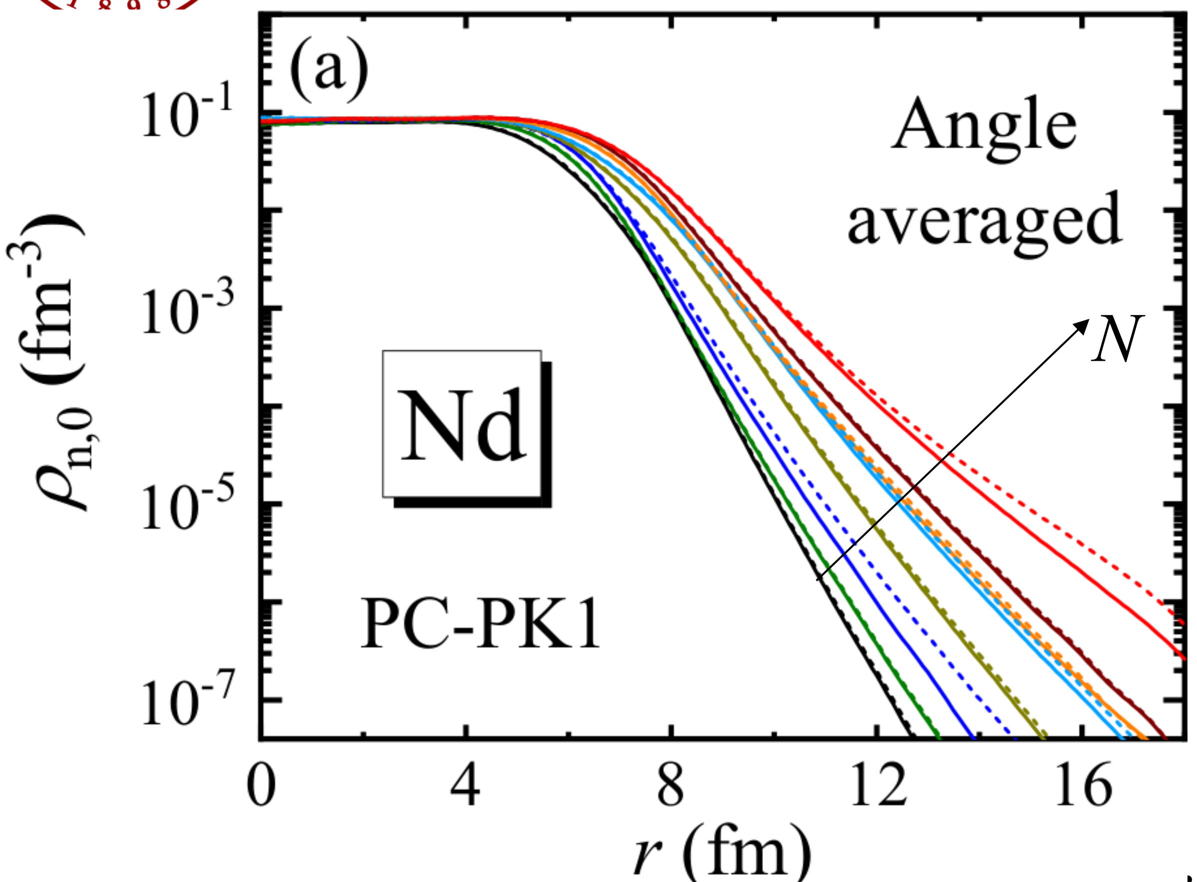


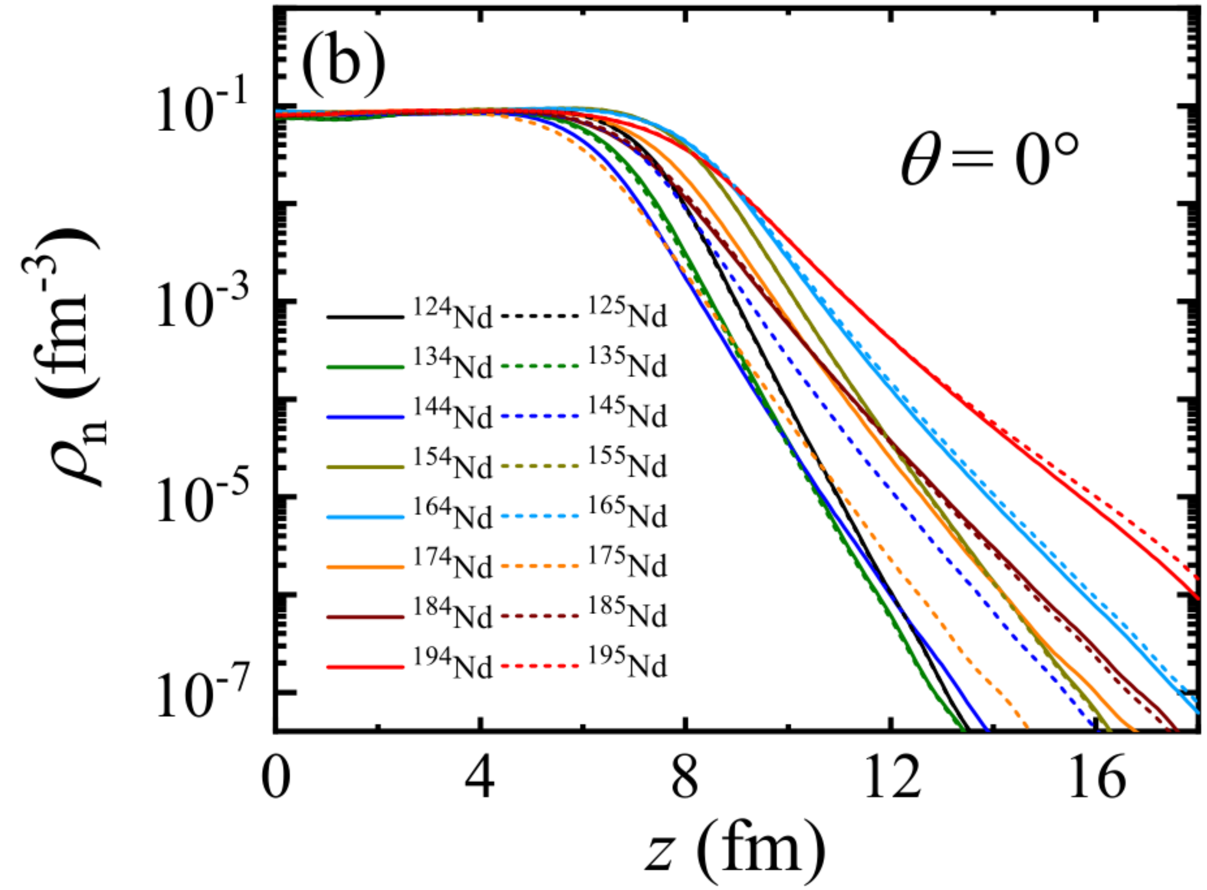
Figure: 3D PES of ^{240}Pu

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)

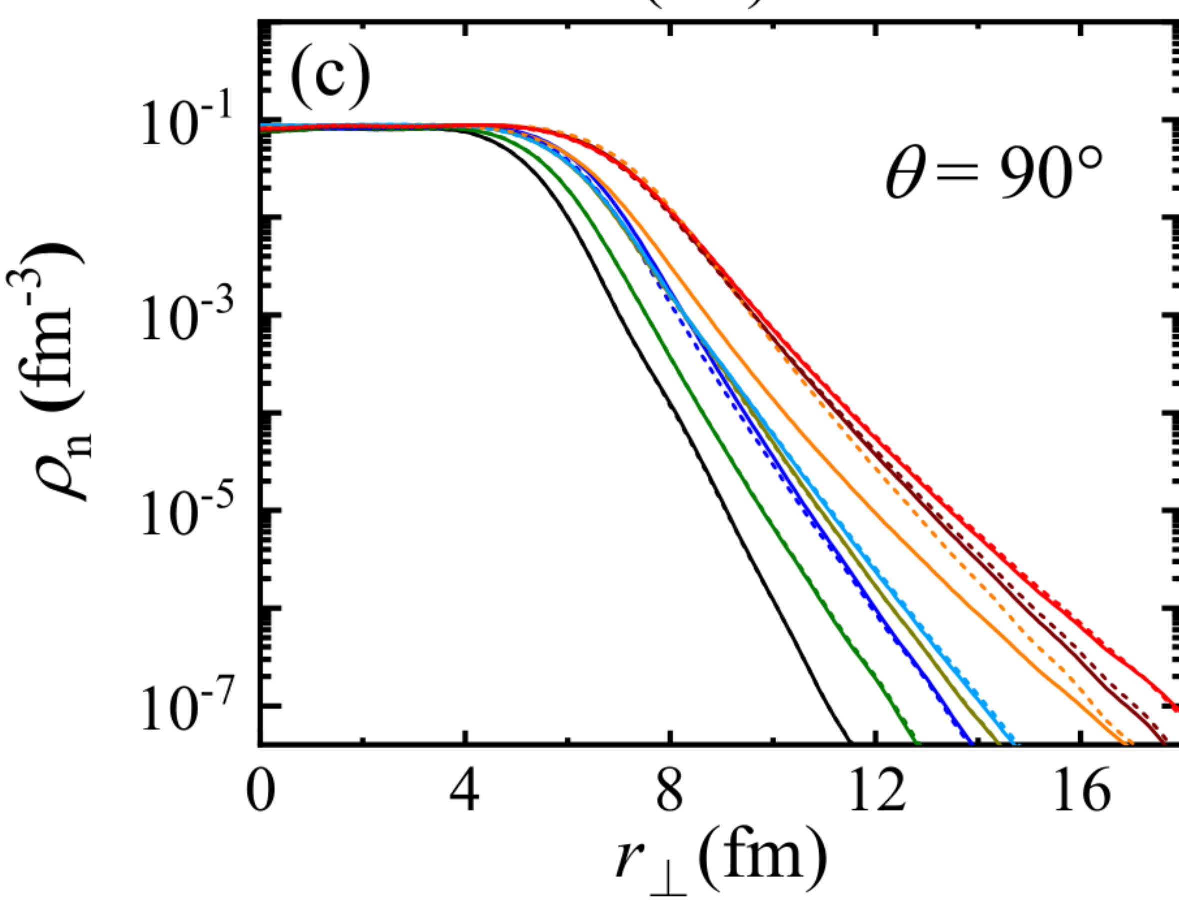
Triaxial deformation only: Abusara, Afanasjev, Ring PRC 85, 024314 (2012)

Neutron density distributions



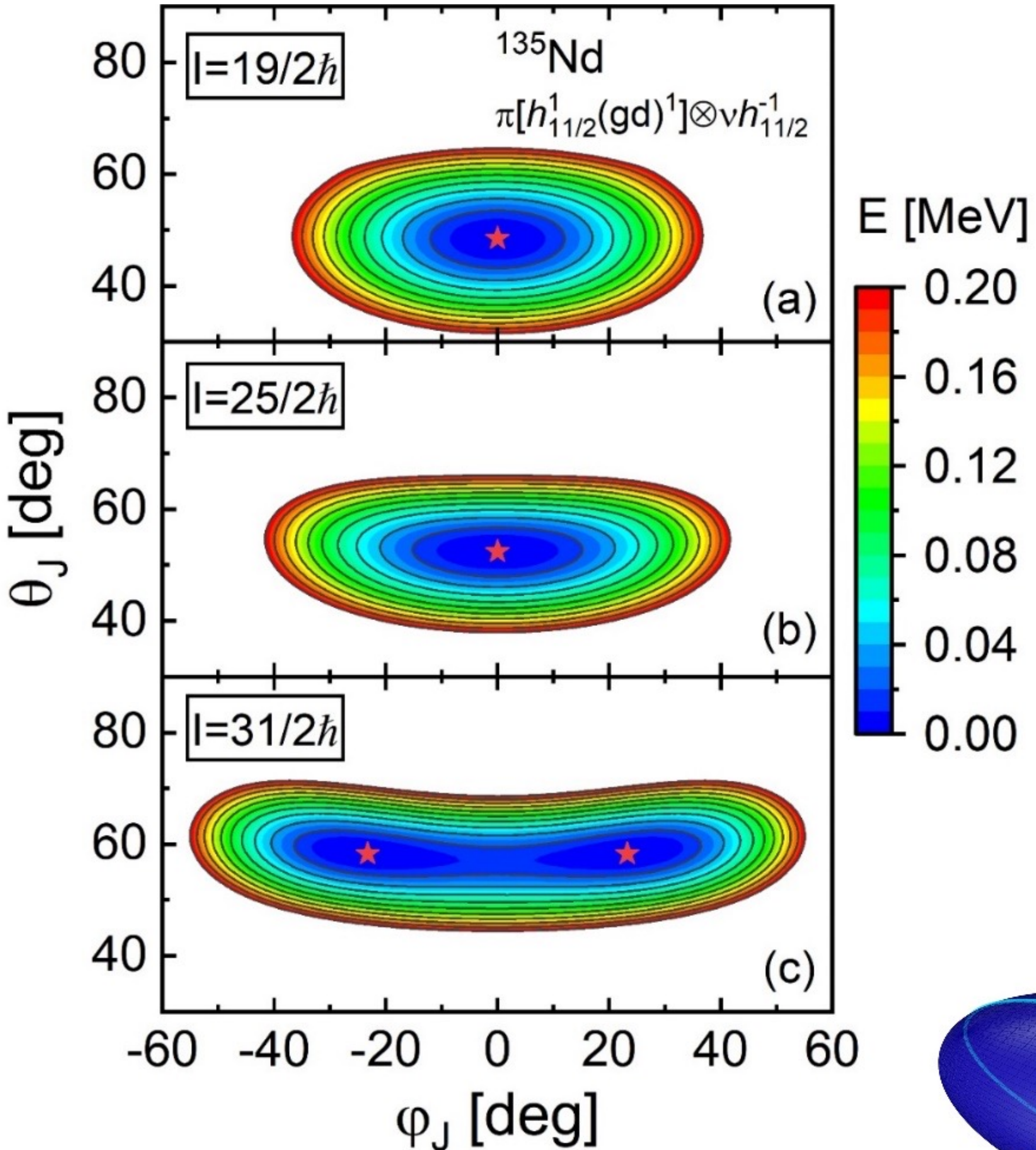


- ✓ Angle-averaged density $\rho_{n,0}$ increases monotonically with N.
- ✓ An increase of $\rho_{n,0}$ is shown at ^{195}Nd.
- ✓ Density behavior at $\theta = 0°$ with N is related to deformation effect.



(DRHBc Mass Table Collaboration), PRC 102, 024314 (2020)

总能量关于 (φ_J, θ_J) 的平面



PHYSICAL REVIEW C **105**, L011301 (2022)

Dynamics of rotation in chiral nuclei

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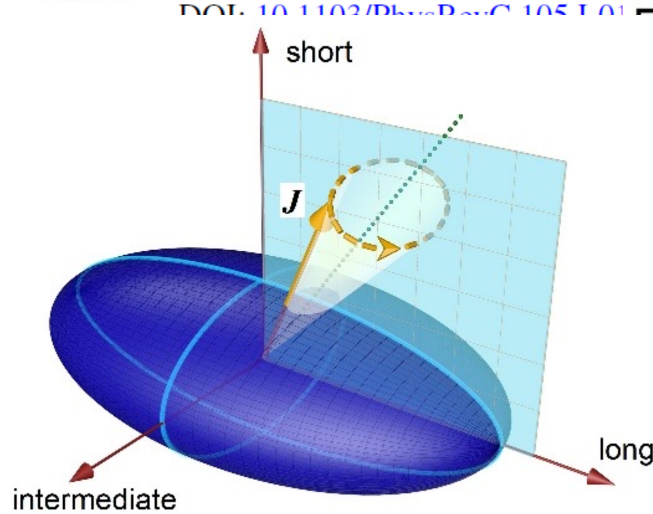
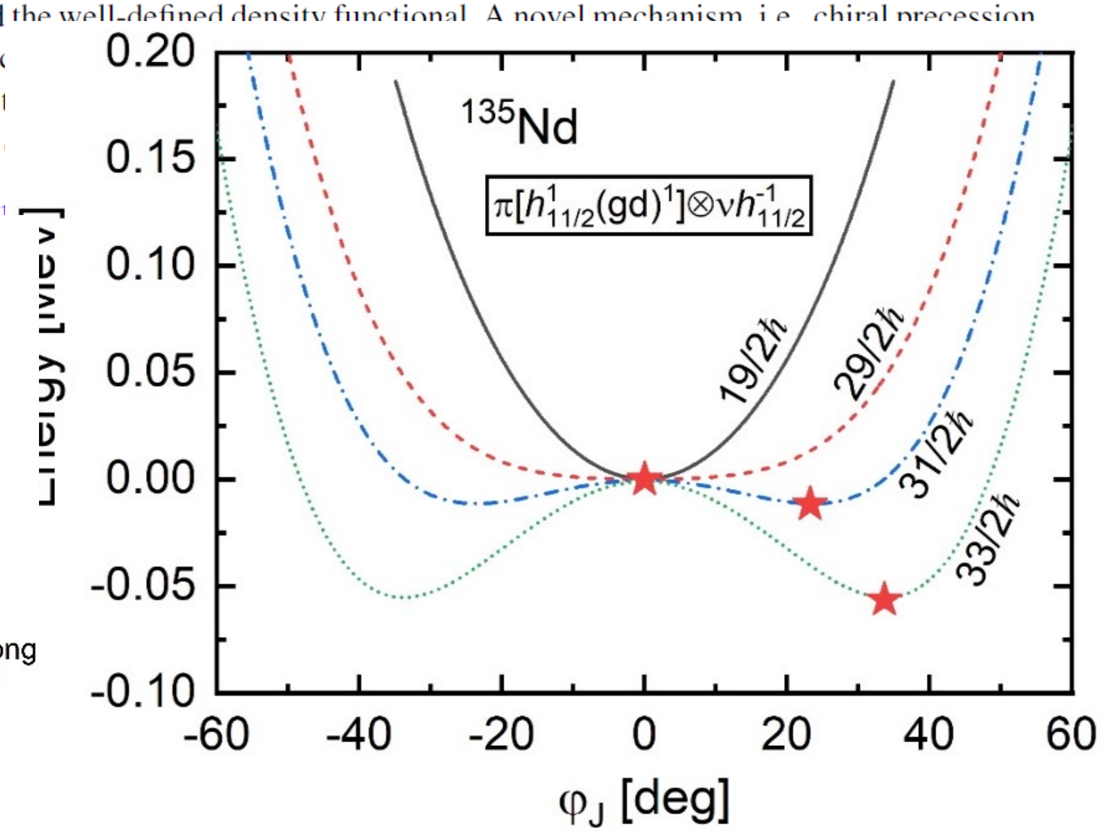
(Received 28 June 2021; revised 16 September 2021; accepted 14 January 2022; published 31 January 2022)

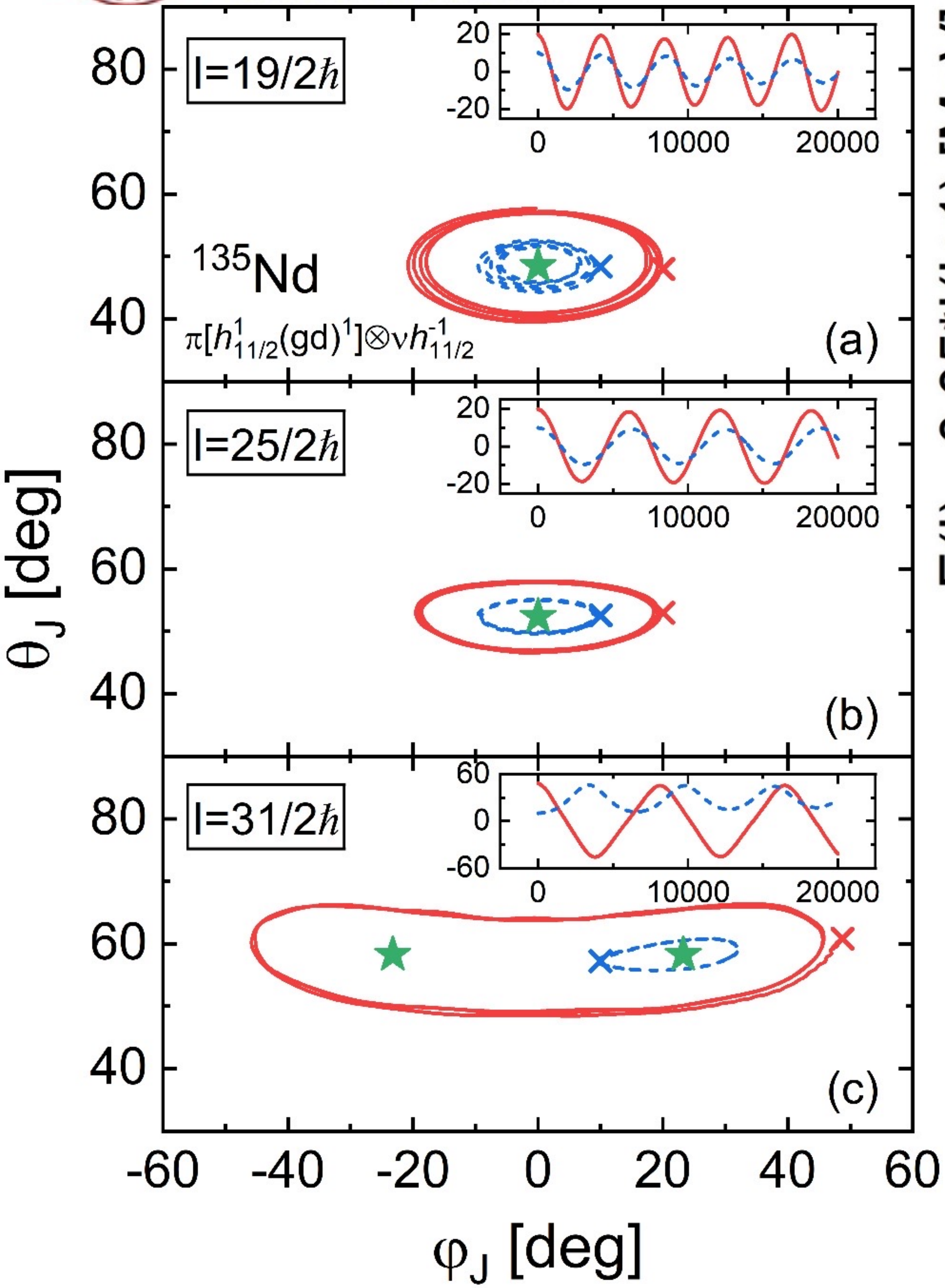
The dynamics of chiral nuclei is investigated for the first time with the time-dependent and tilted axis cranking covariant density functional theories on a three-dimensional space lattice in a microscopic and self-consistent way. The experimental energies of the two pairs of the chiral doublet bands in ^{135}Nd are well reproduced without any adjustable parameters beyond the well-defined density functional. A novel mechanism, i.e., chiral precession, is revealed from the microscopic ... harmonicity is associated with a ... provides a fully microscopic and ...

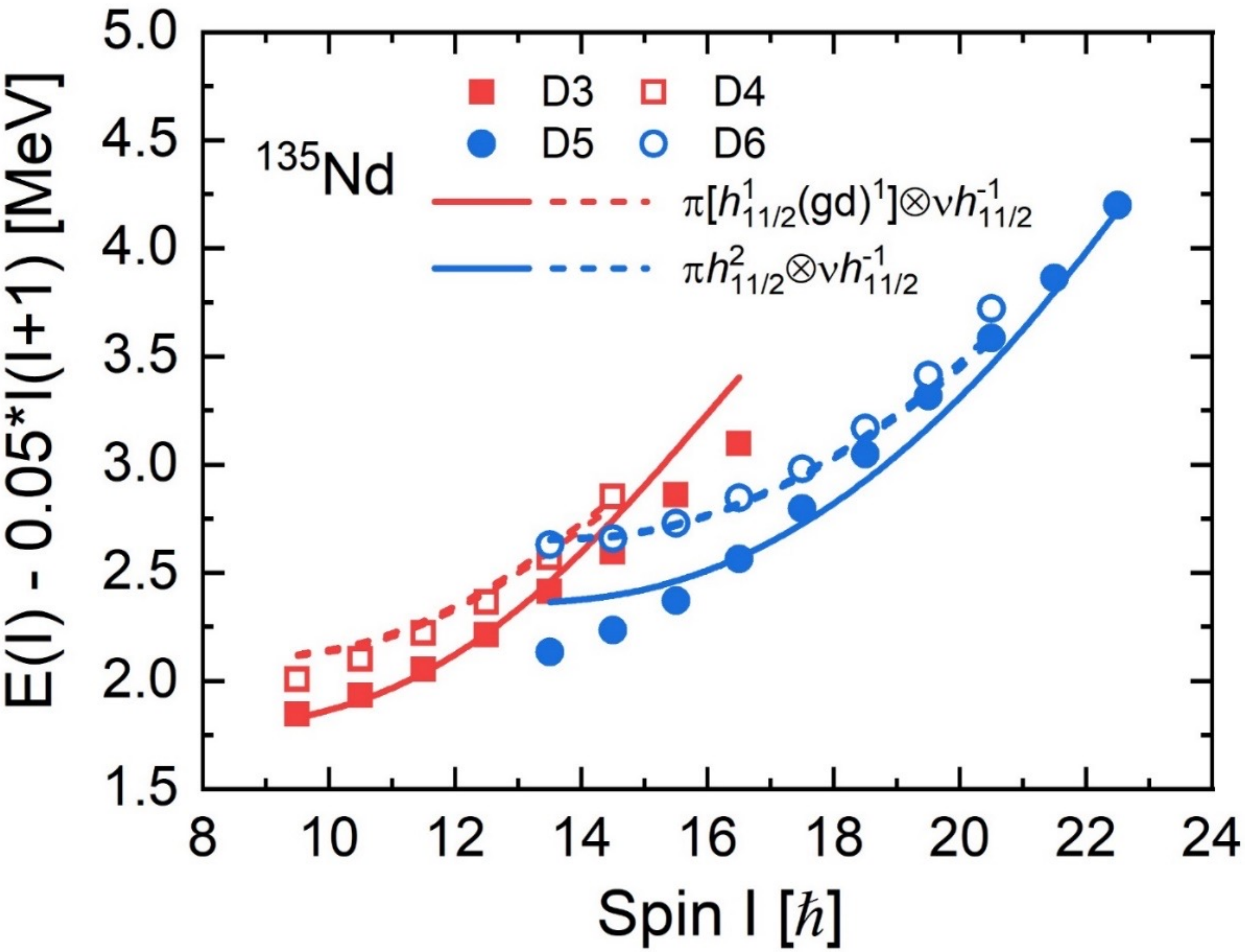




- 随着自旋 I 增加, 总能量相对于角动量倾斜角 φ_J 的位能曲线逐渐变软, 当自旋 $I \geq 31/2\hbar$, 系统出现三维转动.

角动量倾斜角的演化轨迹

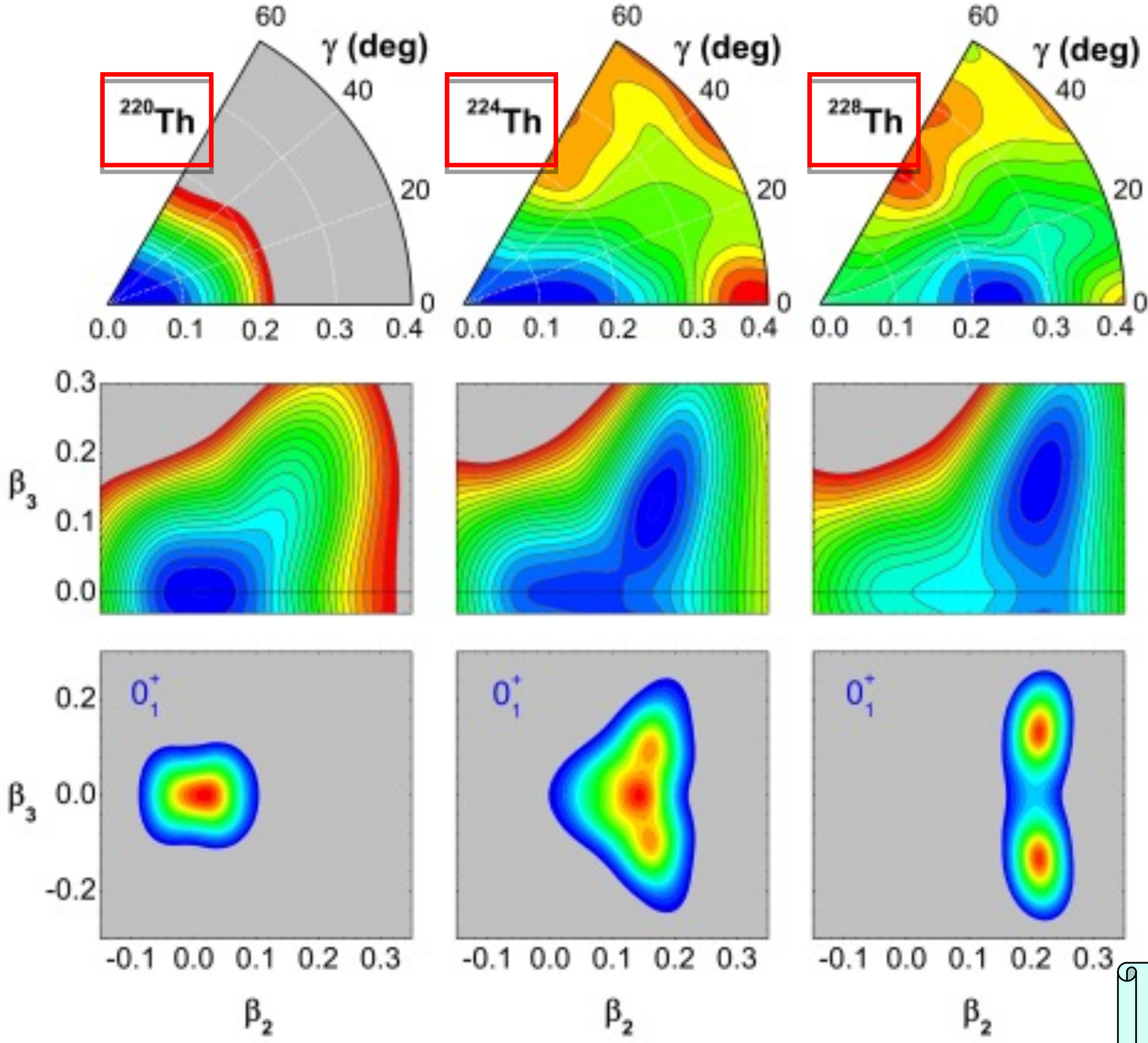




- 结合推转和 TDCDFT 含时演化提取出振动能量, 可以描述手征晕带和伴带
- 理论计算再现了手征双带 D3&D4 和 D5&D6 的实验能谱

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