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Novel nuclear structure towards extremes of spin and isospin

Pengwei Zhao (赵鹏巍)

Argonne National Laboratory (ANL)



Nuclei towards extreme spin and isospin



Outline

- Covariant density functional theory
- Valence nucleon dynamics at high spin
- Rod-shaped nuclei at high spin and isospin
- Extending CDFT: a new spectroscopic method
- Summary

Density functional theory

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

Kohn-Sham Density Functional Theory



For any interacting system, there exists a **local single-particle potential** *h(r)*, such that the exact ground-state density of the interacting system can be reproduced by **non-interacting particles** moving in this local potential.

Figure from Drut PPNP 2010

$$E[\rho] \Rightarrow \hat{h} = \frac{\delta E}{\delta \rho} \Rightarrow \hat{h} \varphi_i = \varepsilon_i \varphi_i \Rightarrow \rho = \sum_{i=1}^A |\varphi_i|^2$$

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

Density functional theory for nuclei

- ✓ Energy density functional from effective Hamiltonians
 - $E = \langle \Psi | H | \Psi \rangle \simeq \langle \Phi | H_{eff}(\hat{\rho}) | \Phi \rangle = E[\hat{\rho}]$
- ✓ More degrees of freedom: spin, isospin, pairing, ...
- ✓ Nuclei are self-bound systems
 DFT for the intrinsic density
- ✓ Probably not exact, but a very good approximation
- ✓ Adjust to properties of nuclear matter and/or finite nuclei
- ✓ Connect to ab-initio results?





Why Covariant?

- ✓ Large fields S≈-400 MeV, V≈350 MeV
- ✓ Relativistic saturation mechanism
- ✓ Large spin-orbit splitting
- ✓ Pseudo-spin Symmetry

. . .

- ✓ Success of Relativistic Brueckner
- ✓ Consistent treatment of time-odd fields

P. Ring Physica Scripta, T150, 014035 (2012) Cohen, Furnstahl, Griegel PRL 67, 961(1991) Brockmann, Machleidt, PRC42, 1965 (1990)





Search for new covariant density functionals



Covariant Density Functional Theory

Elementary building blocks

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

Densities and currents

Isoscalar-scal

Isoscalar-scalar
$$\rho_{S}(\mathbf{r}) = \sum_{k} \psi_{k}(\mathbf{r})\psi_{k}(\mathbf{r})$$

Isoscalar-vector $j_{\mu}(\mathbf{r}) = \sum_{k}^{occ} \bar{\psi}_{k}(\mathbf{r})\gamma_{\mu}\psi_{k}(\mathbf{r})$
Isovector-scalar $\vec{\rho}_{S}(\mathbf{r}) = \sum_{k}^{occ} \bar{\psi}_{k}(\mathbf{r})\vec{\tau}\psi_{k}(\mathbf{r})$

occ

ar
$$\vec{\rho}_S(\mathbf{r}) = \sum_k \psi_k(\mathbf{r}) \vec{\tau} \psi_k(\mathbf{r})$$

or $\vec{j}_\mu(\mathbf{r}) = \sum_k \phi_k(\mathbf{r}) \vec{\tau} \gamma_\mu \psi_k(\mathbf{r})$

Energy Density Functional

$$egin{aligned} E_{kin} &= \sum_k v_k^2 \int ar{\psi}_k (-\gamma
abla + m) \psi_k d\mathbf{r} \ E_{2nd} &= rac{1}{2} \int (lpha_S
ho_S^2 + lpha_V
ho_V^2 + lpha_{tV}
ho_{tV}^2) d\mathbf{r} \ E_{hot} &= rac{1}{12} \int (4 eta_S
ho_S^3 + 3 \gamma_S
ho_S^4 + 3 \gamma_S
ho_V^4) d\mathbf{r} \ E_{der} &= rac{1}{2} \int (\delta_S
ho_S igtarrow
ho_S + \delta_V
ho_V igtarrow
ho_V + \delta_{tV}
ho_{tV} igtarrow
ho_{tV}) d\mathbf{r} \ E_{em} &= rac{e}{2} \int j_\mu^p A^\mu d\mathbf{r} \end{aligned}$$

Covariant Functional: PC-PK1



Binding energies of 60 nuclei Charge radii of 17 nuclei

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

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

Nuclear Mass



Extending CDFT for nuclear rotations

The cranking model is a first-order approximation for a variation after projection onto good angular momentum. Beck, Mang, Ring, Z. Phys. 231, 26 (1970)

Tilted axis cranking CDFT

Meson exchange version:

3-D Cranking: Madokoro, Meng, Matsuzaki, Yamaji, PRC 62, 061301 (2000)

2-D Cranking: Peng, Meng, Ring, Zhang, PRC 78, 024313 (2008)

Point-coupling version:

Simple and more suitable for systematic investigations

2-D Cranking: *PWZ, Zhang, Peng, Liang, Ring, Meng, PLB* 699, 181 (2011) 2-D Cranking + Pairing: *PWZ, Zhang, Meng, PRC* 92, 034319 (2015)

Self-consistent microscopic investigations

- Fully taken into account polarization effects
- self-consistently treated the nuclear currents
- no additional parameter beyond a well-determined functional



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Valence nucleon dynamics



Magnetic rotation Ferromagnet

✓ near spherical nuclei; weak E2 transitions

- \checkmark rotational bands with $\Delta I = 1$
- \checkmark strong M1 transitions
- \checkmark B(M1) decrease with spin
- \checkmark shears mechanism



Frauendorf, Rev. Mod. Phys., 73, 463 (2001)

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

Magnetic Rotation in ⁶⁰Ni



PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

MR in ¹⁹⁸Pb



Yu, PWZ, Zhang, Ring, Meng PRC 85 (2012) 024318



Valence nucleon dynamics



Antimagnetic rotation



 \checkmark near spherical nuclei; weak E2 transitions

- \checkmark rotational bands with $\Delta I = 2$
- \checkmark no M1 transitions
- \checkmark B(E2) decrease with spin
- \checkmark two "shears-like" mechanism

A~100



A~140 Eu-143; Dy-144

Rajbanshi PLB 2015; Sugawara PRC 2009

Frauendorf, Rev. Mod. Phys., 73, 463 (2001) PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011) Meng, Peng, Zhang, PWZ, Front. Phys. 8, 55 (2013)

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Anti-MR in ¹⁰⁵Cd: Two shears-like mechanism





PWZ, Peng, Liang, Ring, Meng, PRL 107, 122501(2011)

- ✓ The two proton angular momenta are pointing opposite to each other and are nearly perpendicular to the neutron angular momentum. They form the blades of the two shears.
- Increasing Ω, the two proton blades close towards to each other and generate the total angular momentum.

AMR in ¹⁰⁵Cd: Energy and B(E2)



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Exotic deformation

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



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Two important mechanisms

- ✓ Adding valence neutrons
 Itagaki, PRC2001; Maruhn, NPA2010
- ✓ Rotating the system



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Angular momentum

DD-ME2, 3D HO basis with N = 12 major shells



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

≻C-12, C-13, C-14

constant moments of inertia (MOI); like a rotor

≻C-15, C-16, C-17, C-18

abrupt increase of MOI;

some changes in structure

≻C-19; C-20

constant moments of inertia; much larger



Proton density and single-particle levels



Rod shape is obtained in all isotopes by tracing the corresponding rod-shaped configuration.

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

Valence neutron density and single-particle levels



Rotation can lower prolate valence neutron orbitals (easier to be occupied)

- 1. pull down prolate proton orbitals.
- 2. enhance proton deformation



ħω (MeV)

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

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(C)DFT and Shell Model

(C)DFT

Shell Model

Universal density functionals

Symmetry broken Single config. fruitful physics No Configuration mixing

Applicable for almost all nuclei
 No spectroscopic properties

Non-universal effective interactions

No symmetry broken Single config. little physics Configuration mixing

intractable for deformed heavy nuclei
 spectroscopy from multi config.

a theory combining the advantages from both approaches?



Configuration Interaction Projected DFT (CI-PDFT)

Successful projected shell model based on the Nilsson potential

Hara and Sun IJMPE1995

- 1. Covariant Density Functional Theory a minimum of the energy surface
- 2. Configuration space multi-quasiparticle states
- 3. Angular momentum projection rotational symmetry restoration
- 4. Shell model calculation configuration mixing / interaction from CDFT

Energy Density Functional

good angular momentum; from low- to high- spin;

Nuclear Spectroscopy

CI-PDFT: to provide a global study of many nuclear properties with no parameters beyond a well-established density functional.

PWZ, Ring, Meng, arXiv:1607.04241

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First application for ⁵⁴Cr

PWZ, Ring, Meng, arXiv:1607.04241

- Axial symmetry assumed
- Density functional: PC-PK1+ δ-force BCS
- Configuration space
 0-qp and 2-qp excitations &
 E < 6.5 MeV

$$|0\rangle, \quad \alpha^{\dagger}_{\nu}\alpha^{\dagger}_{\nu'}|0\rangle, \quad \alpha^{\dagger}_{\pi}\alpha^{\dagger}_{\pi'}|0\rangle$$



The configuration space consists of 37 states including 18 two-quasi-neutron, 18 two-quasi-proton excited states, and the quasi-particle vacuum $|0\rangle$.

Level scheme for ⁵⁴Cr

PWZ, Ring, Meng, arXiv:1607.04241



time-odd interaction; beyond 2-qp configurations;



Towards neutron-rich nuclei

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Summary

Covariant density functional theory has been improved and extended for many nuclear properties.

- A new covariant density functional PC-PK1:
 improves isospin dependence
 good performance for nuclear global properties towards neutron-rich...
- Titled axis cranking CDFT

valence nucleon dynamics: magnetic and anti-magnetic rotations in nuclei

- exotic shape towards high isospin and spin
 Coherent effects between spin and isospin to stabilize the exotic rod shape.
- A new tool for nuclear spectroscopy: CI-PDFT
 merits of (C)DFT and Shell Model preserved
 no parameters beyond a well-established density functional

Collaborations

Beijing

Qibo Chen

Jie Meng

Jing Peng

Shuangquan Zhang

Munich

Peter Ring

Chongqing

<u>Zhipan Li</u>

Jiangming Yao

Kyoto Naoyuki Itagaki

Thank you for your attention!

Cranking Relativistic Kohn-Sham Equation:



Deformed nuclei



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

Improved isospin dependence

Maybe more reliable for neutron-rich exotic nuclei ...

Deformed nuclei



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

Improved isospin dependence

Maybe more reliable for neutron-rich exotic nuclei ...

PWZ, Ring, Meng, arXiv:1607.04241

Important configurations and their probability amplitudes in the yrast state

	E	K	Configurations	0	2	4	6	8	10
gs	0.00	0	-	0.959	0.856	0.623	0.280	0.150	0.113
2n1	2.68	1	$(2p_{3/2})_{k=1/2}\otimes(1f_{5/2})_{k=1/2}$		0.314	0.448	0.241	0.098	0.100
	3.36	1	$(2p_{3/2})_{k=1/2}\otimes(2p_{3/2})_{k=-3/2}$		0.225	0.308	0.164	0.055	0.000
	4.64	2	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=3/2}$		-0.044	-0.146	-0.076	-0.037	-0.064
	4.64	1	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=-3/2}$		0.068	0.126	0.085	0.037	0.028
	2.39	0	$(1f_{7/2})_{k=5/2}\otimes(1f_{7/2})_{k=-5/2}$	0.265	0.146	-0.084	-0.232	-0.228	-0.166
2p1	2.55	1	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=-5/2}$		0.224	0.430	0.521	0.400	0.341
	2.55	4	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=5/2}$			0.013	0.205	0.183	0.146
	2.71	0	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-3/2}$	-0.055	-0.028	0.020	0.283	0.297	0.280
2p2	3.56	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-5/2}$		-0.047	-0.127	-0.386	-0.416	-0.409
	3.56	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=5/2}$			-0.018	-0.270	-0.320	-0.332
	3.71	1	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-3/2}$		0.076	0.159	-0.088	-0.277	-0.256
	3.71	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=3/2}$		-0.043	-0.075	0.070	0.178	0.152
	4.42	1	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-7/2}$		-0.152	-0.142	-0.019	0.020	0.061
	4.42	6	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=7/2}$				-0.130	-0.069	-0.054
	4.57	2	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=-7/2}$		0.009	-0.073	-0.180	-0.204	-0.227
	4.57	5	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=7/2}$				0.194	0.216	0.192
	5.58	3	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=-7/2}$			0.032	0.148	0.286	0.367
	5.58	4	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=7/2}$			-0.002	-0.152	-0.251	-0.355

PWZ, Ring, Meng, arXiv:1607.04241

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Spin I =

PWZ, Ring, Meng, arXiv:1607.04241

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	3.56	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=5/2}$			-0.018	-0.270	-0.320	-0.332		
	3.71	1	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-3/2}$		0.076	0.159	-0.088	-0.277	-0.256		
	3.71	2	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=3/2}$		-0.043	-0.075	0.070	0.178	0.152		
	4.42	1	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-7/2}$		-0.152	-0.142	-0.019	0.020	0.061		
	4.42	6	$(1f_{7/2})_{k=5/2}\otimes(1f_{7/2})_{k=7/2}$				-0.130	-0.069	-0.054		
	4.57	2	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=-7/2}$		0.009	-0.073	-0.180	-0.204	-0.227		
	4.57	5	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=7/2}$				0.194	0.216	0.192		
	5.58	3	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=-7/2}$			0.032	0.148	0.286	0.367		
	5.58	4	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=7/2}$			-0.002	-0.152	-0.251	-0.355		

Spin I =

PWZ, Ring, Meng, arXiv:1607.04241

Important configurations and their probability amplitudes in the yrast state

Snin I =

	Opin i –										
	E	K	Configurations	0	2	4	6	8	10		
gs	0.00	0	-	0.959	0.856	0.623	0.280	0.150	0.113		
2n1	2.68	1	$(2p_{3/2})_{k=1/2}\otimes (1f_{5/2})_{k=1/2}$		0.314	0.448	0.241	0.098	0.100		
	3.36	1	$(2p_{3/2})_{k=1/2}\otimes(2p_{3/2})_{k=-3/2}$		0.225	0.308	0.164	0.055	0.000		
	4.64	2	$(2p_{3/2})_{k=1/2}\otimes (1f_{5/2})_{k=3/2}$		-0.044	-0.146	-0.076	-0.037	-0.064		
	4.64	1	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=-3/2}$		0.068	0.126	0.085	0.037	0.028		
	2.39	0	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-5/2}$	0.265	0.146	-0.084	-0.232	-0.228	-0.166		
2p1	2.55	1	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-5/2}$		0.224	0.430	0.521	0.400	0.341		
	2.55	4	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=5/2}$			0.013	0.205	0.183	0.146		
	2.71	0	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=-3/2}$	-0.055	-0.028	0.020	0.283	0.297	0.280		
2p2	3.56	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-5/2}$		-0.047	-0.127	-0.386	-0.416	-0.409		
	3.56	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=5/2}$			-0.018	-0.270	-0.320	-0.332		
	3.71	1	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-3/2}$		0.076	0.159	-0.088	-0.277	-0.256		
	3.71	2	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=3/2}$		-0.043	-0.075	0.070	0.178	0.152		
	4.42	1	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-7/2}$		-0.152	-0.142	-0.019	0.020	0.061		
	4.42	6	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=7/2}$				-0.130	-0.069	-0.054		
	4.57	2	$(1f_{7/2})_{k=3/2}\otimes(1f_{7/2})_{k=-7/2}$		0.009	-0.073	-0.180	-0.204	-0.227		
	4.57	5	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=7/2}$				0.194	0.216	0.192		
	5.58	3	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=-7/2}$			0.032	0.148	0.286	0.367		
	5.58	4	$(1f_{7/2})_{k=1/2}\otimes(1f_{7/2})_{k=7/2}$			-0.002	-0.152	-0.251	-0.355		

Nuclear Matter

Saturation properties:

Model	$ ho_0$	E/A	M_D^*/M	M_L^*/M	E_{sym}	L	K_{sym}	K_0	K_{asy}
	(fm^{-3})	(MeV)			(Mev)	(MeV)	(MeV)	(MeV)	(MeV)
NL3	0.148	-16.25	0.59	0.65	37.4	119	101	272	-611
PK1	0.148	-16.27	0.61	0.66	37.6	116	55	283	-640
TW99	0.153	-16.25	0.55	0.62	32.8	55	-125	240	-457
DD-ME1	0.152	-16.2	0.58	0.64	33.1	56	-101	245	-435
PKDD	0.15	-16.27	0.57	0.63	36.8	90	-81	262	-622
PC-LA	0.148	-16.13	0.58	0.64	37.2	108	-61	264	-711
PC-F1	0.151	-16.17	0.61	0.67	37.8	117	74	255	-628
PC-PK1	0.153	-16.12	0.59	0.65	35.6	113	95	238	-582
DD-PC1	0.152	-16.06	0.58	0.64	33	70	-108	230	-529

~0.16 ~16 0.55~0.6 0.8±0.1 32~36 88±25

~240 ~550

Related experiment is highly demanded!



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

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