北京大學

CRC 110 Celebrating Meeting

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Nuclear structure at New Facilities with Rare Isotope Beams

Jie MENG （孟 杰）

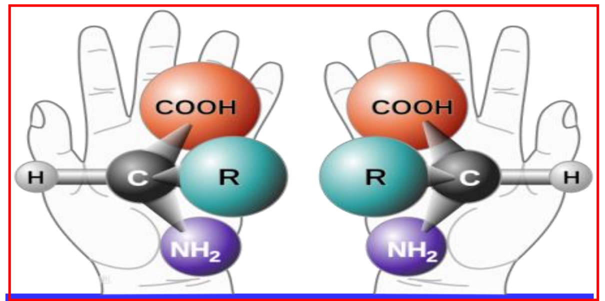
School of Physics，Peking University（北京大学物理学院）

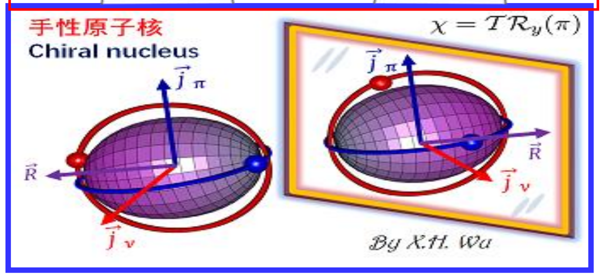
Collaborative Research Centre

国家自然科学基金委员会 National Natural Science Foundation of China

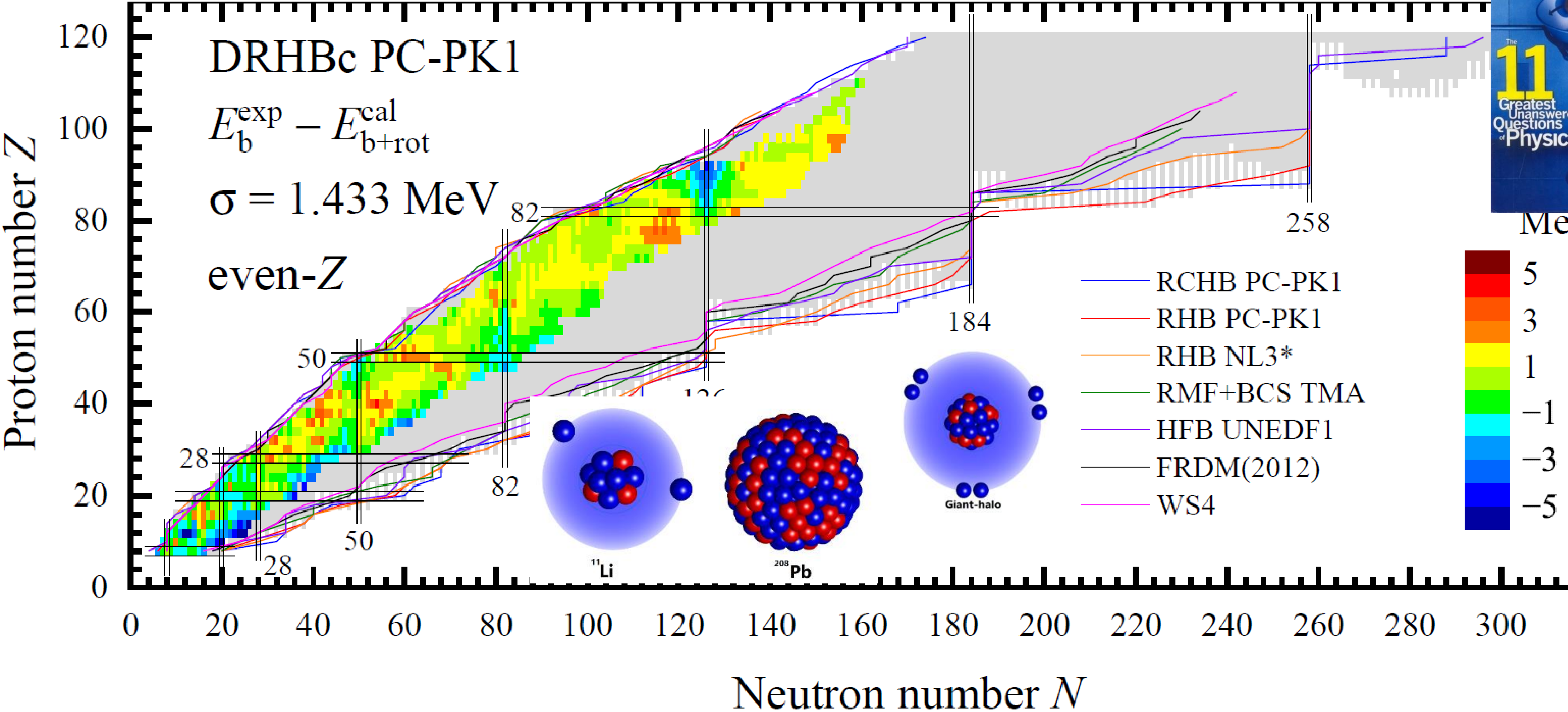
DFG Deutsche Forschungsgemeinschaft

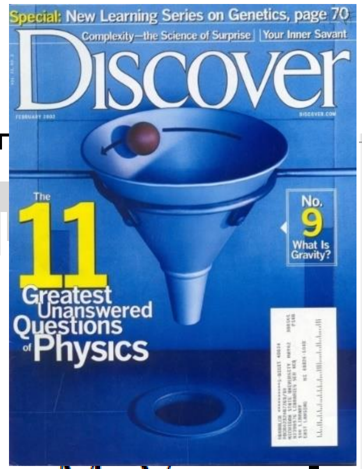
Existence Limit of nuclei

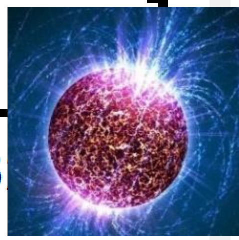




■	stable nuclei	~ 300 nuclei
□	unstable nuclei observed	~ 2700 nuclei
—	drip-lines（predictions)	~10000 nuclei
=	magic numbers	





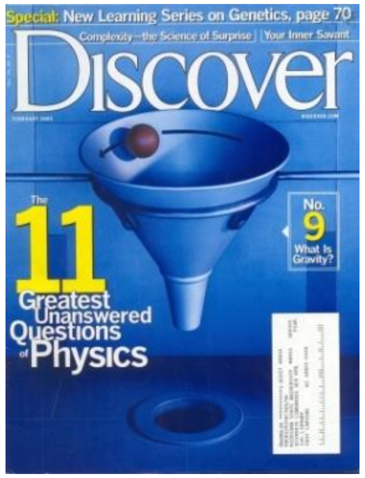


PC-PK1 + DRHBc : 4829 bound even-*Z* nuclei with 8 ≤ Z ≤ 120

DRHBc Collaboration, **At. Data Nucl. Data Tables** 144, 101488 (2022)

How were the heavy elements from iron to Uranium made？

Discovery： "11 greatest unanswered questions of Physics"

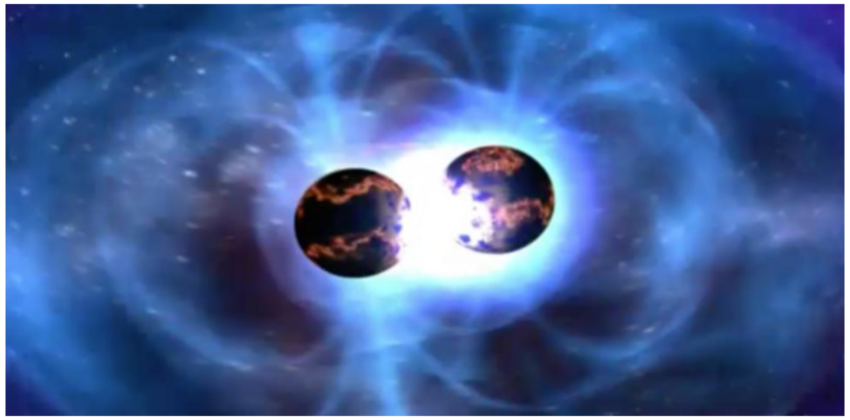


Key mechanism： rapid neutron capture process (r-process)

r-process sites

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

ApJL 848, L12 (2017)

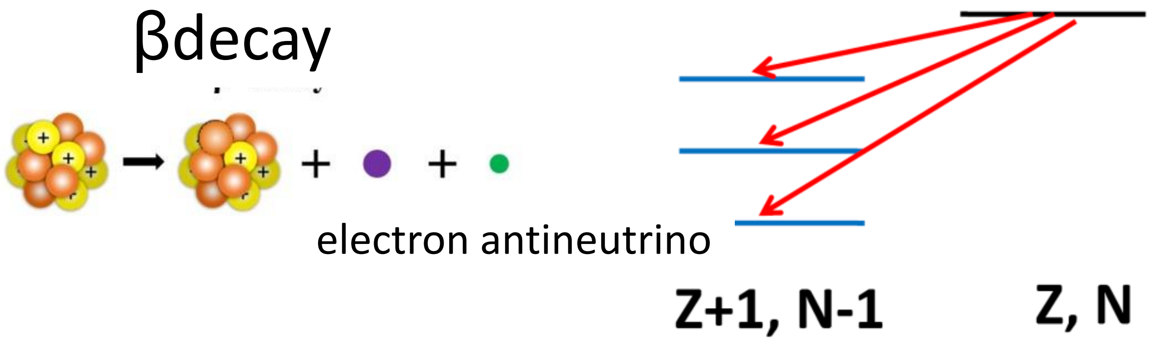


big process in nucleosynthesis study

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

Accurate description: difficult problem in nuclear physics

Gamow-Teller transition



key： difficulties in experiments

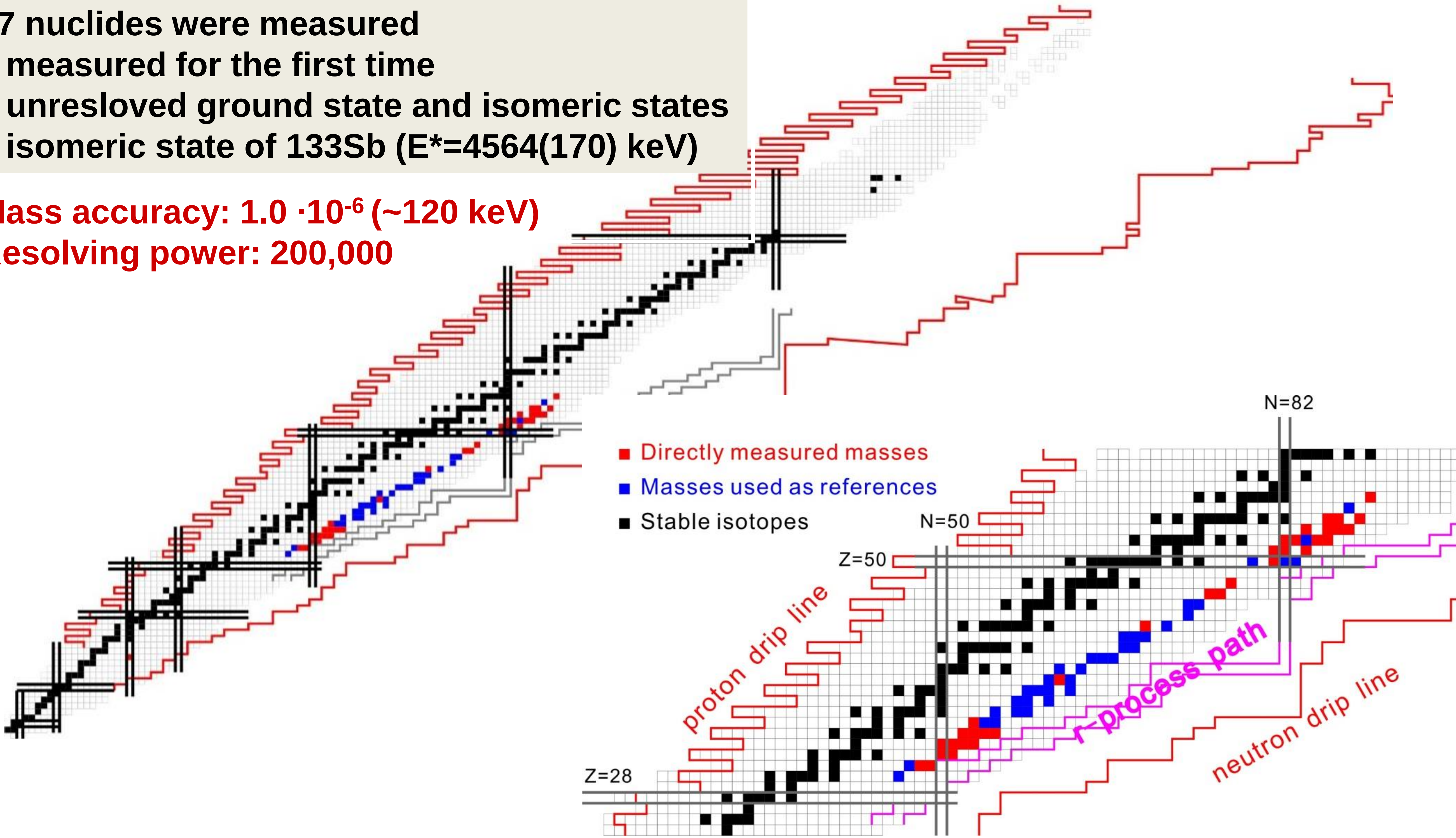
Large-scale accurate theoretical calculations nuclear are demanded

Mass measurement

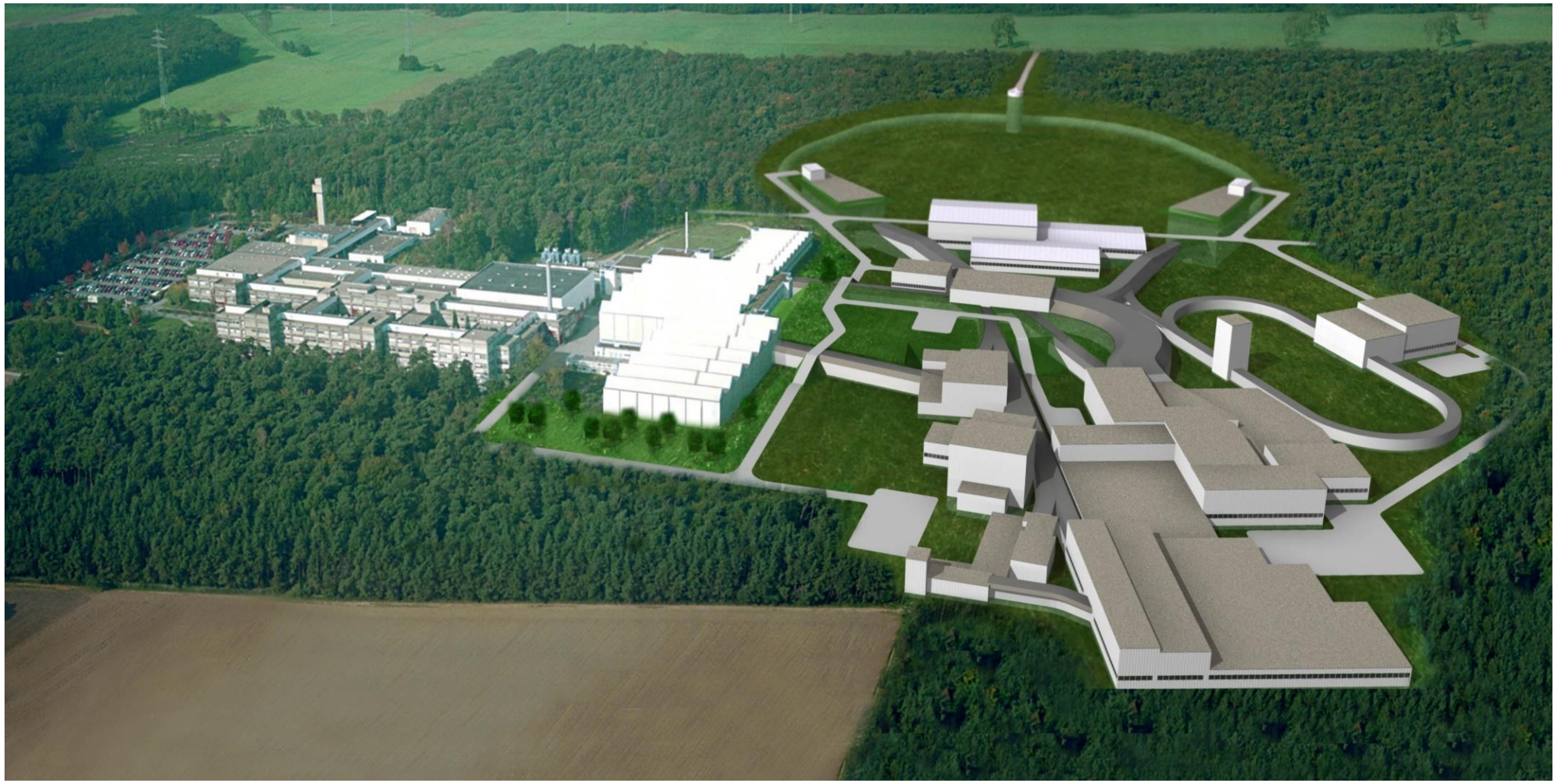
Short-Lived Neutron-Rich Nuclei with the Novel Large-Scale Isochronous Mass Spectrometry at the FRS-ESR Facility Sun et al. NPA 812 (2008) 1-12

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 ·10^{-6} (~120 keV)
Resolving power: 200,000

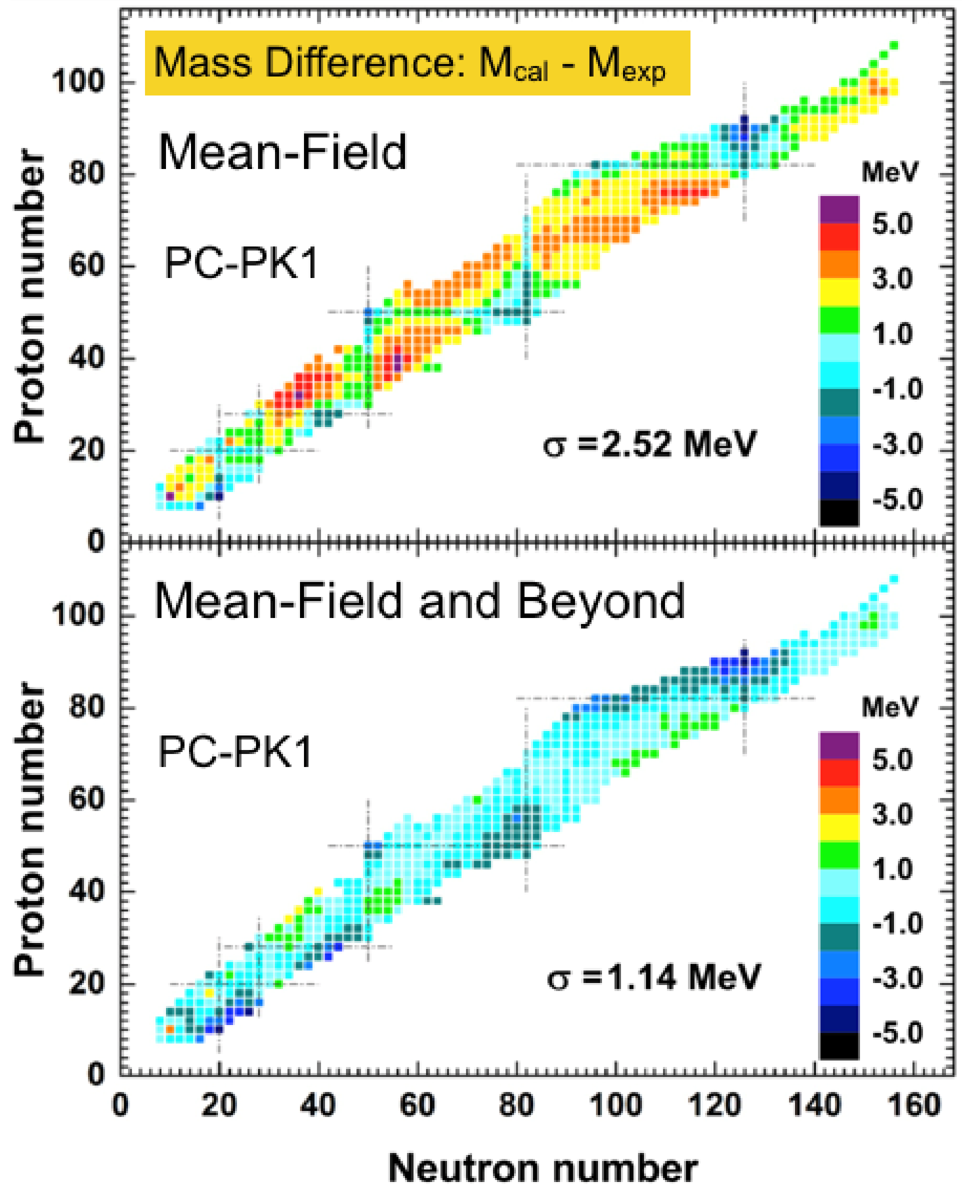


Facility for Antiproton and Heavy Ion Research (FAIR) Darmstadt

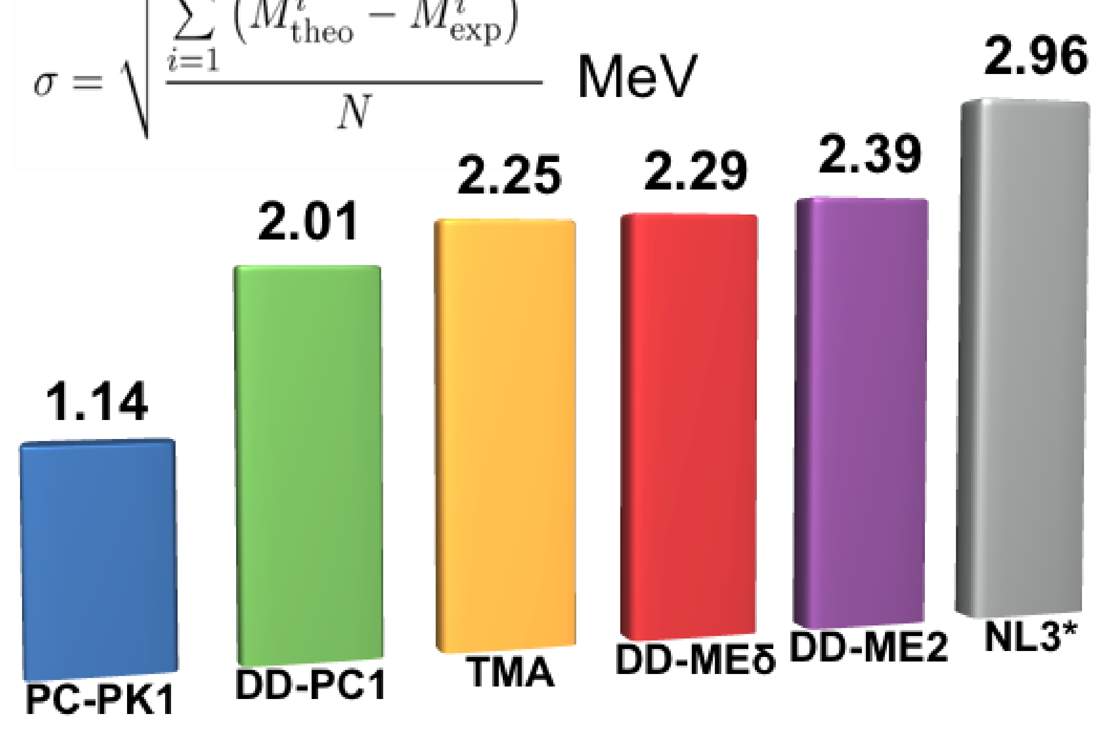


- Relativistic Density Functional
- Physics close to the drip-line
- DRHBc mass table collaboration
- Physics along N=Z nuclei
- Relativistic density functional theory in 3D lattice
    - Linear alpha-chain
    - Nuclear fusion
    - Nuclear fission
    - Chiral dynamics
- ReCD theory
- Toward Relativistic ab initio DFT

Relativistic functional PC-PK1



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



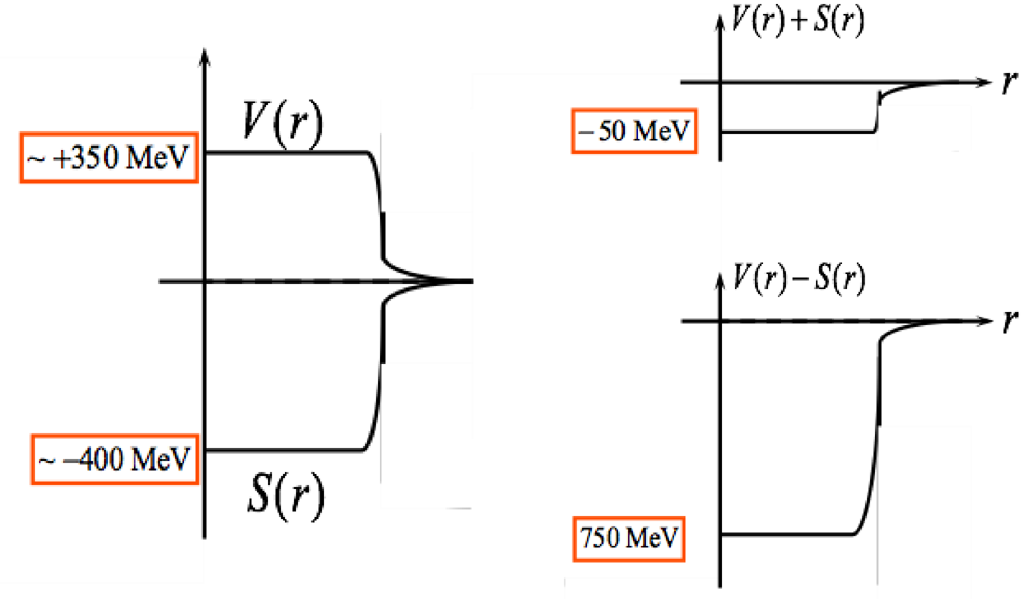
Why relativistic?

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

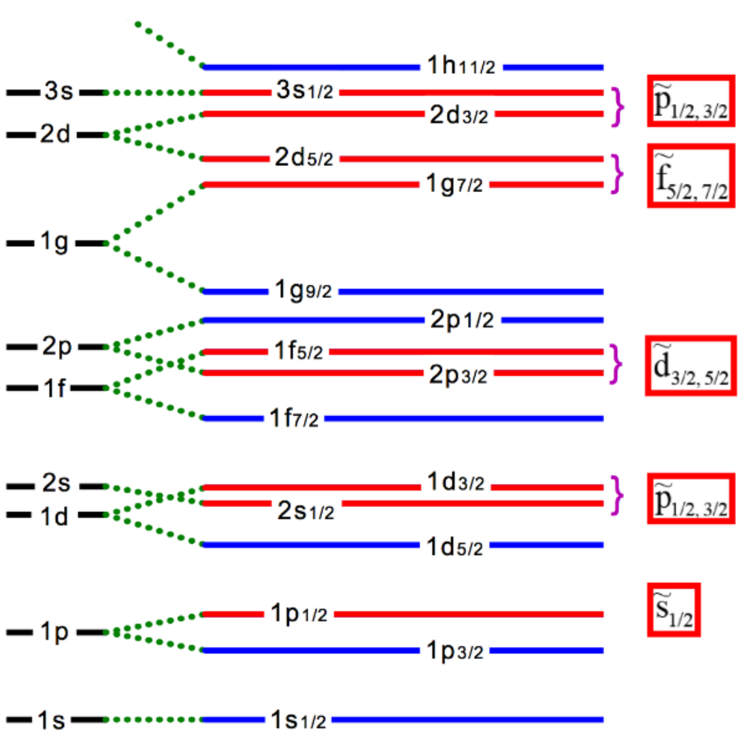
Relativistic Density Functional for Nuclear Structure

Meng (Ed.), World Scientific, Singapore (2016)

- ✓ 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



$\tilde{p}_{1/2,3/2}$, $\tilde{f}_{5/2,7/2}$, $\tilde{d}_{3/2,5/2}$, $\tilde{p}_{1/2,3/2}$, $\tilde{s}_{1/2}$

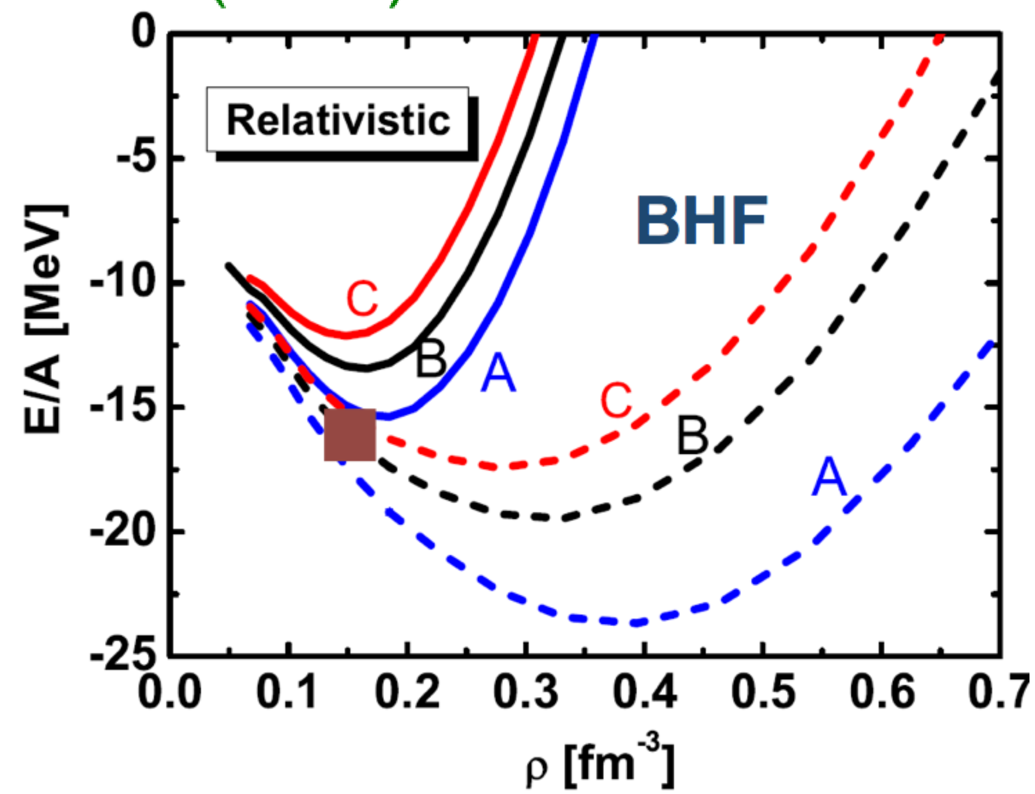
$$\begin{array}{lll} n-1, & l+2, & j=l+3/2 \\ n, & l, & j=l+1/2 \end{array}$$

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

Hecht & Adler NPA137(1969)129

Arima, Harvey & Shimizu PLB 30(1969)517

Ginocchio PRL 78, 436



Brockmann & Machleidt, PRC42, 1965 (1990)

Relativistic Density Functional Theory

Relativistic Density Functional for Nuclear Structure
Meng (Ed.), World Scientific, Singapore (2016)

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

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

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

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

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

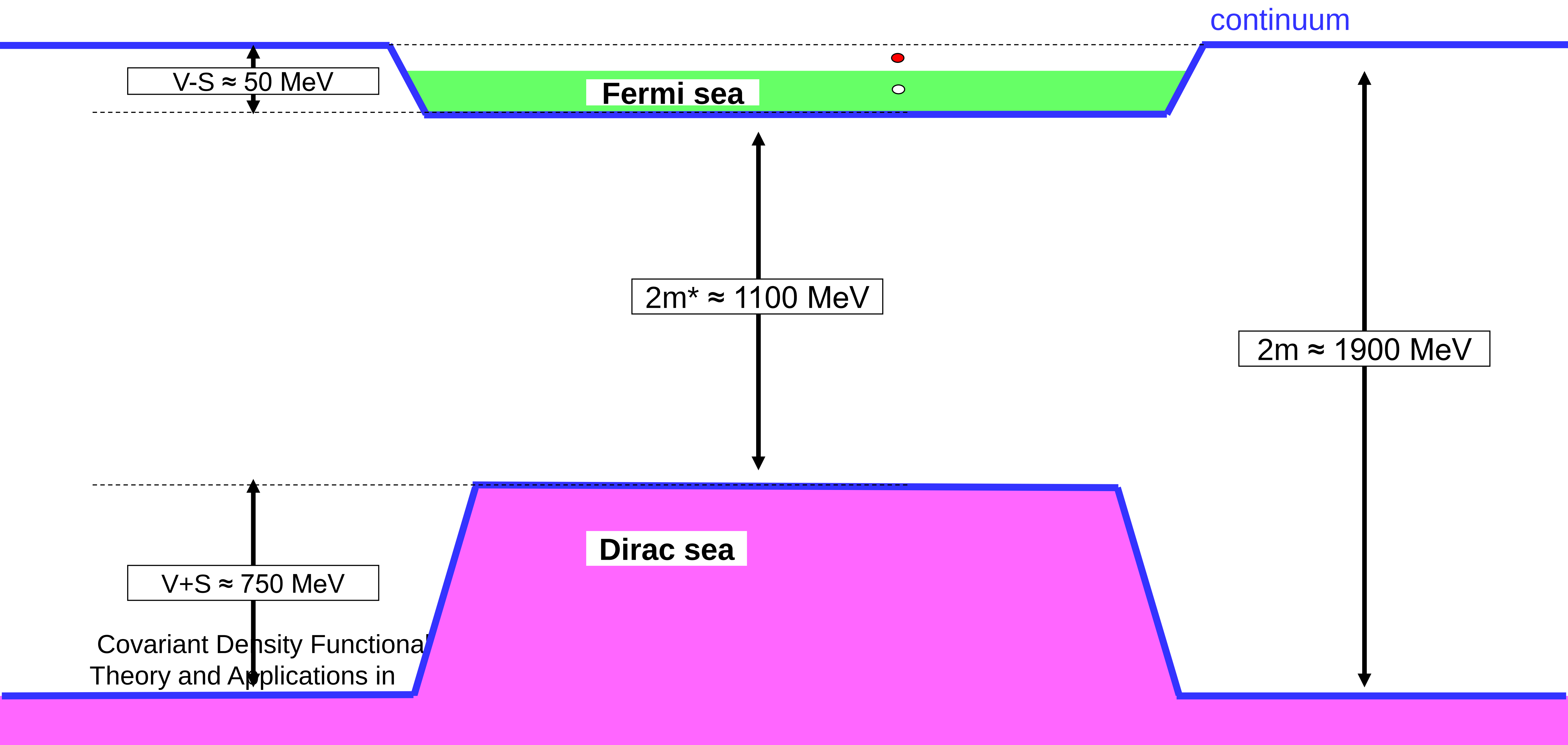
$$E_{em} = \frac{e}{2}\int j_\mu^p A^\mu d\mathbf{r}$$

Dirac equation

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

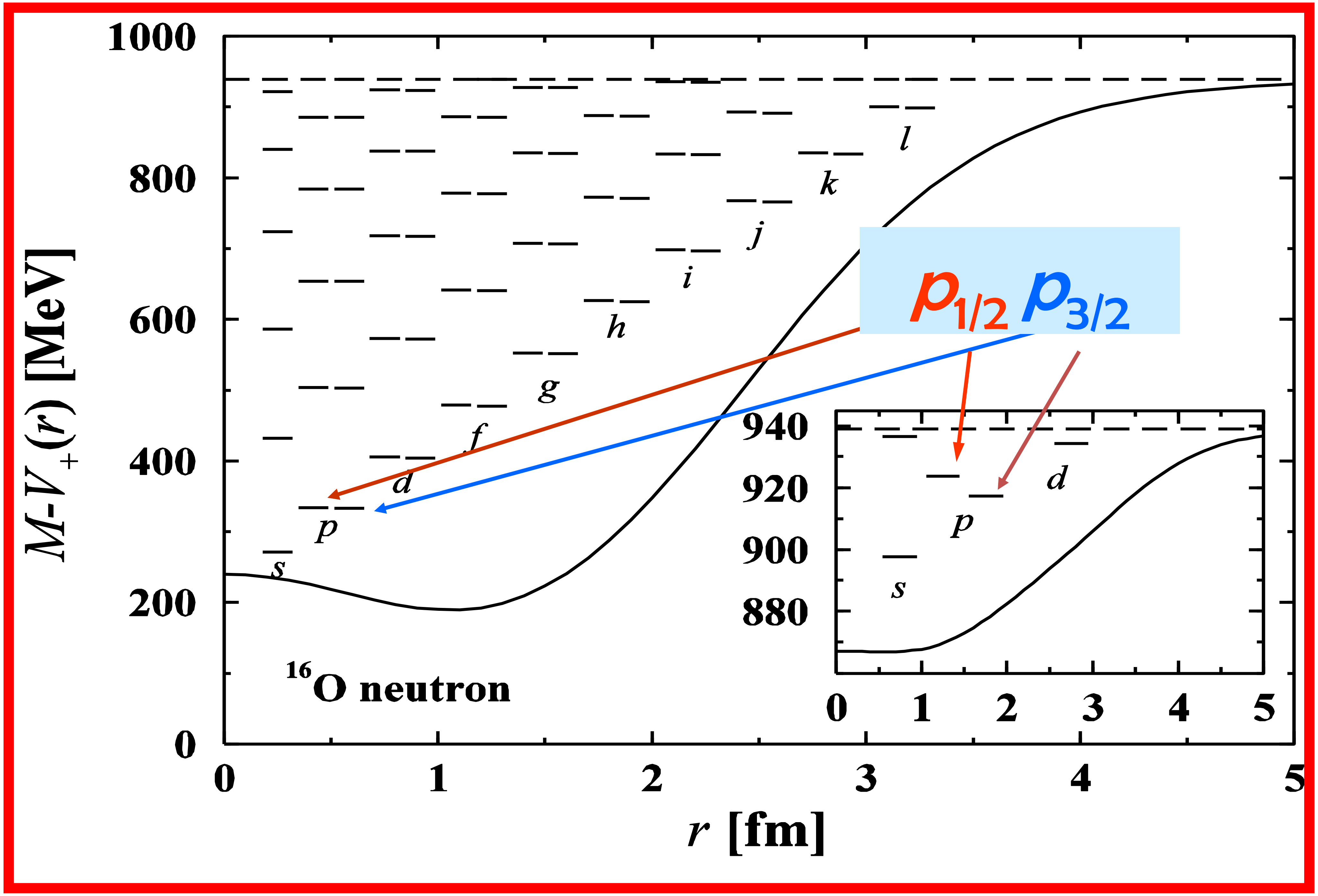
scalar potential: $S(r) \approx -400$ MeV

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



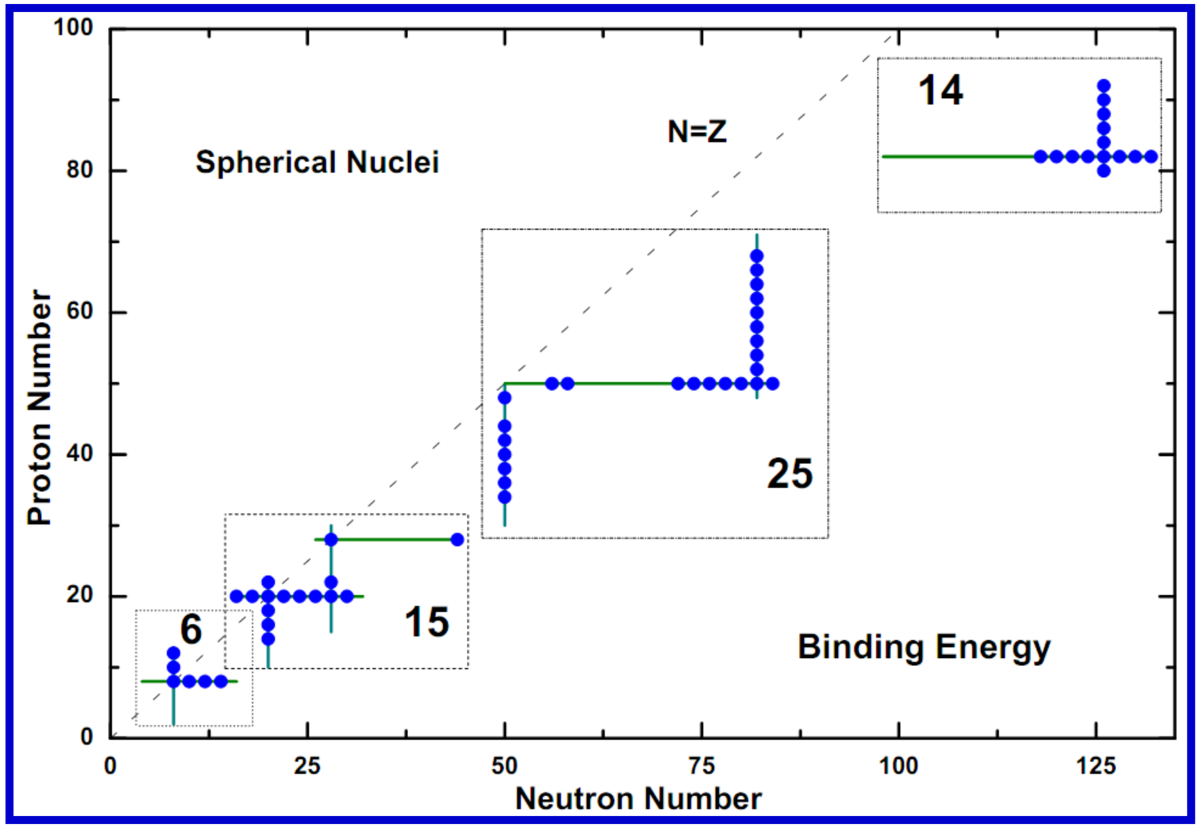
Covariant Density Functional Theory and Applications in

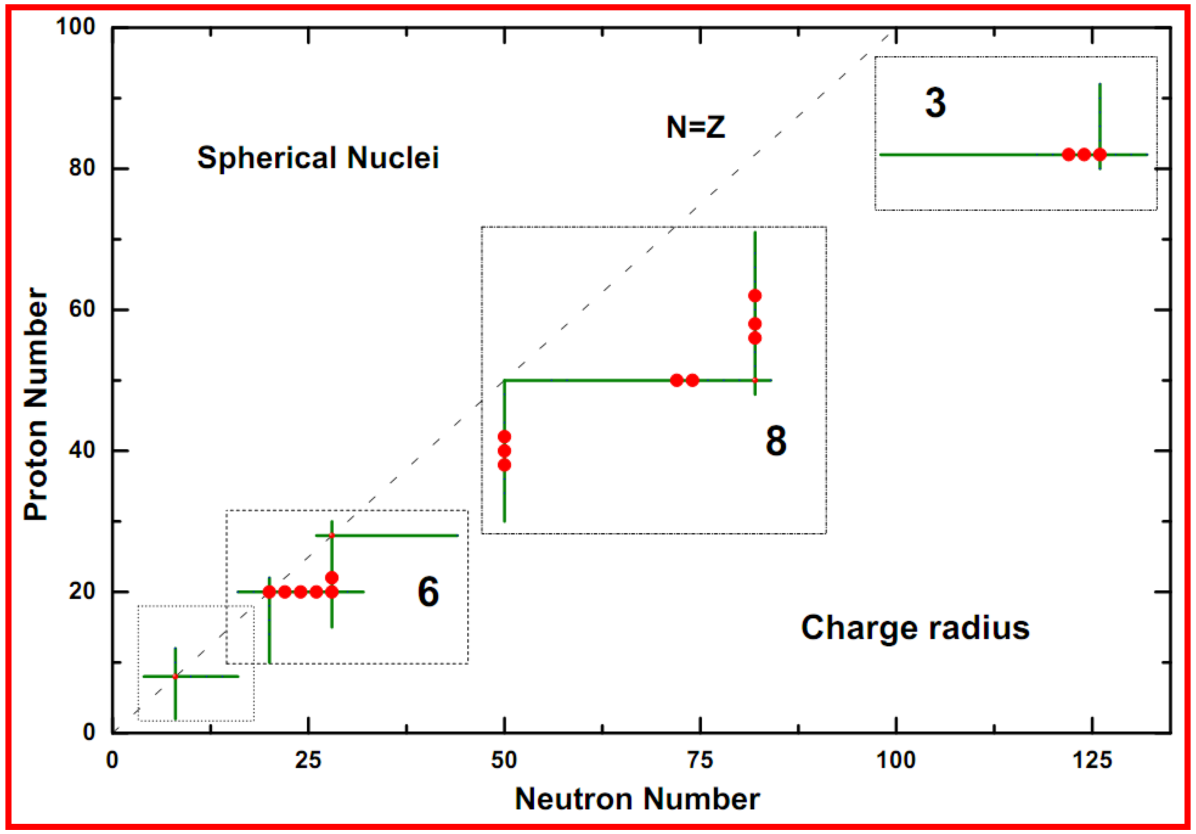
Dirac Sea: Spin symmetry



S. G. Zhou, J. Meng and P. Ring, PRL92(03)262501

Relativistic functional PC-PK1

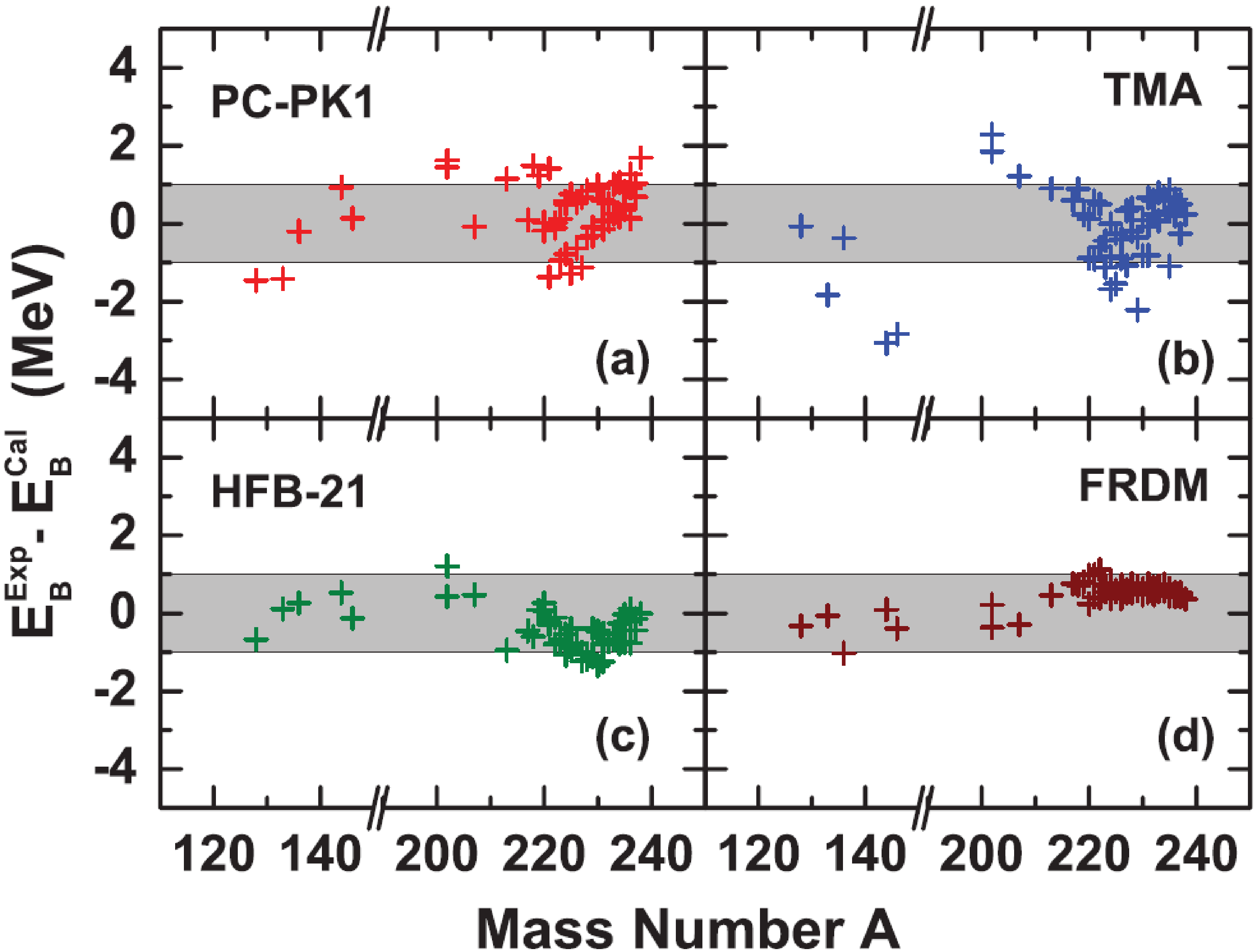




Coupl.	Cons.	PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}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

Predictive power



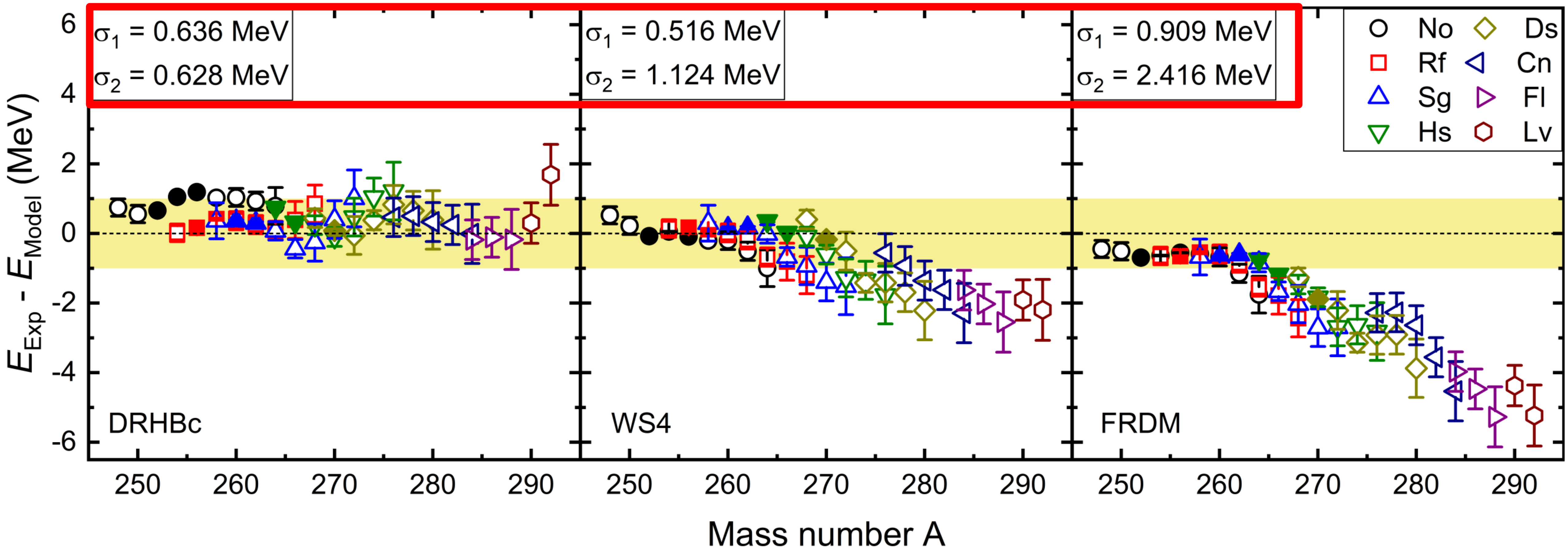
P. W. Zhao, *et al*. Phys. Rev. C, 86 024324 (2012)

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

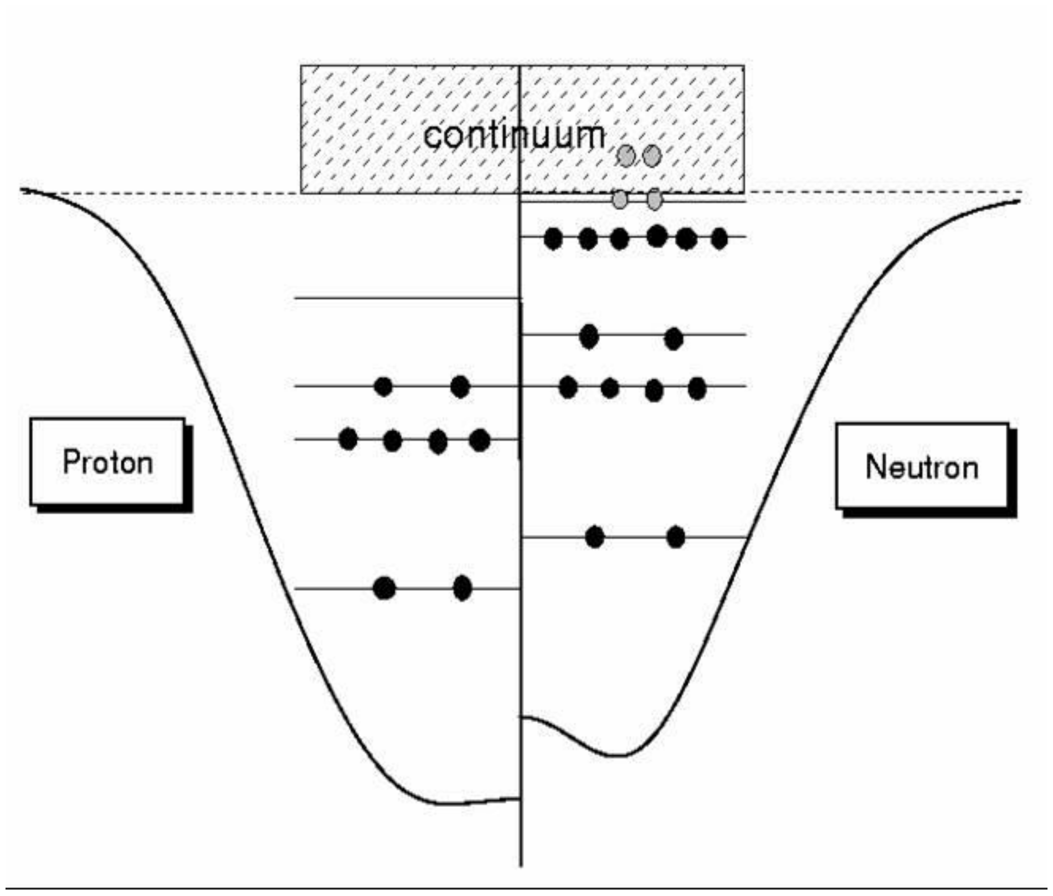


Kaiyuan Zhang, et al

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

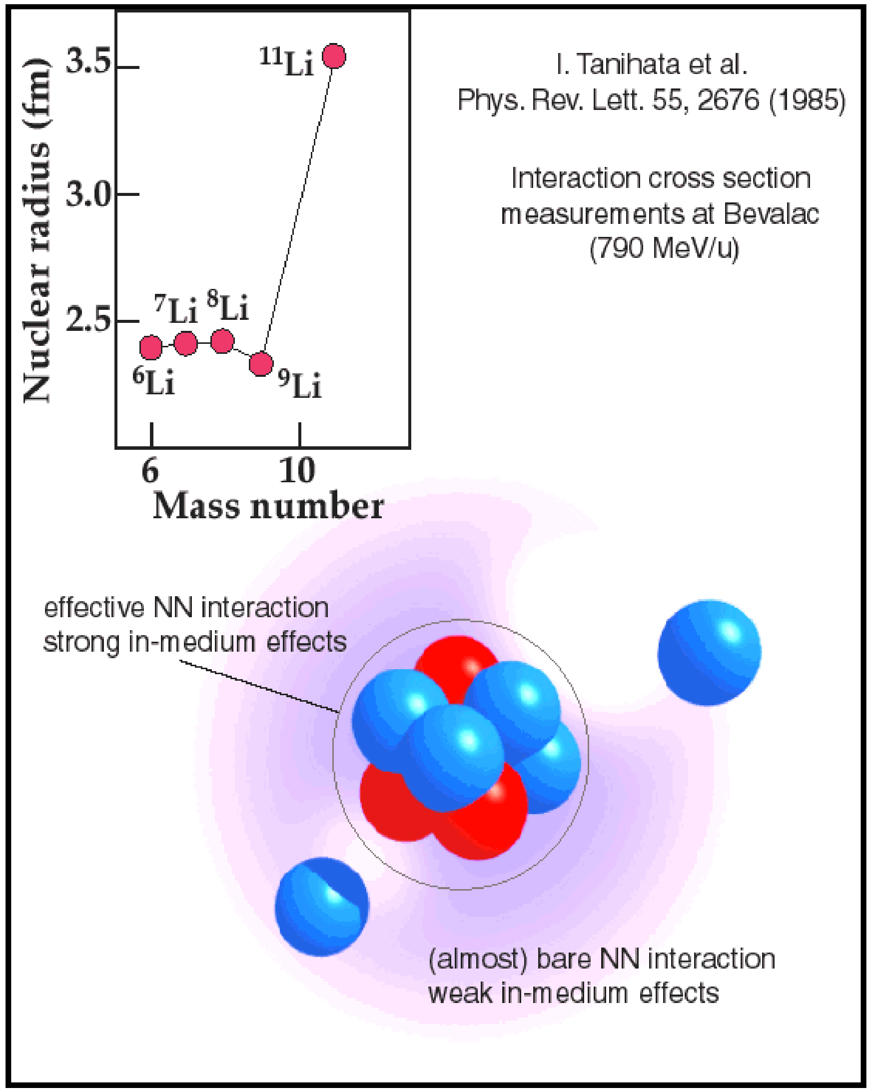
Physics close to the drip-line

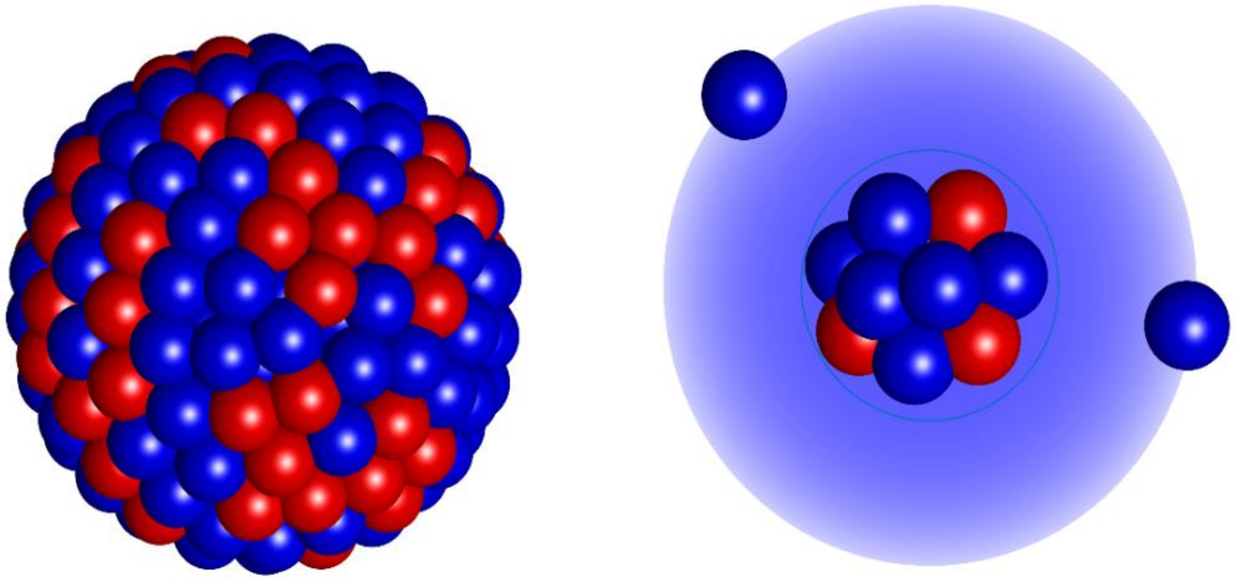


Continuum, deformation, clustering, …

New phenomena in exotic nucleus

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





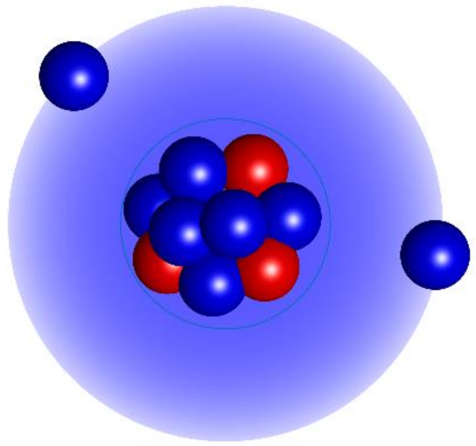
From Xin-Hui Wu

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…

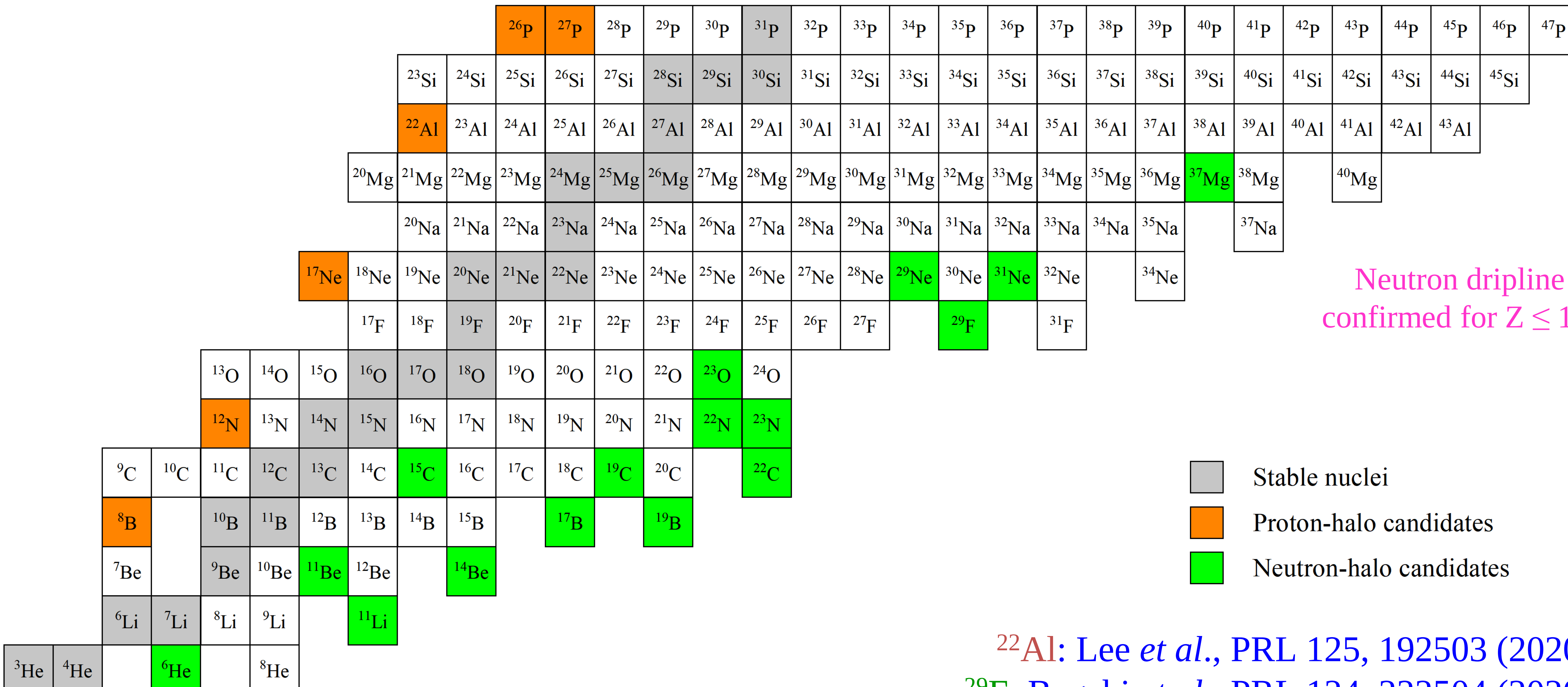
- Meng, Toki, Zhou, Zhang, Long & Geng, Prog. Part. Nucl. Phys. 57 (2006) 470
- Meng and Zhou, J. Phys. G: 42 (2015) 093101

Halo nuclei



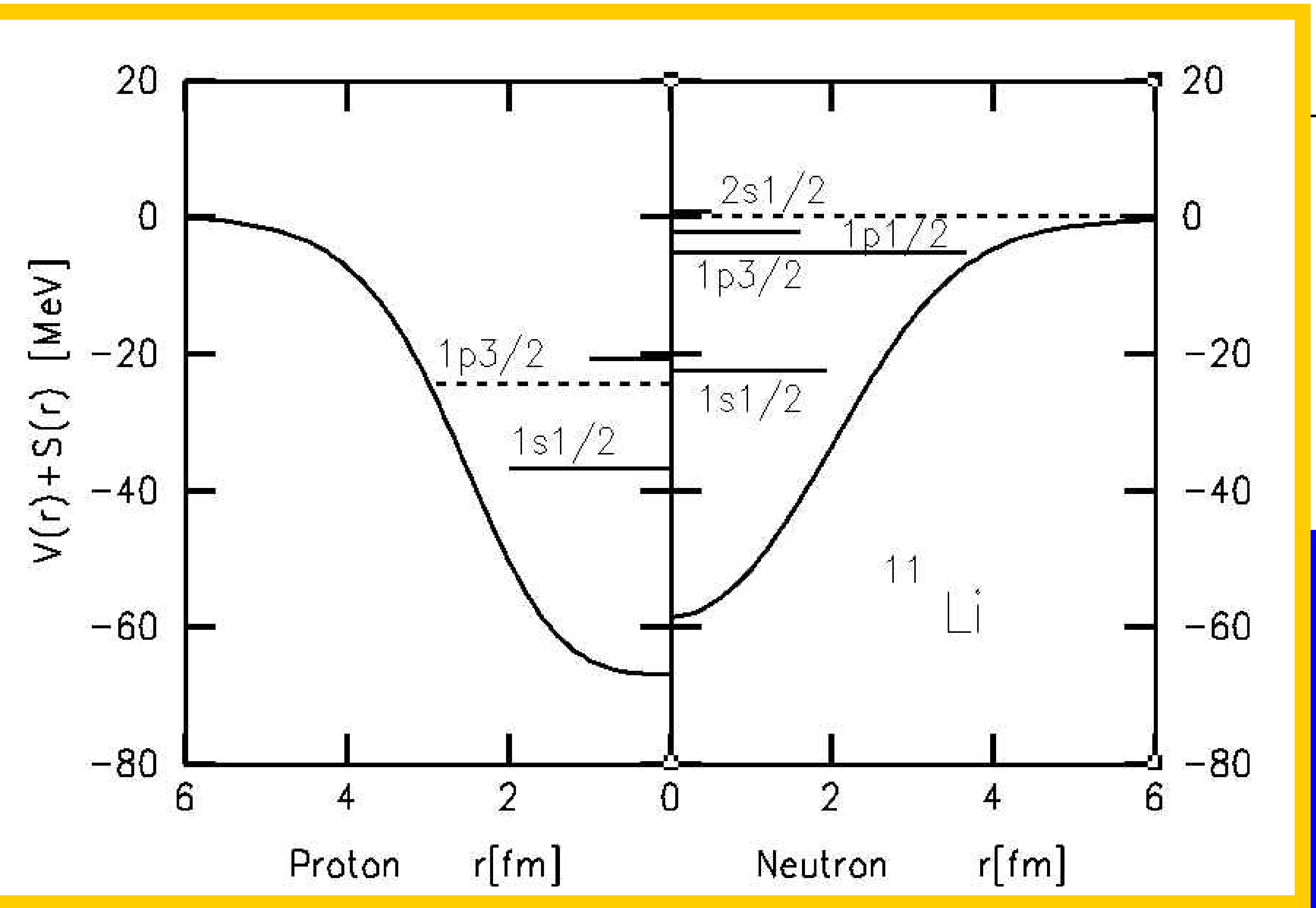
➢ Halo nuclei have attracted lots of attention since the discovery of the halo phenomenon in ^{11}Li.

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



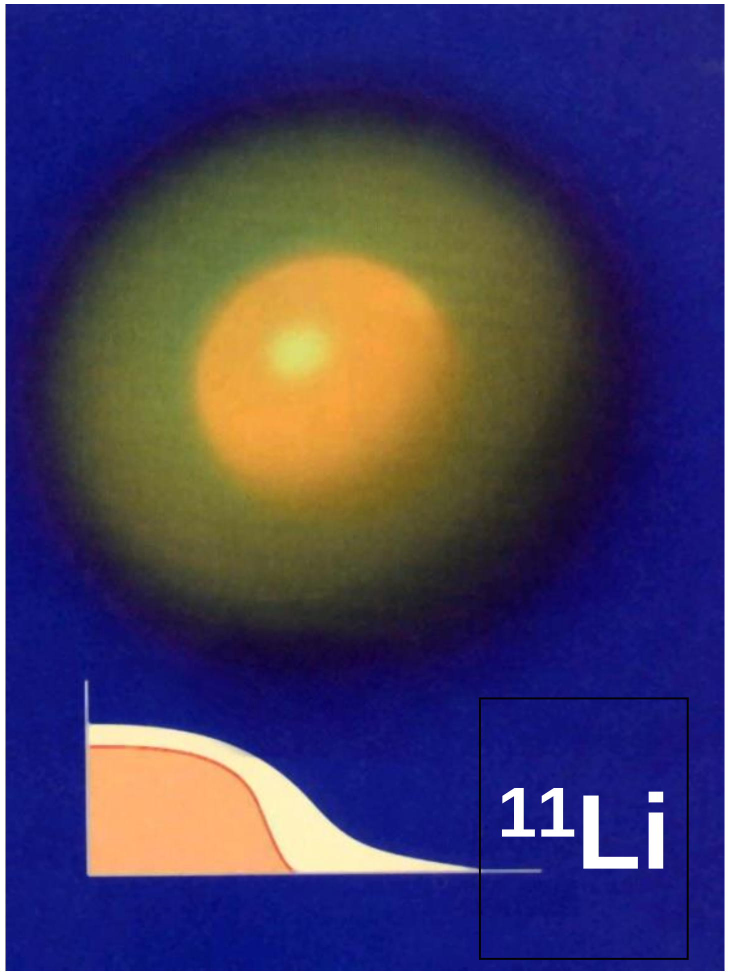
^{22}Al: Lee *et al.*, PRL 125, 192503 (2020)
^{29}F: Bagchi *et al.*, PRL 124, 222504 (2020)
^{37}Mg: Kobayashi *et al.*, PRL 112, 242501 (2014)

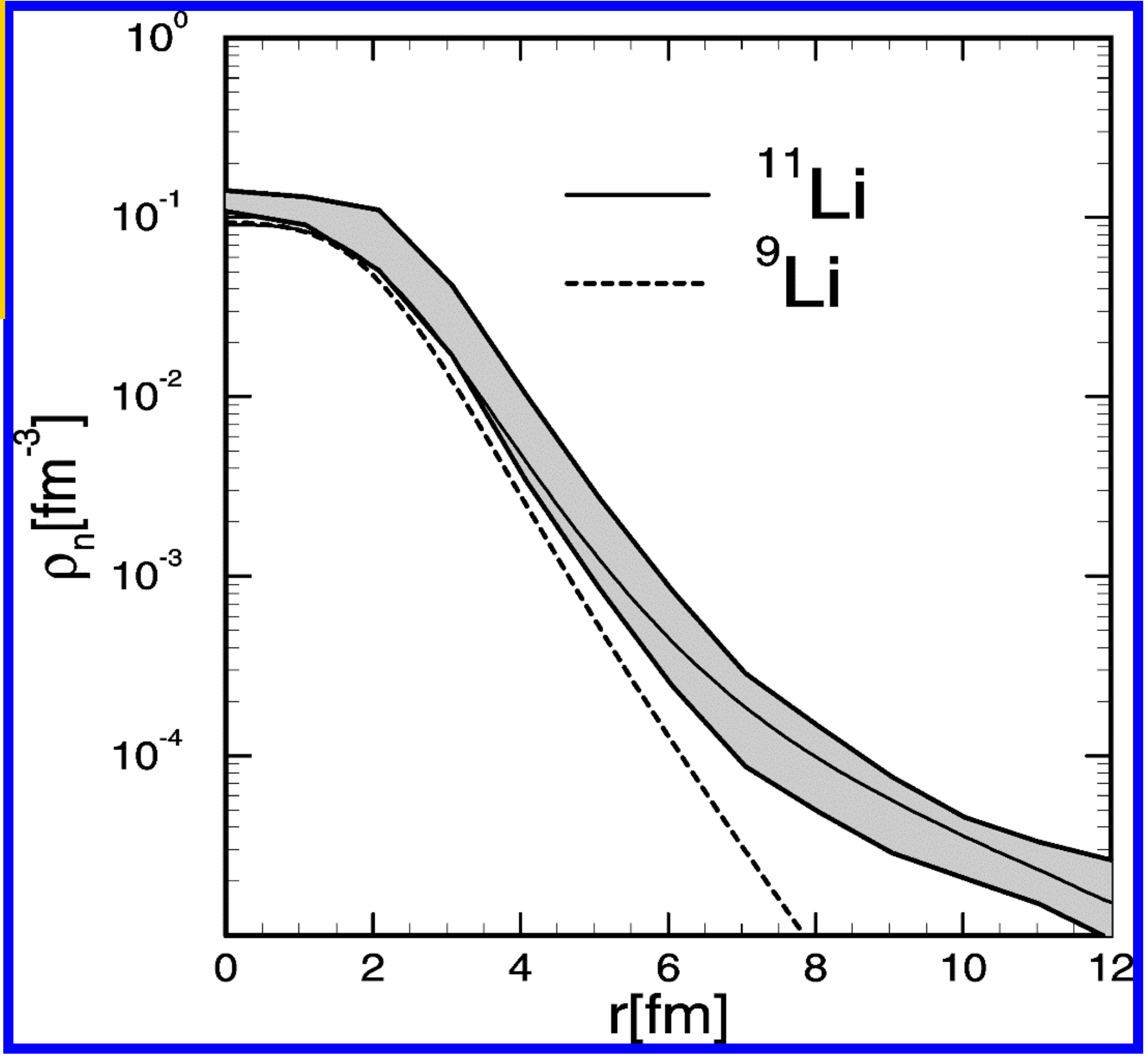
Density in 11-Li



RCHB: Relativist. Continuum Hartree-Bogoliubov theory with

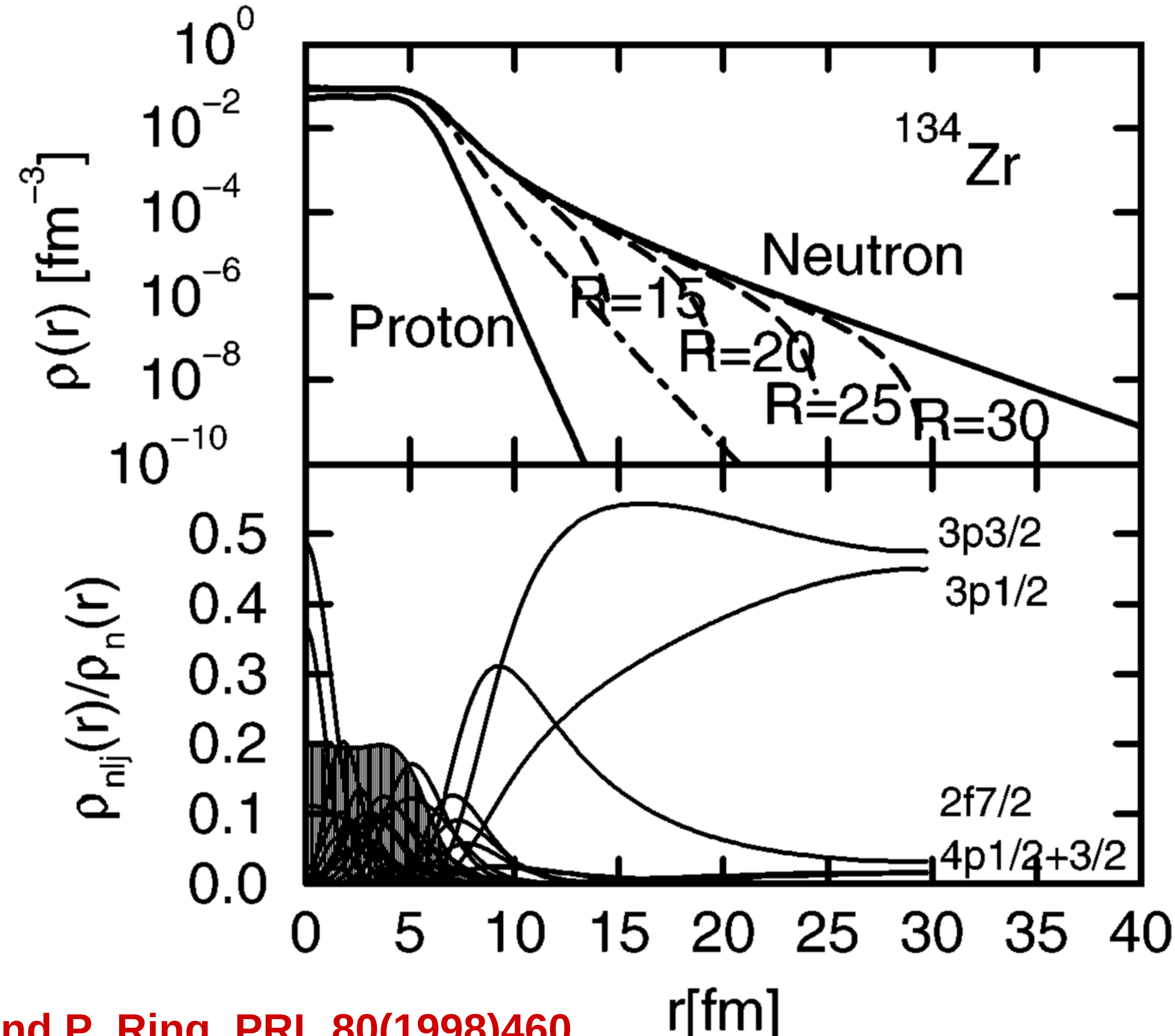
denstiy dependent pairing force





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

Giant halos

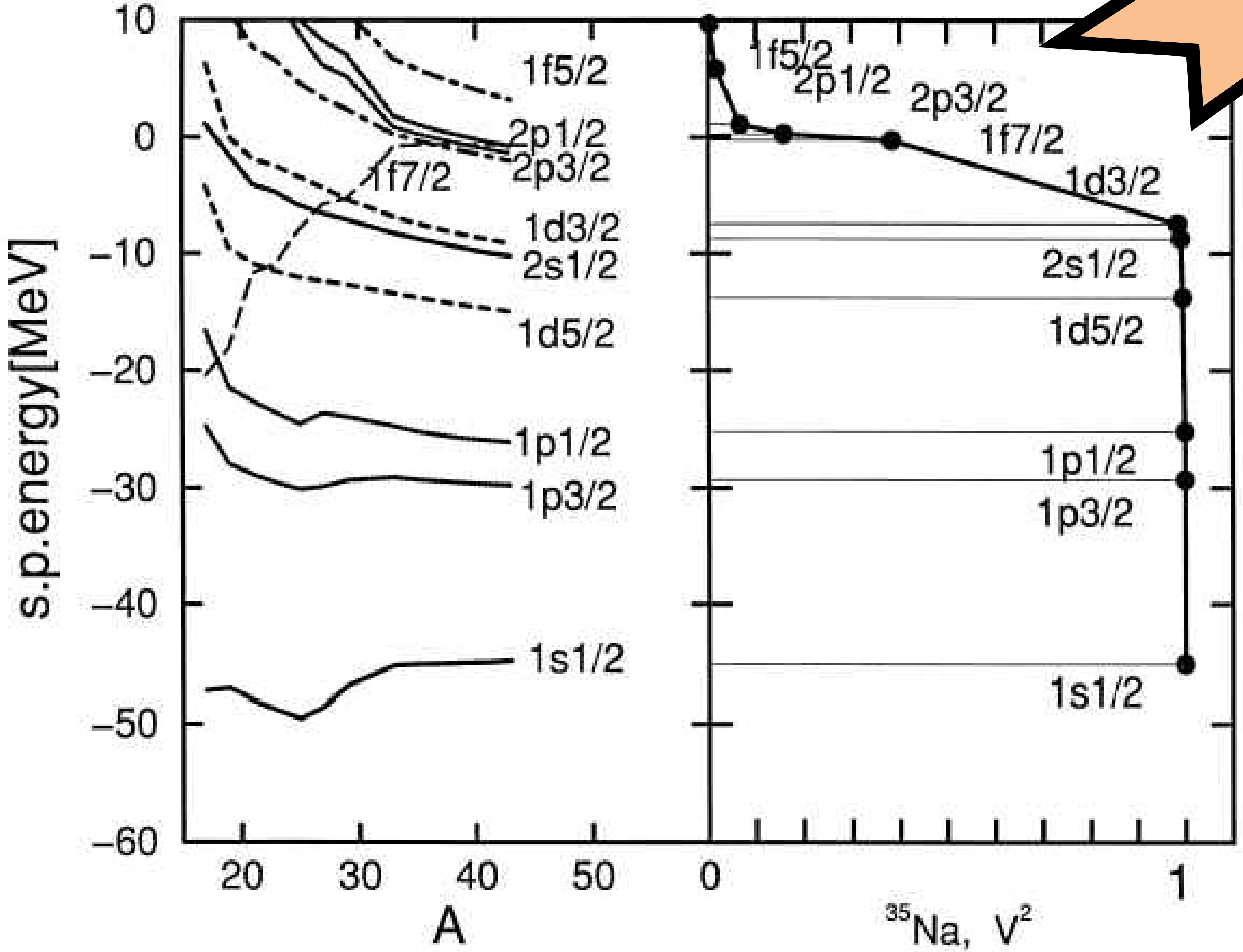


J. Meng and P. Ring, PRL 80(1998)460

Halo in 35-Na

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

Prediction of giant halos in Na isotopes

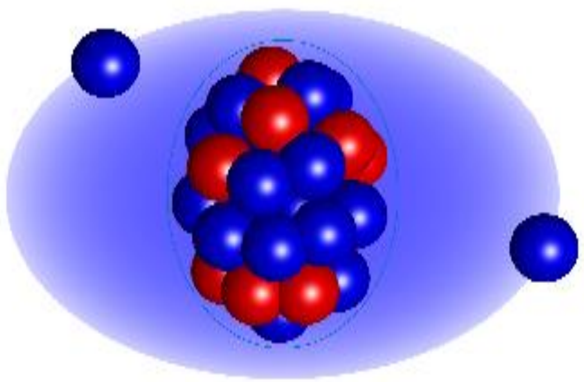


Deformed halos

✓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)

✓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.

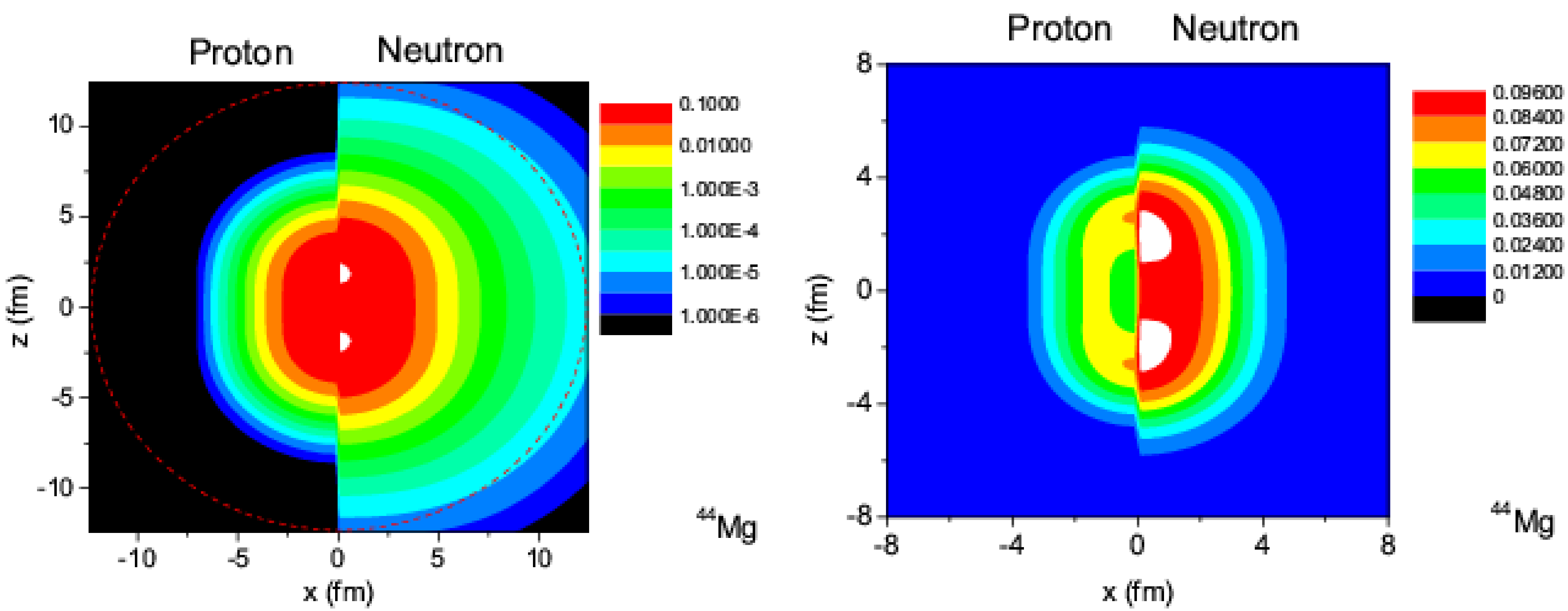
Sun, Zhao, and Zhou, PLB 785, 530 (2018)
Zhang, Wang, and Zhang PRC 100, 034312 (2019)
Sun, Zhao, and Zhou, NPA 1003, 122011 (2020)
Yang *et al.*, PRL 126, 082501 (2021)

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

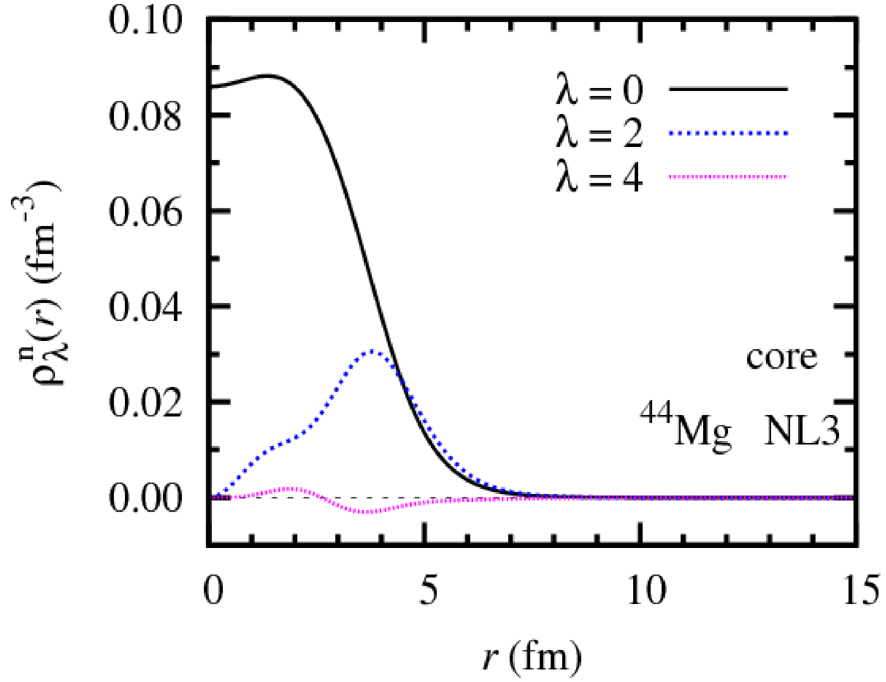
- Prolate deformation
- Large spatial extension in neutron density distribution

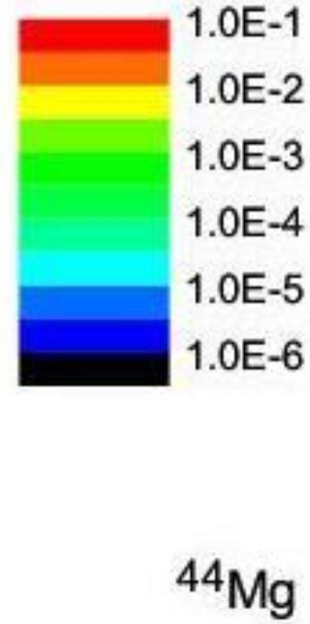


Viewpoint: A Walk Along the Dripline by Paul Cottle and Kirby Kemper
http://link.aps.org/doi/10.1103/Physics.5.49

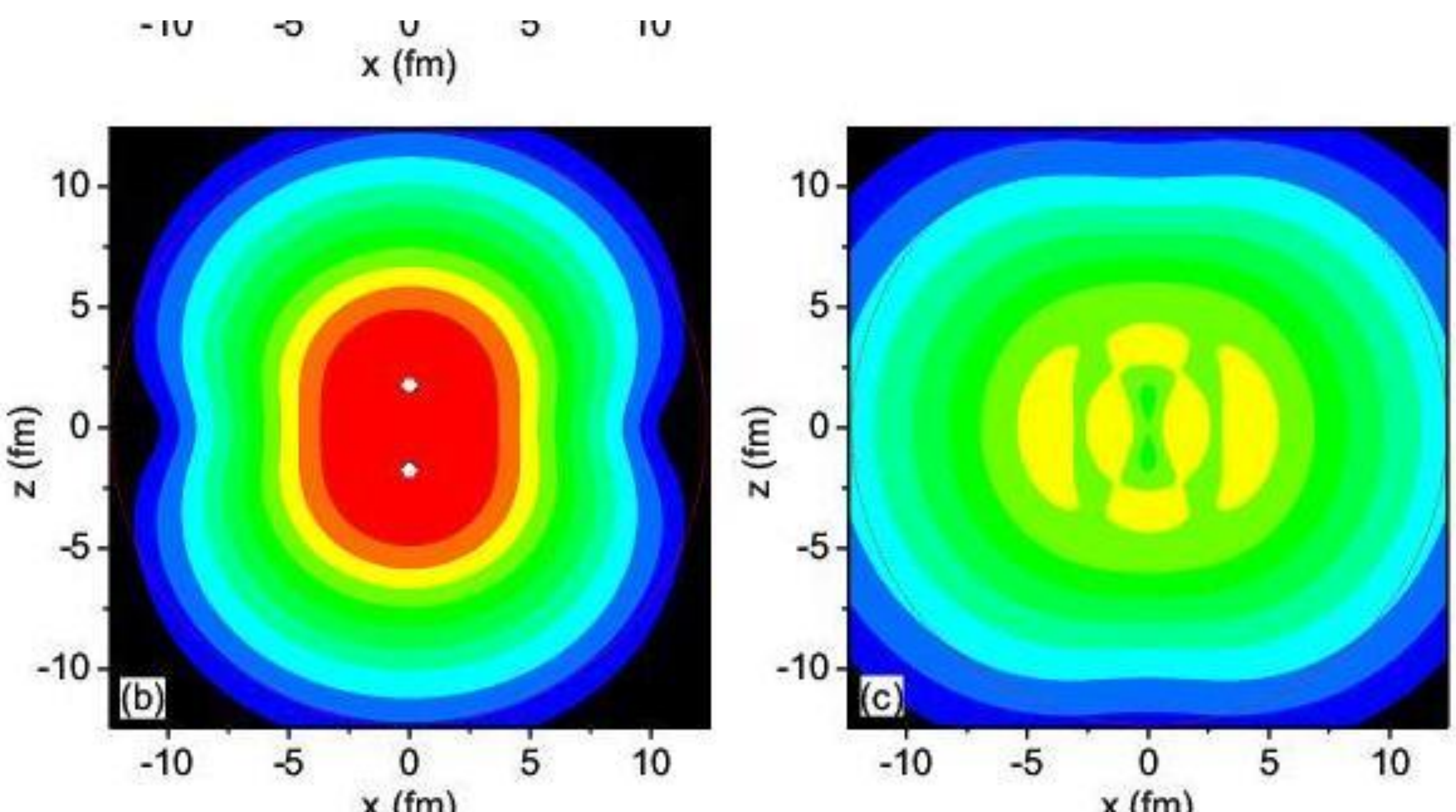
Prolate core & oblate halo

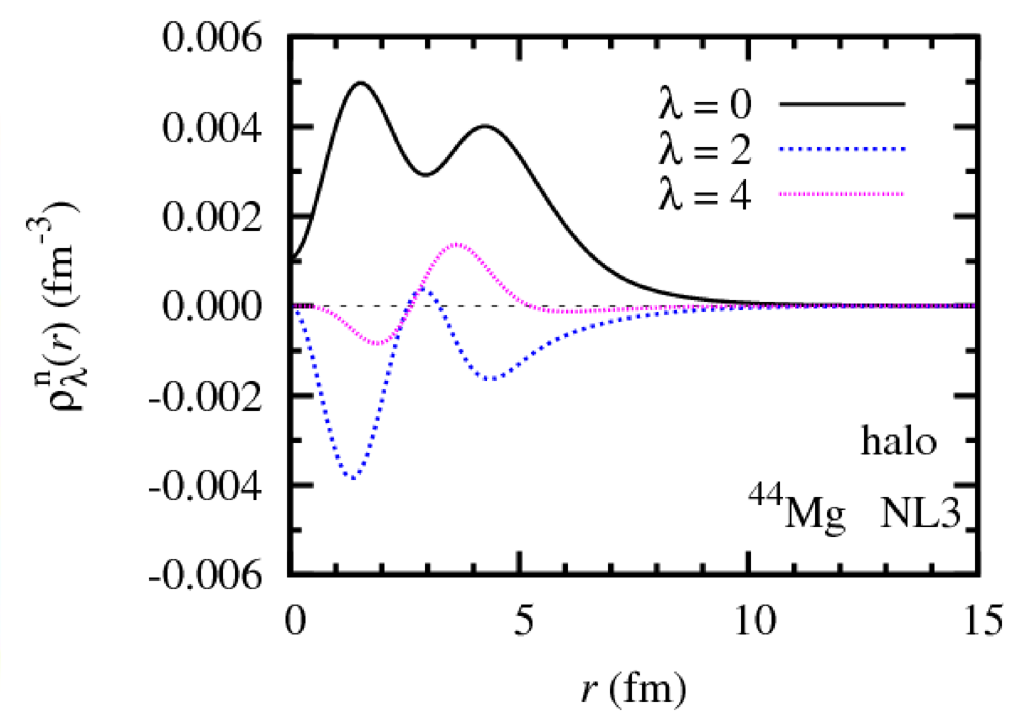
Zhou, Meng, Ring & Zhao, Phys. Rev. C 82, 011301 (2010)





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

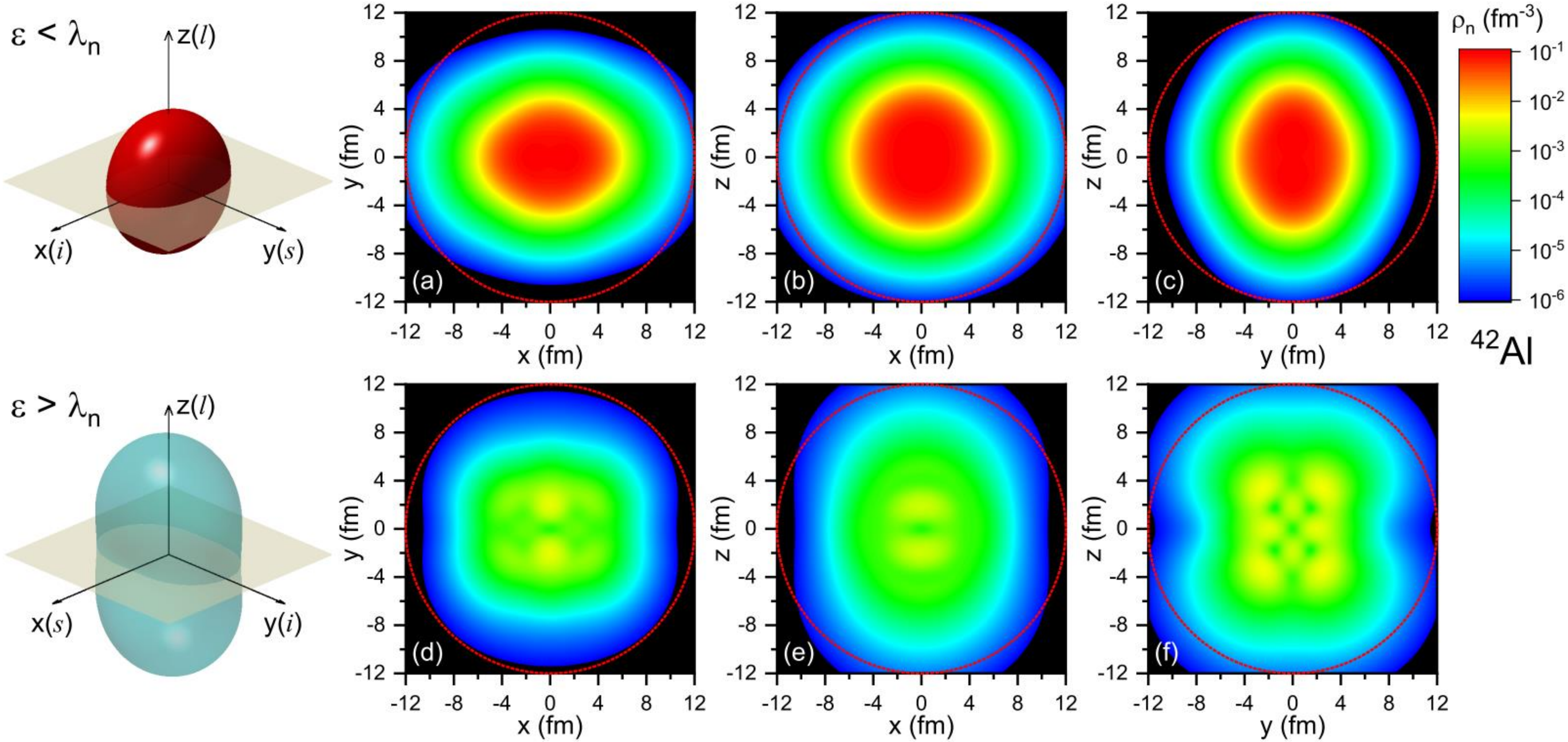




Viewpoint: A Walk Along the Dripline by Paul Cottle and Kirby Kemper

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

Halo in triaxial nucleus ^{42}Al



✓ Core: $r = 3.85$ fm, $\beta = 0.38$, $\gamma = 50°$, $z > x > y$

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

DRHBc mass table collaboration

Since December 5, 2018, PC-PK1 + DRHBc

RCHB mass table

First nuclear mass table including continuum effects

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

Contents lists available at ScienceDirect

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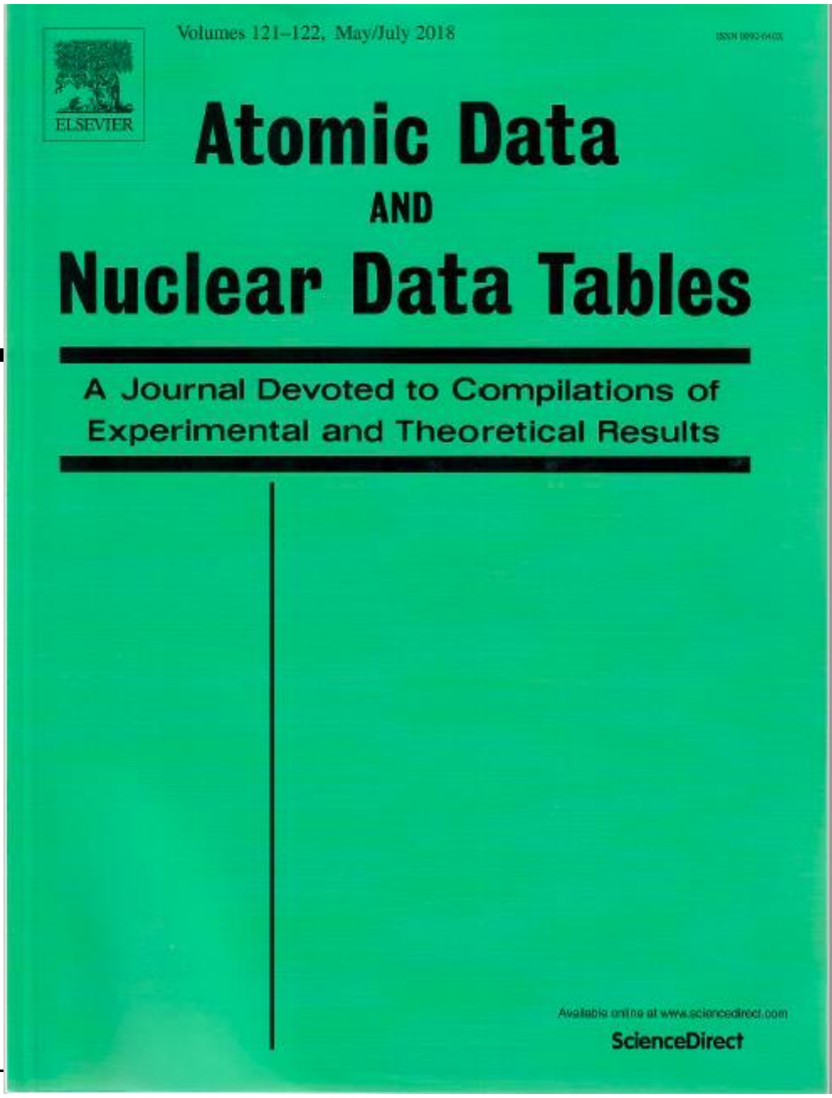

The limits of the nuclear landscape explored by the relativistic continuum Hartree–Bogoliubov theory

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

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

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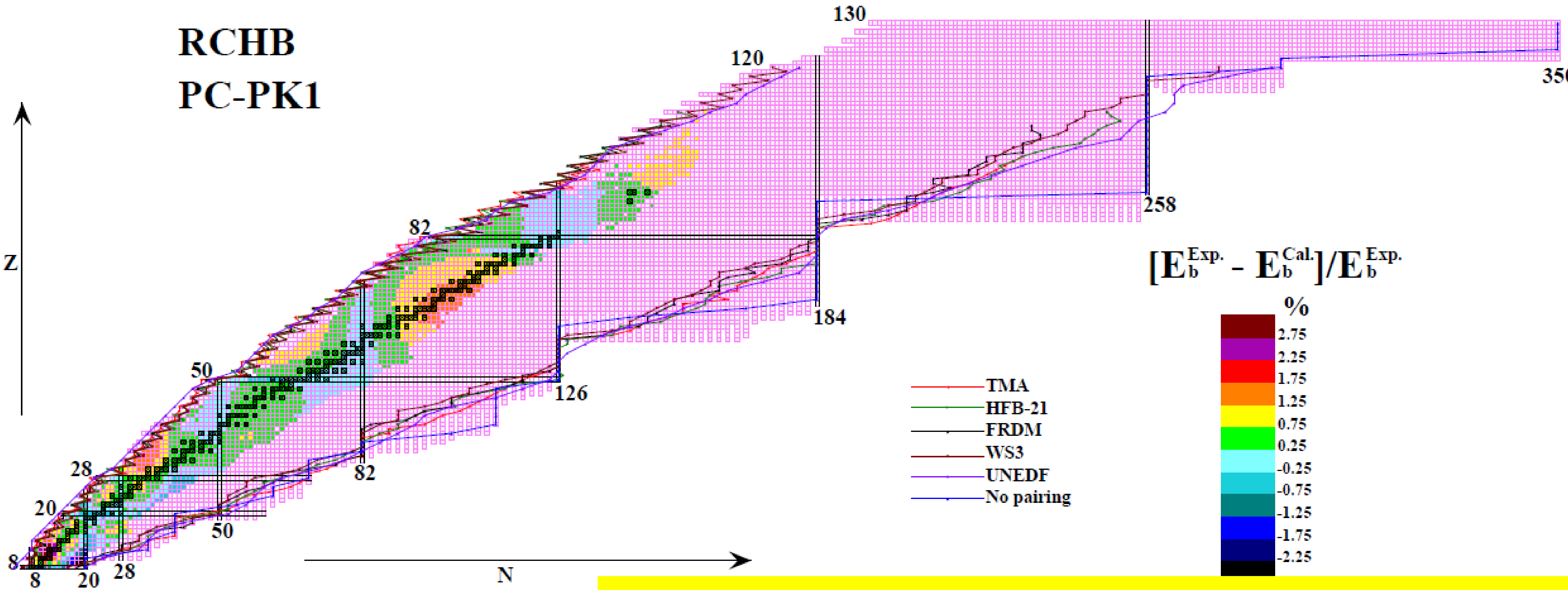
ABSTRACT

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

Drip-lines in variant models

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



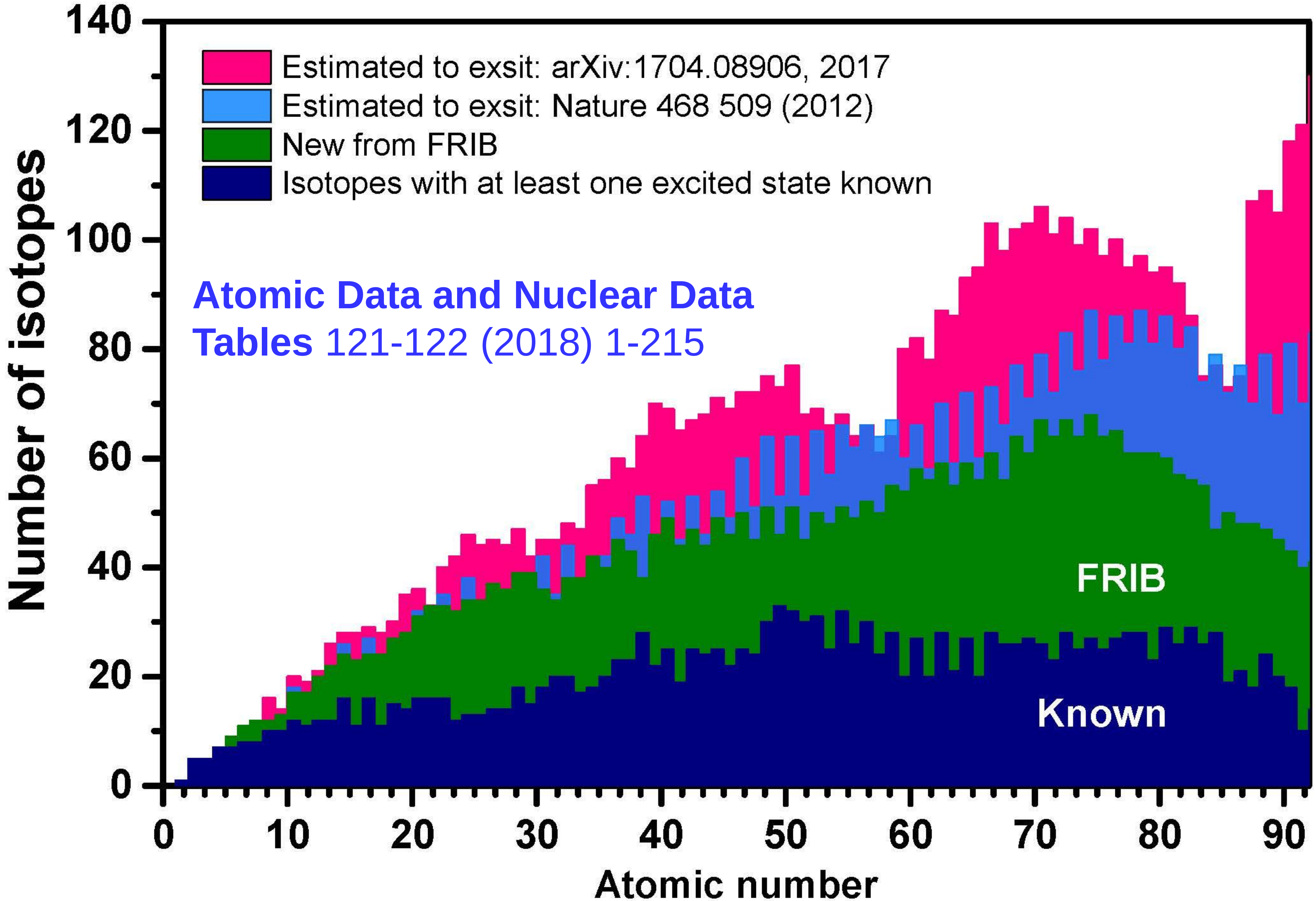
8 ⩽ Z ⩽ 120： 9035 nuclei predicted to be bound
Atomic Data and Nuclear Data Tables 121-122 (2018) 1-215

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



DRHBc mass table collaboration

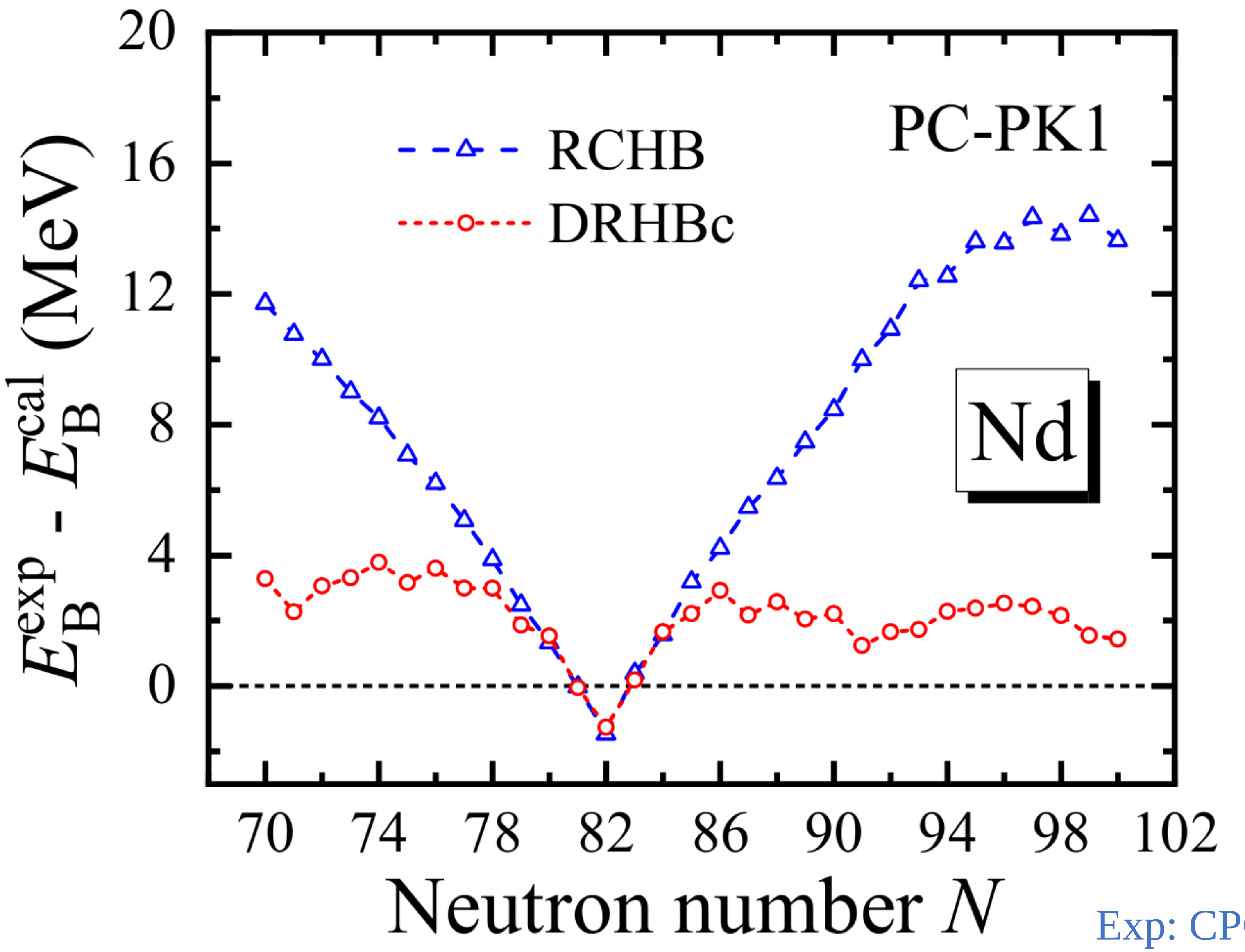
PC-PK1 + DRHBc

I. **Even–even nuclei**

II. **Even Z–Odd N nuclei**

III. **Odd-Z nuclei**

Deformation improve the accuracy



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

- ✓ With deformation included, the data can be better reproduced
  DRHBc 2.38 MeV RCHB 9.08 MeV.
- ✓ The rotational correction energy is expected to further improve the results for odd nuclei.

1st Paper by DRHBc Collaboration

PHYSICAL REVIEW C
covering nuclear physics

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*
[3]*Department of Physics, Pusan National University, Busan 46241, Korea*
[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*
[6]*School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China*

DRHBc Mass Table: even-even Nuclei

Atomic Data and Nuclear Data Tables 144 (2022) 101488

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

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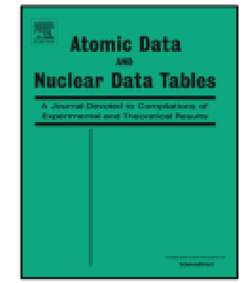
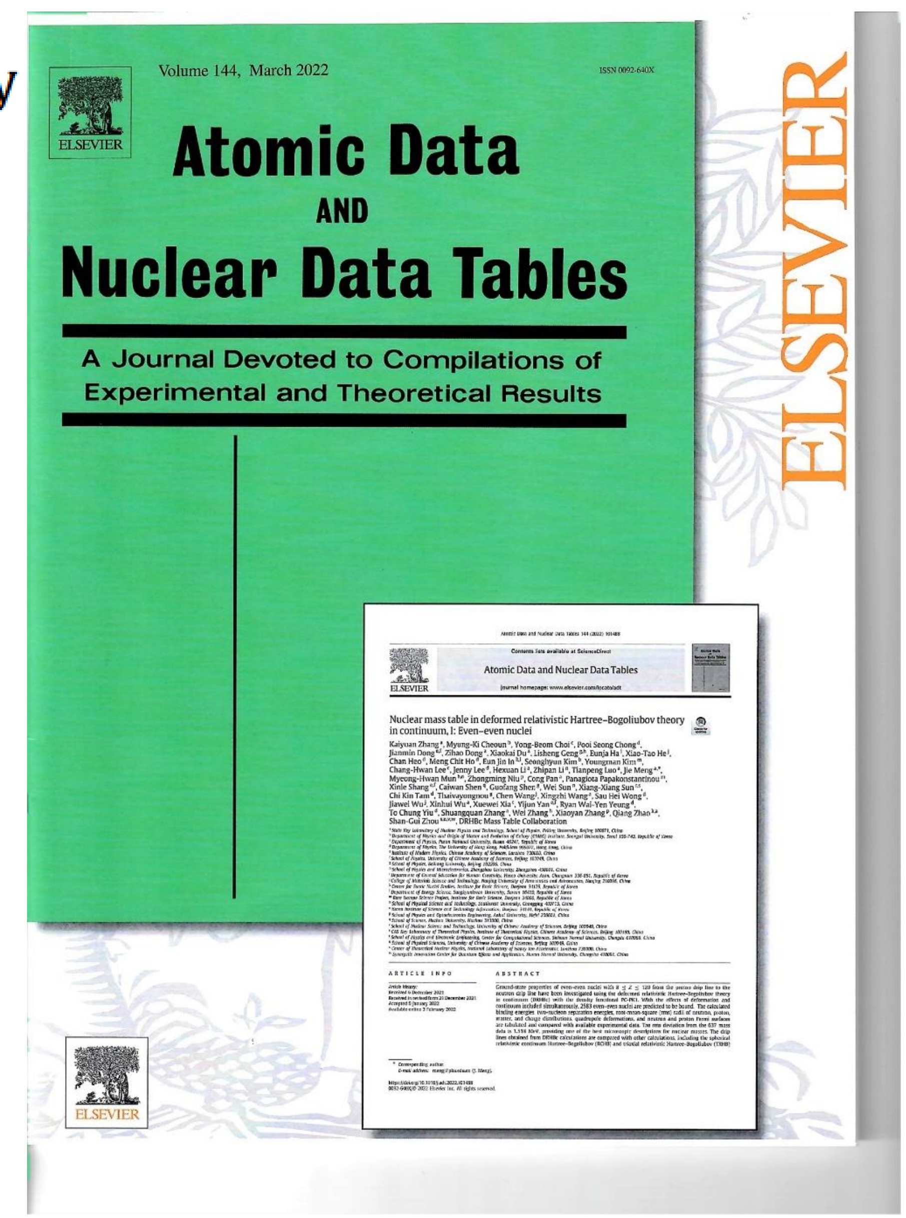


Nuclear mass table in deformed relativistic Hartree–Bogoliubov theory in continuum, I: Even–even nuclei

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



DRHBc for Odd-A and O-O Nuclei

PHYSICAL REVIEW C
covering nuclear physics

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Deformed relativistic
with a point-coupling

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

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*
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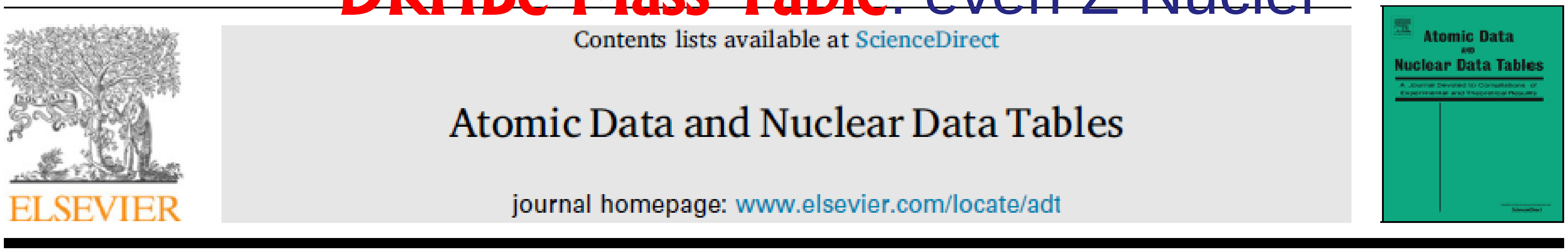
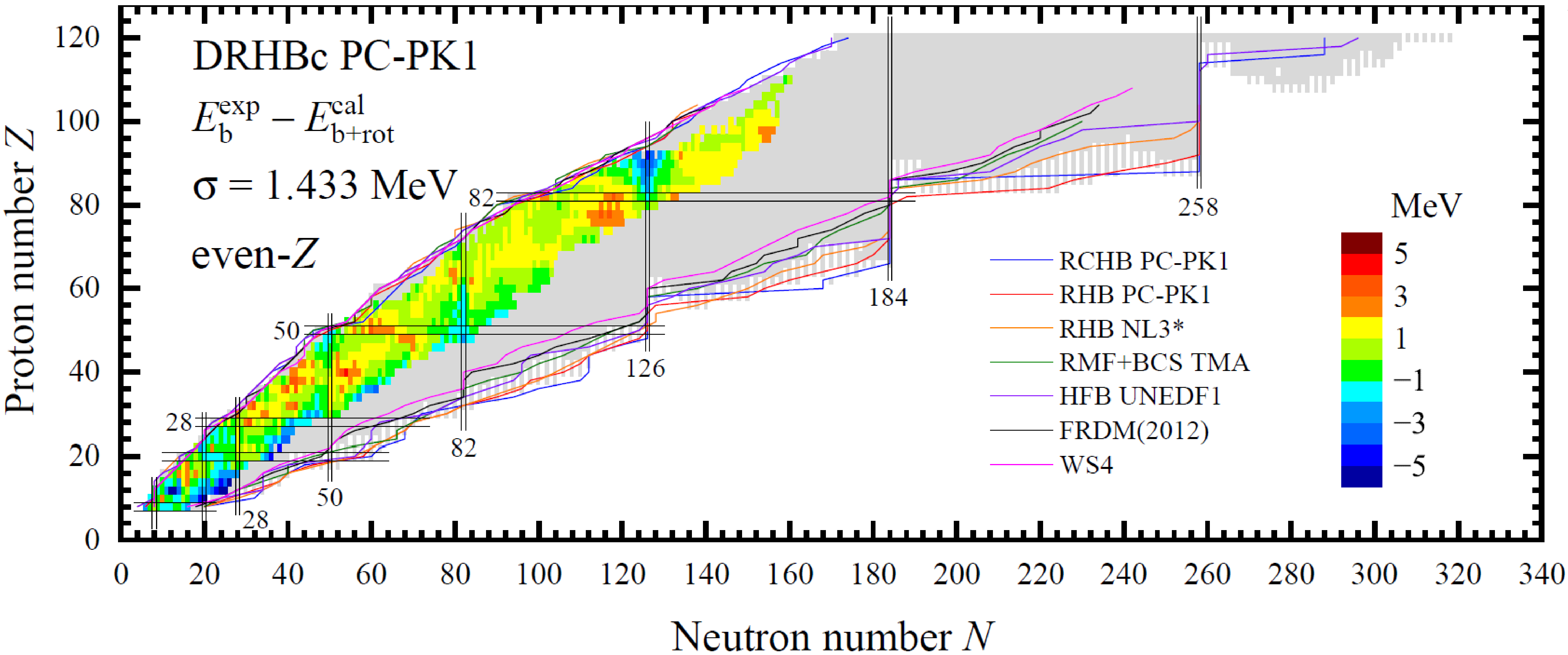
[4] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[5] *School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China*
[6] *School of Physical Science and Technology, Southwest University, Chongqing 400715, China*
[7] *School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, China*

DRHBc Mass Table: even Z Nuclei



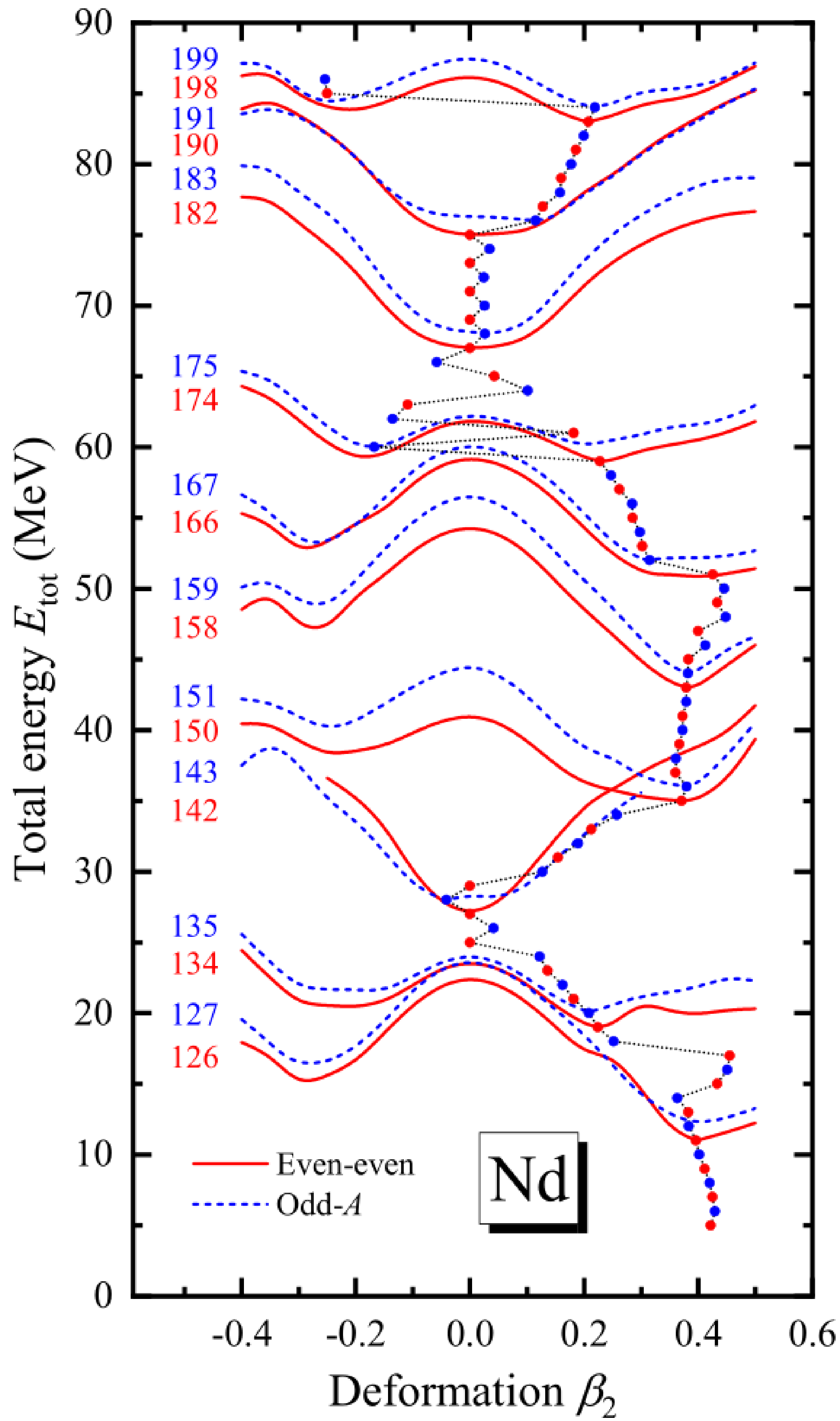


PC-PK1 + DRHBc : 4829 bound even-Z nuclei with $8 \leq Z \leq 120$

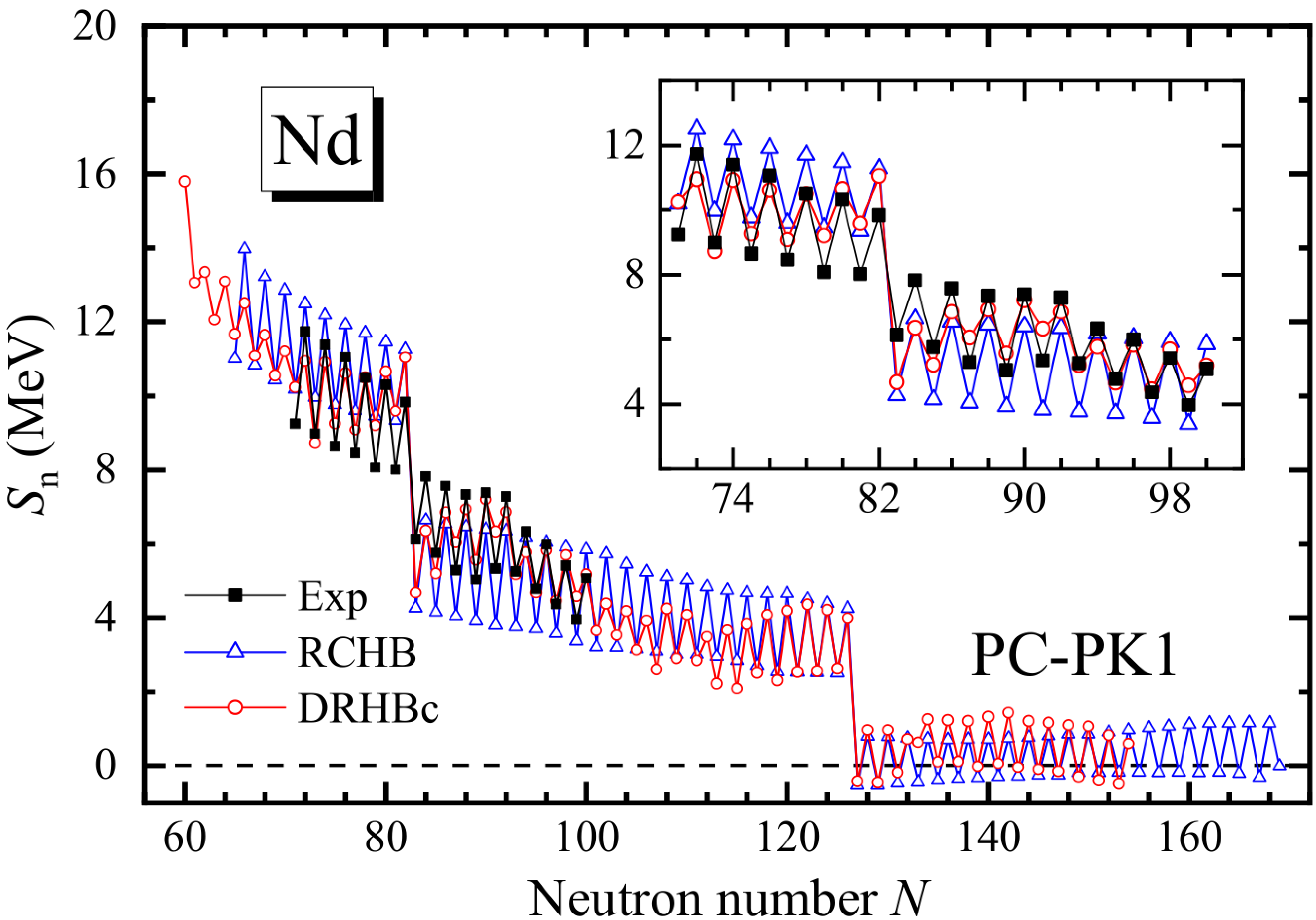
DRHBc Collaboration, **At. Data Nucl. Data Tables** 144, 101488 (2022)

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.

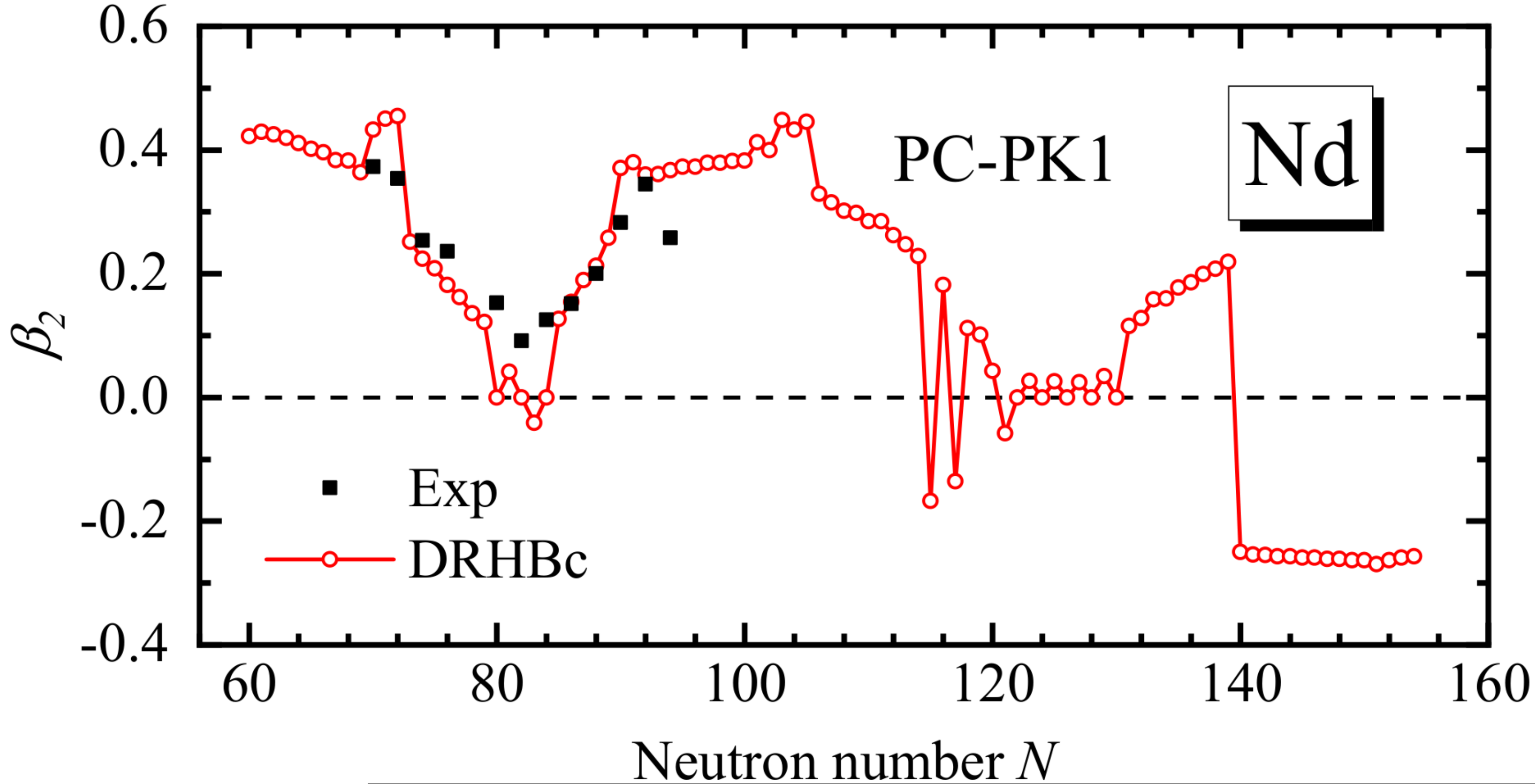


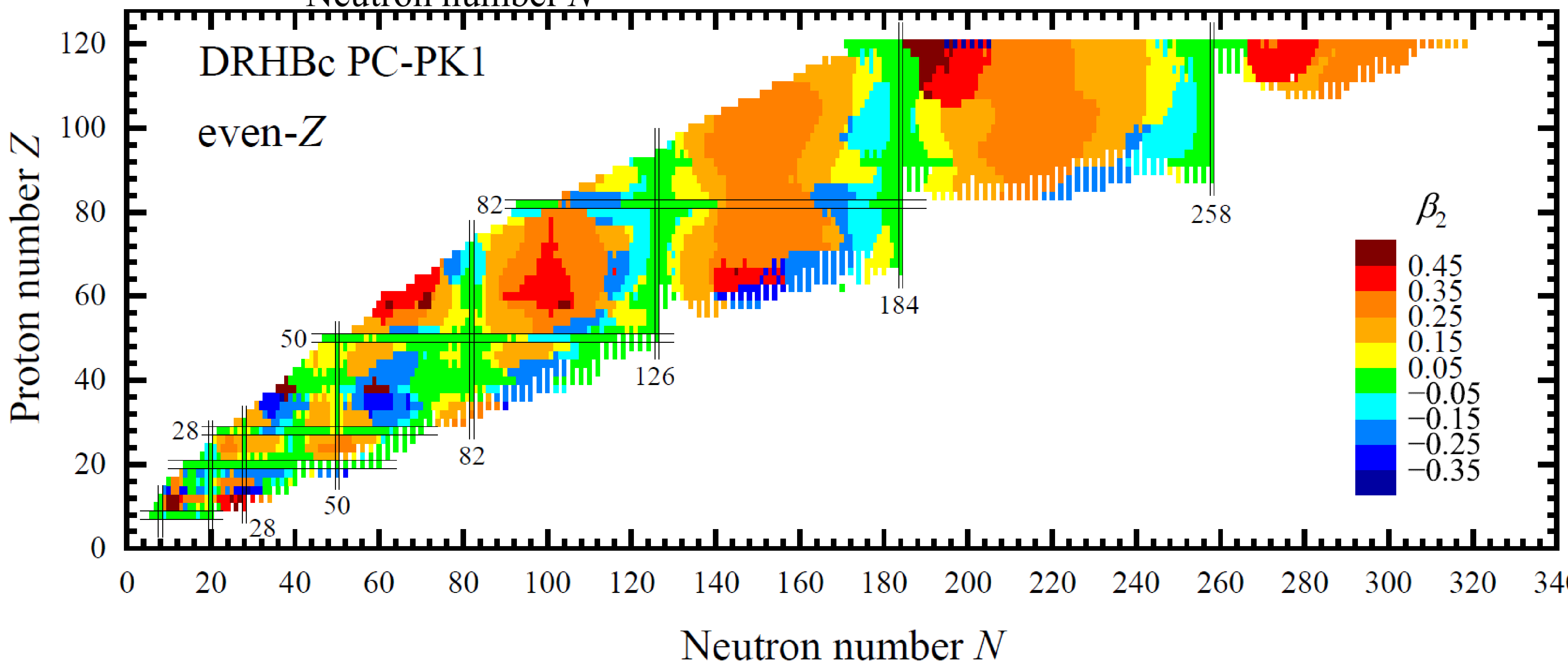
One-neutron separation energy



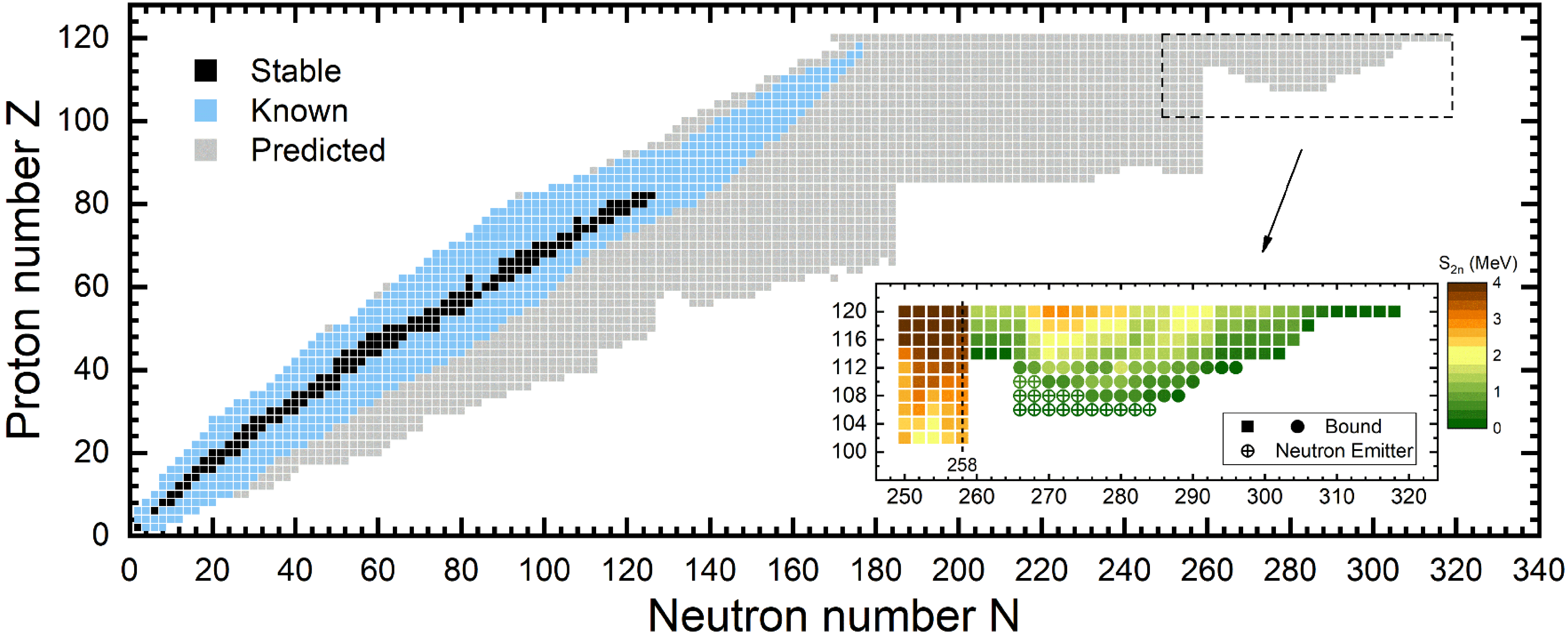
- ✓ Rms deviations: DRHBc: 0.74 MeV RCHB: 1.10 MeV
- ✓ One-neutron drip line: DRHBc: N = 126 RCHB: N = 126

Quadrupole deformation





Possible stability beyond the neutron drip line in DRHBc

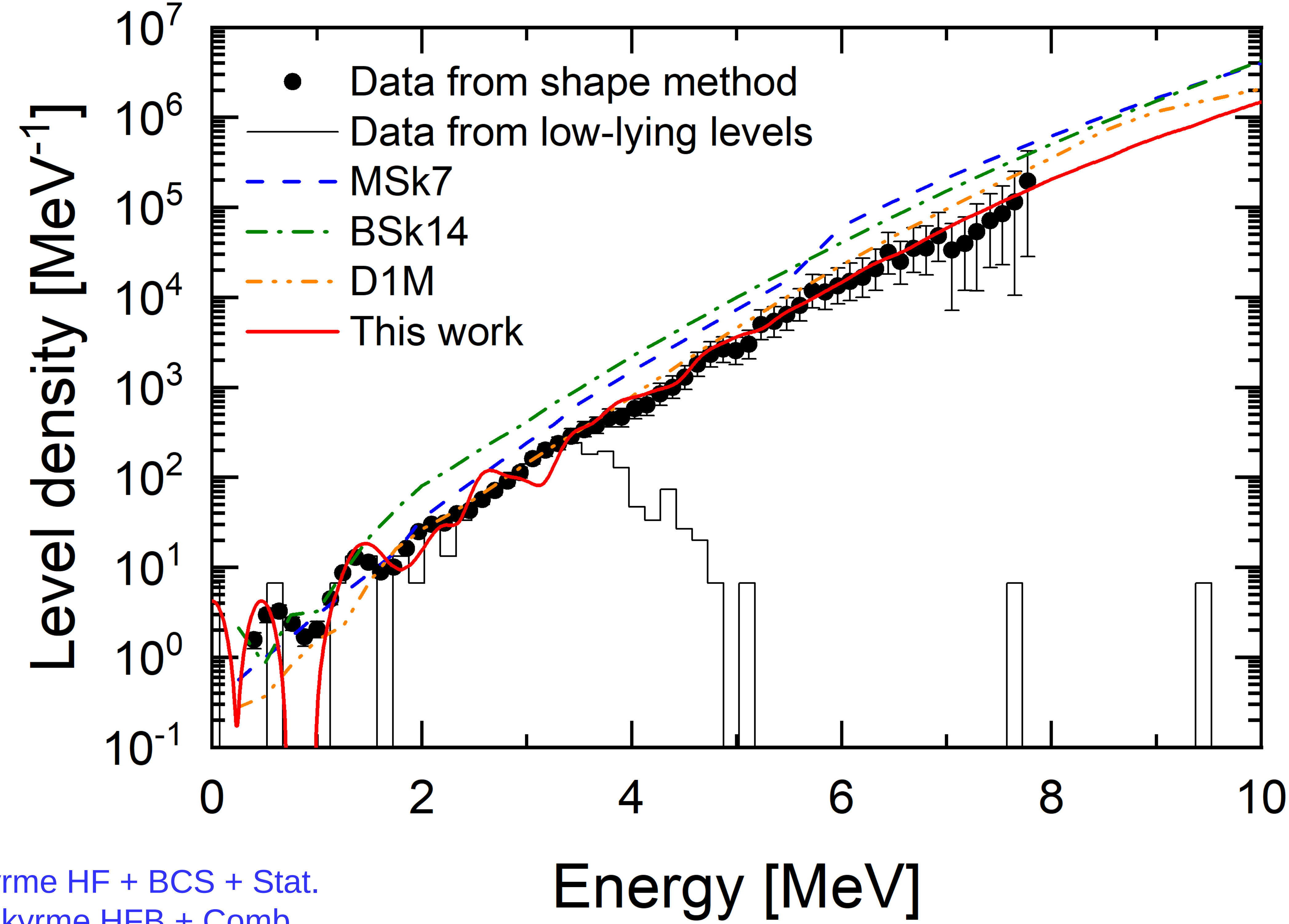


aiyuan Zhang, Xiaotao He, Jie Meng, Cong Pan, Caiwan Shen, Chen Wang, and Shuangquan Zhang, **Phys. Rev. C 104, L021301** – Published 5 August 2021

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)

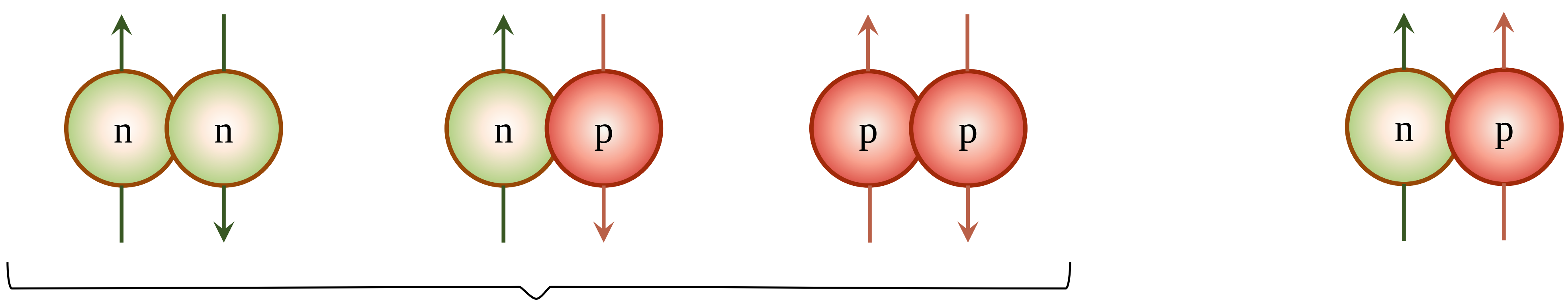
Nuclear level density

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



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

Physics along N=Z nuclei



$T = 1; \quad S = 0; \quad L = 0$

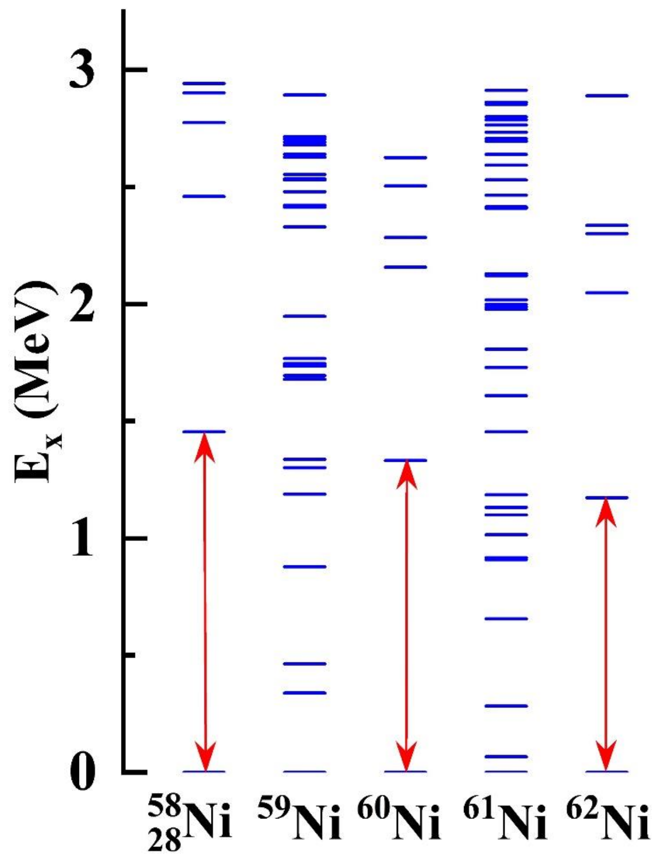
$T = 0; \quad S = 1; \quad L = 0$

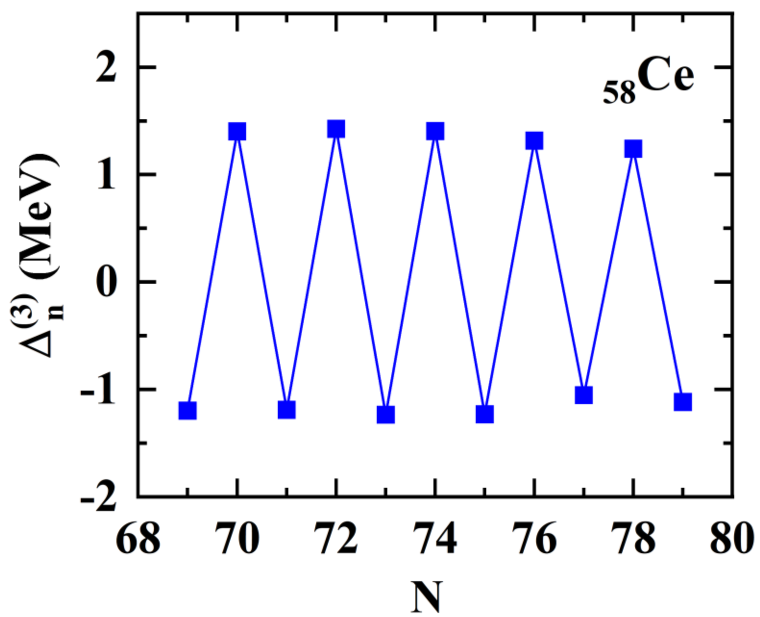
pp + nn + pn pairing

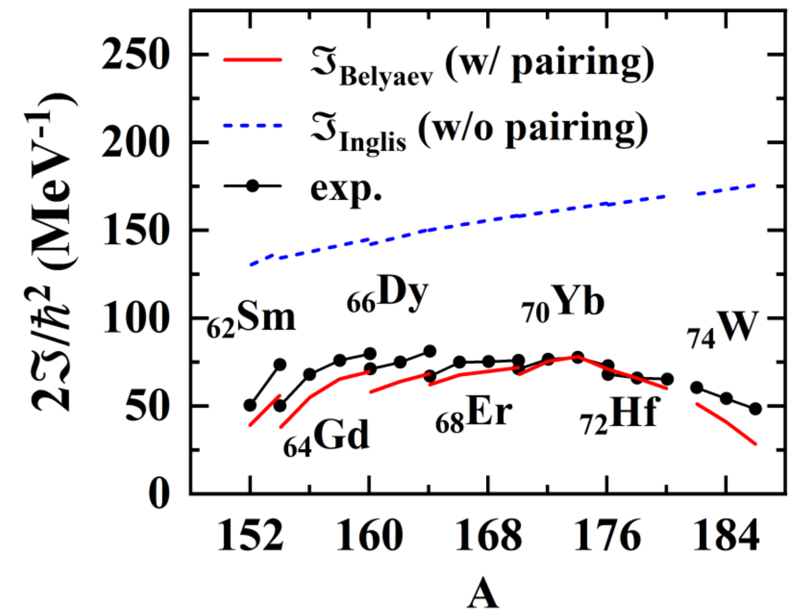
Evidence for pairing correlations

① Low-lying spectra ② O-E mass differences ③ MoI

$$\Delta_n^{(3)}(N,Z) = B(N,Z) - \frac{B(N+1,Z)+B(N-1,Z)}{2}$$





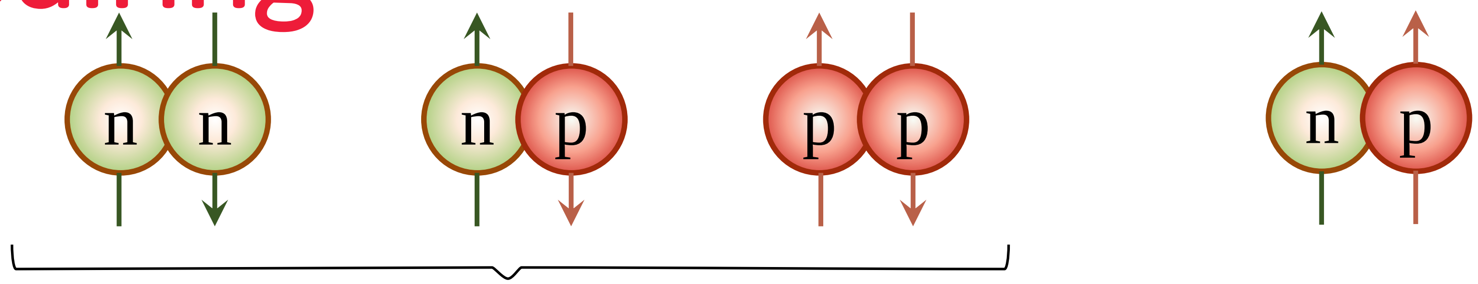


Data from National Nuclear Data Center

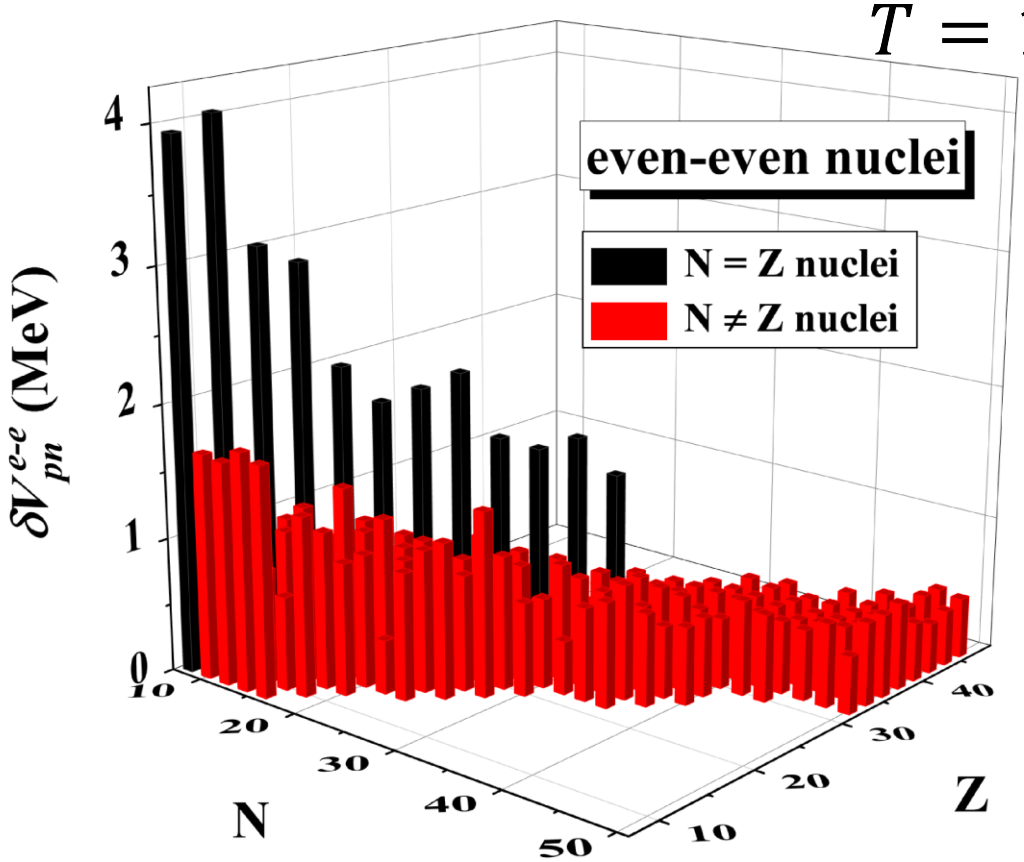
Bohr, Mottelson, Pines, PR 110, 936 (1958)

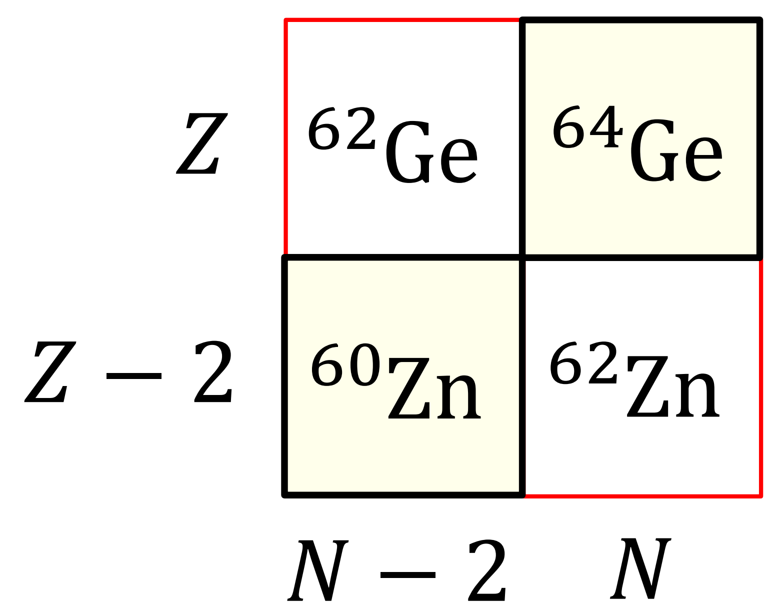
Evidence for pn pairing

- Wigner terms



$T = 1; \quad S = 0; \quad L = 0 \qquad T = 0; \quad S = 1; \quad L = 0$





$$\delta V_{pn}(N,Z) = \frac{1}{4}\left[B(N,Z) + B(N-2,Z-2) - B(N-2,Z) - B(N,Z-2)\right] \sim \frac{\partial^2 B}{\partial N \partial Z}$$

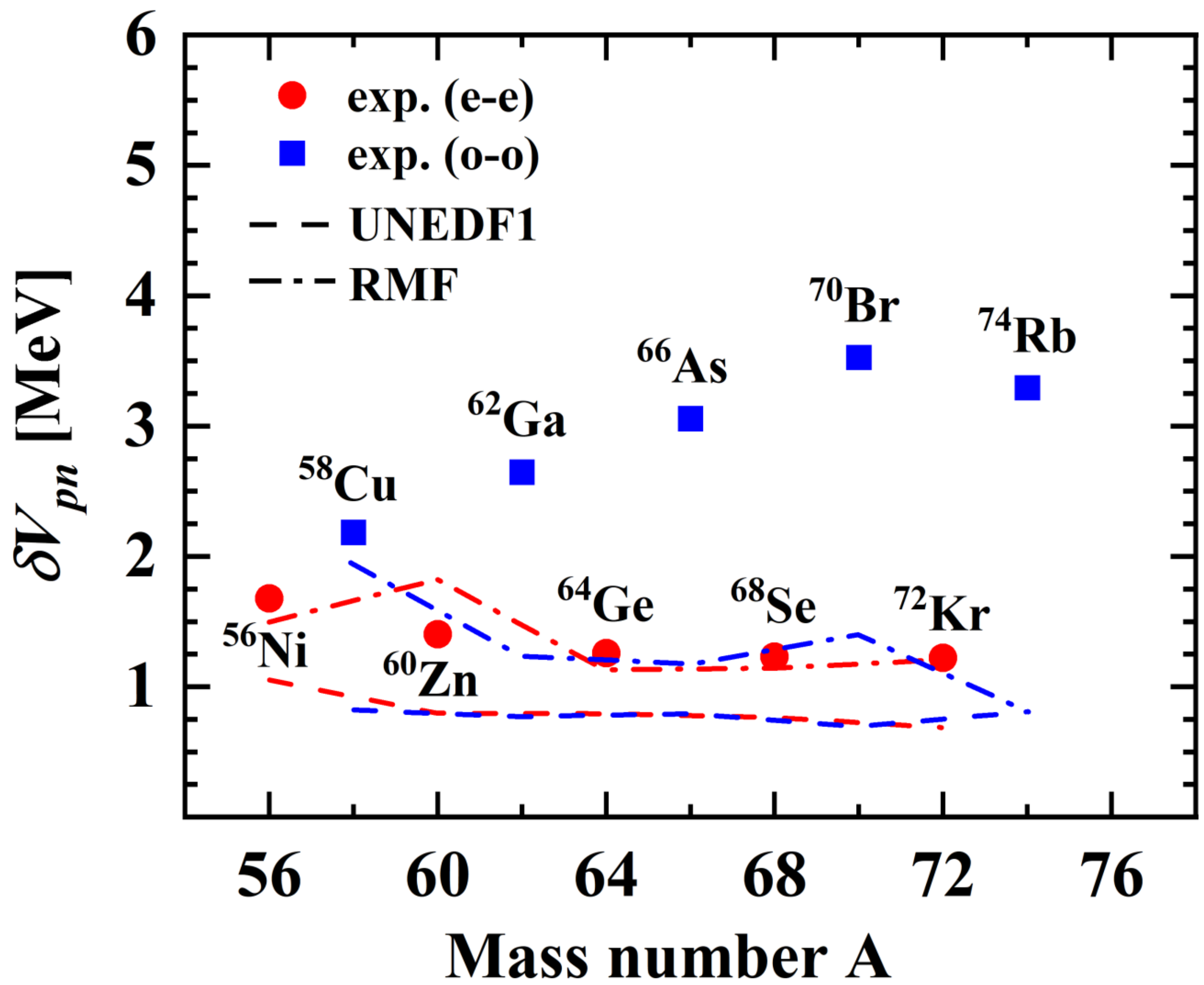
Zhang, Casten, Brenner, PLB 227, 1 (1989); Data from National Nuclear Data Center

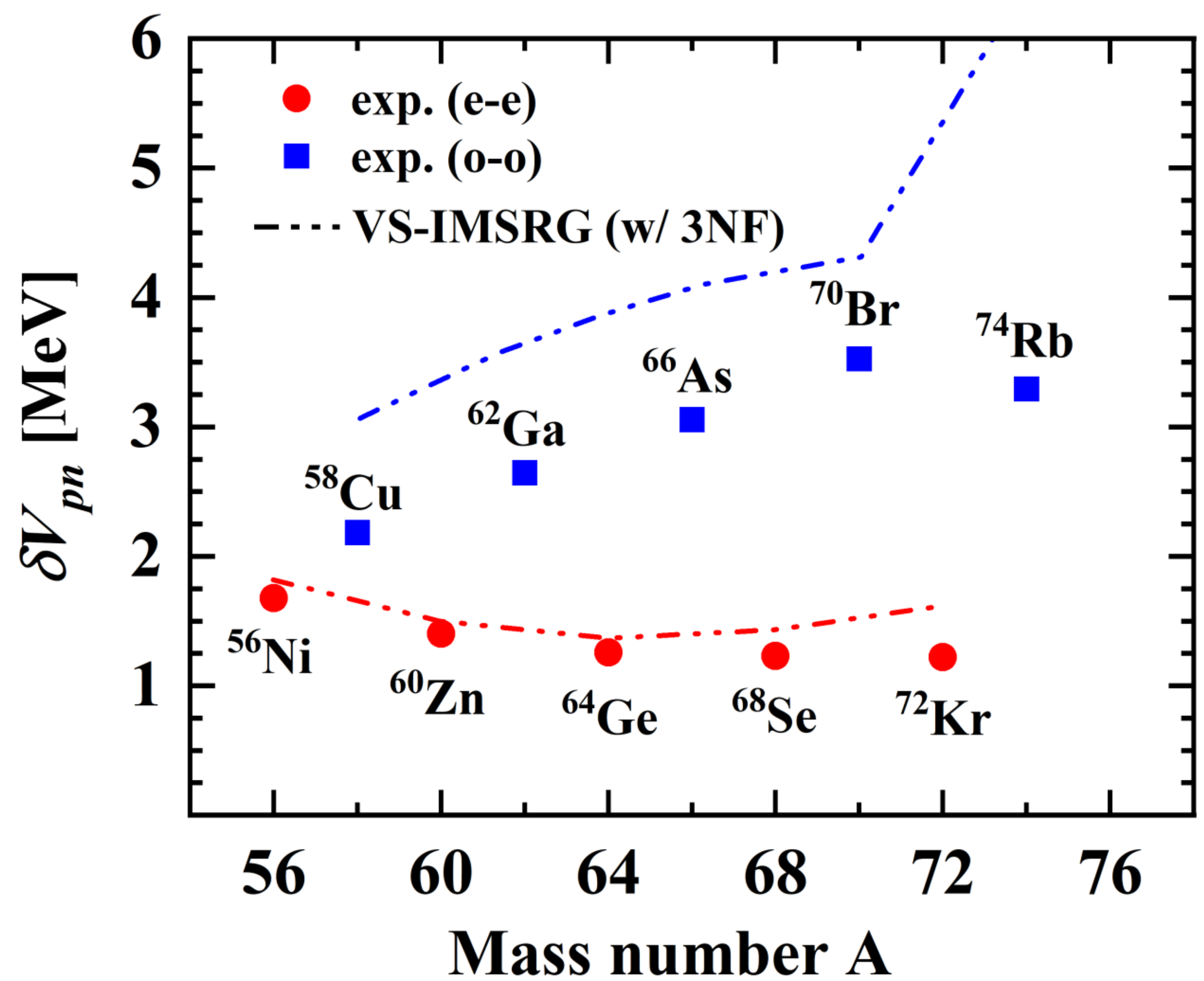
Larger δV_{pn} reflects larger binding energy with $N = Z$

Warner, Bentley, Van Isacker, Nature 2, 311 (2006)

Abnormal bifurcation

The double binding energy differences δV_{pn} between the odd–odd and even–even nuclei along the N= Z line





RMF: Geng *et al*., PTP 113, 785 (2005)
Wang *et al*., PRL 130, 192501 (2023)
UNEDF1: Kortelainen *et al*., PRC 85, 024304 (2012)

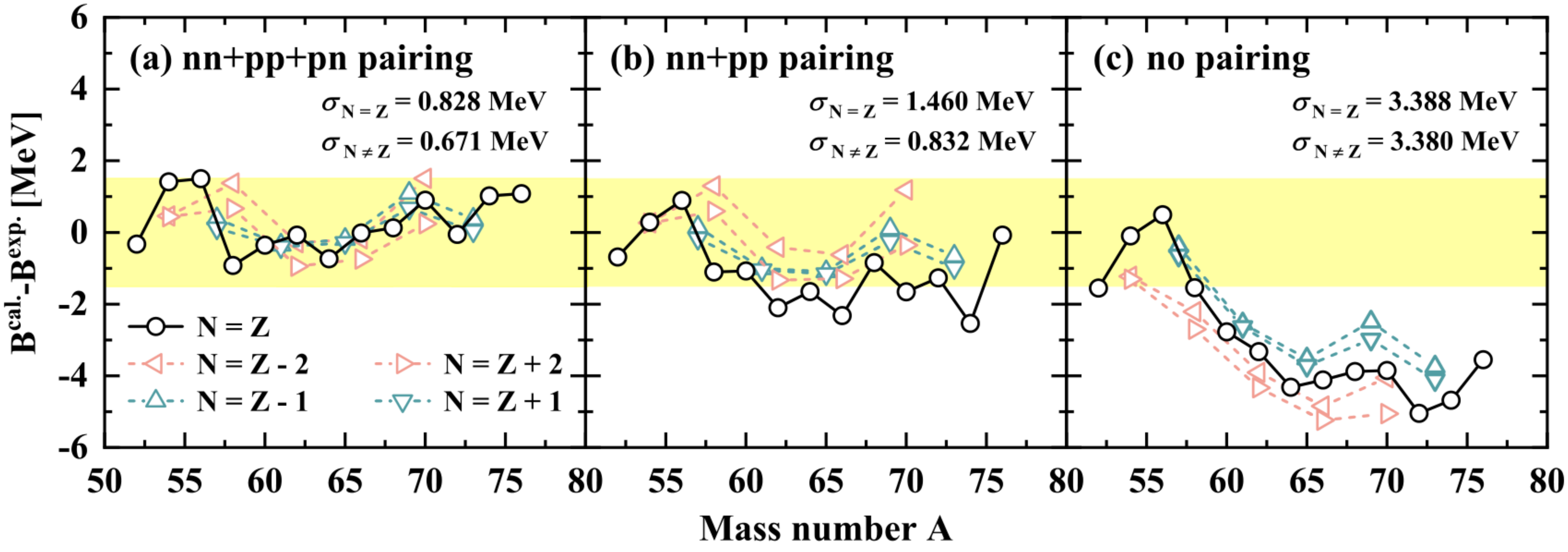
3-body force doesn't work!

Relativistic density functional theory + SLAP

Shell model Like Approach

Yang & Zeng, Acta Physica Sinica 20, 846 (1964)
Zeng & Cheng, NPA 405, 1 (1983)

- **Treating the blocking effects exactly**
- **good particle number**
- **treating simultaneously nn, pp, pn pairing**



Y. P. Wang, Y. K. Wang, F. F. Xu, P. W. Zhao, and J. Meng
Phys. Rev. Lett. **132**, 232501 – Published 4 June 2024

Relativistic density functional theory + SLAP

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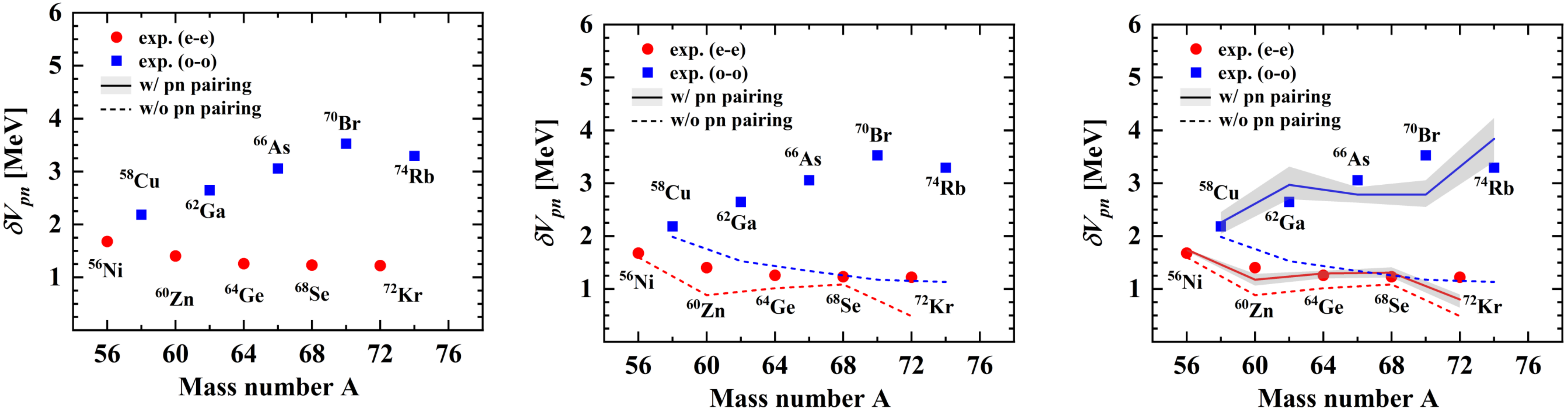
Zeng & Cheng, NPA 405, 1 (1983)

- **Treating the blocking effects exactly**
- **good particle number**
- **treating simultaneously nn, pp, pn pairing**

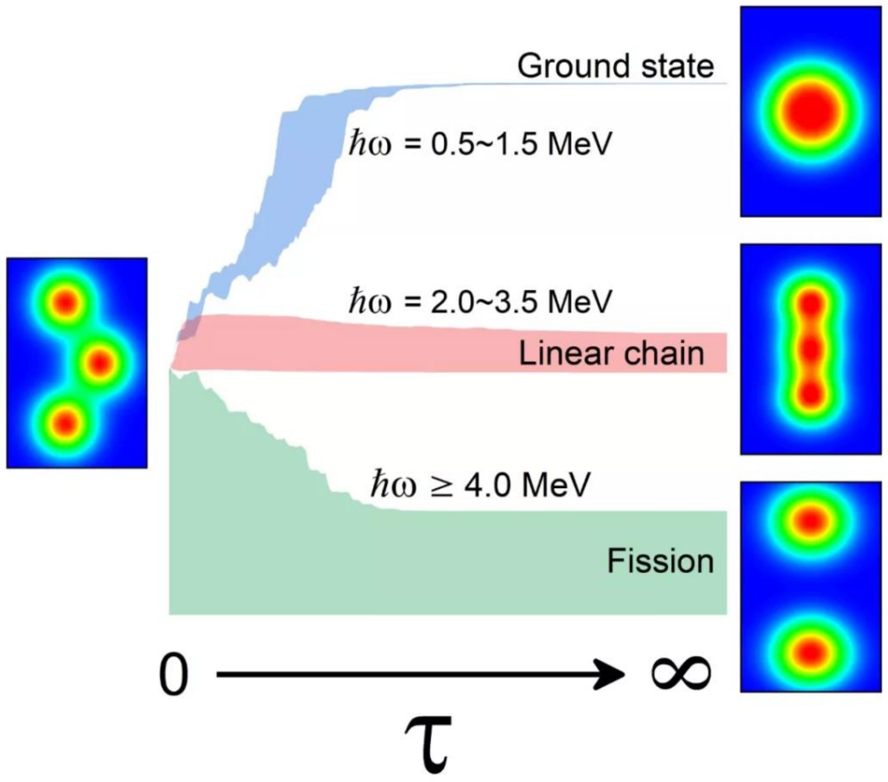
provide excellent interpretation for the abnormal δV_{pn} bifurcation, and signal for the pn pairing correlations for nuclei close to the N = Z line.



Y. P. Wang, Y. K. Wang, F. F. Xu, P. W. Zhao, and J. Meng
Phys. Rev. Lett. **132**, 232501 – Published 4 June 2024

Relativistic density functional theory in 3D lattice

- *Linear alpha-chain*
- *Nuclear fusion*
- *Nuclear fission*
- *Chiral dynamics*



Time-dependent CDFT

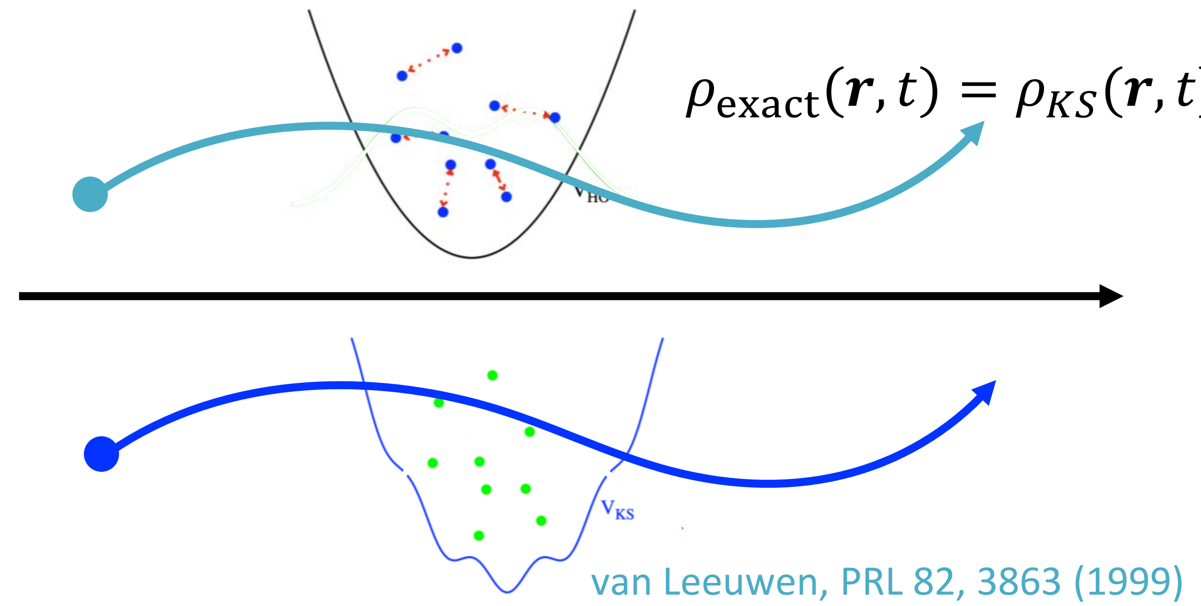
The many-body problem is mapped onto a one-body problem!

Runge-Gross Theorem

There is a unique mapping between the time dependent external potential and the density, for many body systems evolving from a given initial state.

Runge and Gross, PRL 52, 997 (1984)

Time-dependent Kohn-Sham DFT



van Leeuwen, PRL 82, 3863 (1999)

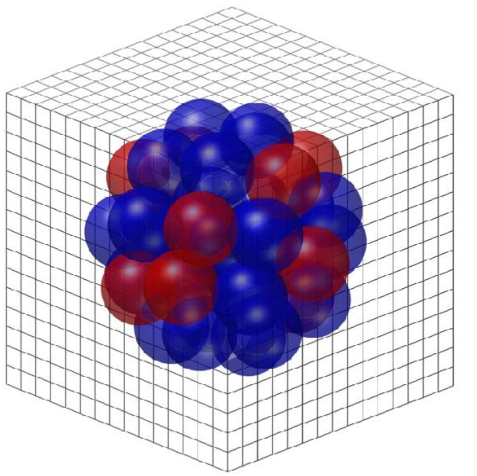
Ren, Zhao, Meng, PLB 801,135194 (2020)

$$i\partial_t \begin{pmatrix} f \\ g \end{pmatrix} = \begin{pmatrix} m + V + S & \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} \\ \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} & -m + V - S \end{pmatrix} \begin{pmatrix} f \\ g \end{pmatrix}$$

$$\rho(\boldsymbol{r},t) = \sum_i^N f_i^2 + g_i^2$$

$$V[\rho](\boldsymbol{r},t)$$ No memory effects !

Applications of the TD-CDFT

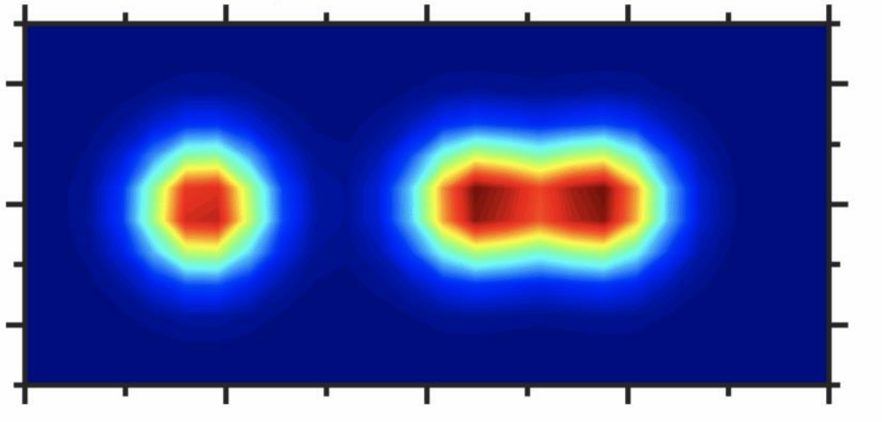


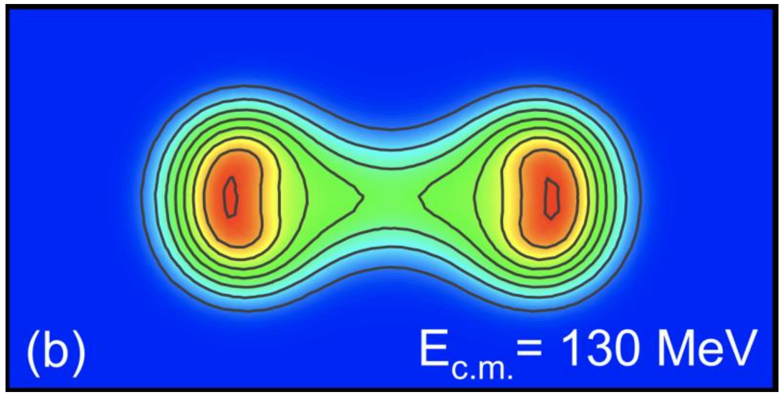
3D Lattice: no spatial symmetry restriction

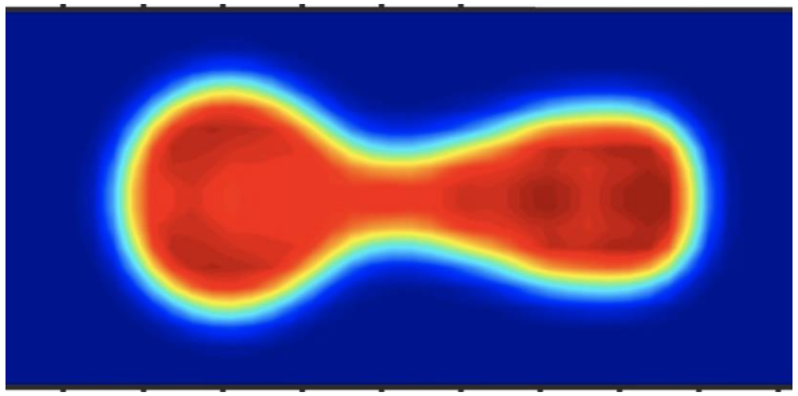
✓ Applications include:

- Linear alpha-chain — PRL 115, 022501 (2015); PLB 801,135194 (2020)
- Nuclear fission — PRL 128, 172501 (2022); PRC 105, 044313 (2022); PRC 107, 014303 (2023)
- Chiral dynamics — PRC, 105, L011301 (2022)
- $^{16}O + ^{16}O$ reaction — PRC 102, 044603 (2020)

…



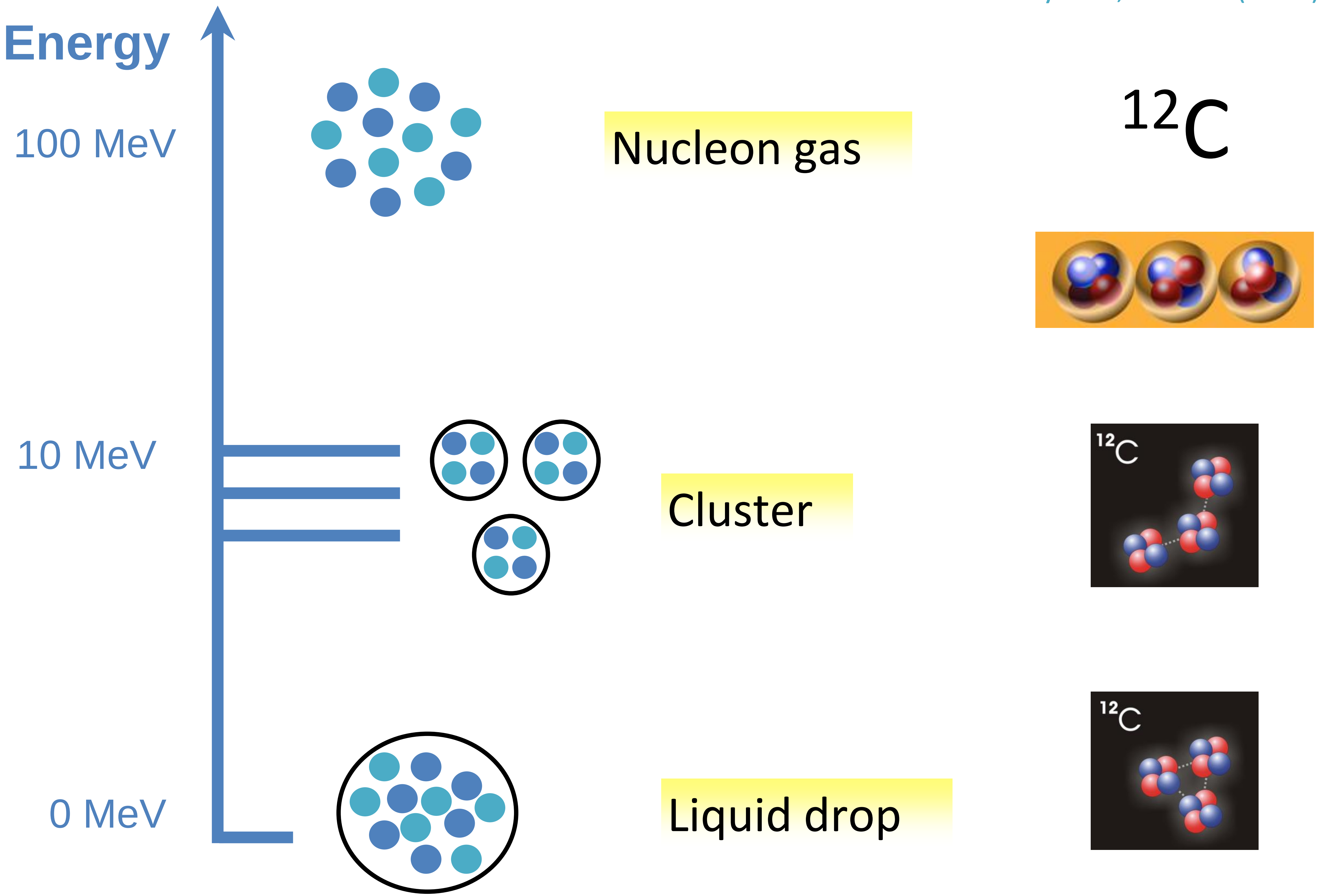




Linear alpha-chain

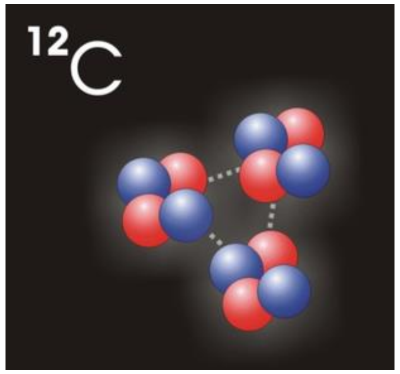
Nuclear cluster

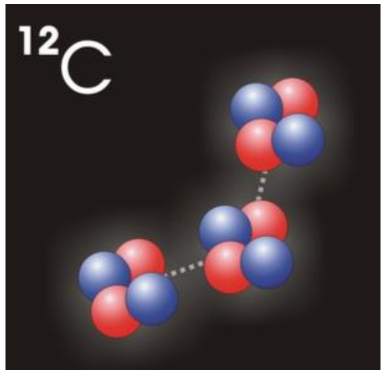
Rev. Mod. Phys. 90, 035004 (2018)



Linear-chain clustering

Strongly deformed states towards a hyper-deformation may exist in light N = Z nuclei due to a cluster structure.





- the linear alpha cluster chain has been searched more than 60 years.
- new radioactive beams provide new opportunities in realizing the linear chain state.

No firm evidence

Two difficulties

✓ antisymmetrization effects

✓ weak-coupling nature

Two mechanisms

✓ adding neutrons (isospin)

✓ rotating the system (spin)

Itagaki, PRC2001; Maruhn, NPA2010; Ichikawa, PRL2011

CDFT is employed without assuming clustering a priori.

Spin and Isospin Coherent Effects

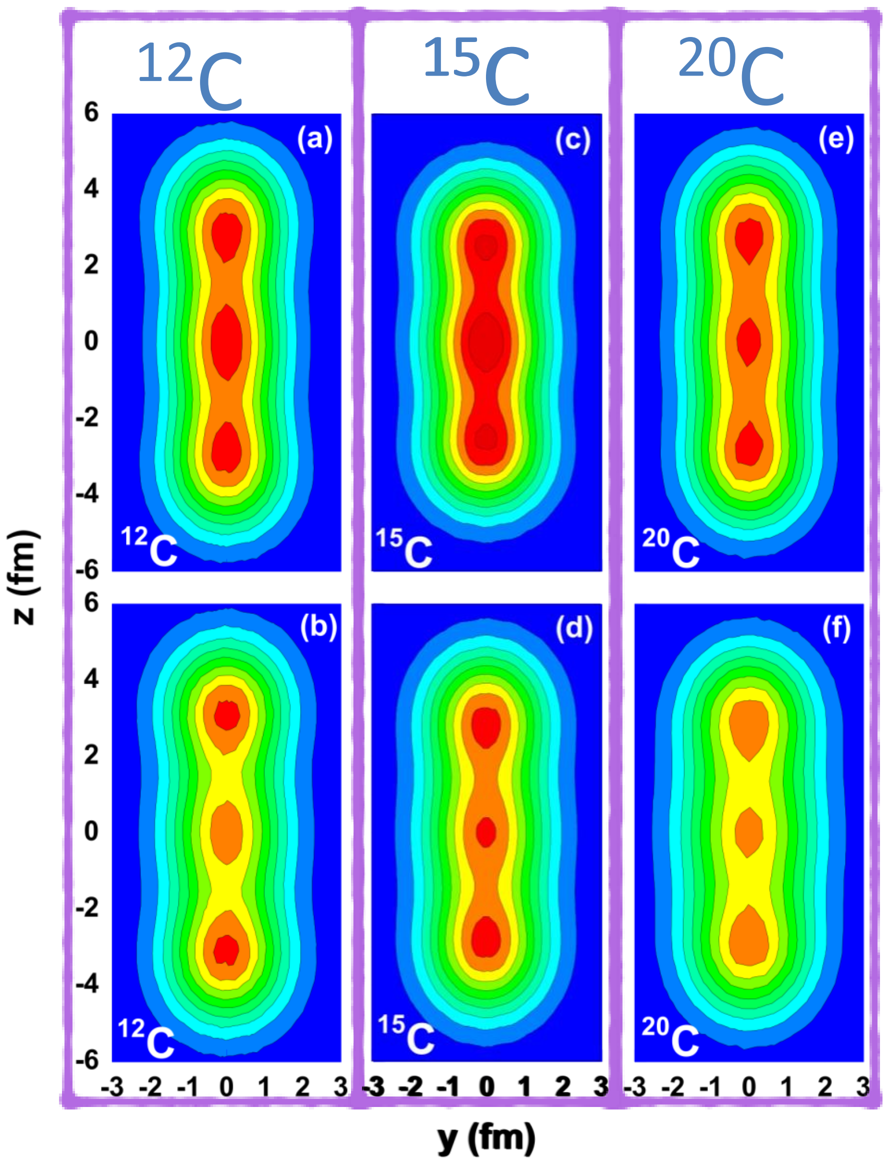
Static calculations with reflection-symmetry

Proton density distribution

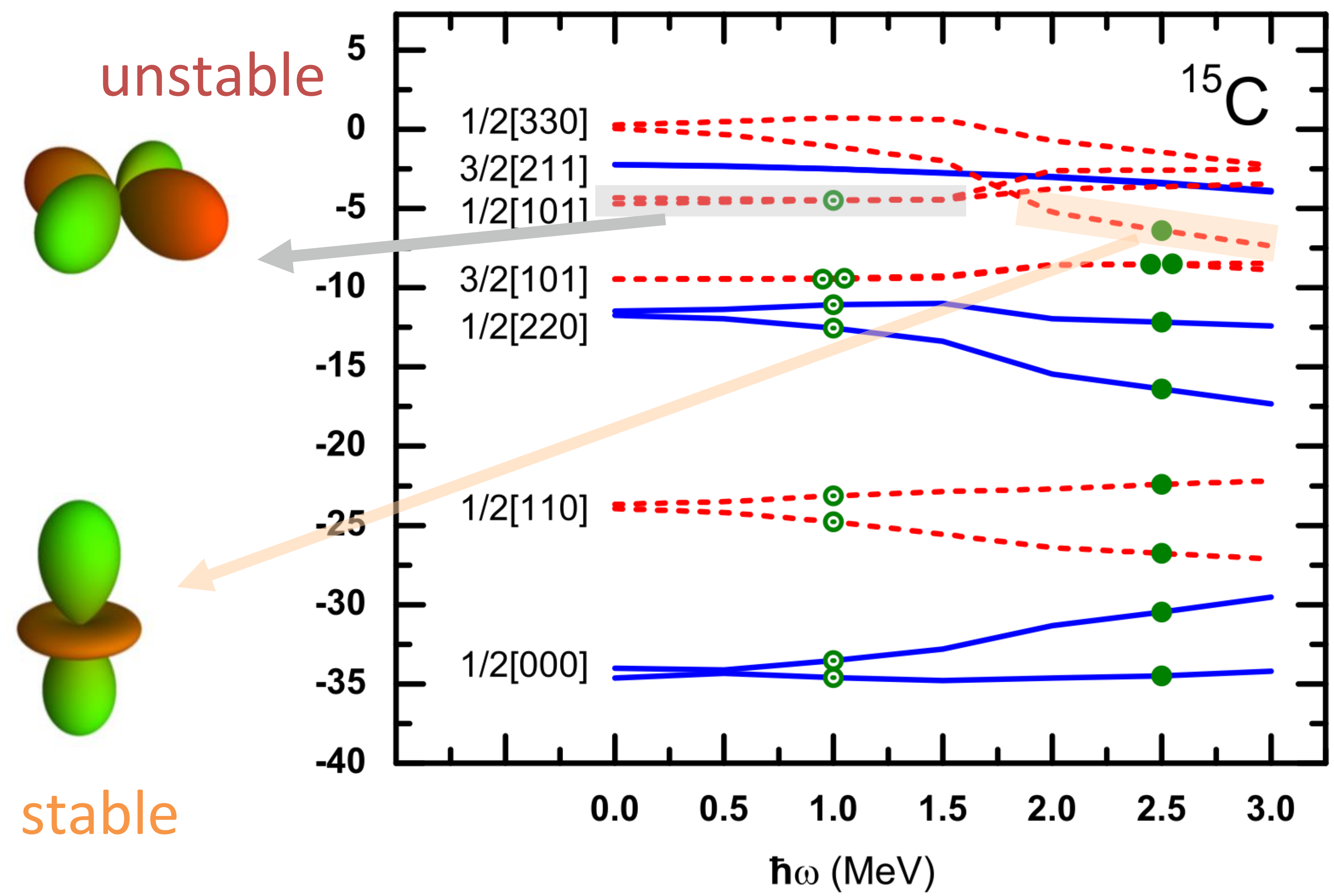
spin

~0 $\hbar$

~10 $\hbar$



neutron orbitals



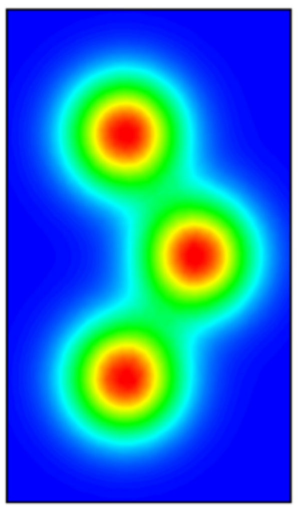
Zhao, Itagaki, Meng, PRL 115, 022501 (2015)

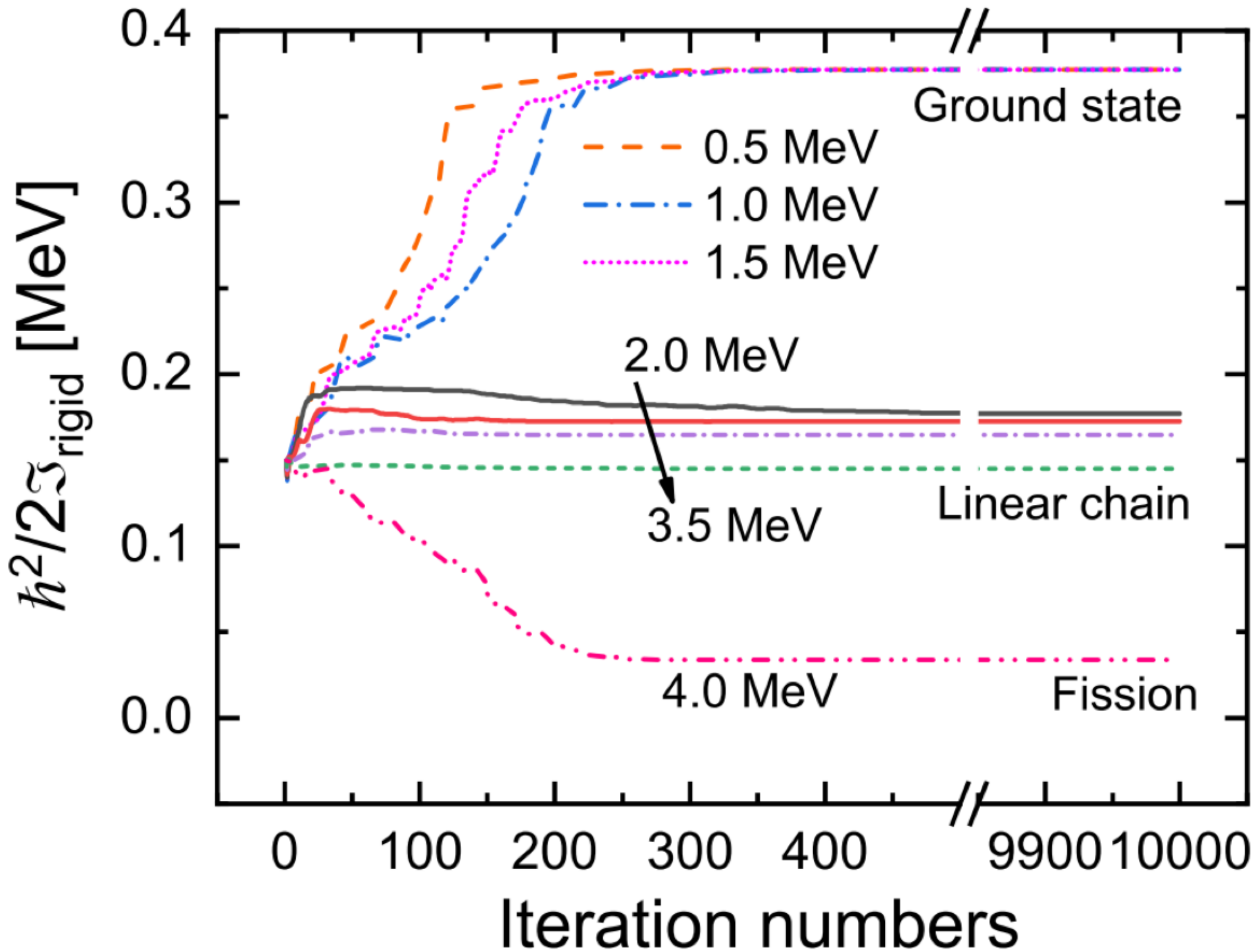
Rod shapes could be realized towards extreme spin and isospin!

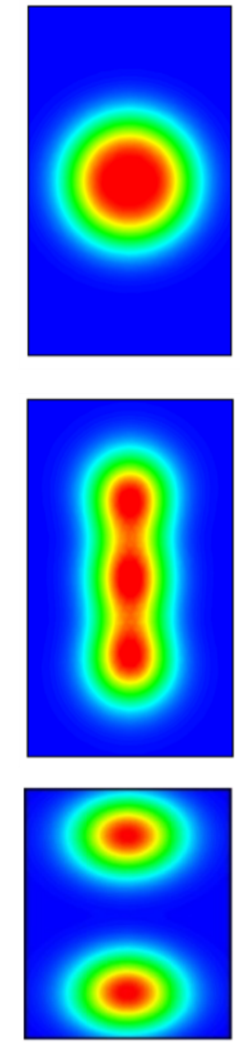
Rod shape against bending and fission

Static calculations in 3D lattice

^{12}C





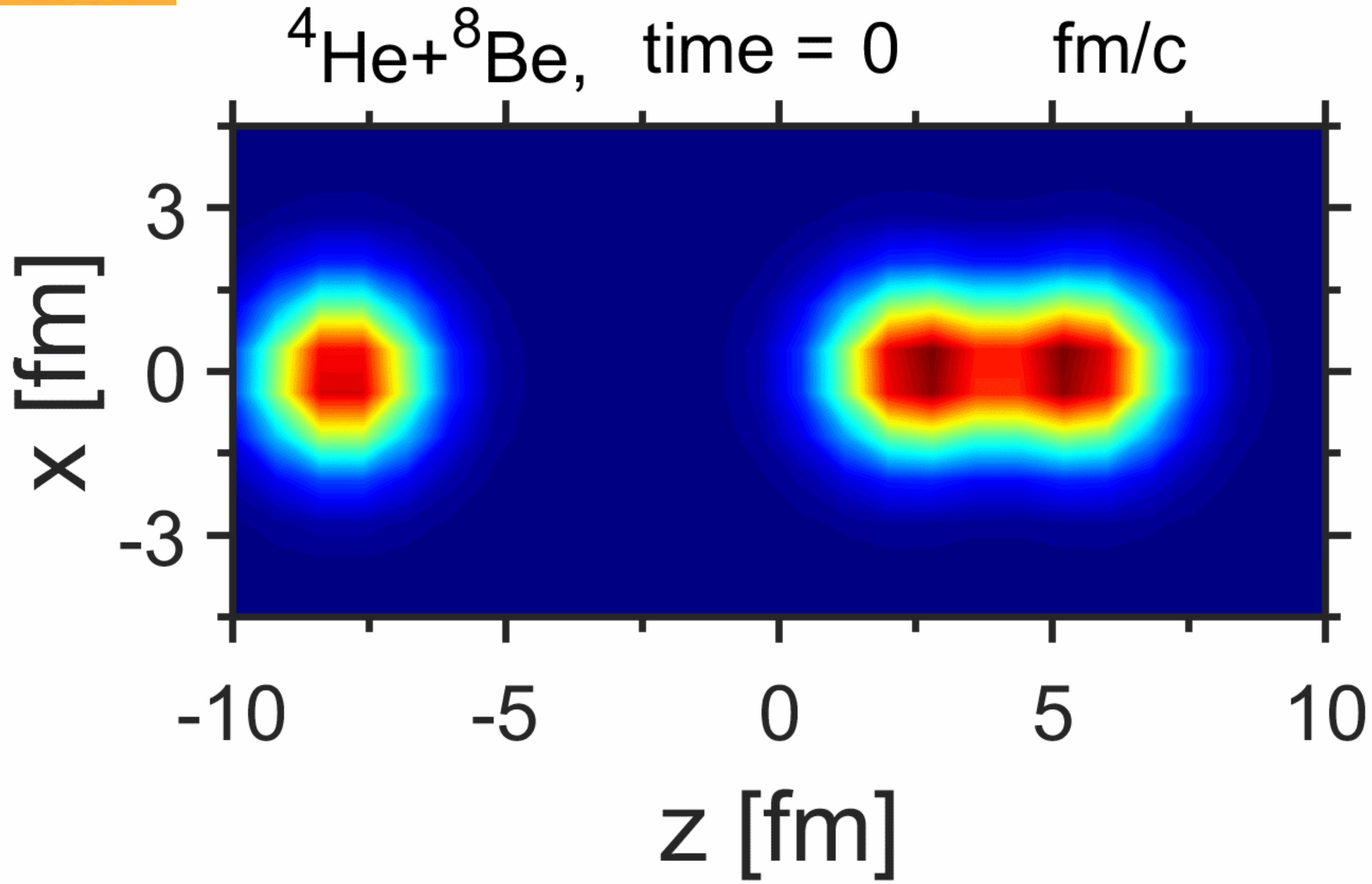


Rod shapes are generated as energy minima at a certain range of rotational frequencies.

Ren, Zhang, Zhao, Itagaki, Maruhn, Meng, Sci. China-Phys. Mech. Astron., 62, 112062 (2019)

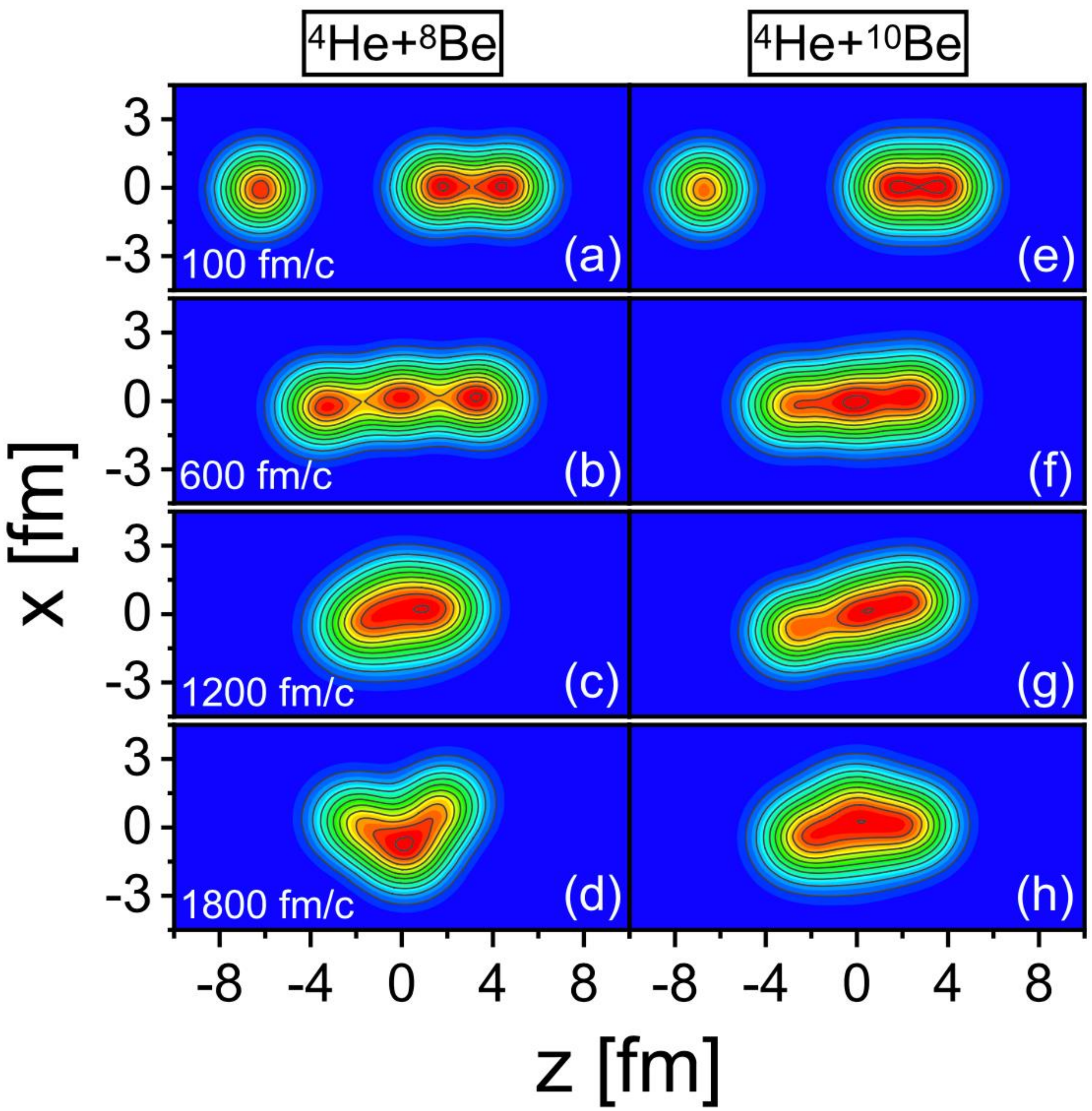
Resonant scattering of ^{4}He + ^{8}Be

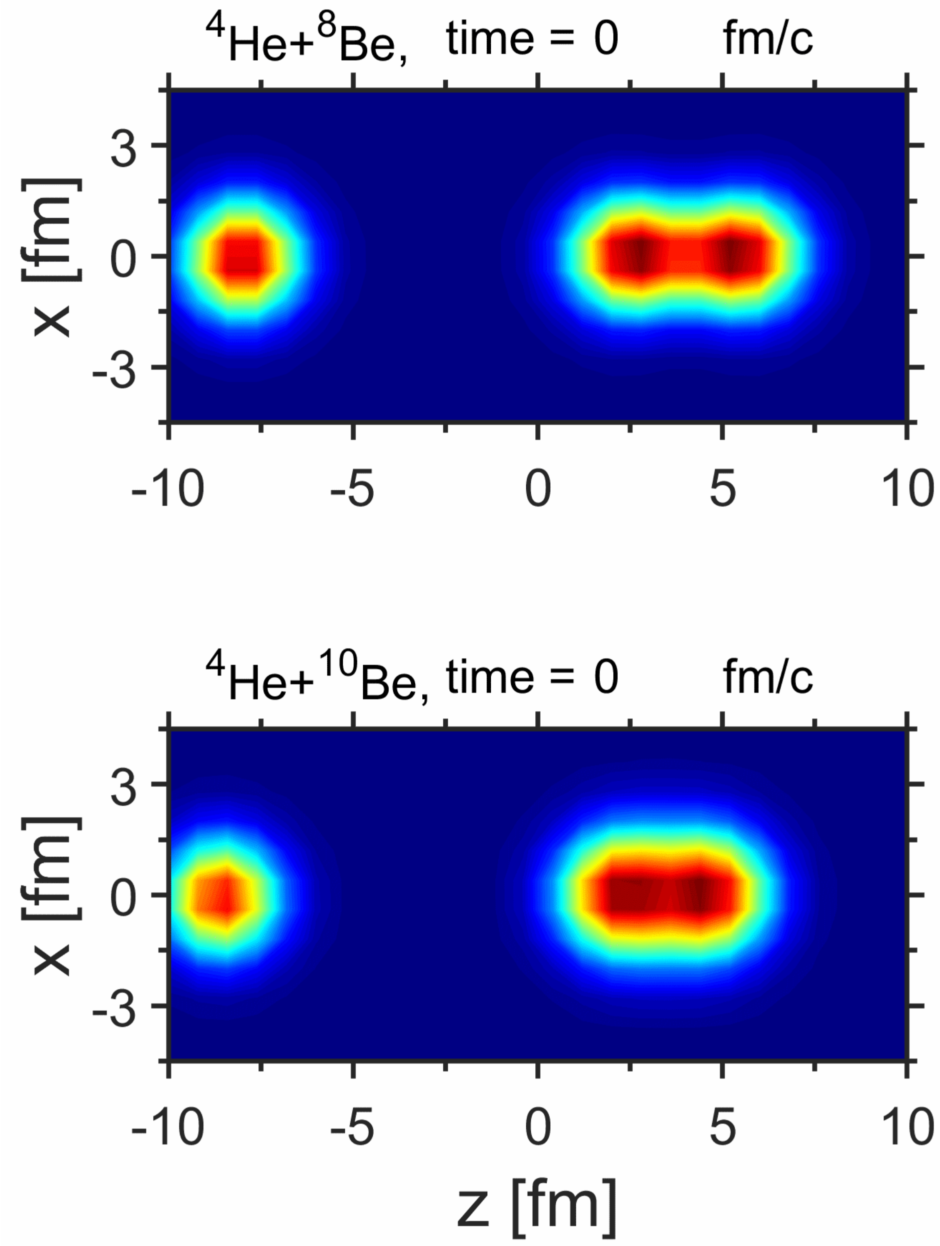
Ren, Zhao, Meng, PLB 801, 135194 (2020)



The linear-chain states are generated, and then evolve to a triangular configuration, and finally to a more compact shape.

$^{4}He + ^{10}Be$



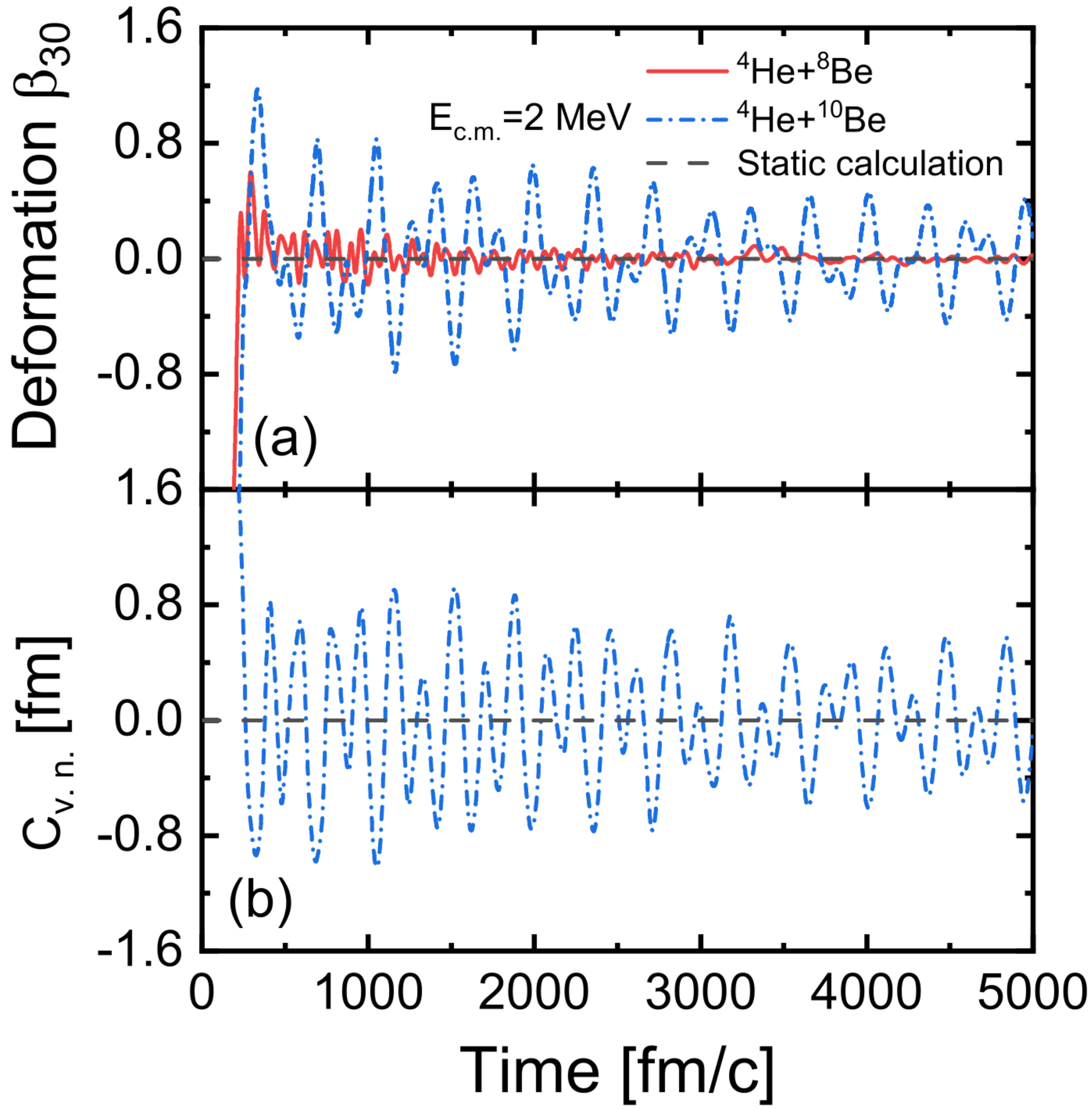


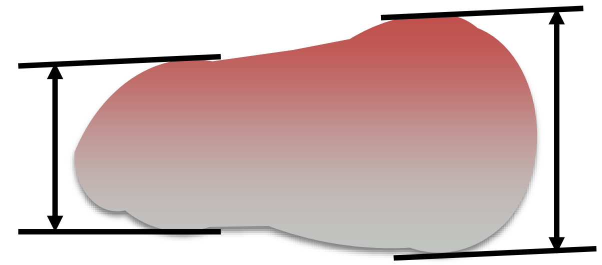
Ren, Zhao, Meng, PLB 801, 135194 (2020)

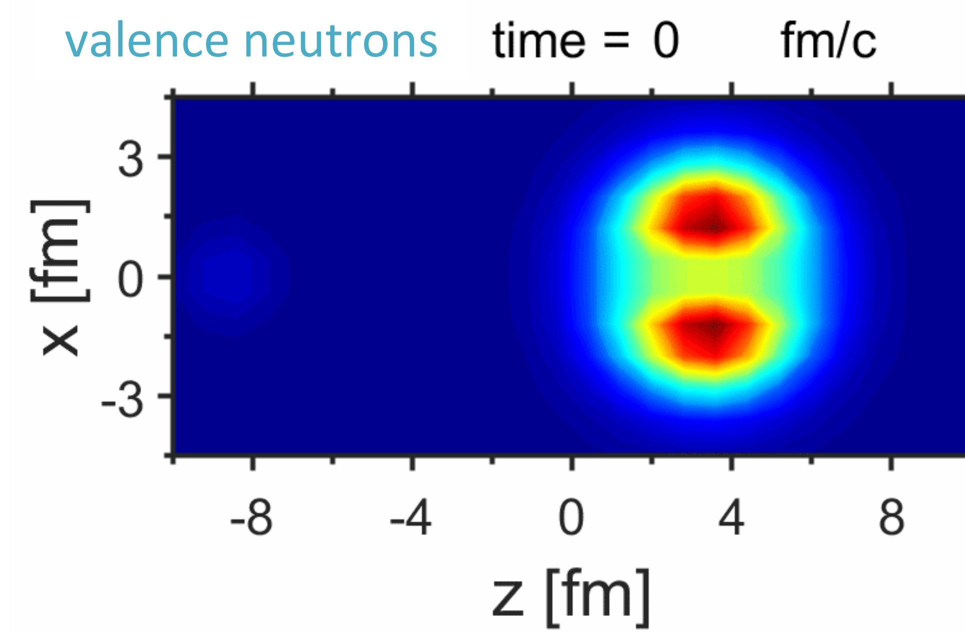
✓ The metastable linear chains can be formed in $^{4}He+^{8}Be$ and $^{4}He+^{10}Be$ collisions.

✓ During the time evolution of the linear-chain configuration, moving clusters can be found.

Octupole deformation





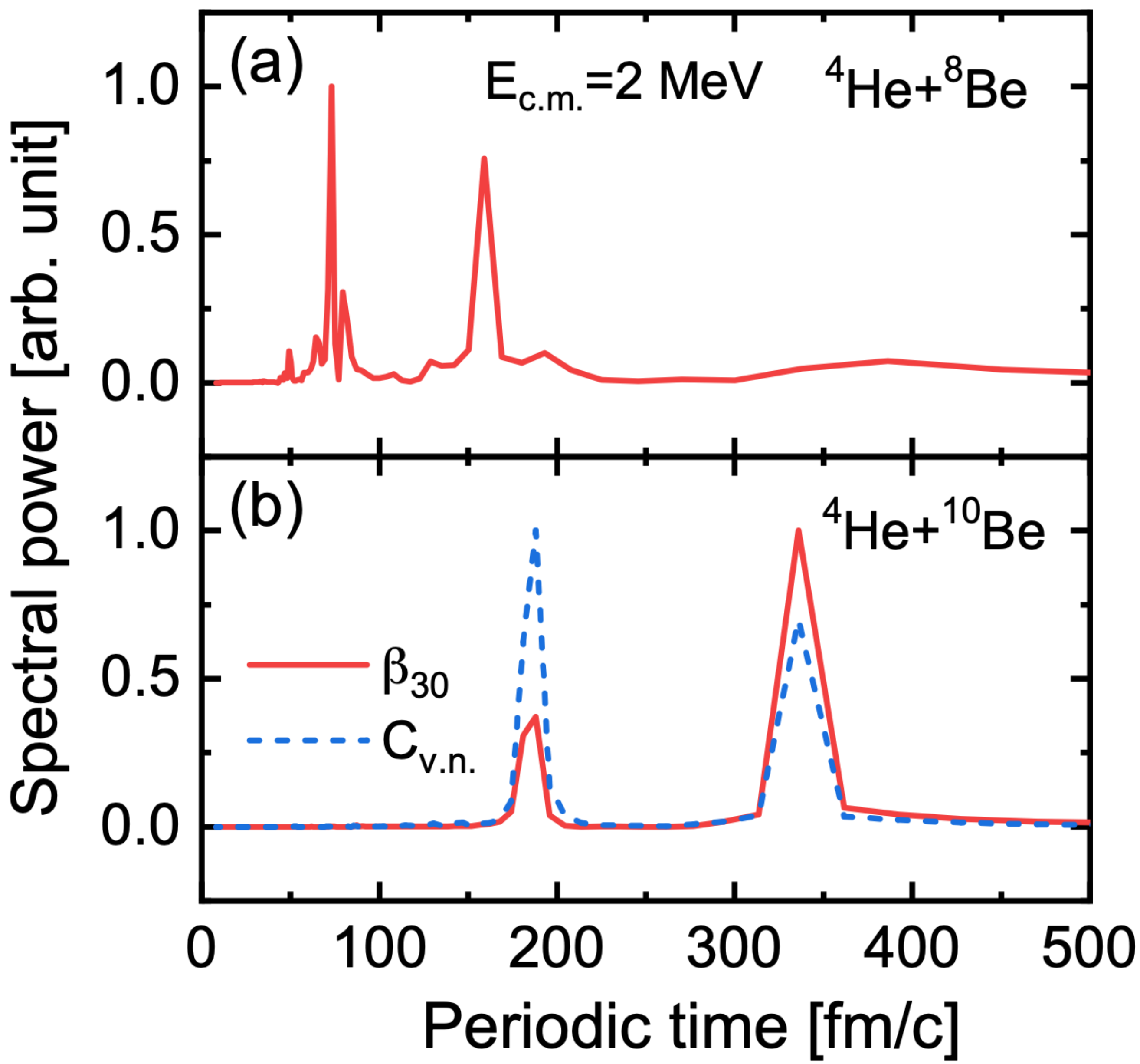


center of valence neutrons

$$C_{\mathrm{v.n.}} = \frac{\int d^3\boldsymbol{r} z(\rho_n - \rho_p)}{\int d^3\boldsymbol{r}(\rho_n - \rho_p)}$$

The oscillation of the two valence neutrons in the longitudinal direction induces the strong oscillation of the octupole deformation.

Dynamical isospin effects



Ren, Zhao, Meng, PLB 801, 135194 (2020)

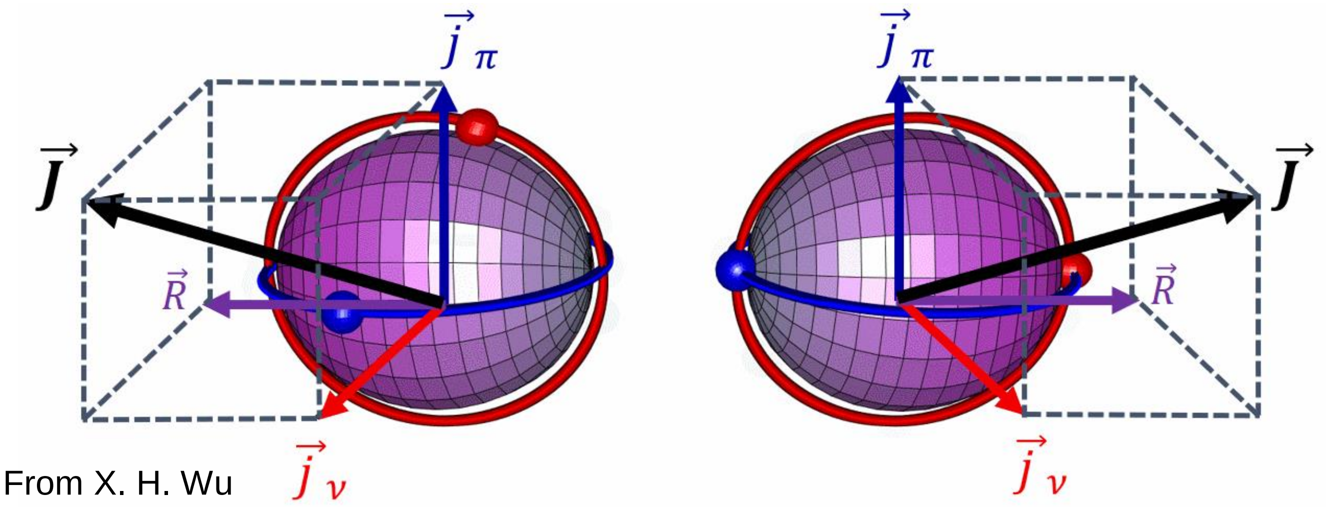
Dynamical isospin effects: slowing down the longitudinal oscillations by the two valence neutrons.

Chiral dynamics

Nuclear spin-chirality

The aplanar (3D-) rotation of a triaxial nucleus could present chiral geometry.

Frauendorf and Meng, Nucl. Phys. A **617**, 131 (1997)



From X. H. Wu

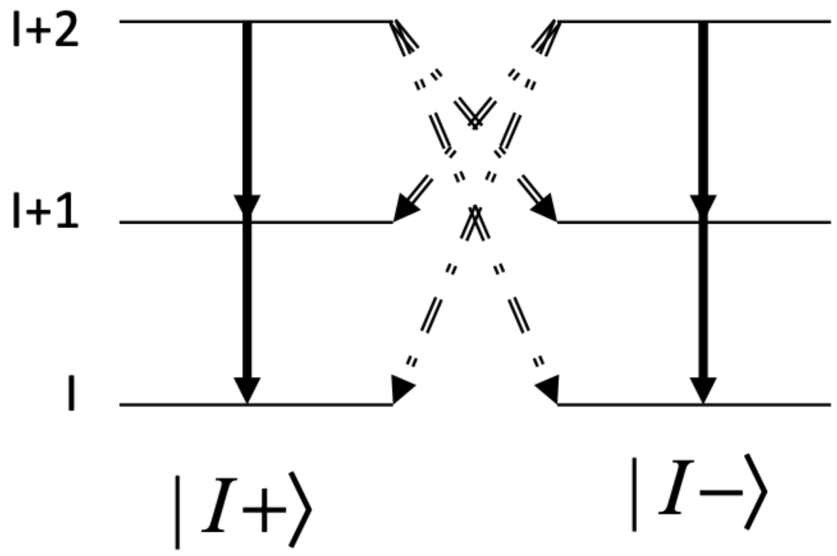
Left-handed $|\mathcal{L}\rangle$ Right-handed $|\mathcal{R}\rangle$

Intrinsic frame：

Chiral Symmetry breaking

$$\hat{\chi} = \hat{T}\hat{R}_y(\pi)$$

$$\hat{\chi}\,|\mathcal{L}\rangle = |\mathcal{R}\rangle \qquad \hat{\chi}\,|\mathcal{R}\rangle = |\mathcal{L}\rangle$$



Lab. frame：

Chiral Symmetry restoration

$$|I+\rangle = \frac{1}{\sqrt{2}}(|\mathcal{L}\rangle) + |\mathcal{R}\rangle)$$

$$|I-\rangle = \frac{i}{\sqrt{2}}(|\mathcal{L}\rangle) - |\mathcal{R}\rangle)$$

Exp. signal：Two near degenerate ΔI =1 bands, called chiral doublet bands

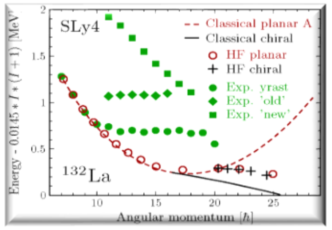
北京大學

Timeline for nuclear chirality

NPA 617, 131

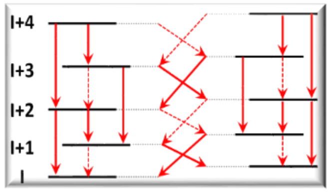
Prediction

PRL 93, 052501



Critical Frequency

PRL 93, 172502

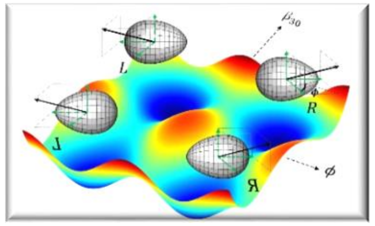


***EM* transition Selection Rule**

PRC 73, 037303

MχD

Sci. Bull. 65, 2001



Chirality-Parity Violation

1997 — **2001** — **2004** — **2006** — **2013** — **2014** — **2016** — **2018** — **2020** →

2001: ^{130}Cs ^{132}La ^{134}Pr ^{136}Pm — **First Evidence** — PRL 86, 971

2004: ^{128}Cs — **Lifetime Analysis** — PRL 97, 172501

2013: ^{133}Ce — **First MχD Evidence** — PRL 110, 172504

2014: ^{106}Ag — **Chiral Conundrum Resolution** — PRL 112, 202502

2016: ^{78}Br **MχD with Octupole Correlations** — PRL 116, 112501

2018: ^{128}Cs — **g factor** — PRL 120, 022502

By Yiping Wang et al

Applications of TAC-CDFT for chiral nuclei

$^{102\text{-}107}$Rh, ^{106}Ag, **^{135}Nd**, ^{136}Nd

Zhao PLB 773, 1-5 (2017)

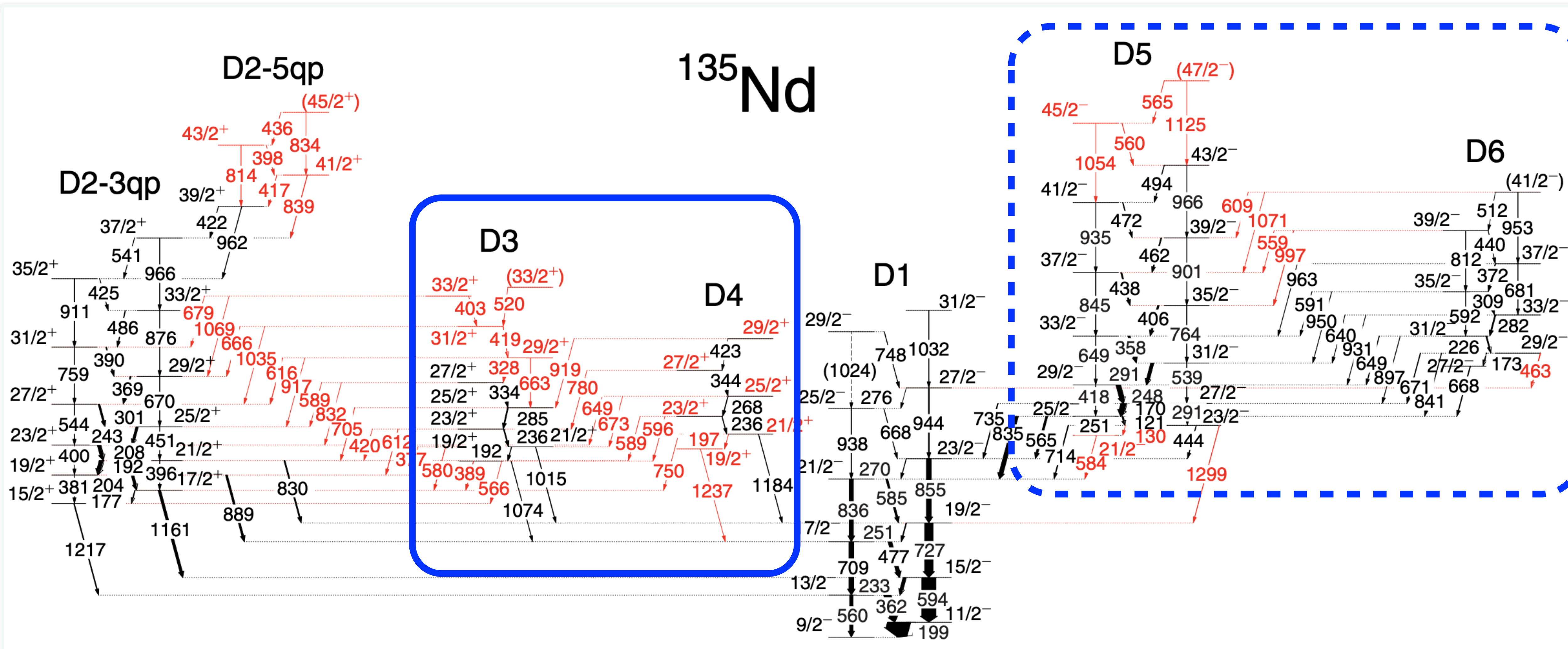
Zhao, Wang, and Chen, PRC 99, 054319 (2019)

Peng and Chen, PLB 810, 135795 (2020)

Peng and Chen, PRC 105, 044318 (2022)

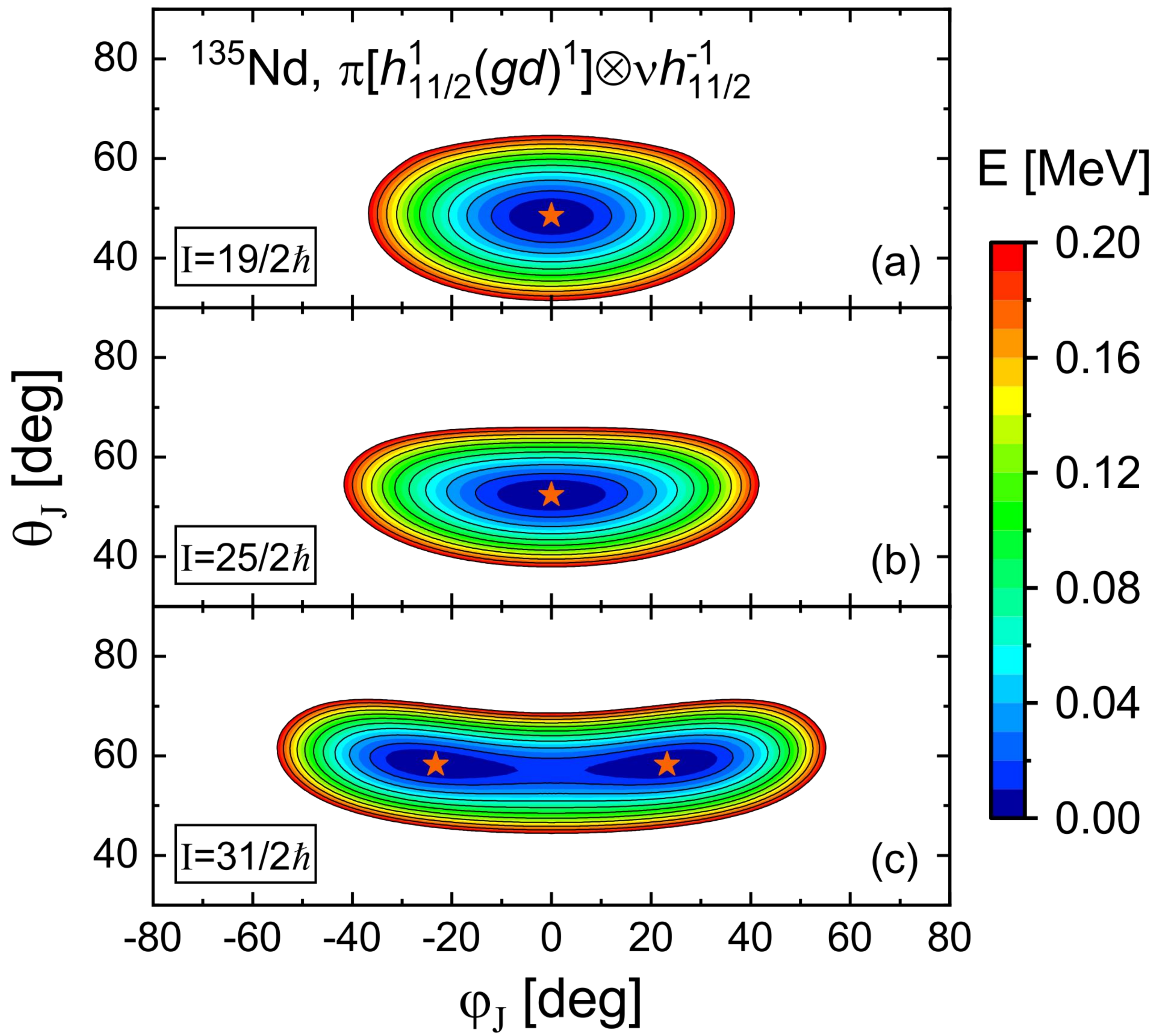
D3-D4 $\pi[h^{1}_{11/2}(gd)^{1}] \otimes \nu h^{-1}_{11/2}$

D5-D6 $\pi h^{2}_{11/2} \otimes \nu h^{-1}_{11/2}$

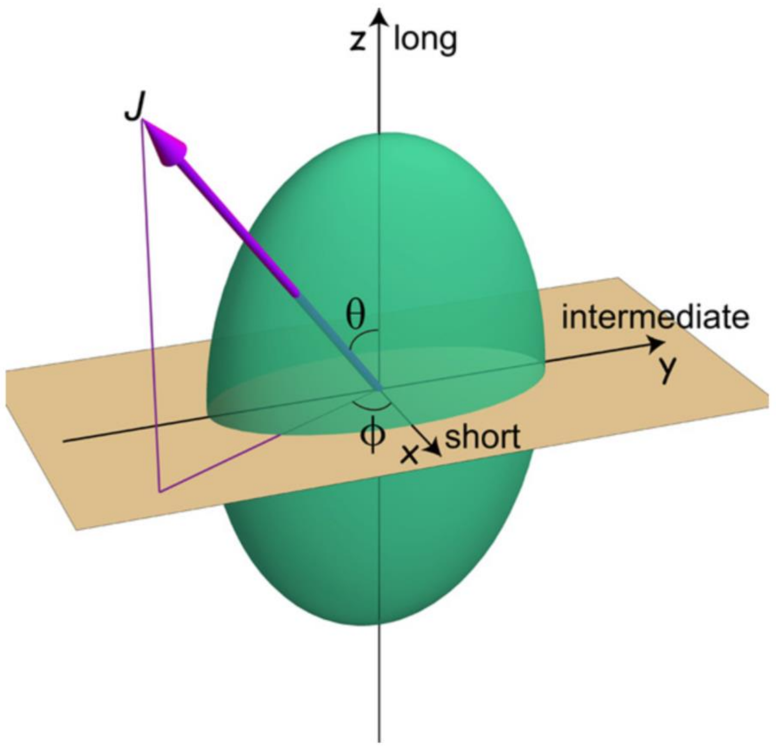


Experimental Data from Lv et al., Phys. Rev. C 100, 024314 (2019)

Energy surface against tilted angles



polar angle θ
azimuth angle φ

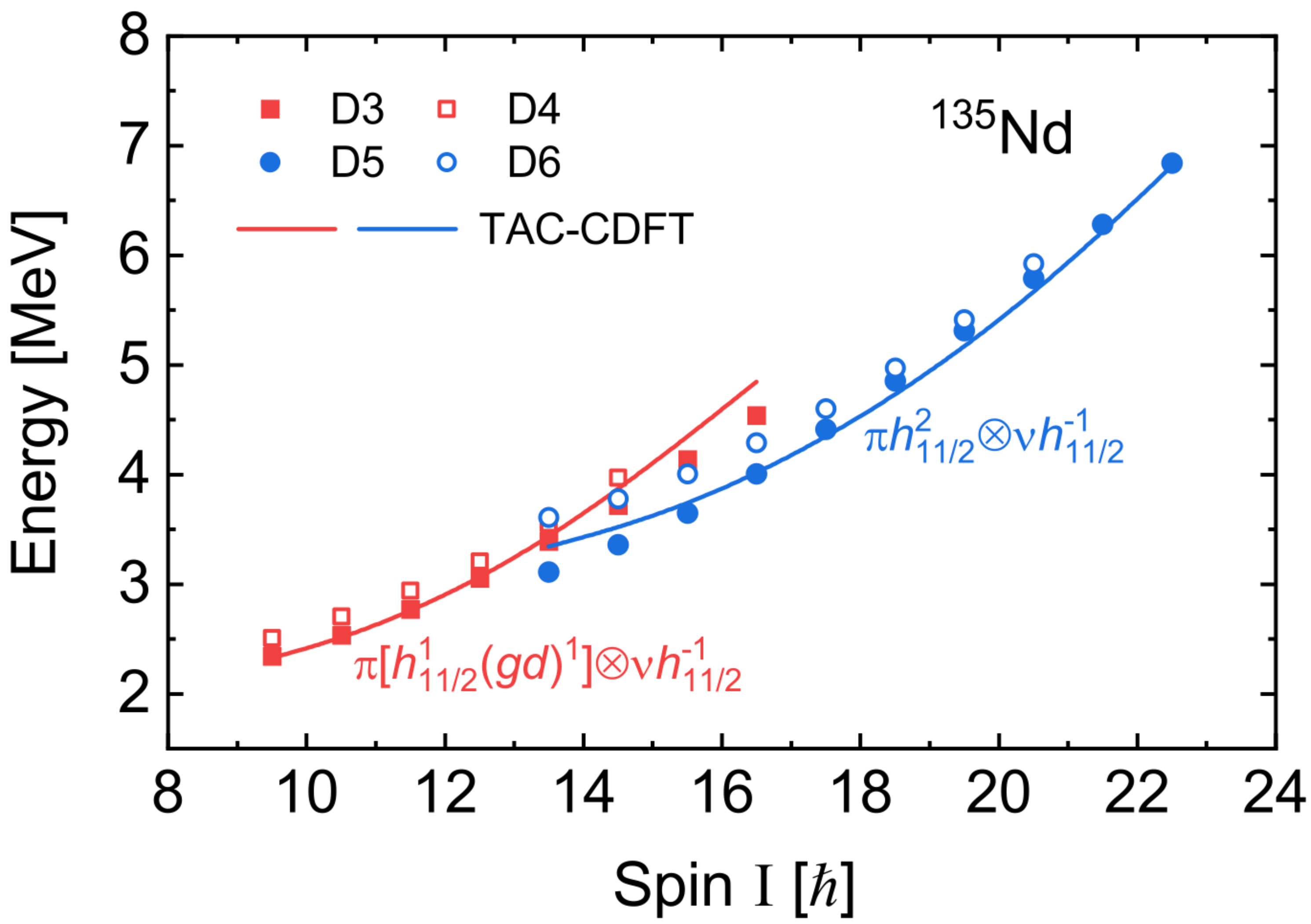


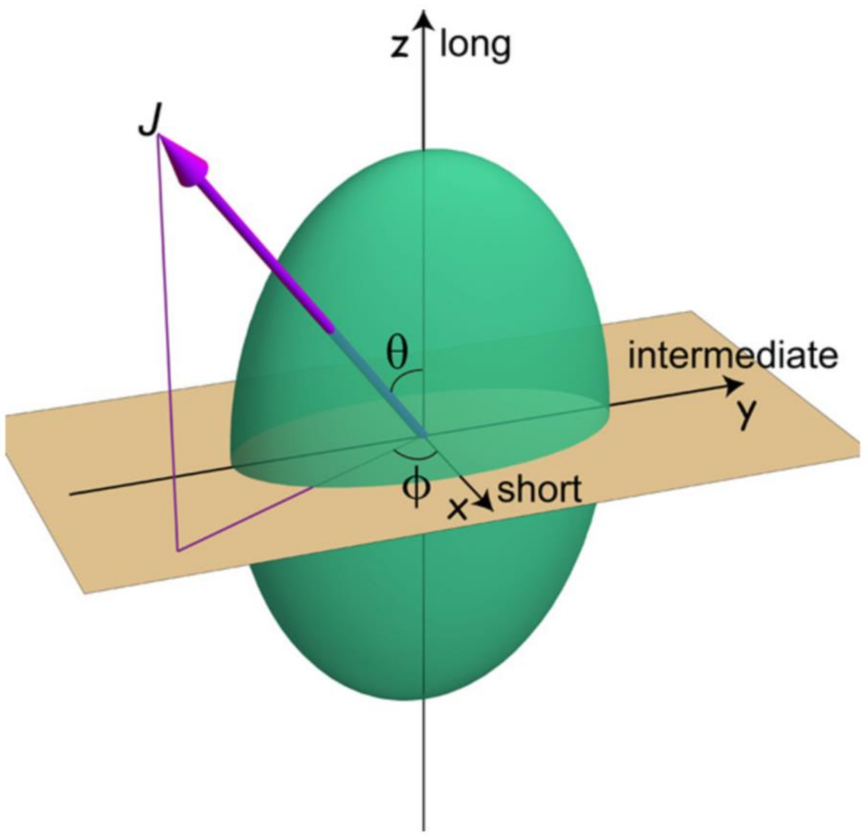
Chiral geometry is clearly seen.

Ren, Zhao, Meng, PRC, **105**, L011301 (2022)

Chiral rotation

The lower bands are well reproduced.





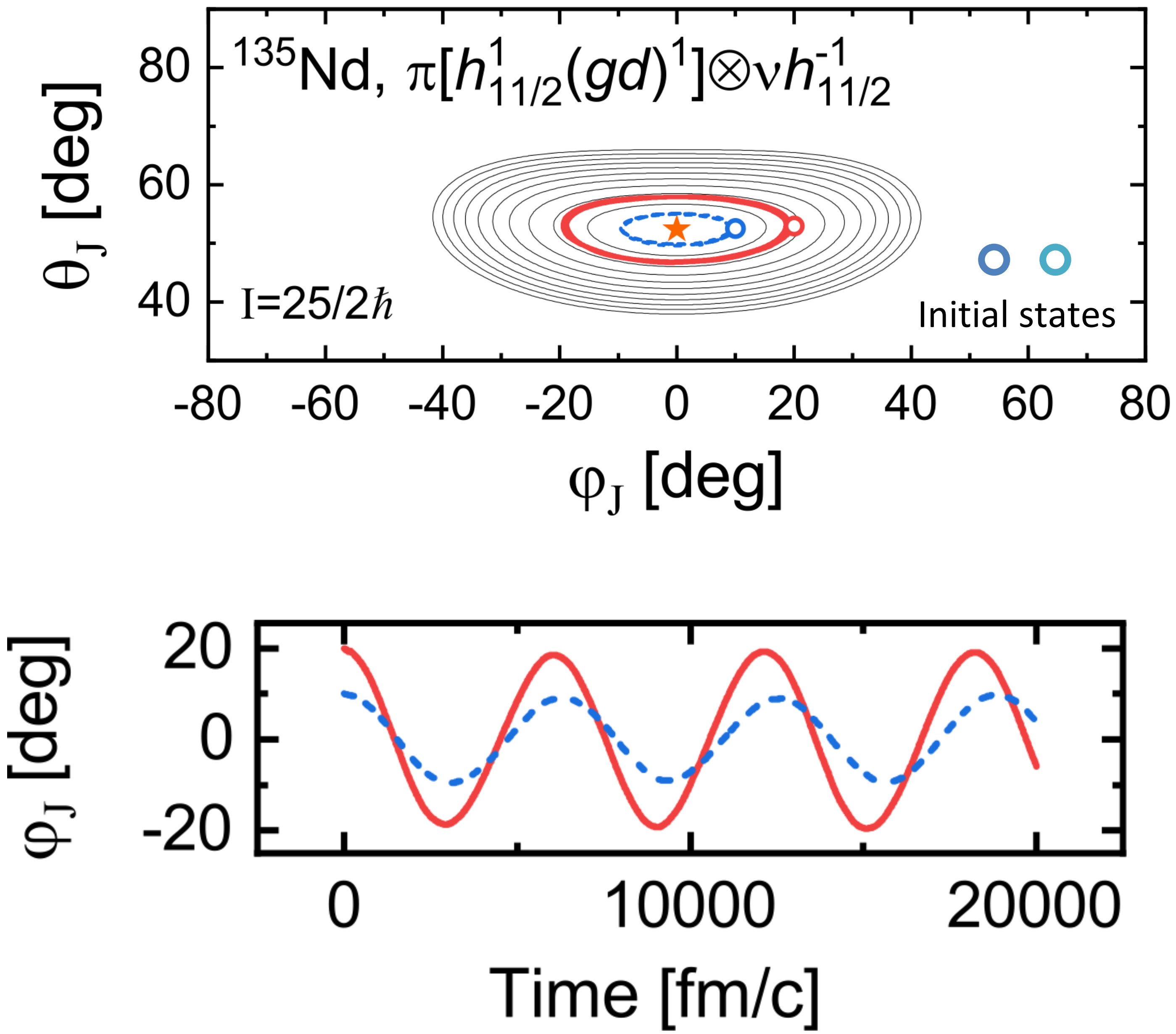
One does NOT get the upper bands !

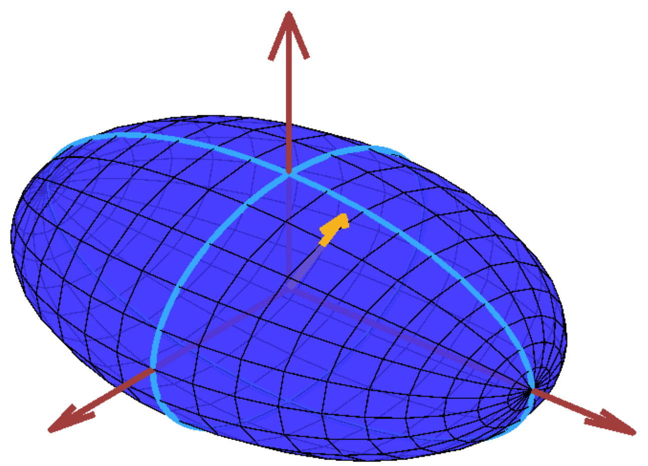
Zhao, PLB **773**, 1 (2017)

Ren, Zhao, Meng, PRC, **105**, L011301 (2022)

Chiral precession in triaxial nuclei

Chiral Precession across left and right sectors

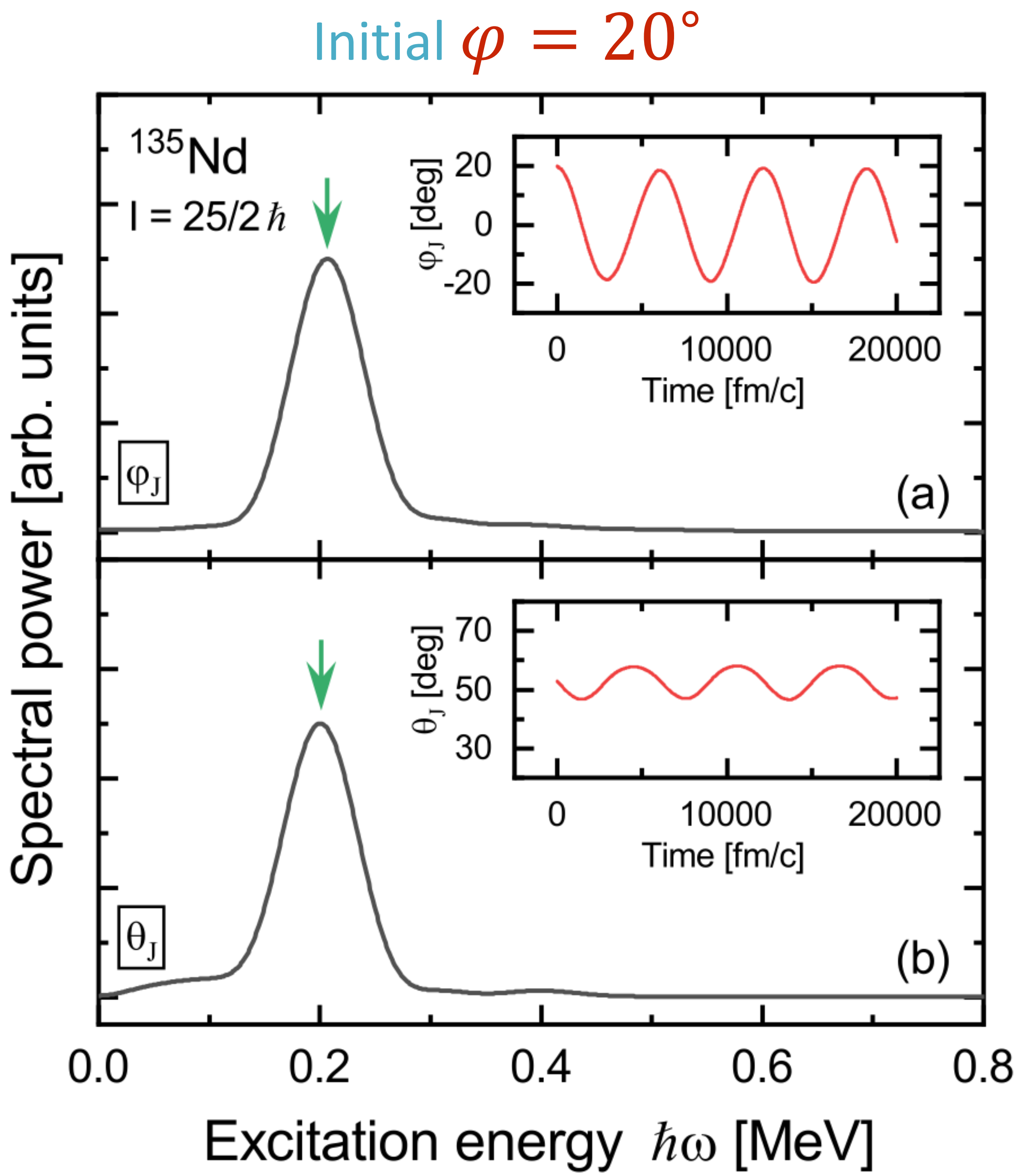


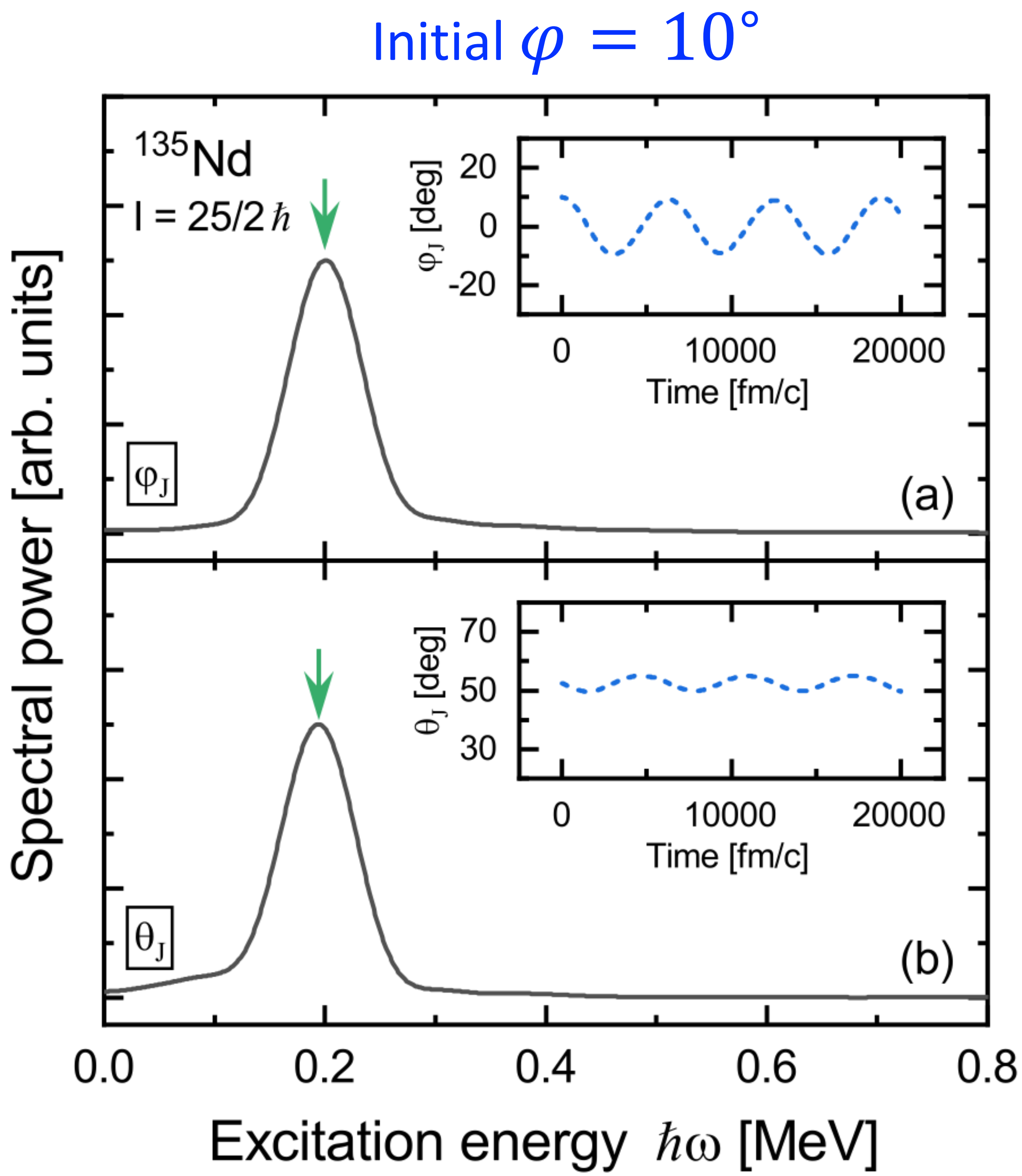


Precession periods are roughly **identical**.

Ren, Zhao, Meng, PRC, **105**, L011301 (2022)

Chiral excitation energies via Fourier analyses

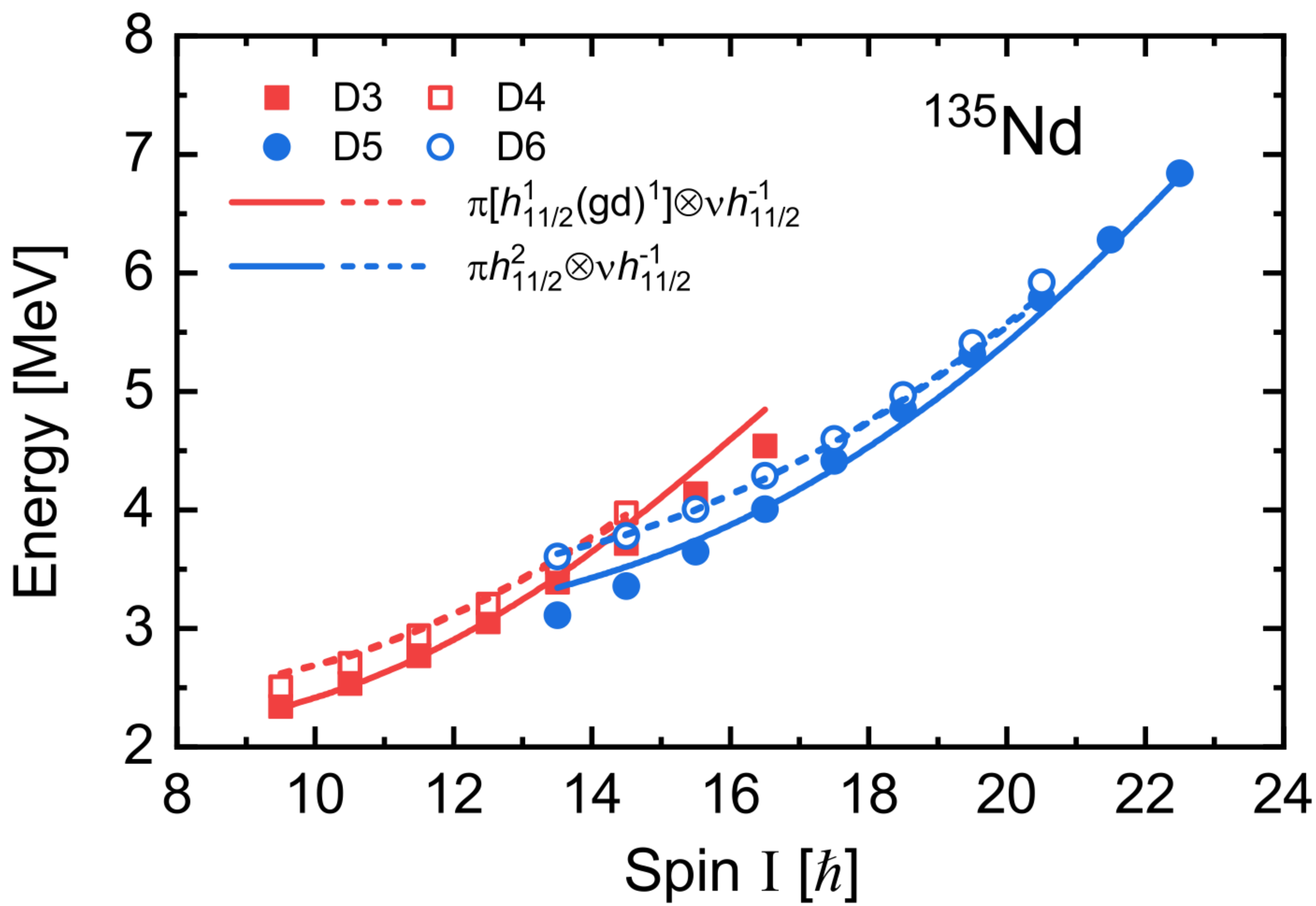




Ren, Zhao, Meng, PRC, **105**, L011301 (2022)

Energy spectrum

Ren, Zhao, Meng, PRC, **105**, L011301 (2022)



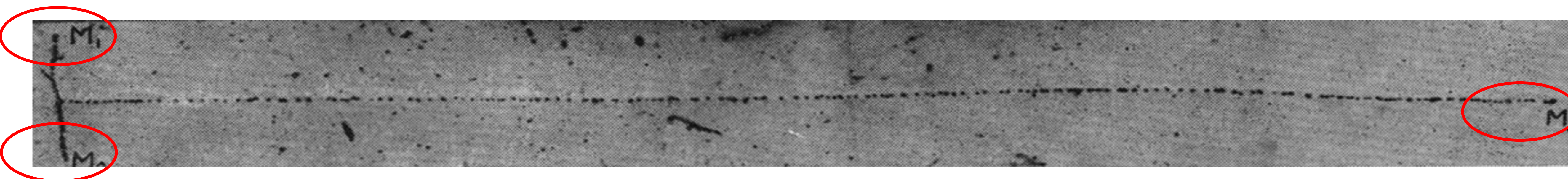
The first fully microscopic and self-consistent description for the ***chiral twin bands*** in the framework of DFTs.

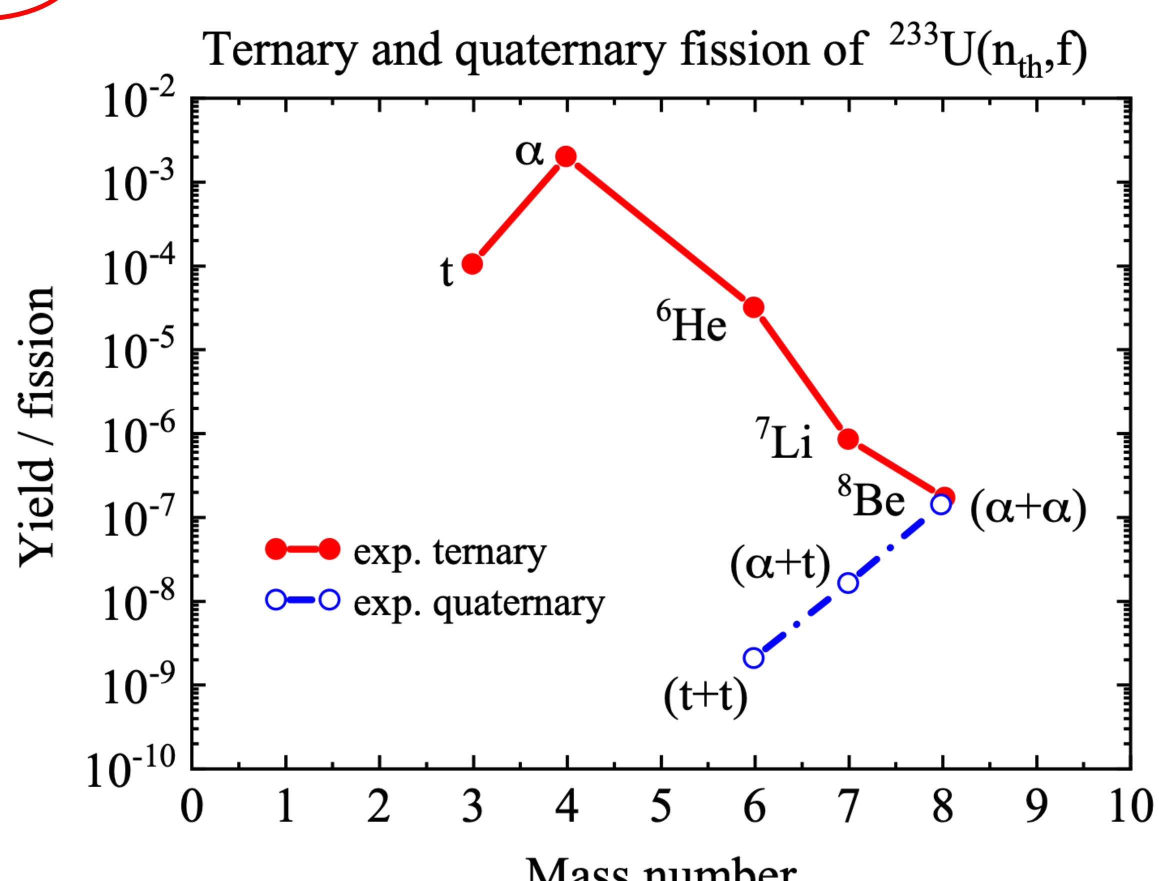
Fission

Ternary and quaternary fission

- The ternary and quaternary fission were discovered by Tsien San-Tsiang, Ho Zah-Wei *et al.* in 1947.

Tsien San-Tsiang, Ho Zah-Wei, L. Vigneron, and R. Chastel, Nature 159, 773 (1947)





F. Gönnenwein, Nucl. Phys. A 734, 213 (2004)

Scission mechanism

- Statistical scission-point model
- Random neck rupture model
- Geometrical definitions
- Ratio between nuclear and Coul. Forces
- Quantum localization method
- …..

Ternary and quaternary fission

No. 4049 June 7, 1947 NATURE 773

LETTERS TO THE EDITORS

The Editors do not hold themselves responsible for opinions expressed by their correspondents. No notice is taken of anonymous communications

Ternary and Quaternary Fission of Uranium Nuclei

AFTER our experimental proof of the existence of tripartition and quadripartition (ternary and quaternary fission) of U^{235} by means of photographic emulsion[1,2], a systematic study of the mass and kinetic energy of fission fragments has been made with the Ilford Nuclear Research C_2 plate. The experimental conditions were similar to those of previous work. C_2 plates soaked with 10 per cent solution of uranyl nitrate were bombarded with slow neutrons produced

Similar experiments have been made recently on the fission of uranium by fast neutrons. Short-range third light particles have been observed with the same frequency, but until now no long-range particle has been detected. Similar results have also been obtained in the case of fission of thorium by fast neutrons (observation made by the senior author in collaboration with Mrs. H. Faraggi).

TSIEN SAN-TSIANG
HO ZAH-WEI
L. VIGNERON
R. CHASTEL

Laboratoire de Chimie Nucléaire,
Collège de France, Paris.
March 15.

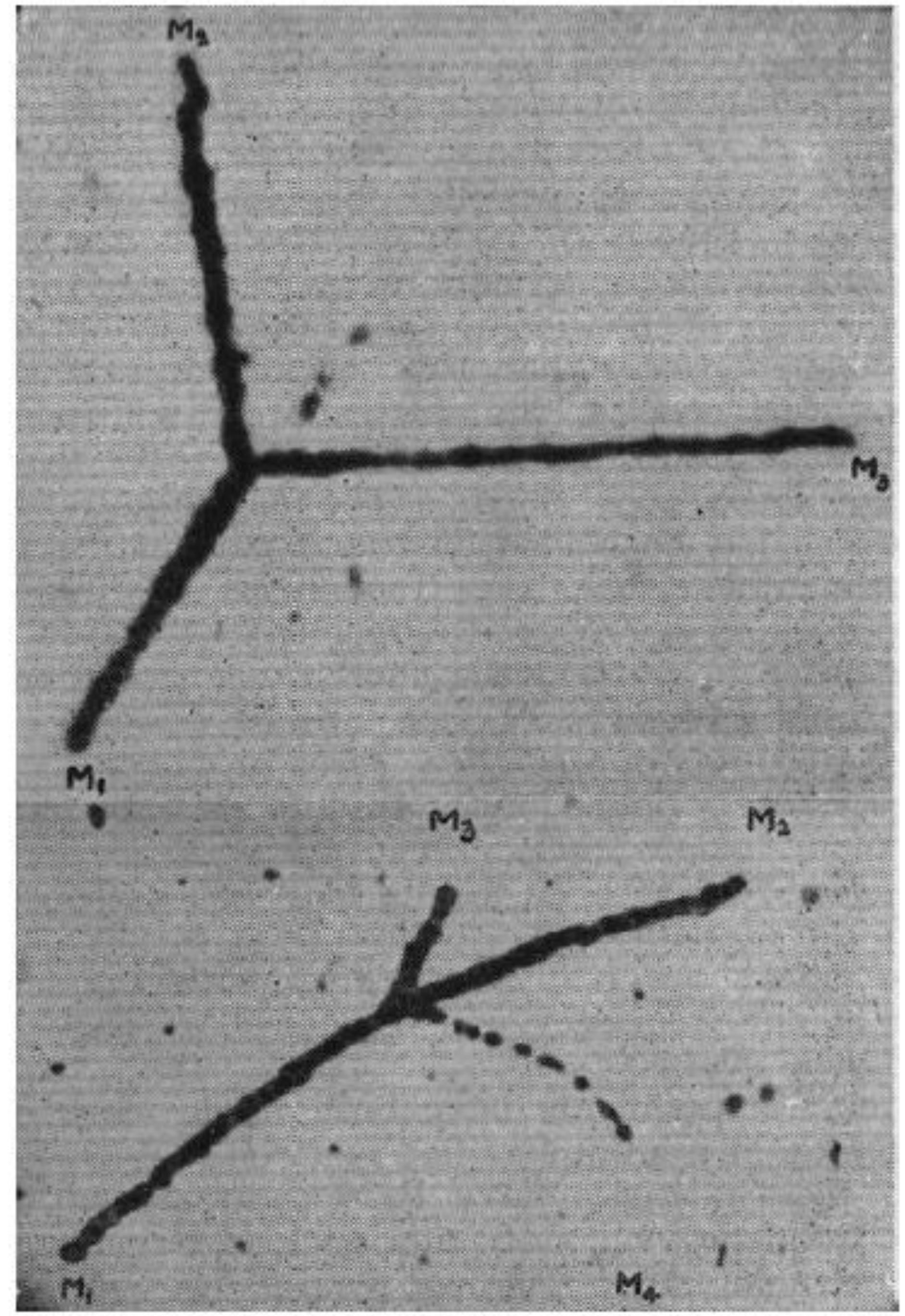


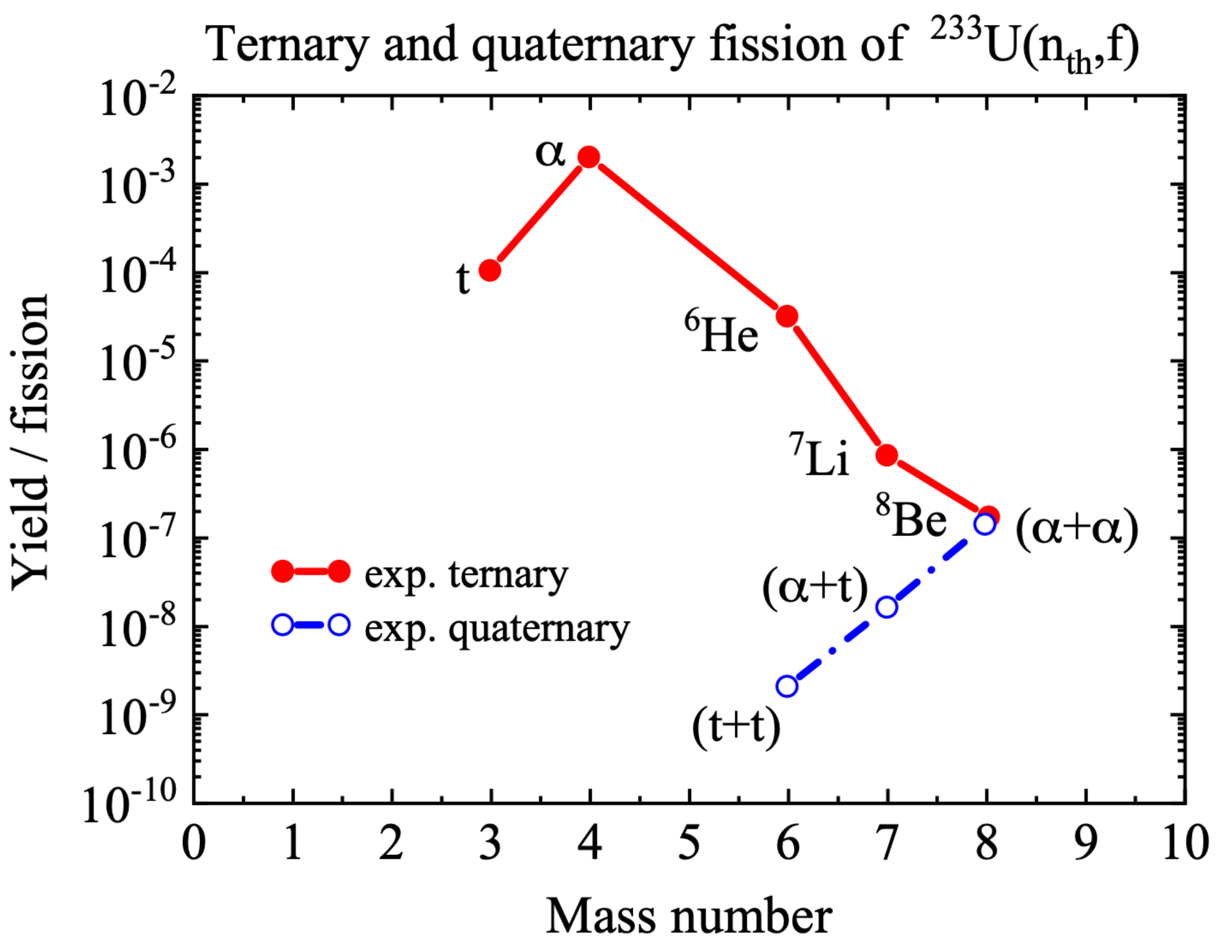
Fig. 2 (above); Fig. 3 (below)

Fig. 2. TRIPARTITION OF URANIUM NUCLEUS WITH THREE FRAGMENTS OF COMPARABLE MASSES: $m_1 = 127$; $m_2 = 77$; $m_3 = 32$

Fig. 3. QUADRIPARTITION OF URANIUM NUCLEUS

Ternary and quaternary fission

How are heavy nuclei ruptured?



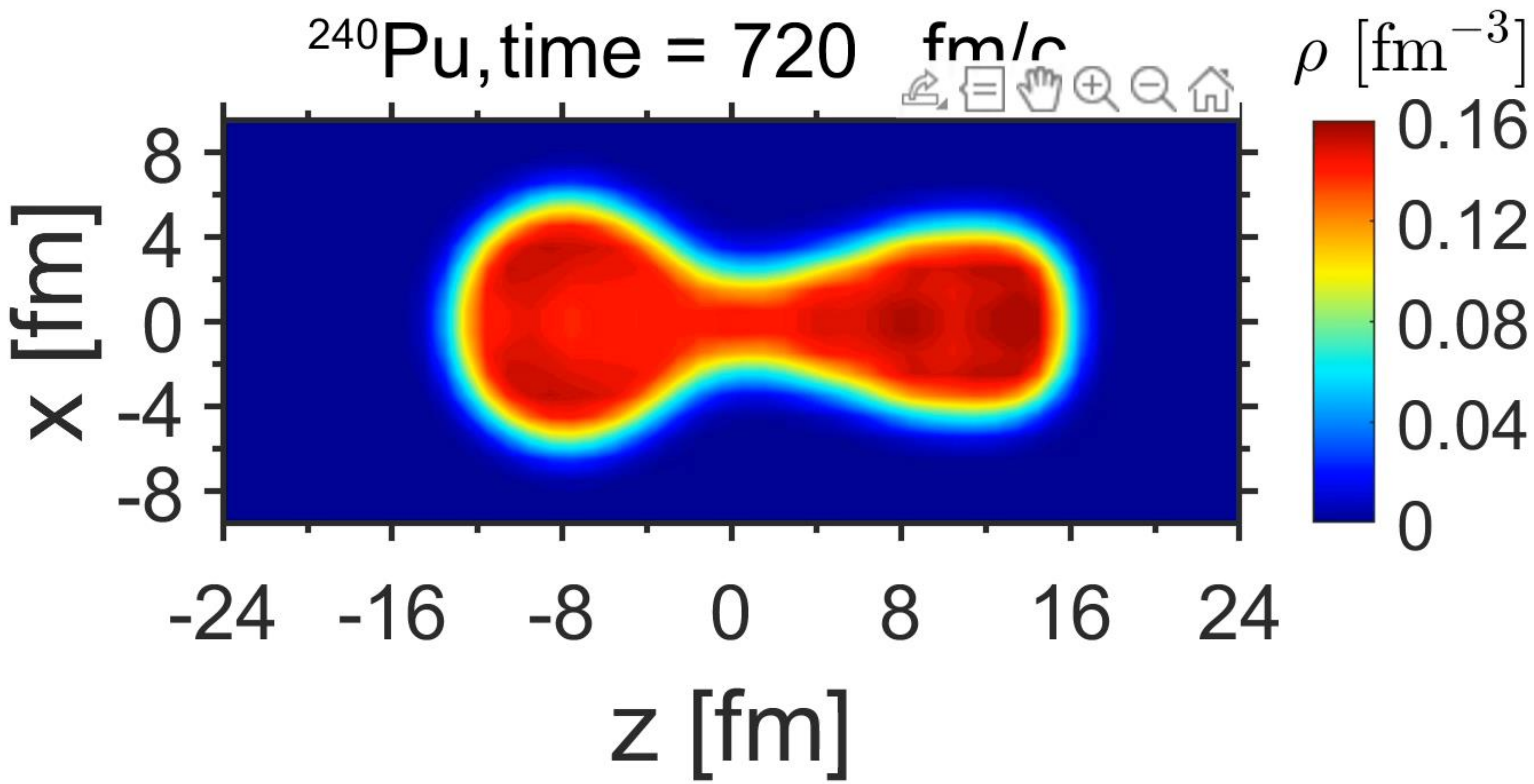
Scission mechanism

- Statistical scission-point model
- Random neck rupture model
- Geometrical definitions
- Ratio between nuclear and Coul. forces
- Quantum localization method
- …

Tsien San-Tsiang, Ho Zah-Wei, L. Vigneron, and R. Chastel, Nature (London) 159, 773 (1947)

F. Gönnenwein, NPA 734 (2004) 213

^{240}Pu: Nuclear density



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

Localization function

$$D_{q\sigma}(\boldsymbol{r}) = \left[\sum_{\alpha\in q} |\boldsymbol{\nabla}\phi_\alpha(\boldsymbol{r},\sigma)|^2 - \frac{\left|\sum_{\alpha\in q}\phi^*_\alpha(\boldsymbol{r},\sigma)\boldsymbol{\nabla}\phi_\alpha(\boldsymbol{r},\sigma)\right|^2}{\rho_{q\sigma}(\boldsymbol{r})} \right]$$

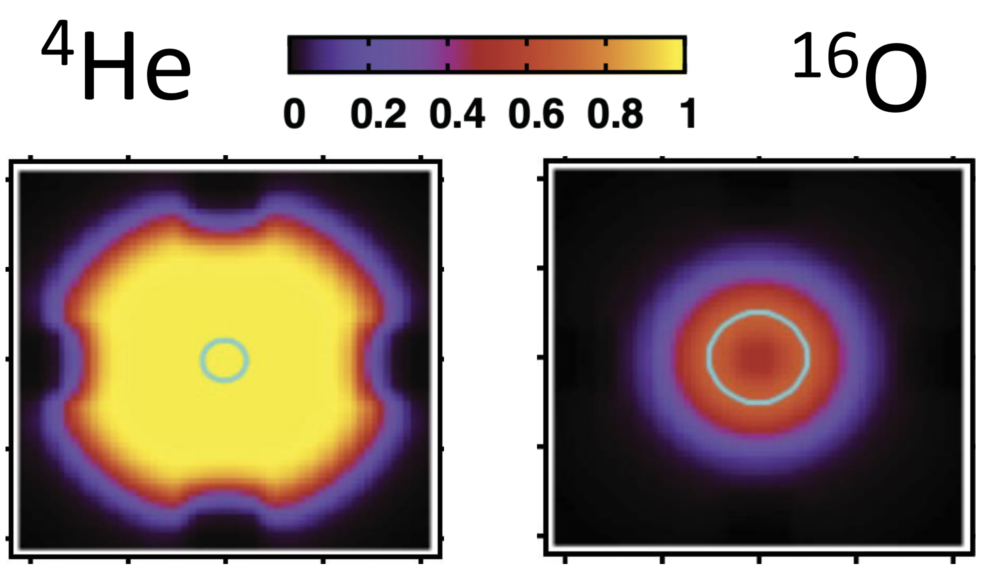
the probability of finding two like-particles in the vicinity of each other —〉 Localization!

Becke and Edgecombe, J. Chem. Phys., **92**, 5397 (1990)

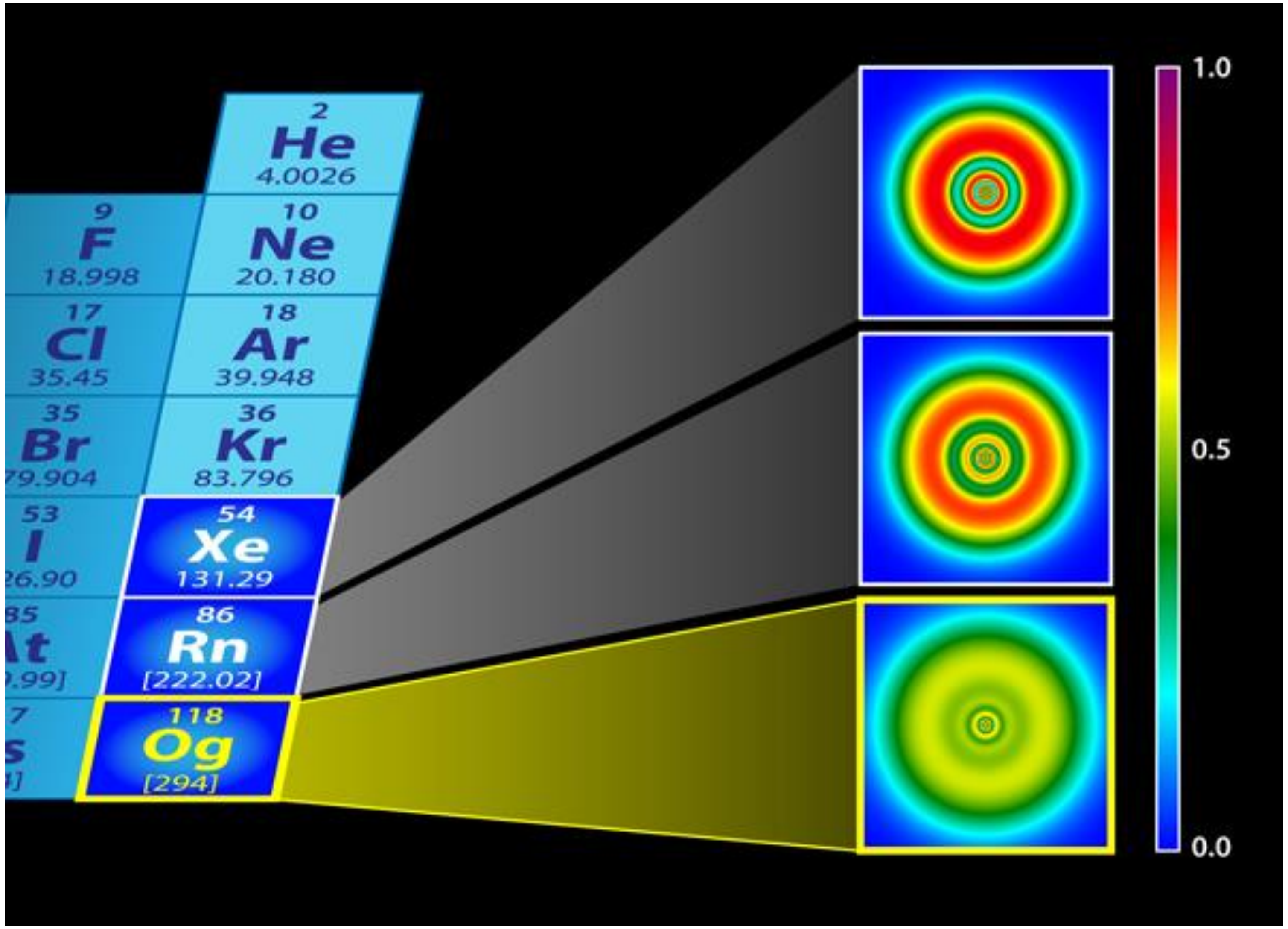
$$\mathcal{C}_{q\sigma}(\boldsymbol{r}) = \left[1 + \left(\frac{D_{q\sigma}(\boldsymbol{r})}{\tau^{\mathrm{TF}}_{q\sigma}(\boldsymbol{r})} \right)^2 \right]^{-1}$$

C = 1/2; Thomas-Fermi Gas

C = 1; Highly Localized



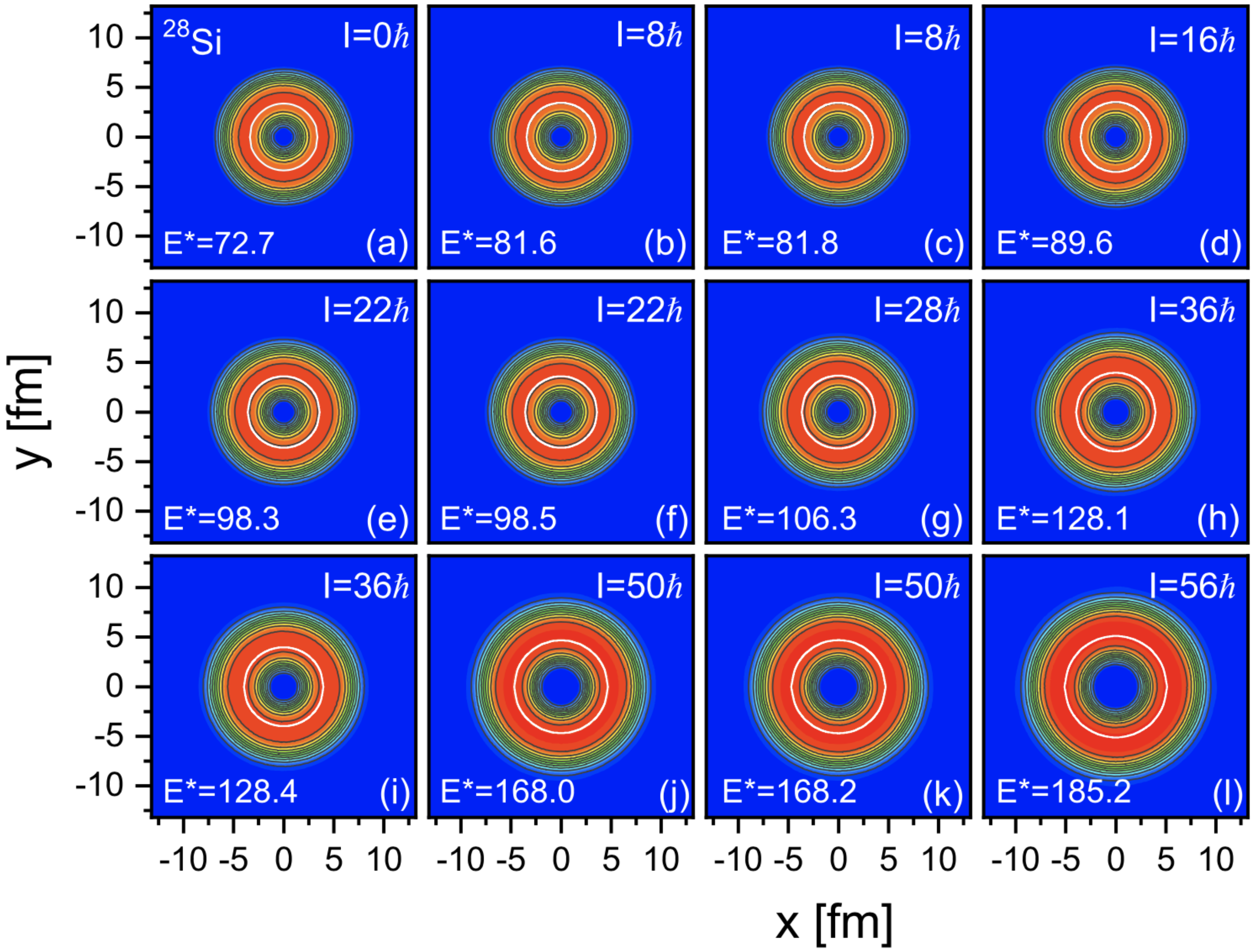
Reinhard, et al., Phys. Rev. C **83**, 034312 (2011)



Jerabek et al., Phys. Rev. Lett. 120, 053001 (2018)

Localization function

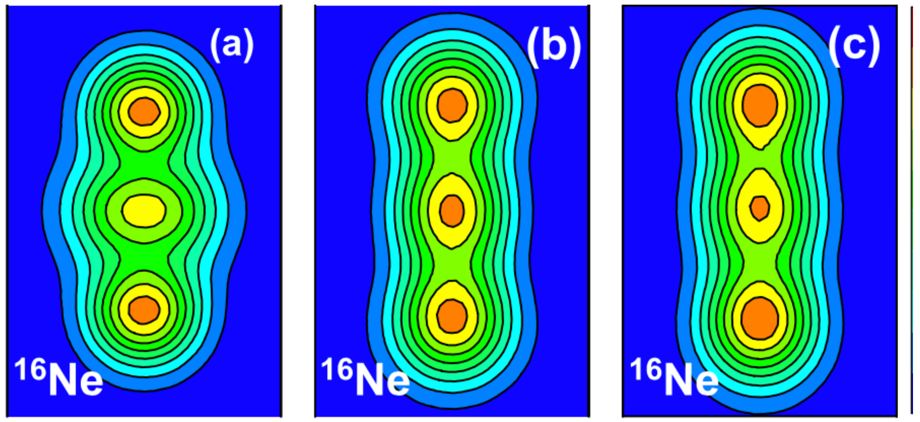
Toroidal states in ^{28}Si



Cao et al., Phys. Rev. C, **99**, 014606 (2019)

Ren, Zhao, Zhang, Meng, Nucl. Phys. A, **996**, 121696, (2020)

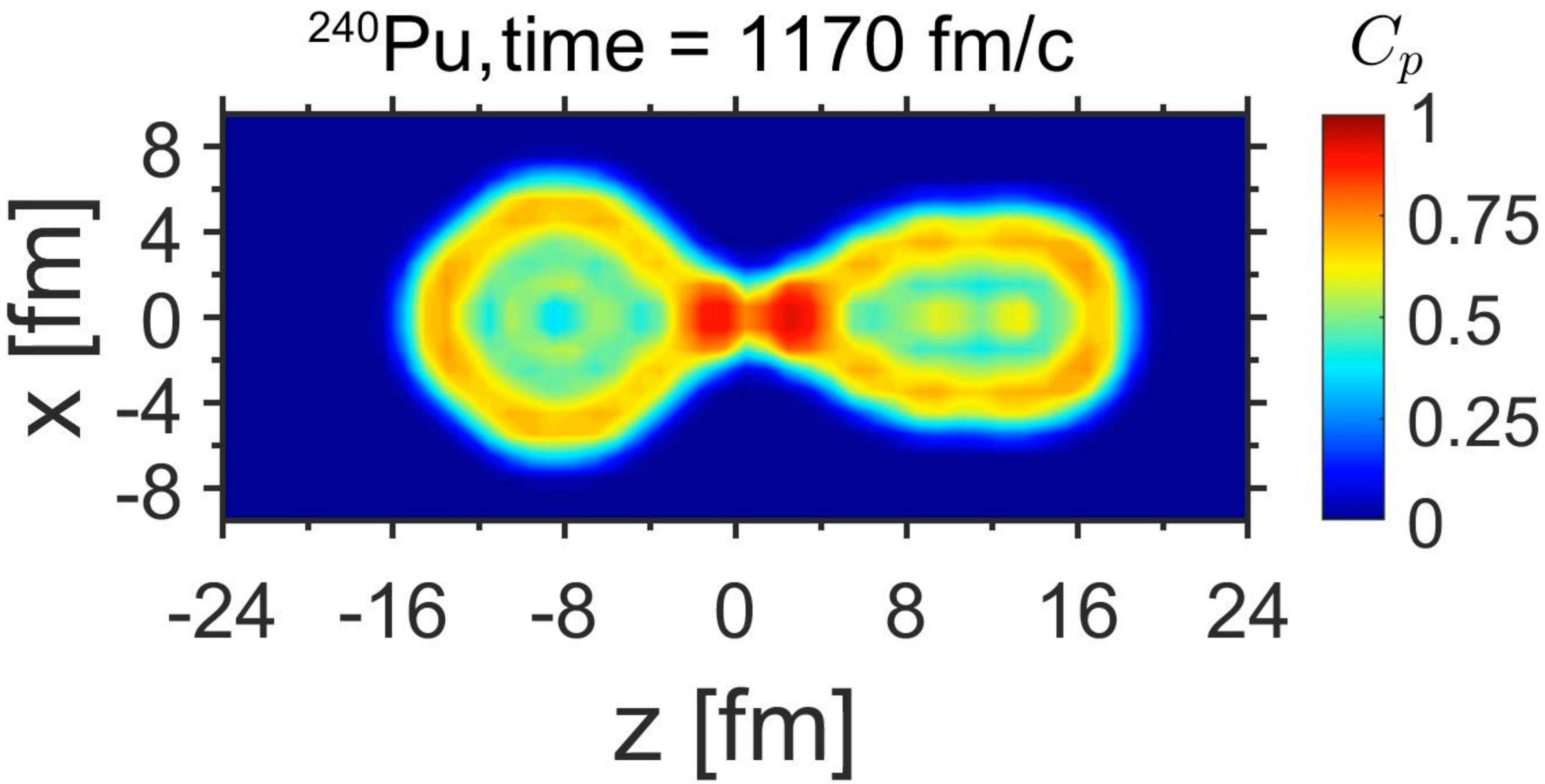
molecular α-chain nuclei



Zhang, Ren, Zhao, Vretenar, Nikšić, Meng, PRC, 105, 024322 (2022)

^{240}Pu : Localization function

PRL 128, 172501 (2022)



Scission point between two alpha-like particles

Toward a comprehensive description of nuclear fission

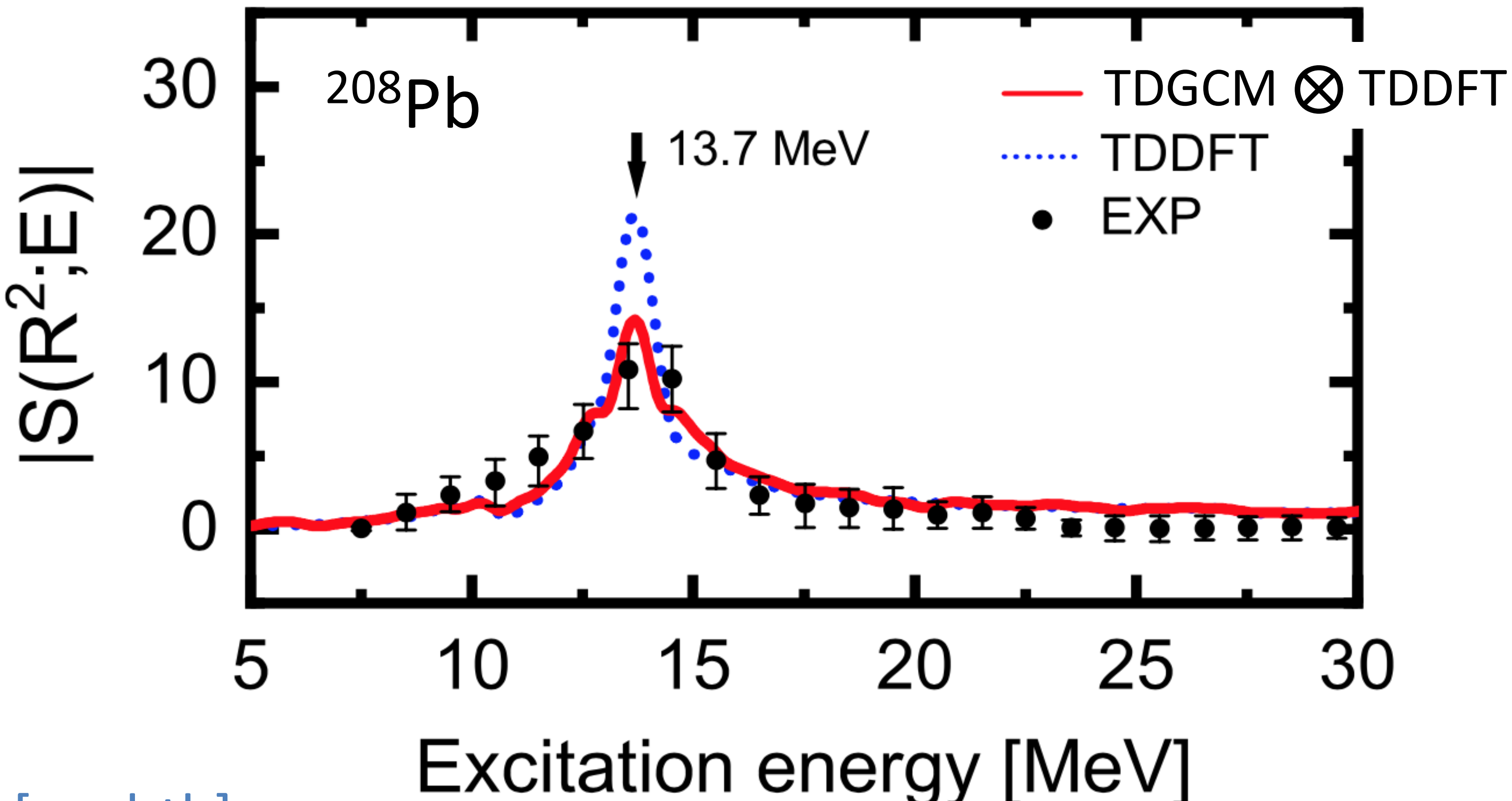
TDGCM+GOA

- ☑ collective degrees of freedom
- ☑ quantum correlations (beyond MF)
- ☐ no dissipation (adiabatic)

TD-CDFT

- ☑ independent nucleons
- ☐ no quantum correlations (MF)
- ☑ dissipative dynamics （nonadiabatic）

"TDGCM ⊗ TDDFT" $|\Psi(t)\rangle = \int da f(a,t)|\Phi(a,t)\rangle$



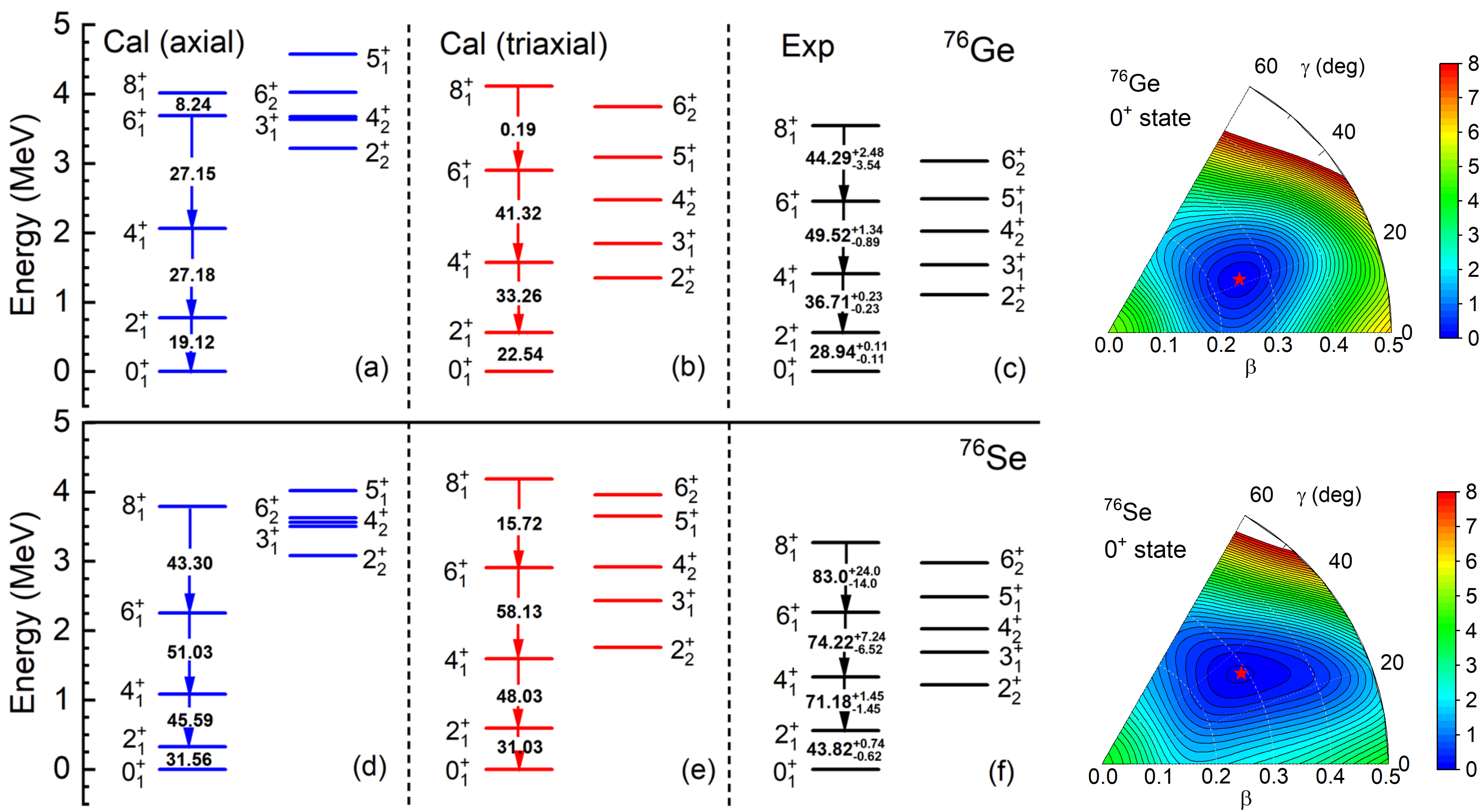
arXiv:2304.13369 [nucl-th]

ReCD theory

Relativistic Configuration-interaction Density functional theory

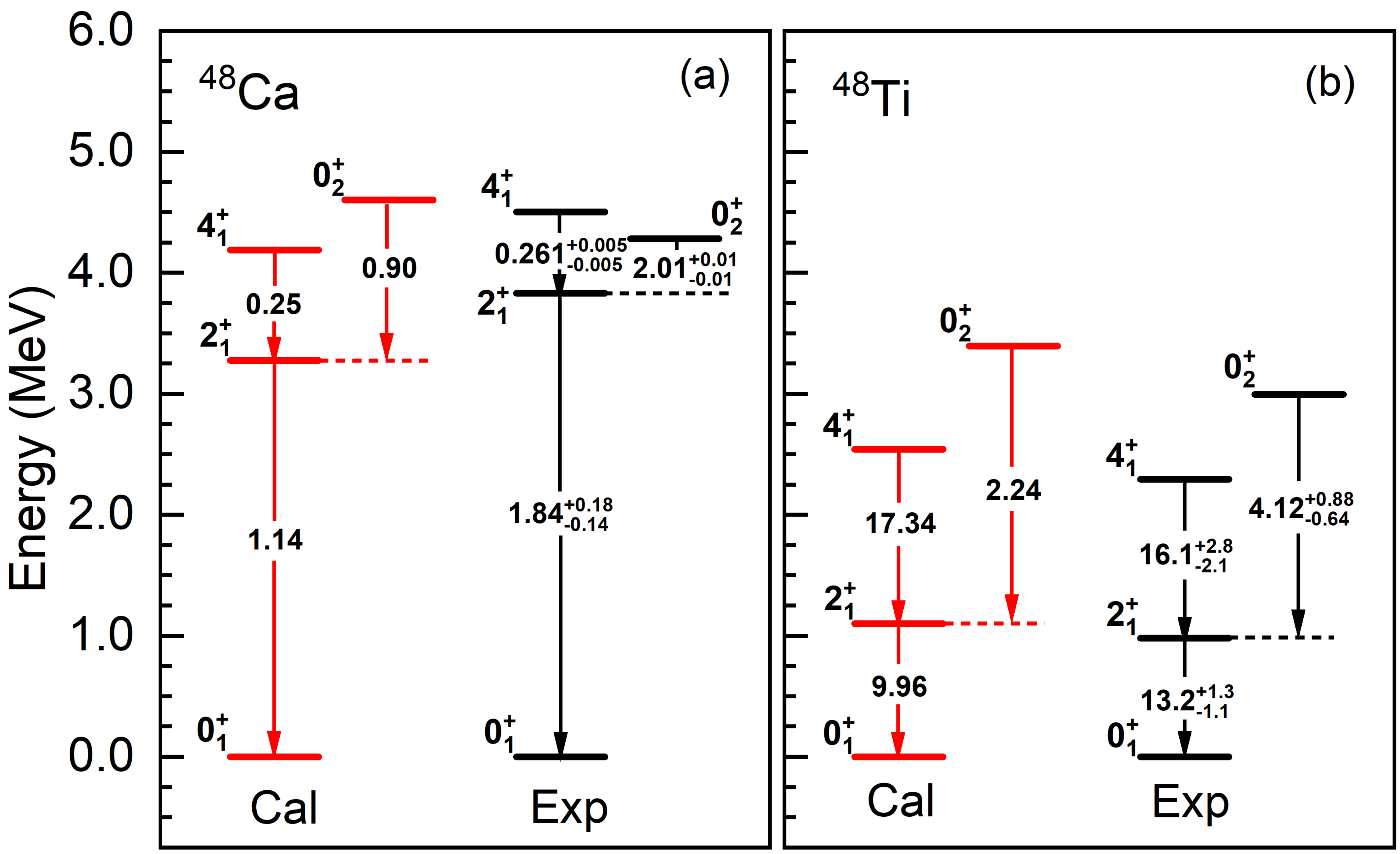
1. A self-consistent relativistic DFT calculation
2. Construction of intrinsic configuration space
3. Angular momentum projection
4. Shell-model diagonalization

ReCD: nuclear spectroscopy



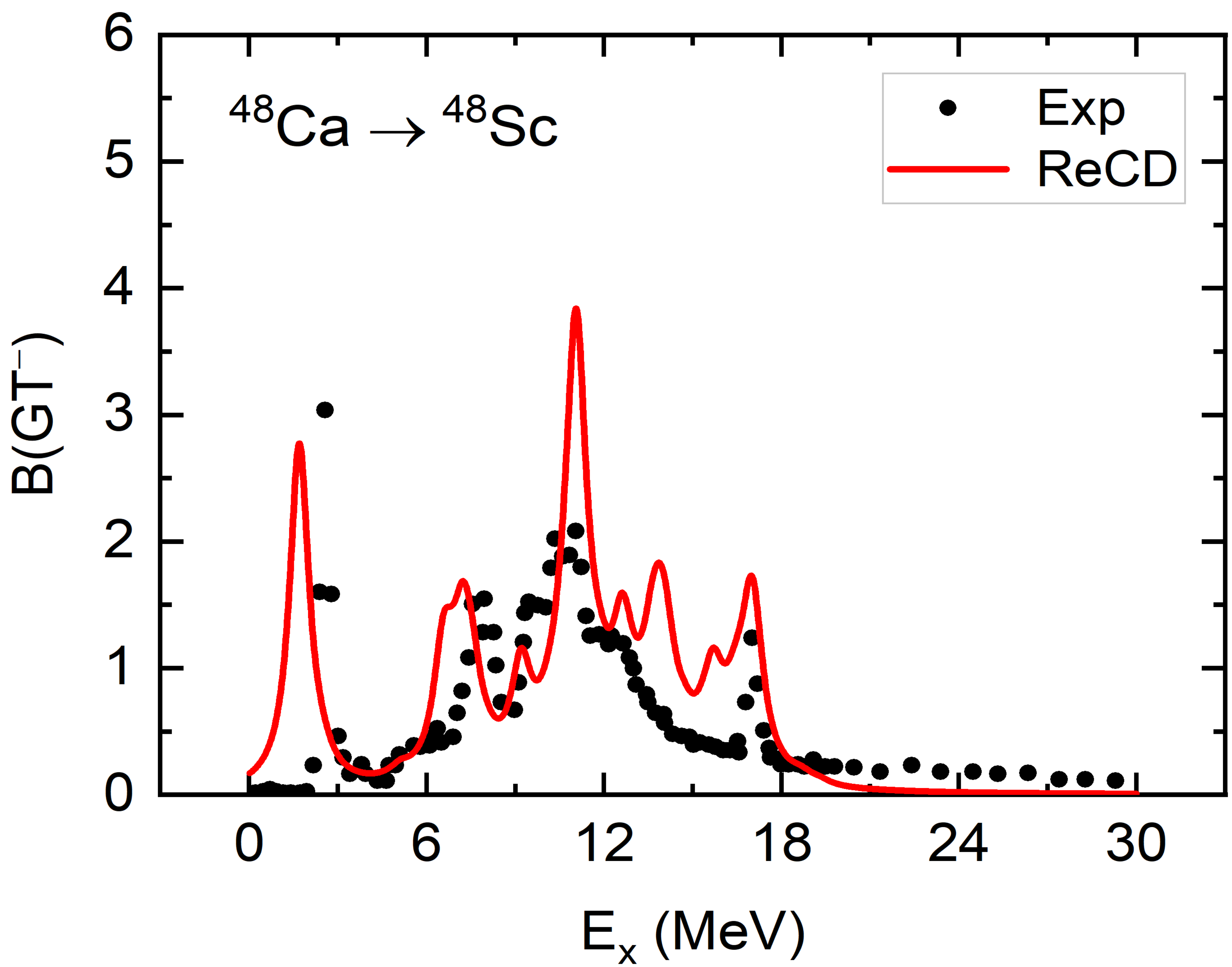
- The energy spectra and the E2 transition probabilities are reproduced satisfactorily

ReCD: nuclear spectroscopy



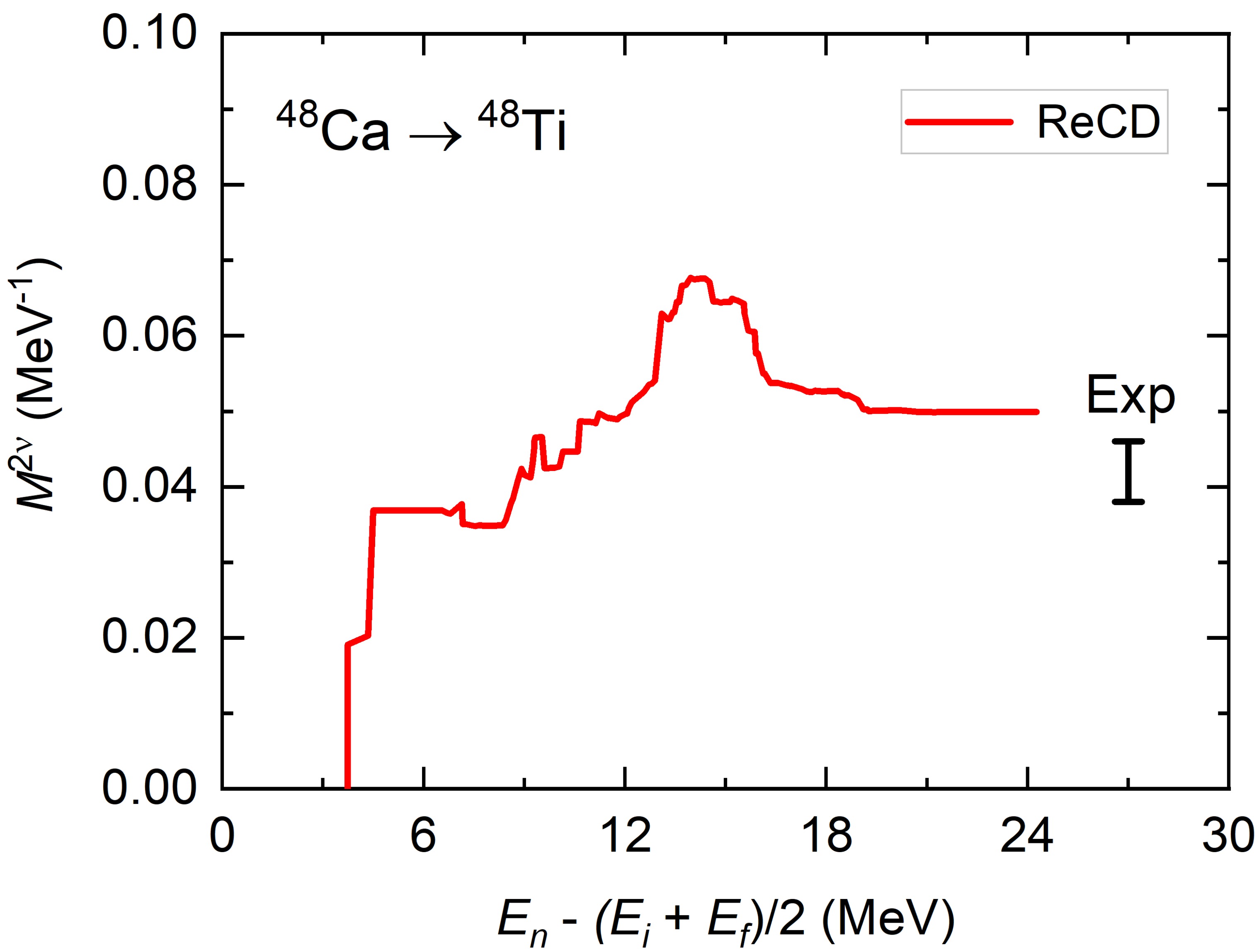
- The energy spectra and the E2 transition probabilities are reproduced satisfactorily

ReCD: spin-isospin excitations

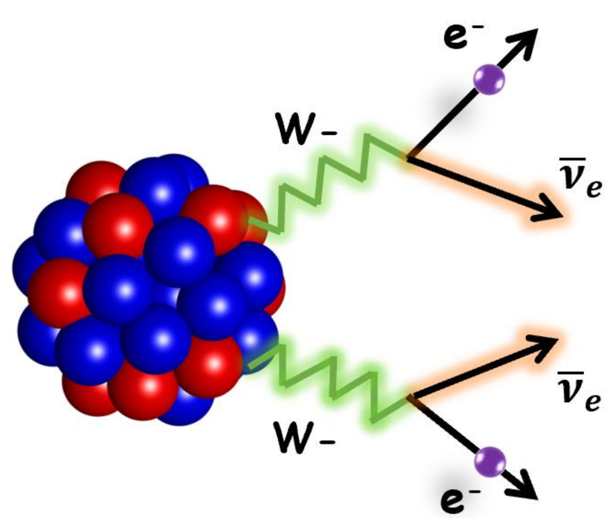


- The Gamow-Teller strength distribution around the whole energy region is reproduced satisfactorily

ReCD: nuclear weak decay



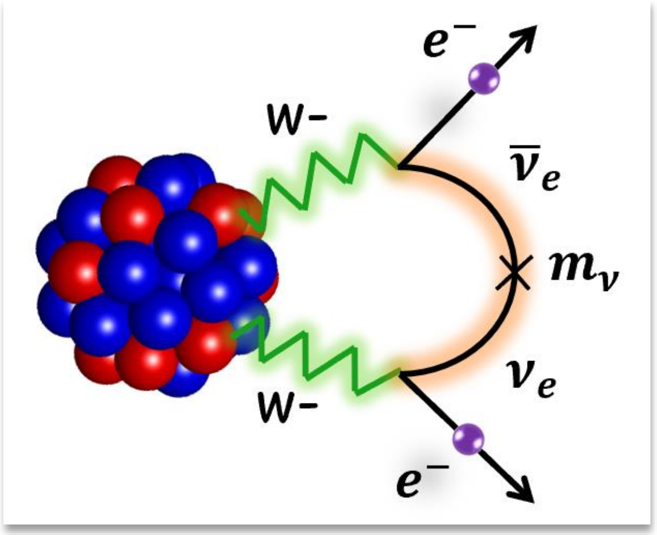
- The $2\nu\beta\beta$ decay NME can be reproduced **without introducing the quenching factor** to the axial-vector coupling constant g_A



$$M^{2\nu} = q^2 \sum_n \frac{\langle f| \sum_a \hat{\boldsymbol{\sigma}}_a \tau_a^+ |1_n^+\rangle\langle 1_n^+| \sum_b \hat{\boldsymbol{\sigma}}_b \tau_b^+ |i\rangle}{E_n - 1/2(E_i + E_f)}$$

Nuclear $0\nu\beta\beta$ decay

- Violation of **lepton number**
- **Majorana nature** of neutrinos
- **Matter dominance** in the Universe
- Neutrino **mass scale** and **hierarchy**



Avignone, Elliott, Engel, Rev. Mod. Phys. 80, 481 (2008)

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

Isotopes	$T^{0\nu}_{1/2}$ (yr)	Collaborations
^{48}Ca	$> 5.8 \times 10^{22}$	ELEGANT VI
^{76}Ge	$> 1.8 \times 10^{26}$	GERDA, MAJORANA, CDEX
^{82}Se	$> 3.5 \times 10^{24}$	CUPID-0, NνDEx
^{100}Mo	$> 1.5 \times 10^{24}$	CUPID-Mo
^{130}Te	$> 3.2 \times 10^{25}$	CUORE
^{136}Xe	$> 2.3 \times 10^{26}$	KamLAND-Zen, EXO-200, PandaX
^{150}Nd	$> 2.0 \times 10^{22}$	NEMO-3

- ✓ No $0\nu\beta\beta$-decay signal has been observed so far.
- ✓ Current limit on the decay half-life ranges from 10^{22} yr to 10^{26} yr.

Agostini, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

$0\nu\beta\beta$-decay nuclear matrix elements

- $0\nu\beta\beta$ decay rates (inversion of the decay half-life) :

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q, Z)|M^{0\nu}|^2 f(\Lambda), \quad f(\Lambda) \Rightarrow \langle m_{\beta\beta}\rangle^2$$

Nuclear matrix element $M^{0\nu} = \langle \Psi_f | \hat{O}^{0\nu} | \Psi_i \rangle$

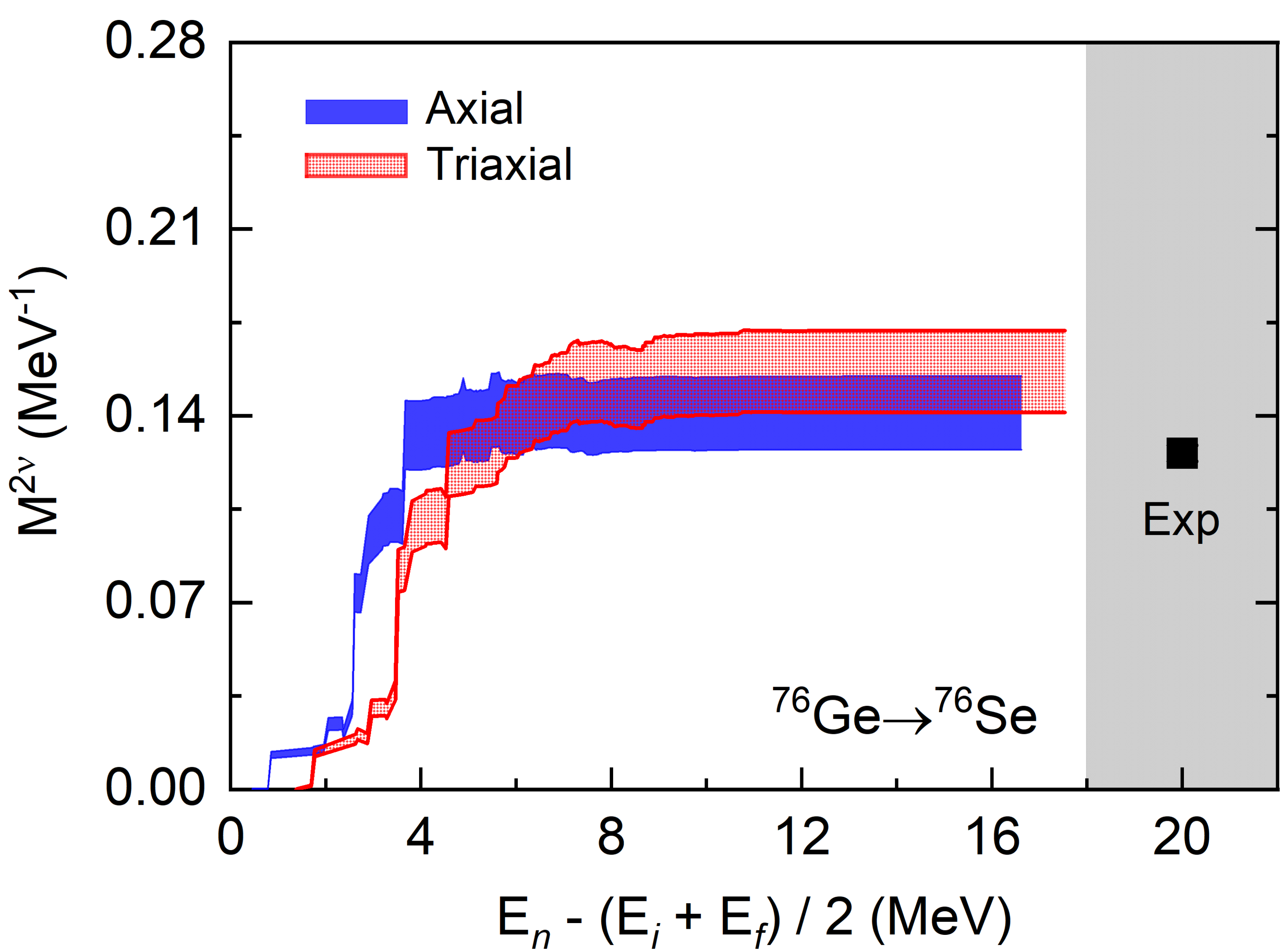
Theoretical studies on $\nu\beta\beta$ decay **build a bridge** between **data** and **underlying new physics**

PHYSICAL REVIEW LETTERS **123,** 102501 (2019)

Evidence for Rigid Triaxial Deformation in ^{76}Ge from a Model-Independent Analysis

A. D. Ayangeakaa,[1,*] R. V. F. Janssens,[2,3,†] S. Zhu,[4,‡] D. Little,[2,3] J. Henderson,[5] C. Y. Wu,[5] D. J. Hartley,[1] M. Albers,[4] K. Auranen,[4] B. Bucher,[5,§] M. P. Carpenter,[4] P. Chowdhury,[6] D. Cline,[7] H. L. Crawford,[8] P. Fallon,[8] A. M. Forney,[9] A. Gade,[10,11] A. B. Hayes,[7] F. G. Kondev,[4] Krishichayan,[3,12] T. Lauritsen,[4] J. Li,[4] A. O. Macchiavelli,[8] D. Rhodes,[10,11] D. Seweryniak,[4] S. M. Stolze,[4] W. B. Walters,[9] and J. Wu[4]

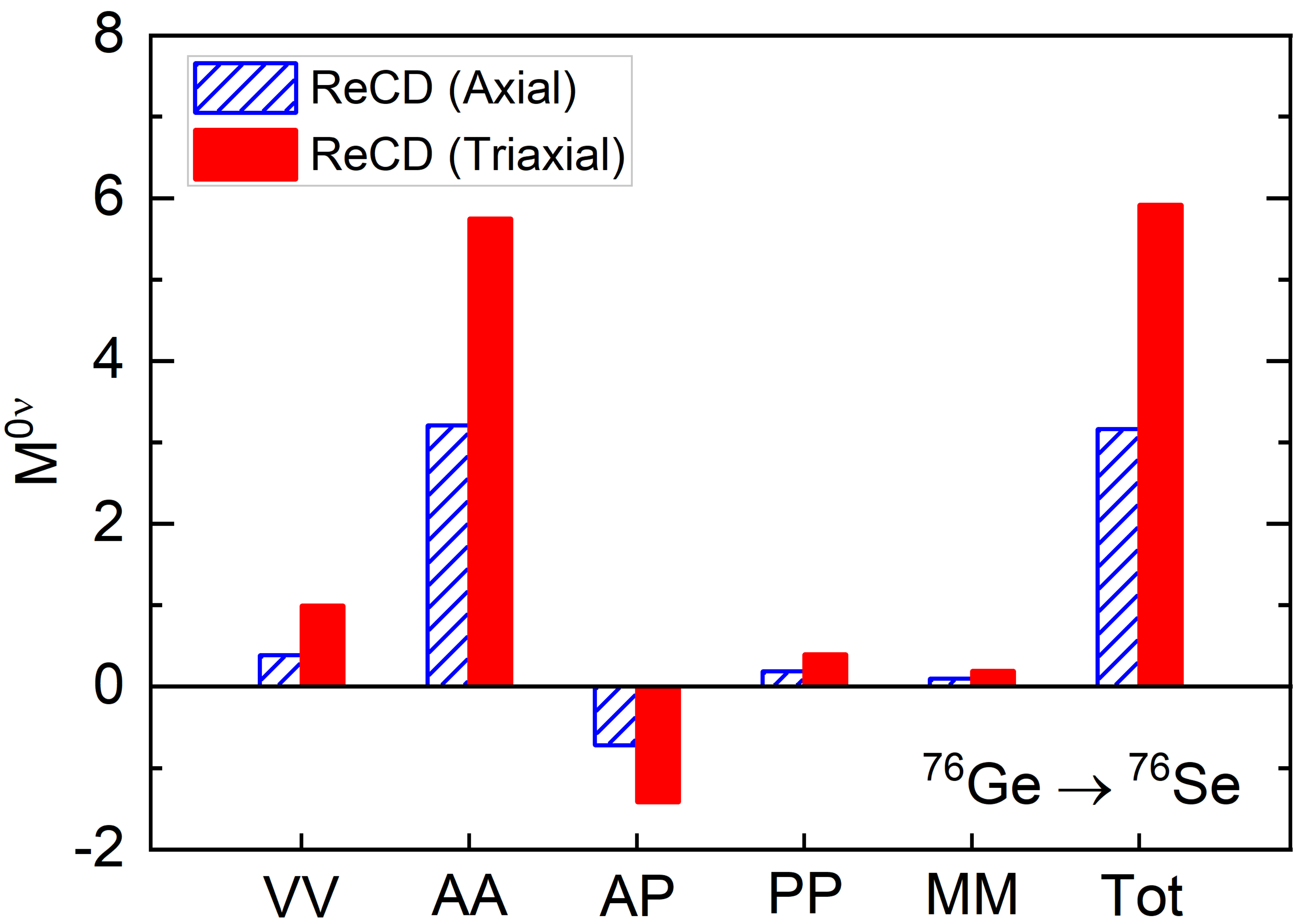
NME of the $2\nu\beta\beta$ decay



$$M^{2\nu} = q^2 \sum_n \frac{\langle \Psi_f | \sum_a \boldsymbol{\sigma}_a \tau_a^+ | \Psi_{1_n^+} \rangle \langle \Psi_{1_n^+} | \sum_b \boldsymbol{\sigma}_b \tau_b^+ | \Psi^i \rangle}{E_n - (E_i + E_f)/2}$$

- All possible **odd-odd intermediate 1^+ states** needs to be considered (around 200 1^+ states are included).
- The two-body currents are not considered ⇒ quenching factor ***q*** ranging from **0.68 to 0.77 are adopted** in our calculations.

NME: triaxial effects



$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

half-life decreases by a **factor of four**

$$\propto \varepsilon \frac{i.a.}{A} Mt$$

Less detector materials are needed

Y. K. Wang, P. W. Zhao, J. Meng, Science Bulletin, accepted

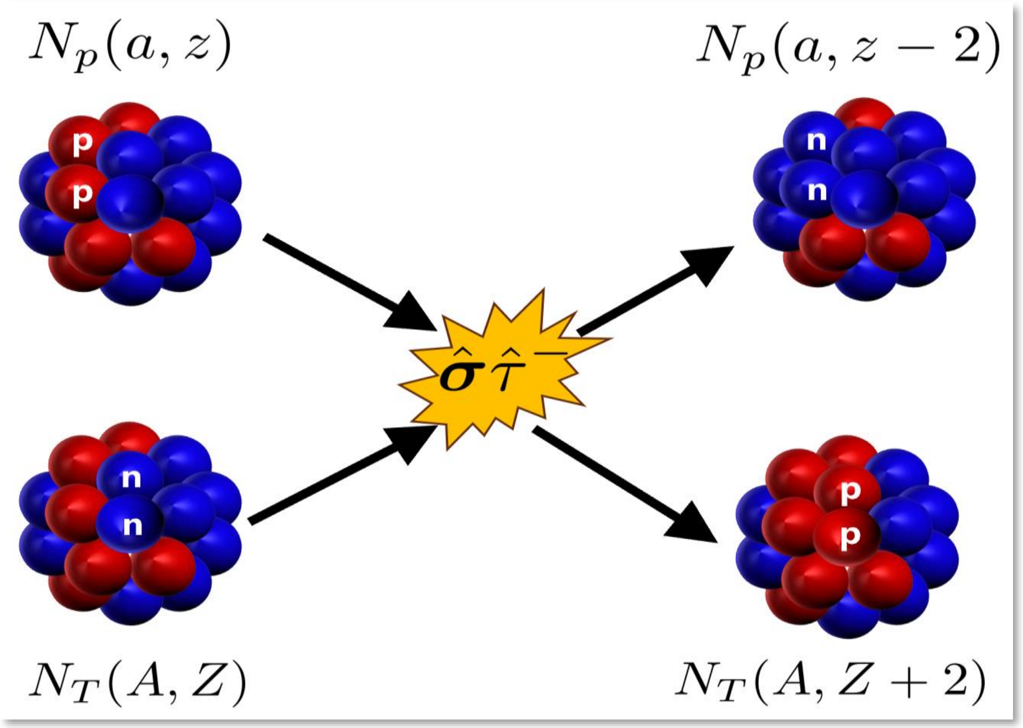
- Triaxial deformation **enhances** the $0\nu\beta\beta$-decay NME **by a factor around two**.

Double Gamow-Teller transition

- DGT cross section can be factorized as: reaction factor, and DGT-transition NMEs between initial state and the final state

Santopinto et al., PRC 98, 061601(R) (2018)

Therefore, DGT-transition NMEs can be fixed by the experimental cross section



$$N_T(A, Z) + N_p(a, z) \rightarrow N_T(A, Z+2) + N_p(a, z-2)$$

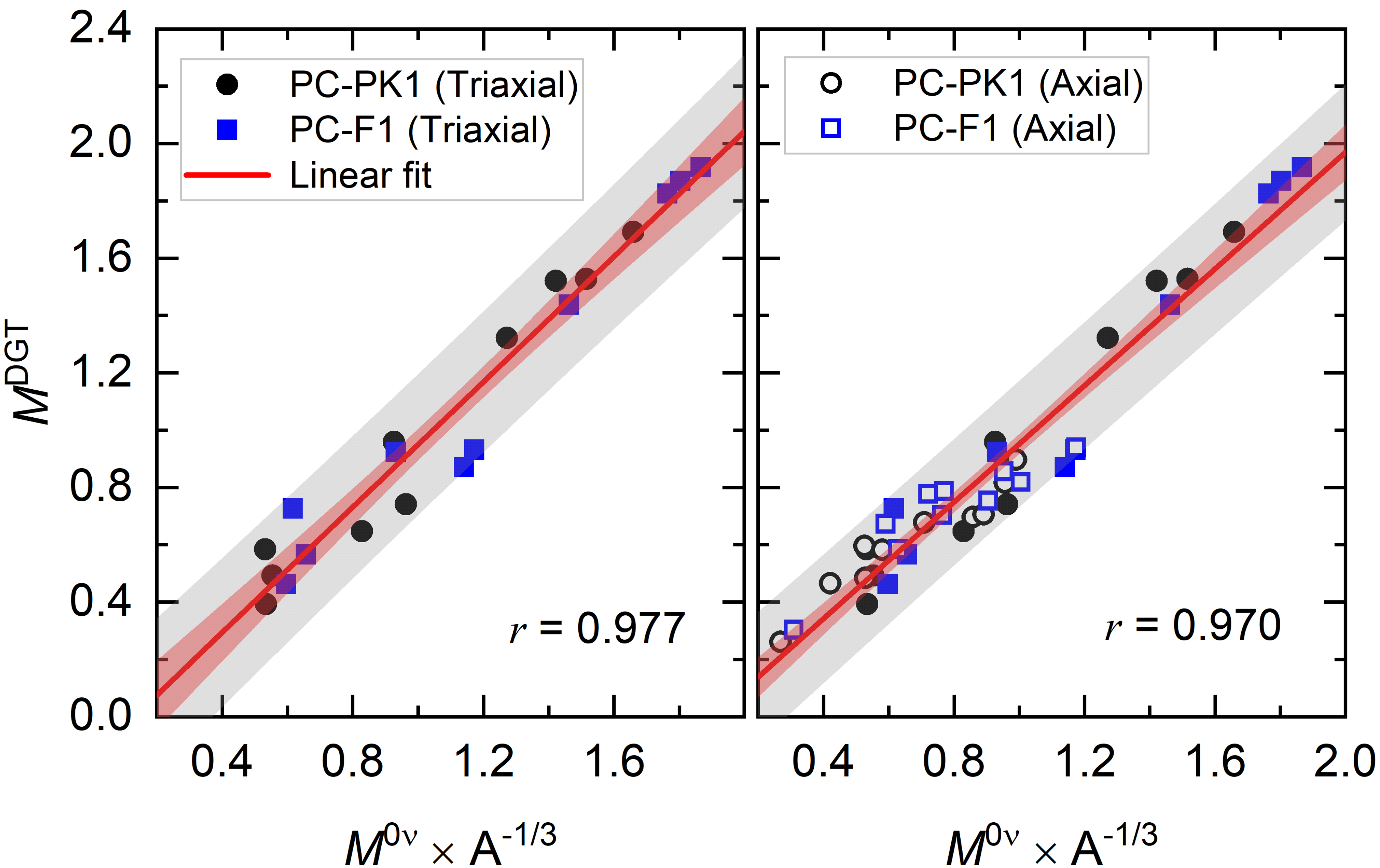
- Same initial and final states + similar decay operator ⇒ correlation between DGT transition and $0\nu\beta\beta$ decay?

Rodríguez et al., PLB 719, 174 (2013), Cappuzzello et al., EPJA 51, 145 (2015)

Constraining the $0\nu\beta\beta$ decay NME by DGT transitions!

Shimizu et al., PRL 120, 142502 (2018), Yao et al., PRC 106, 014315 (2022), lv et al., PRC 108, L051304 (2023)

Correlation between $0\nu\beta\beta$ decay and DGT transition



10 nuclei:

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{128}Te, ^{130}Te, ^{136}Xe

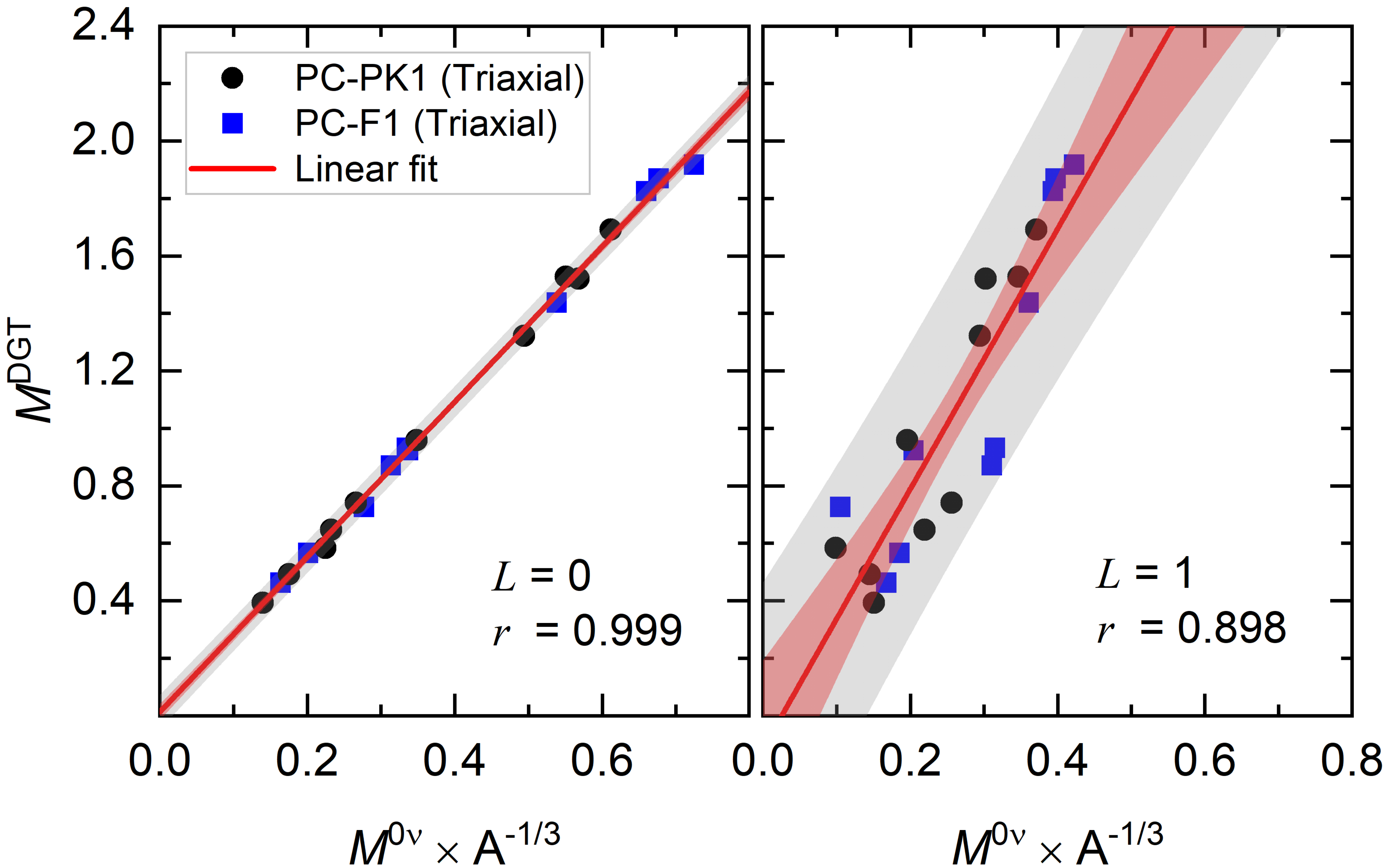
Axial and triaxial deformations

Full model space

- A strong linear correlation between $0\nu\beta\beta$ decay and DGT transition is demonstrated
- The linear correlation is robust against nuclear deformations

Y. K. Wang, P. W. Zhao, J. Meng, PLB, under review

Decomposition of the NMEs

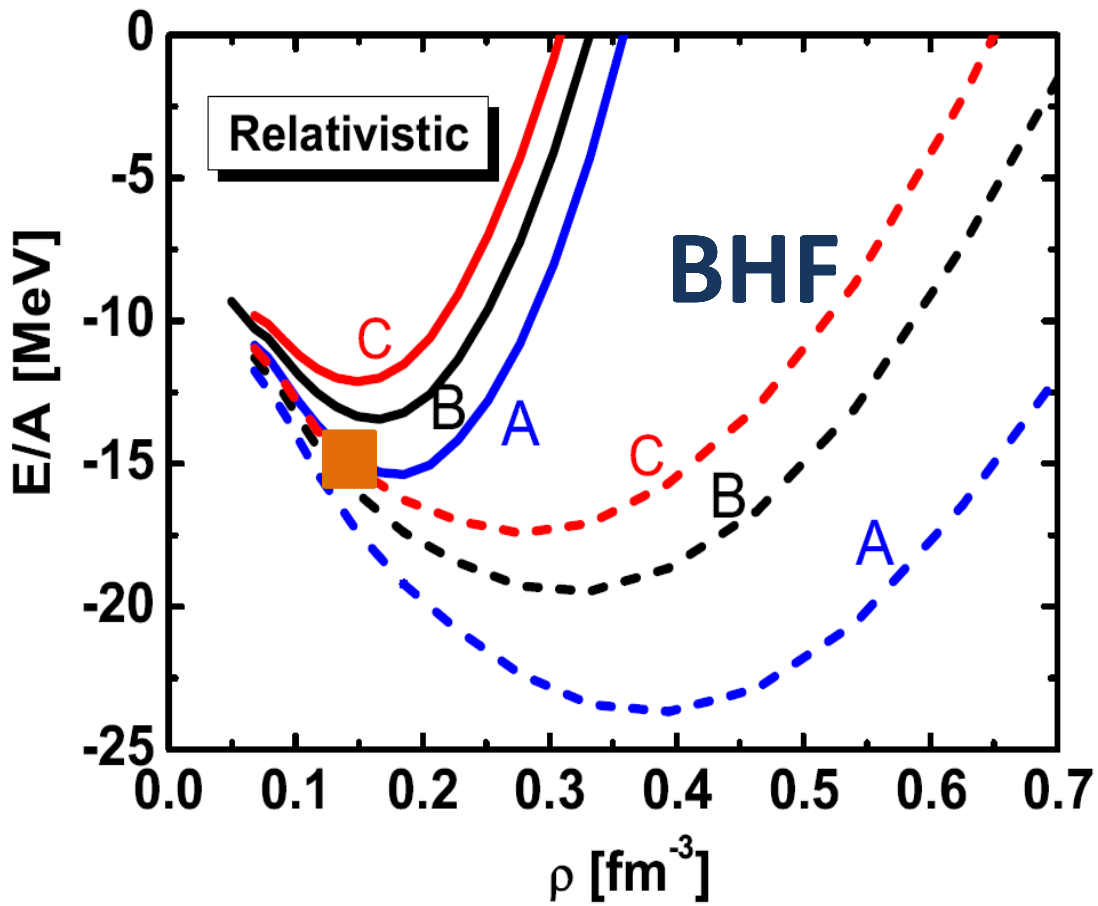


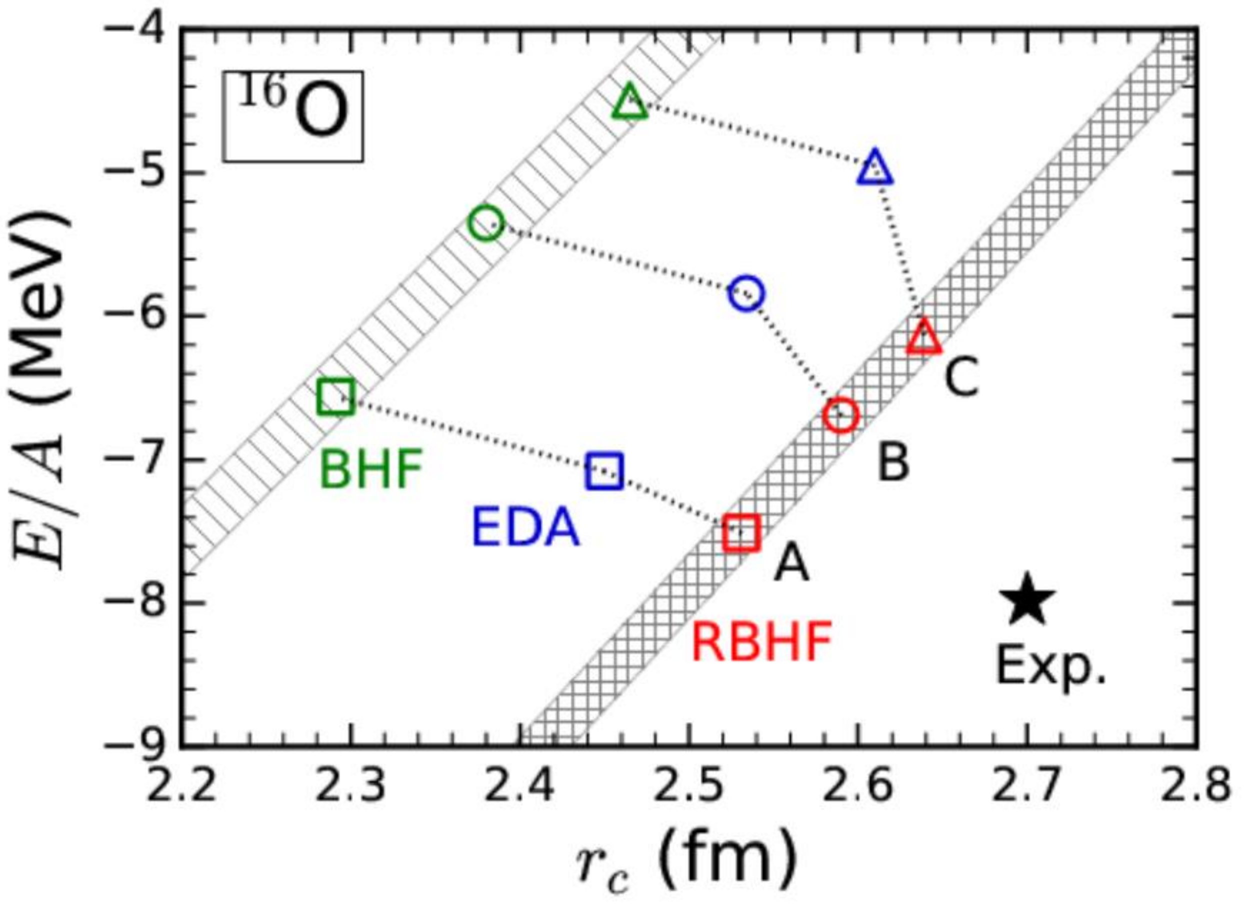
$$\hat{\mathcal{O}}^{0\nu} = \sum_L \hat{\mathcal{O}}_L^{0\nu}$$

$$M^{0\nu} = \sum_L M_L^{0\nu}$$

- The **leading order $M_{L=0}^{0\nu}$ is more** strongly correlated with M^{DGT}, while the correlation between $M_{L=1}^{0\nu}$ and M^{DGT} is weaker.

Toward Relativistic ab initio DFT





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

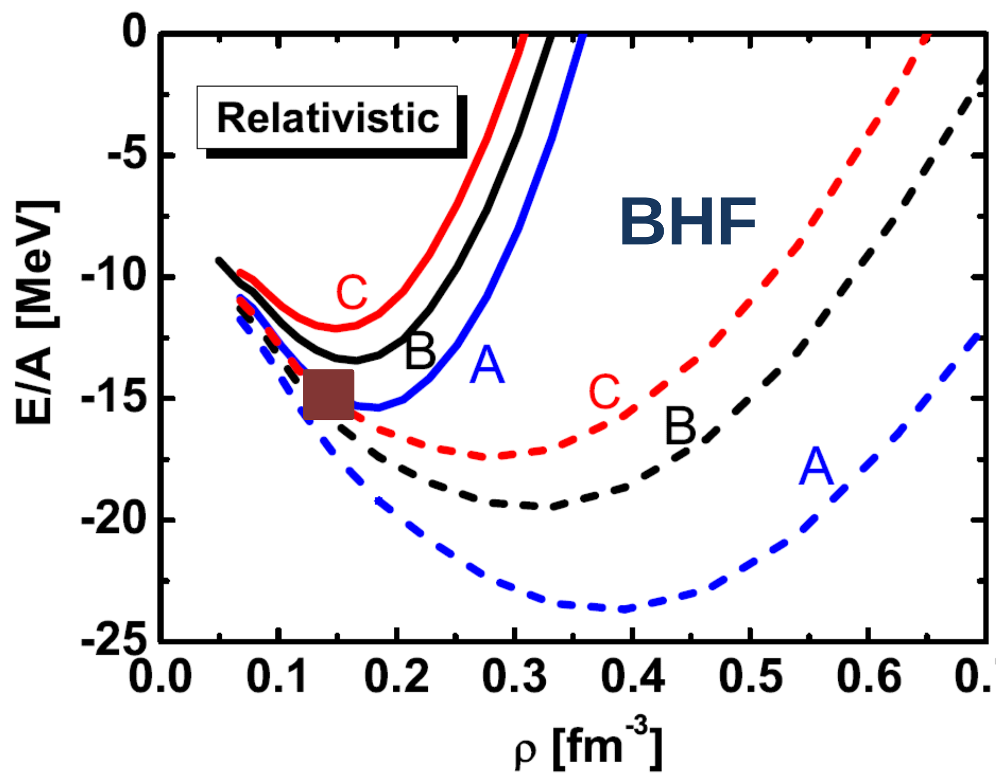
- without additional assumptions
- without additional parameters

ab initio in nuclear physics

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

ab initio in nuclear matter

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



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Toward Relativistic *ab initio* DFT

Progress in Particle and Nuclear Physics 109 (2019) 103713

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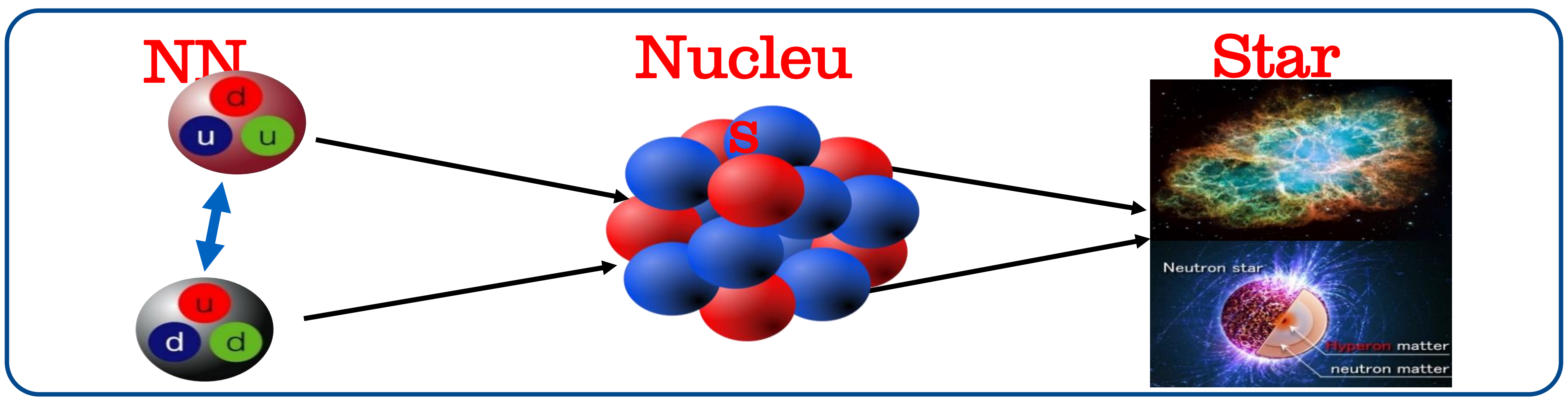
Review

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

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



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

Brueckner

Effective

Relativistic NN interaction

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➢ Chiral Nucleon-Nucleon Interaction

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

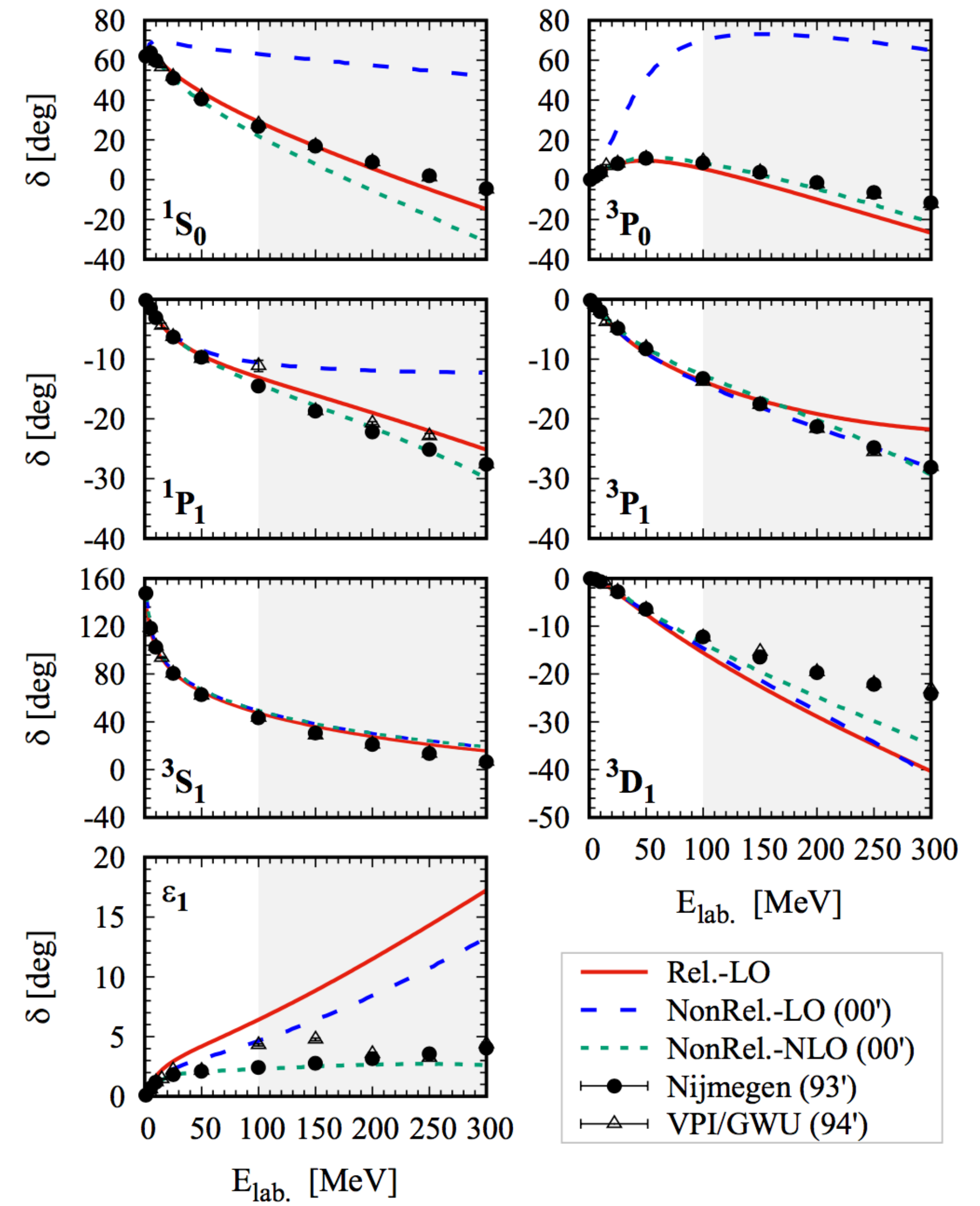
Jun-Xu Lu, Chun-Xuan Wang, Yang Xiao, Li-Sheng Geng, Jie Meng, and Peter Ring

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)



➢ 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

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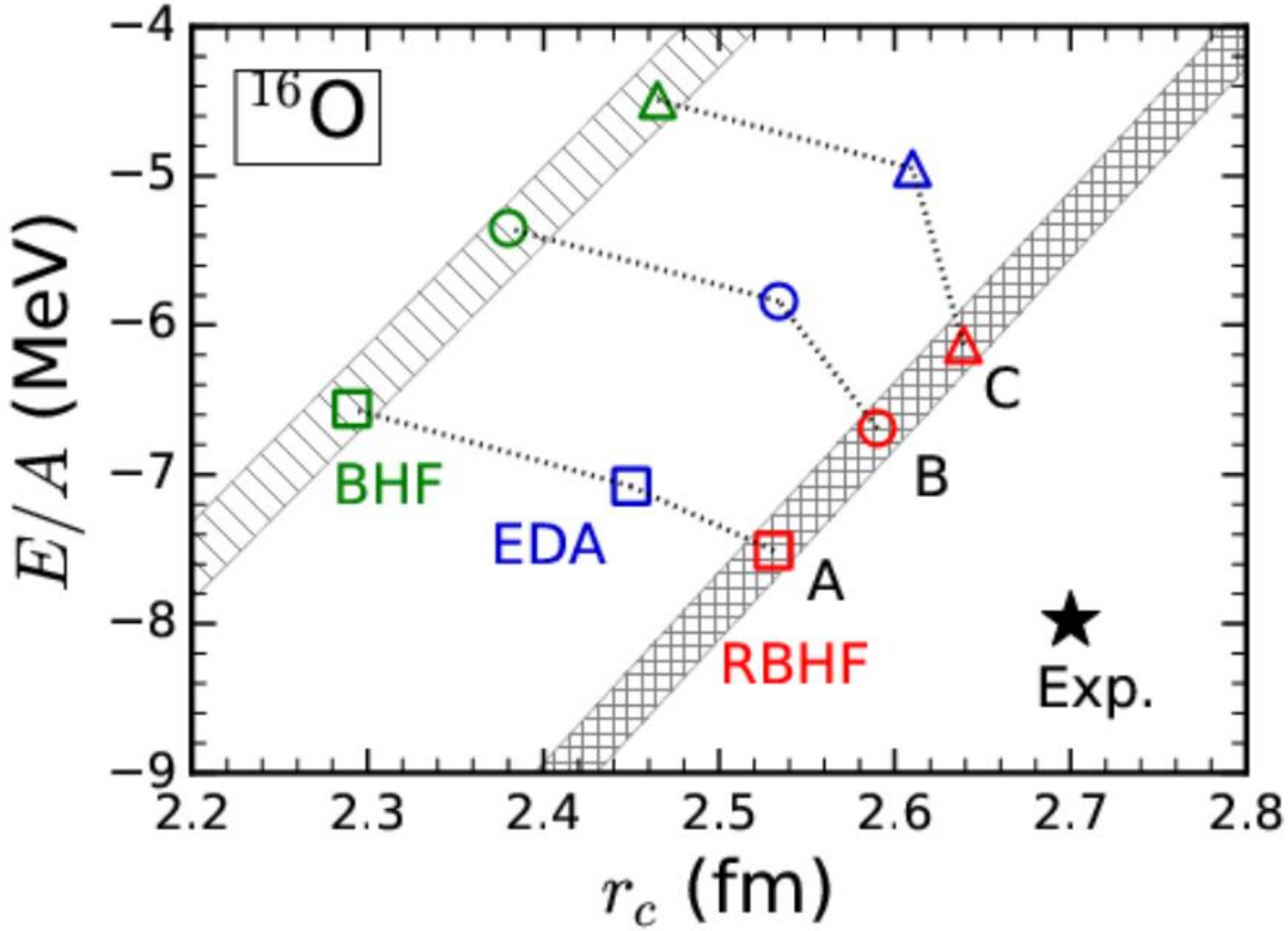
Doubly Charmed Tetraquark T_{cc}^+ from Lattice QCD near Physical Point

Yan Lyu, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, and Jie Meng

Phys. Rev. Lett. **131**, 161901 – Published 16 October 2023

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



RBHF improves the description over EDA or BHF.

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

Shen, Hu, Liang, Meng, Ring, Zhang, **Chin. Phys. Lett. 33** (2016) 102103

Shen, Liang, Meng, Ring, Zhang, **Phys. Rev. C** 96, 014316 (2017)

ab initio calculation

Relativistic Brueckner Hartree-Fock Theory

PHYSICAL REVIEW C **98**, 054302 (2018)

Relativistic Brueckner-Hartree-Fock theory in nuclear matter without the average momentum approximation

Hui Tong (童辉),[1] Xiu-Lei Ren (任修磊),[1,2] Peter Ring,[1,3] Shi-Hang Shen (申时行),[1]
Si-Bo Wang (王锶博),[1] and Jie Meng (孟杰)[1,4,5,*]
[1] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, Chi*
[2] *Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[3] *Physik-Department der Technischen Universität München, D-85748 Garching, Germany*

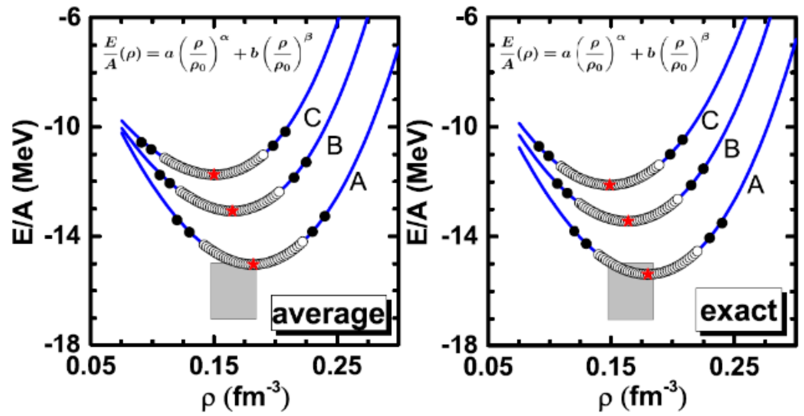


FIG. 1. Binding energy per nucleon for nuclear matter as a function of the total density ρ. Results for Bonn potentials A, B, C with (left panel) and without (right panel) c.m. momentum approximation are shown. The RBHF results are represented by open and solid circles, where open circles stand for the data used in the fit and solid circles indicate the validity of the results of the fit (solid curves). The red stars indicate the saturation points obtained from RBHF results.

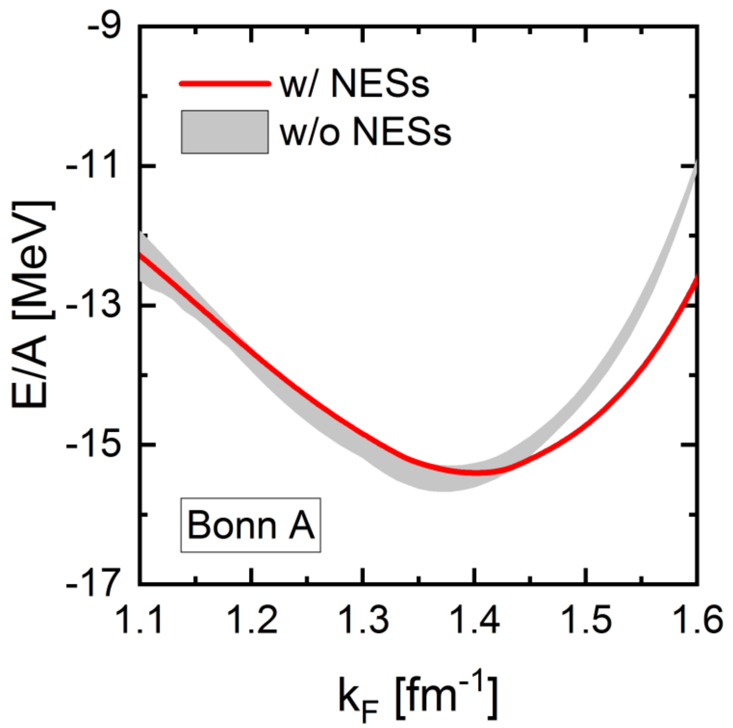
PHYSICAL REVIEW C **103**, 054319 (2021)

Nuclear matter in relativistic Brueckner-Hartree-Fock theory with Bonn potential in the full Dirac space

Sibo Wang,[1] Qiang Zhao,[1] Peter Ring,[1,2] and Jie Meng[1,3,*]
[1] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2] *Department of Physik, Technische Universität München, D-85747 Garching, Germany*
[3] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

(Received 25 March 2021; accepted 11 May 2021; published 24 May 2021)

Starting from the Bonn potential, the relativistic Brueckner-Hartree-Fock (RBHF) equations are solved for nuclear matter in the full Dirac space, which provides a unique way to determine the single-particle potentials and avoids the approximations applied in the RBHF calculations in the Dirac space with positive-energy states (PESs) only. The uncertainties of the RBHF calculations in the Dirac space with PESs only are investigated, and the importance of RBHF calculations in the full Dirac space is demonstrated. In the RBHF calculations in the full Dirac space, the empirical saturation properties of symmetric nuclear matter are reproduced, and the obtained equation of state agrees with the results based on the relativistic Green's function approach up to the saturation density.



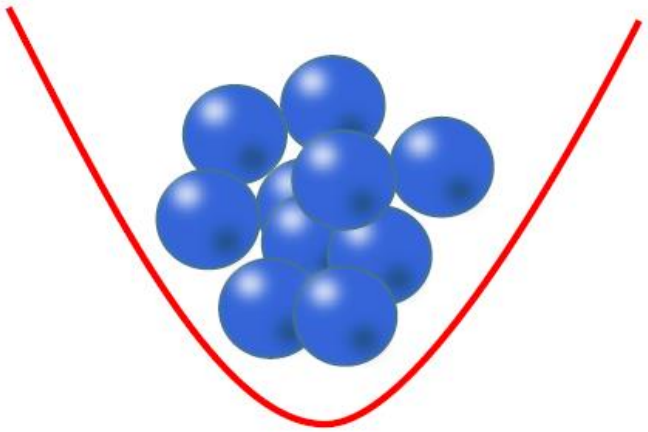
- **Neutron drop is a neutron system confined in an external field. It is an ideal and simple system to investigate the neutron-rich environment by *ab initio* methods and phenomenological density functional theory.** Pudliner et al., PRL 76, 2416 (1996). Gandolfi, Carlson, Pieper, PRL 106, 012501 (2011).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

……

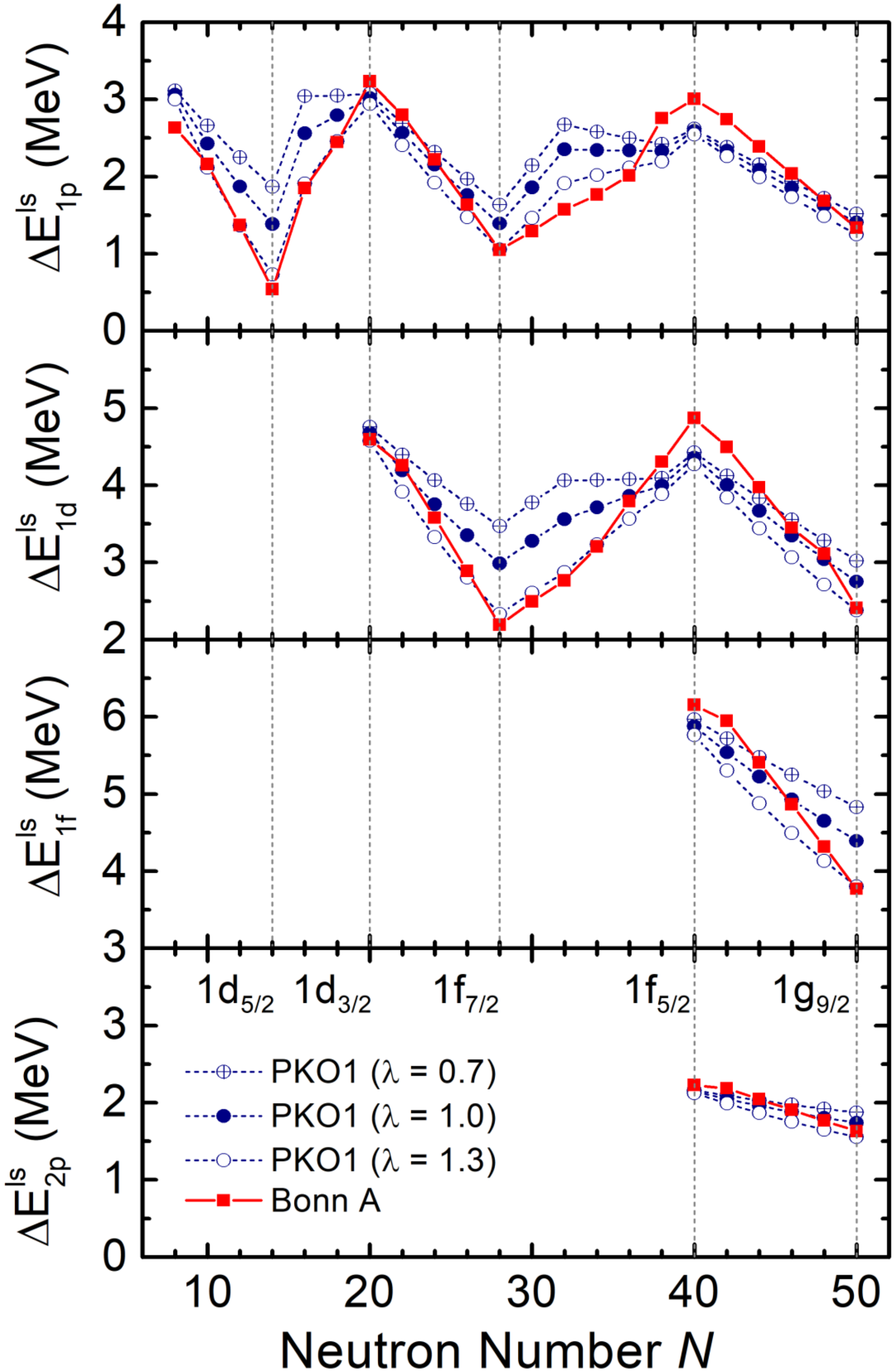
- **A neutron drop provides also an ideal and simple system to investigate the effects of tensor forces.**

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

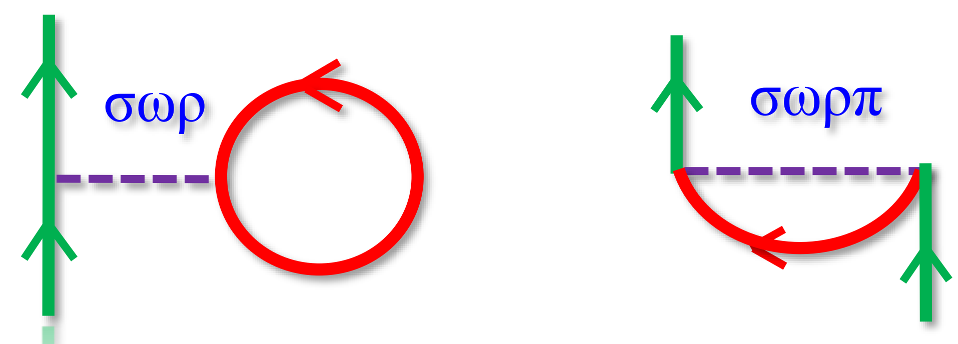
Shen, Liang, Meng, Ring, Zhang,
Effects of tensor forces in nuclear spin–orbit splittings from ab initio calculations.
Phys. Lett. B778 (2018) 344–348



Spin-Orbit Splitting



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



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

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

Fully self-consistent relativistic Brueckner theory

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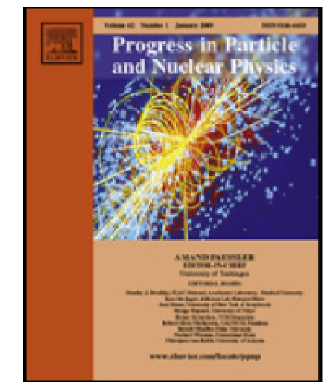

Review

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]

[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*

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Summary

- ✓ Origin of the heavy elements is a fundamental problems in modern science.
- ✓ Predictive power of PC-PK1 is demonstrated. Physics around the neutron drip line and N=Z nuclei are discussed.
- ✓ Status of the DRHBc mass table collaboration is introduced. The effects of the continuum and deformation as well as the related interesting topics are discussed.
- ✓ Relativistic density functional theory solved in 3D lattice and its time-dependent version are introduced together with applications for Linear-chain, Chiral dynamics, Fission, etc.
- ✓ Strategy to build density functional based on QCD-spirited interaction and *ab inito* calculation are outlined.

Group members

Professors:

Jie Meng

Shuangquan Zhang

Pengwei Zhao

Peter Ring

Oversea distinguished professor

Dario Vretenar

High-end foreign experts

Research Fellow:

Yakun Wang

Students:

Yan Lyu

Cong Pan

Yanyu Chen

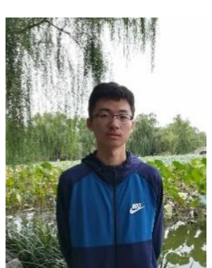
Yiping Wang

Dandan Zhang

Xiaokai Du

Fangfang Xu

Weijiang Zou



Xiaofei Jiang

Bo Li

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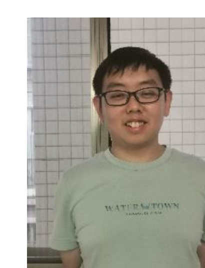
Teng Qu

Chang Zhou

Tianxing Huang



Peng Guo

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Thank you for your attention!