International Nuclear Physics Conference (INPC2016)
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Microscopic studies on nuclear spin-isospin properties

--- a personal perspective on covariant density functional theory

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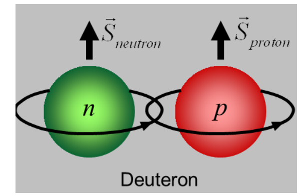
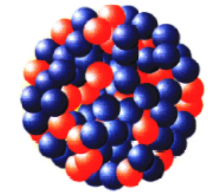
Research interests and tools

Research interests: **Spin and Isospin properties in atomic nuclei**

Spin and **Isospin** are essential degrees of freedom in nuclear physics



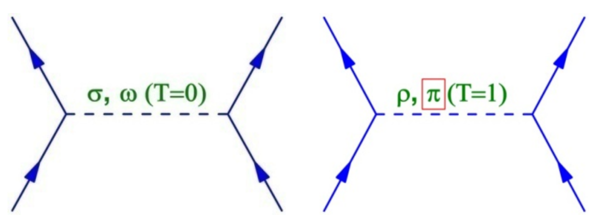


*Relevant studies in **nuclear physics** × **nuclear astrophysics** × **particle physics***

Research tools: **Covariant density functional theory (CDFT)**

- Fundamental: **Kohn-Sham** Density Functional Theory
- Scheme: **Yukawa** meson-exchange nuclear interactions

$$\mathscr{L} = \bar{\psi}\left[i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - \gamma^\mu\left(g_\omega\omega_\mu + g_\rho\vec{\tau}\cdot\vec{\rho}_\mu + e\frac{1-\tau_3}{2}A_\mu\right) - \frac{f_\pi}{m_\pi}\gamma_5\gamma^\mu\partial_\mu\vec{\pi}\cdot\vec{\tau}\right]\psi$$
$$+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^\mu\cdot\vec{\rho}_\mu$$
$$+\frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} - \frac{1}{2}m_\pi^2\vec{\pi}\cdot\vec{\pi} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

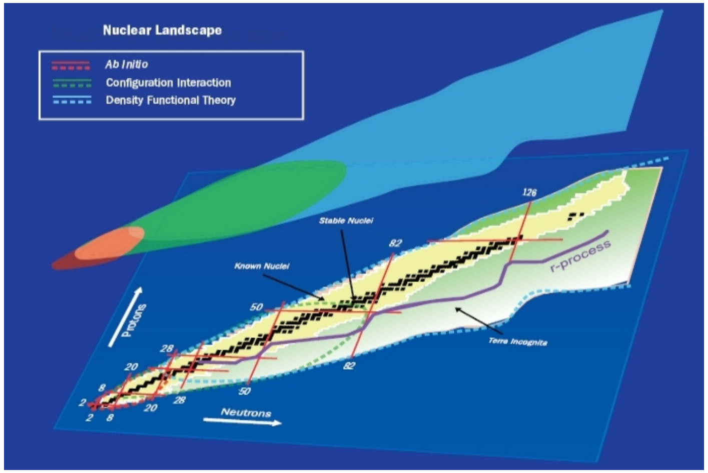


Nobel Prize 1949
Nobel Prize 1998

Covariant density functional theory

Why DFT?

- applicable to almost whole nuclear chart (*ground states* × *excited states*)
- no other method achieves comparable accuracy at the similar computational costs



http://www.unedf.org/

Why covariant (relativistic)?

- Dirac equation
  consistent treatment of **spin** d.o.f. & nuclear saturation properties (**3-body effect**)
- Lorentz covariant symmetry
  unification of time-even and **time-odd** components
- Effective Lagrangian
  connections to underlying theories, QCD at low energy

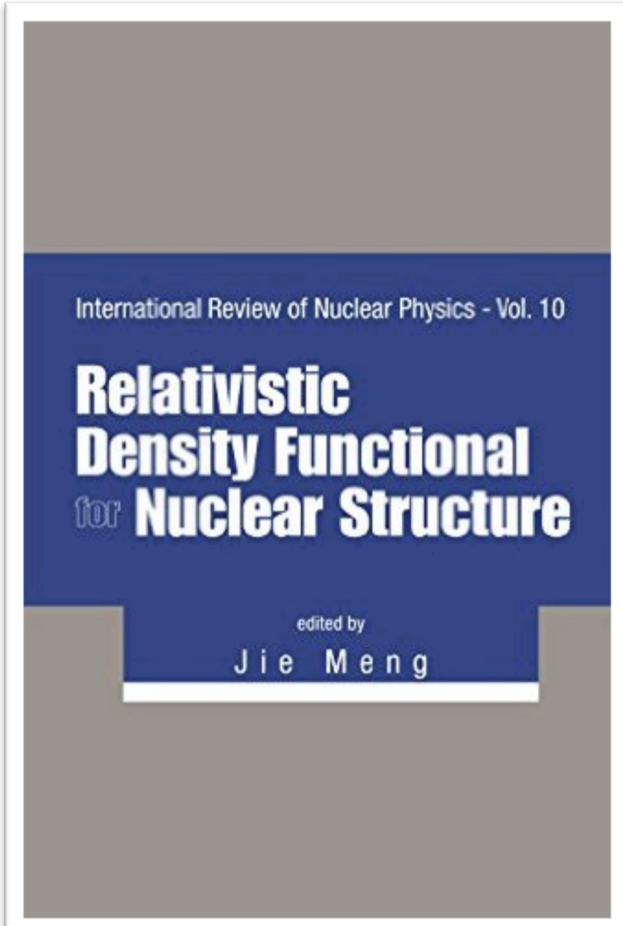
cf. HAL QCD Collaboration

Covariant density functional theory

From Walecka model in 1974 …………………. to now

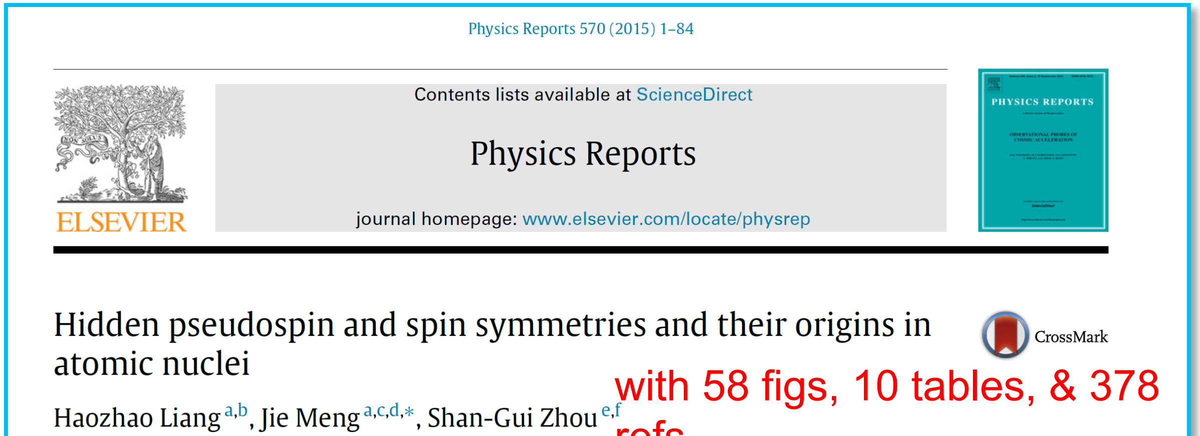
cf. S.-G. Zhou's plenary talk

in Jan 2016

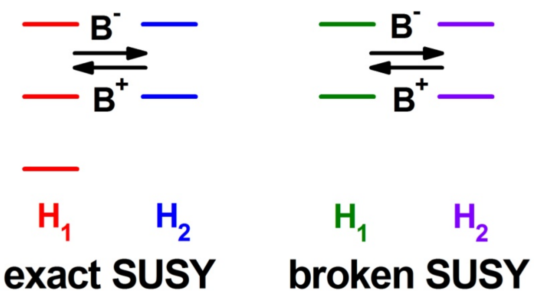


- Concept of Covariant Density Functional Theory (P Ring)
- Relativistic Mean-Field Theory (J Meng, P Ring and P W Zhao)
- Relativistic Mean Field Description of Exotic Nuclei (J Meng, P Ring, P W Zhao and S G Zhou)
- Relativistic Hartree–Fock–Bogoliubov Theory: Ground States and Excitations (W H Long, J Meng and N Van Giai)
- Superheavy Nuclei and Fission Barriers (B N Lu, J Zhao, E G Zhao and S G Zhou)
- Relativistic Symmetries in Nuclear Single-Particle Spectra (J Y Guo, H Z Liang, J Meng and S G Zhou)
- Structure of Hypernuclei in Relativistic Approaches (K Hagino and J M Yao)
- Rotating Nuclei: From Ground State to the Extremes of Spin and Deformation (A V Afanasjev)
- Novel Rotational Excitations (J Meng, S Q Zhang and P W Zhao)
- Small Amplitude Motion (N Paar and Y Niu)
- Nuclear Shell Structure and Response with Quasiparticle-Vibration Coupling (E Litvinova and P Ring)
- Beyond the Relativistic Mean-Field Approximation — Collective Correlations (Z P Li, T Nikšić, D Vretenar and J M Yao)
- Heavy Element in Astrophysical Nucleosynthesis (B H Sun and Z M Niu)
- Relativistic Density Functional Theory for Finite Nuclei and Neutron Stars (J Piekarewicz)
- Relativistic Versus Non-Relativistic Mean Field (P-G Reinhard)

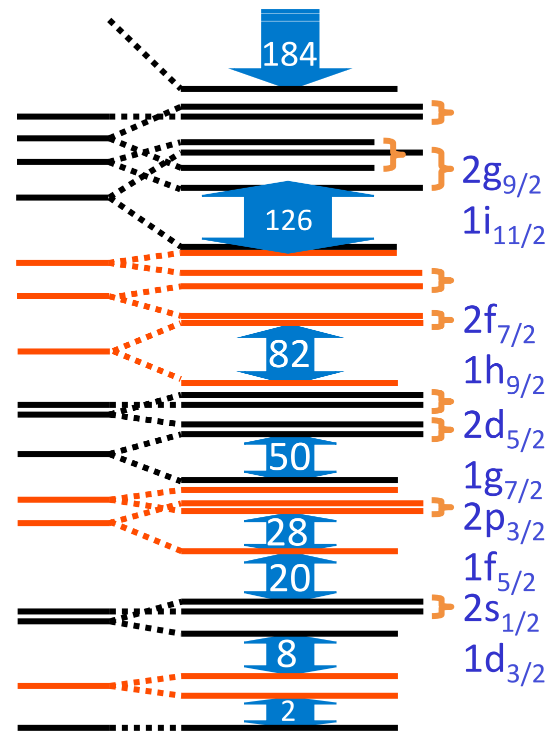
Our studies on pseudospin symmetry


Physics Reports 570 (2015) 1–84
Contents lists available at ScienceDirect
Physics Reports
journal homepage: www.elsevier.com/locate/physrep
Hidden pseudospin and spin symmetries and their origins in atomic nuclei
Haozhao Liang[a,b], Jie Meng[a,c,d,*], Shan-Gui Zhou[e,f]

with 58 figs, 10 tables, & 378 refs



- **Pseudospin symmetry**
  near degeneracy between $\begin{cases}(n-1, l+2, j=l+3/2) \\ (n, l, j=l+1/2)\end{cases}$
  ------ *a relativistic symmetry*

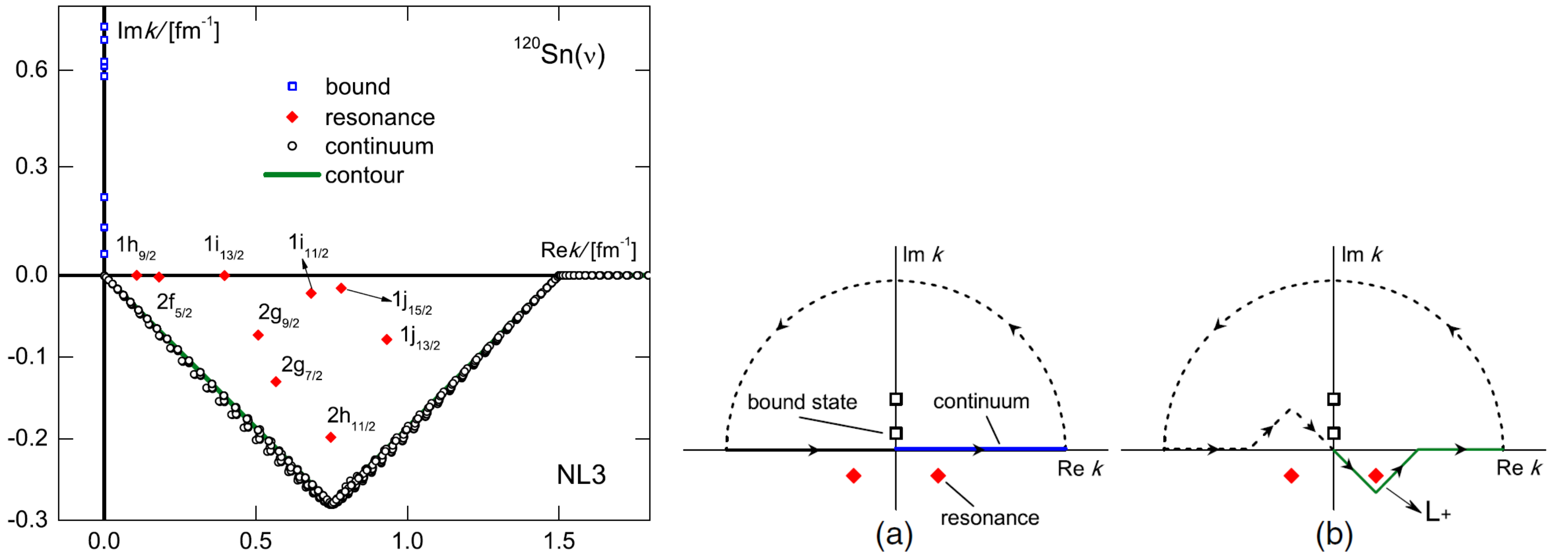


- The origin of PSS deeply hidden in original Hamiltonian H_1 can be traced in its SUSY partner Hamiltonian H_2.
- ΔE_{PSO} can be understood in an explicit and quantitative way.

HZL, Meng, Zhou, *Phys. Rep.* **570**, 1-84 (2015)

Our studies on single-particle resonances

➢ Resonances in relativistic scheme



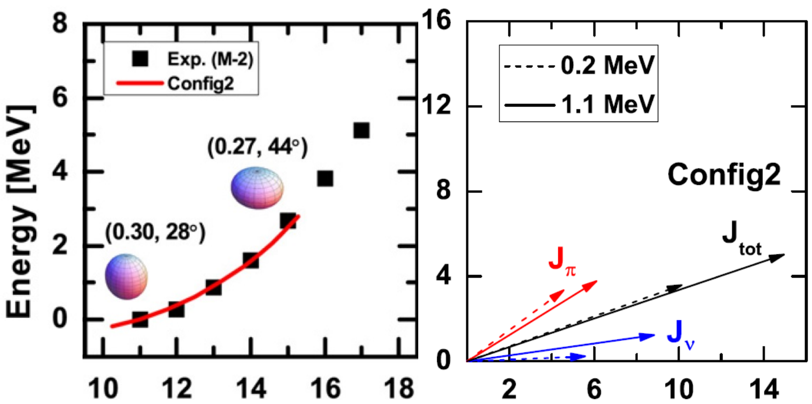
Li, Shi, Guo, Niu, HZL, *Phys. Rev. Lett.* **117**, 062502 (2016)

- solving nucleon equation of motion in complex momentum space → single-particle resonances in relativistic scheme
- This method is not only very effective for narrow resonances, but also can be reliably applied to broad resonances.

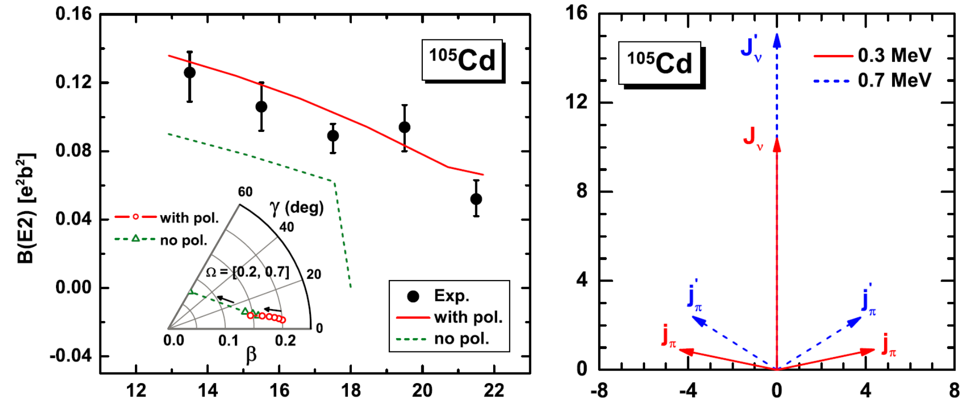
→ halo nuclei

Our studies on (anti-)magnetic rotations

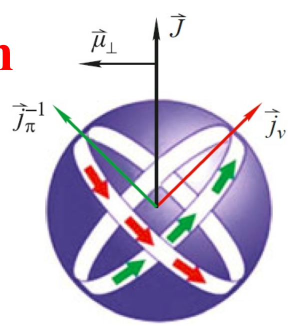
➢ Magnetic rotation in ^{60}Ni



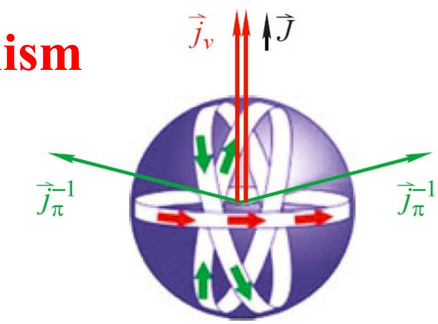
➢ Anti-magnetic rotation in ^{105}Cd



shears mechanism



two-shears-like mechanism



Zhao et al., *Phys. Lett. B* **699**, 181 (2011); *Phys. Rev. Lett.* **107**, 122501 (2011)

- 2D tilted axis cranking model with CDFT → nuclear rotations
- Shears and two-shears-like mechanisms are described and understood self-consistently and microscopically.

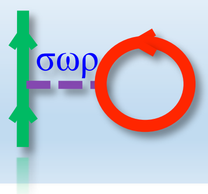
Covariant density functional theory

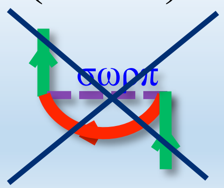
From Walecka model in 1974 …………………. to now

CDFT achieves a great success in nuclear **ground-state** and **excited-state** properties

For simplicity, in most of versions ← relativistic mean-field (**RMF**) theory

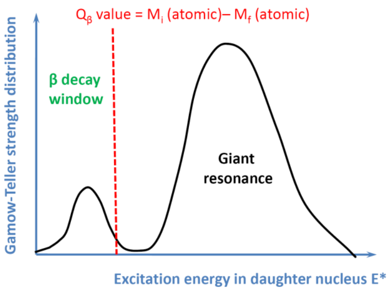
- with local Hartree terms ✓
- without non-local Fock terms ✗

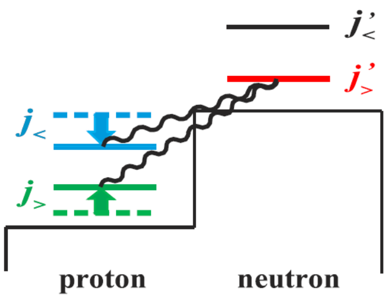




However, "Hartree terms only" show limitations in

- ☐ **properties in spin-isospin channel**
- ☐ **effects of tensor interaction**



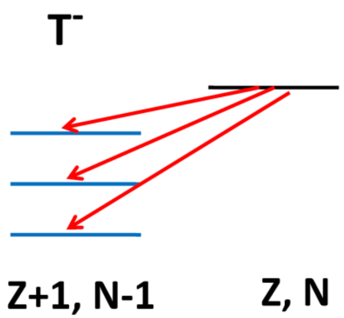


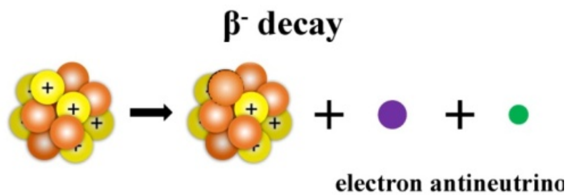
Our works: both **Hartree** and **Fock** terms

Nuclear spin-isospin properties

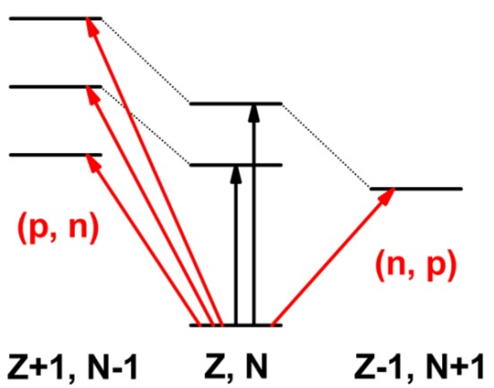
Nuclear spin-isospin excitations

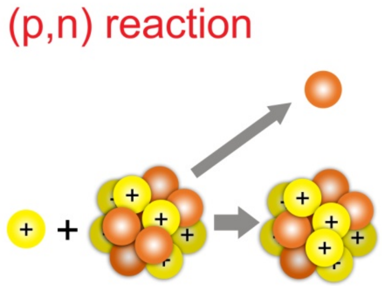
- β-decays in nature





- charge-exchange reactions in lab





Bell	Nucleus
Hammers (iron,wooden)	Probes (e, γ, α, p, n)
Sounds of the Bell	Modes of collective vibrations of nucleus

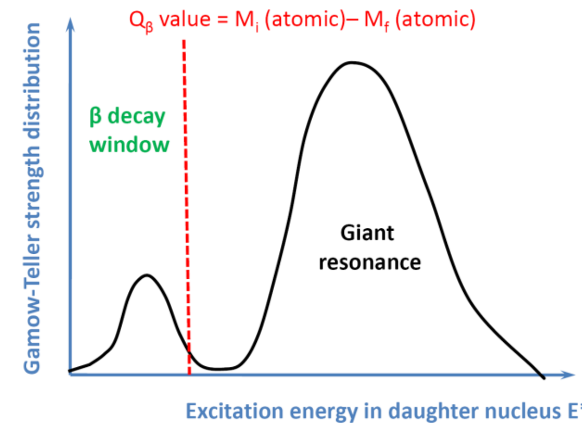
Spin-isospin excitations

These excitations are important to understand

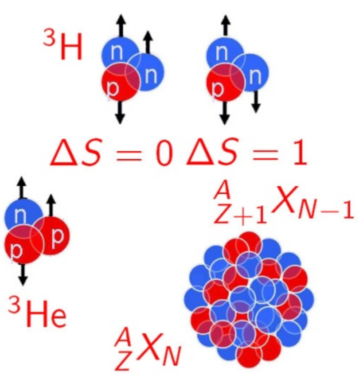
"What are the spin and isospin properties of nuclear force and nuclei?" *(nuclear physics)*

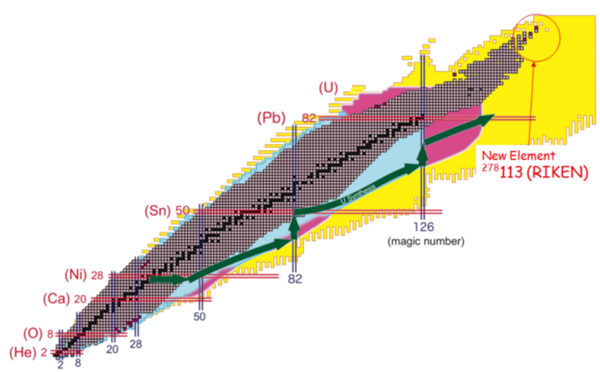
"Where and how does the rapid neutron-capture process (*r*-process) happen?" *(nuclear astrophysics)*

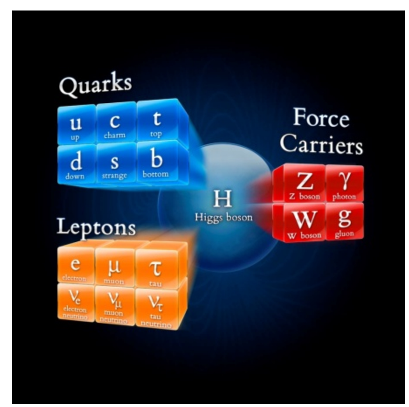
"Does Cabibbo-Kobayashi-Maskawa matrix satisfy the unitary condition?" *(particle physics)*



Key exp. @
RIKEN
RCNP
MSU
GSI
TRIUMF
CERN
……

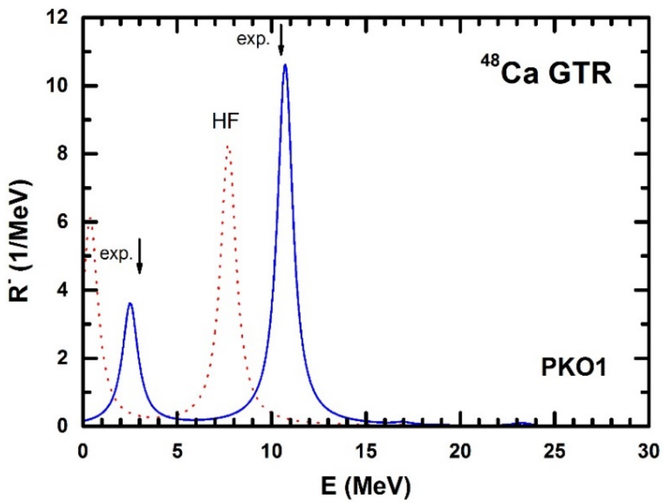


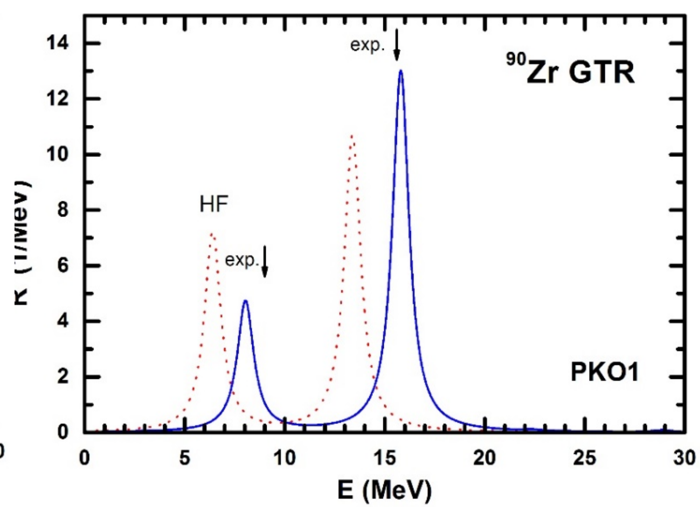




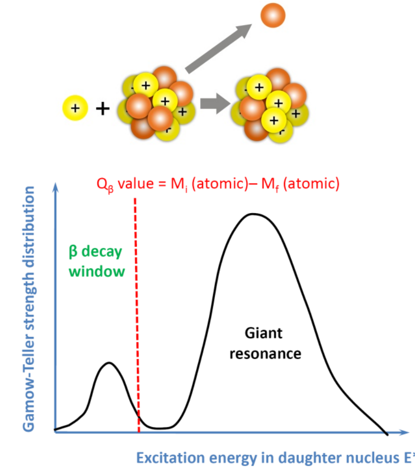
Gamow-Teller resonances

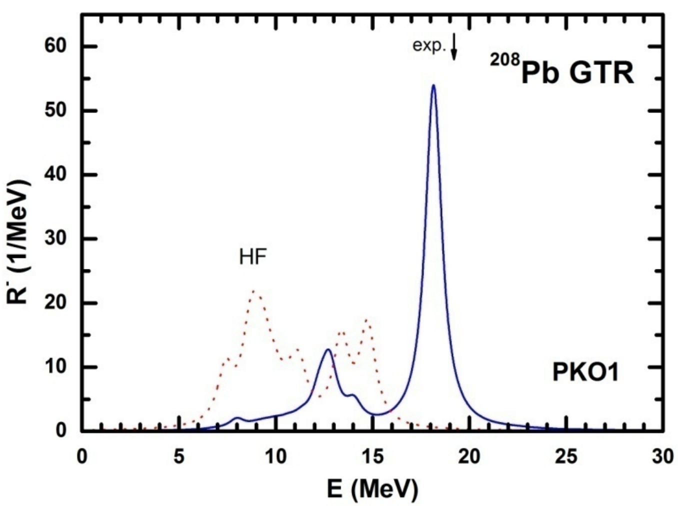
CDFT+RPA for Gamow-Teller resonances $(\Delta S = 1, \Delta L = 0, J^{\pi} = 1^{+})$





exp. @ RCNP

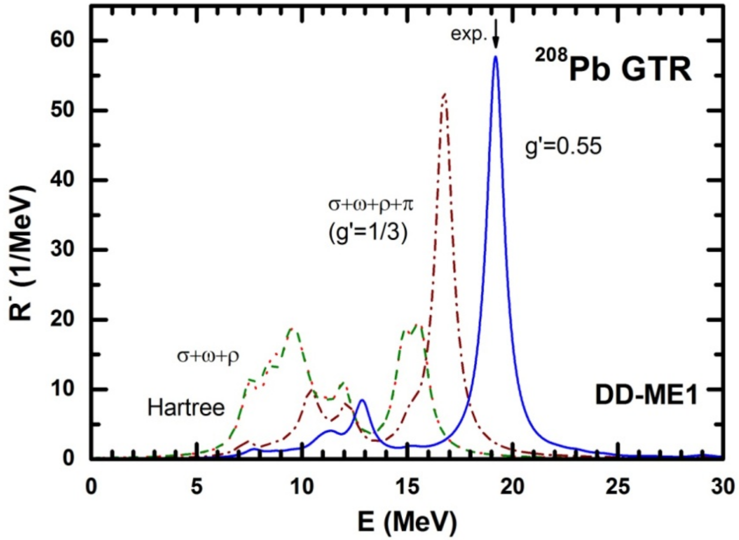




- ✓ GTR excitation energies can be reproduced in a fully self-consistent way.
- ☐ New and most important ingredient: **Fock terms** in CDFT

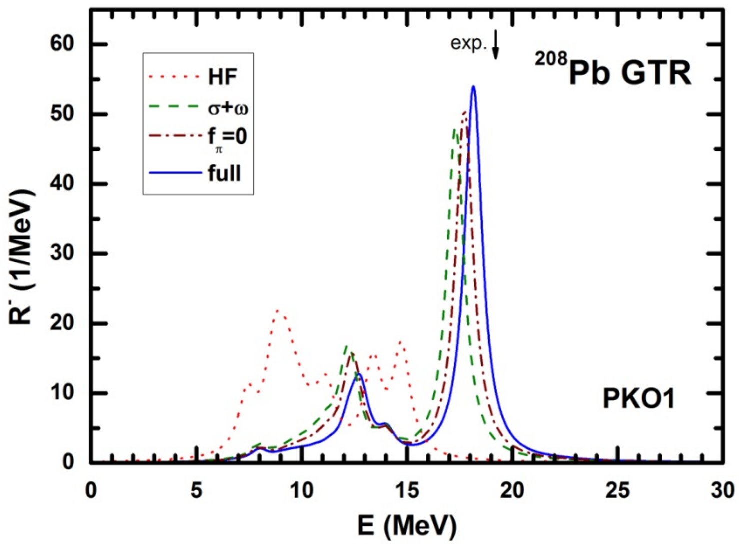
HZL, Giai, Meng, *Phys. Rev. Lett.* **101**, 122502 (2008)

Physical mechanisms of GTR



With only Hartree terms

- No contribution from isoscalar ***σ*** and ***ω*** mesons, because exchange terms are missing.
- ***π***-meson is dominant in this resonance.
- ***g'*** has to be re-fitted to reproduce the experimental data.



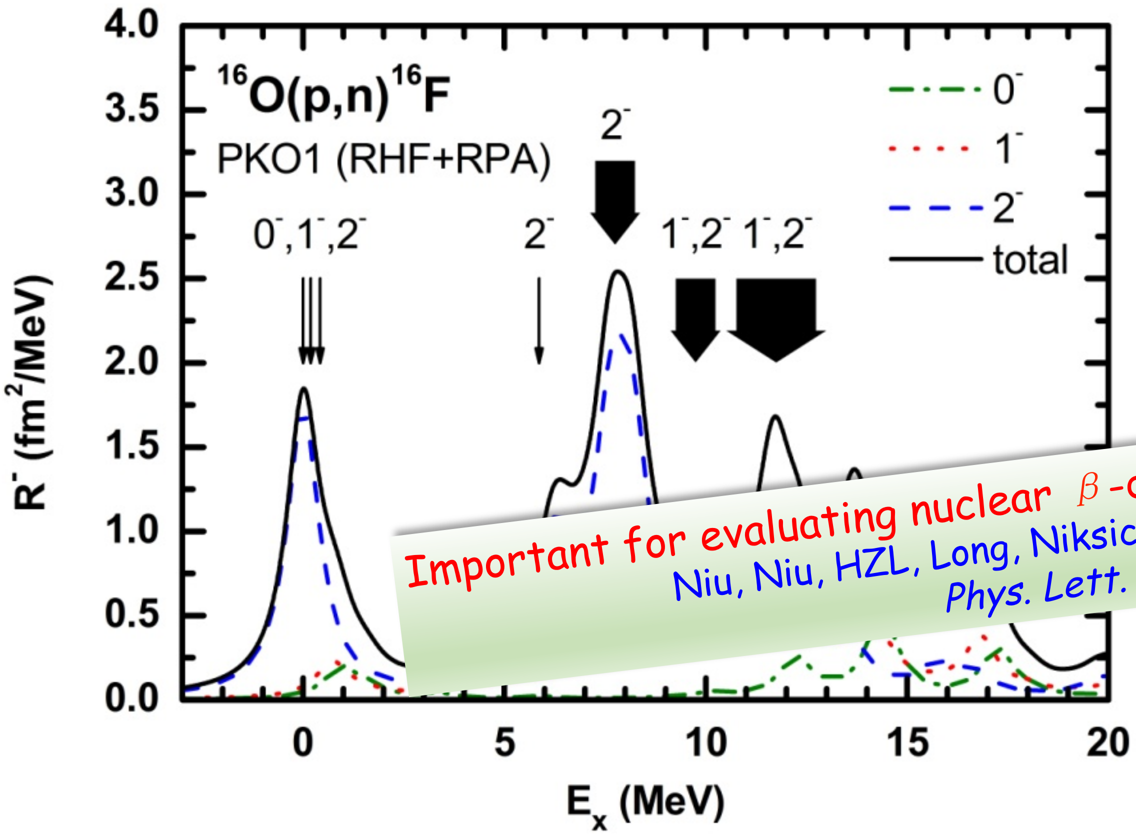
With both Hartree & Fock terms

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

HZL, Giai, Meng, *Phys. Rev. Lett.* **101**, 122502 (2008)
HZL, Zhao, Ring, Roca-Maza, Meng, *Phys. Rev. C* **86**, 021302(R) (2012)

Spin-dipole resonances

CDFT+RPA for spin-dipole resonances ($\Delta S = 1$, $\Delta L = 1$, $J^{\pi} = 0^-, 1^-, 2^-$)



Important for evaluating nuclear β-decay half-lives
Niu, Niu, HZL, Long, Niksic, Vretenar, Meng, *Phys. Lett. B* **723**, 172 (2013)

(Exp.) Wakasa *et al.*, PRC 84, 014614 (2011); (Theory) HZL, Zhao, Meng, *Phys. Rev. C* **85**, 064302 (2012)

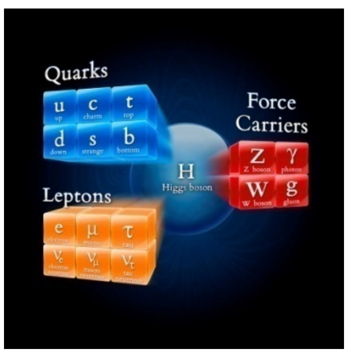
- a crucial test for the theoretical predictive power

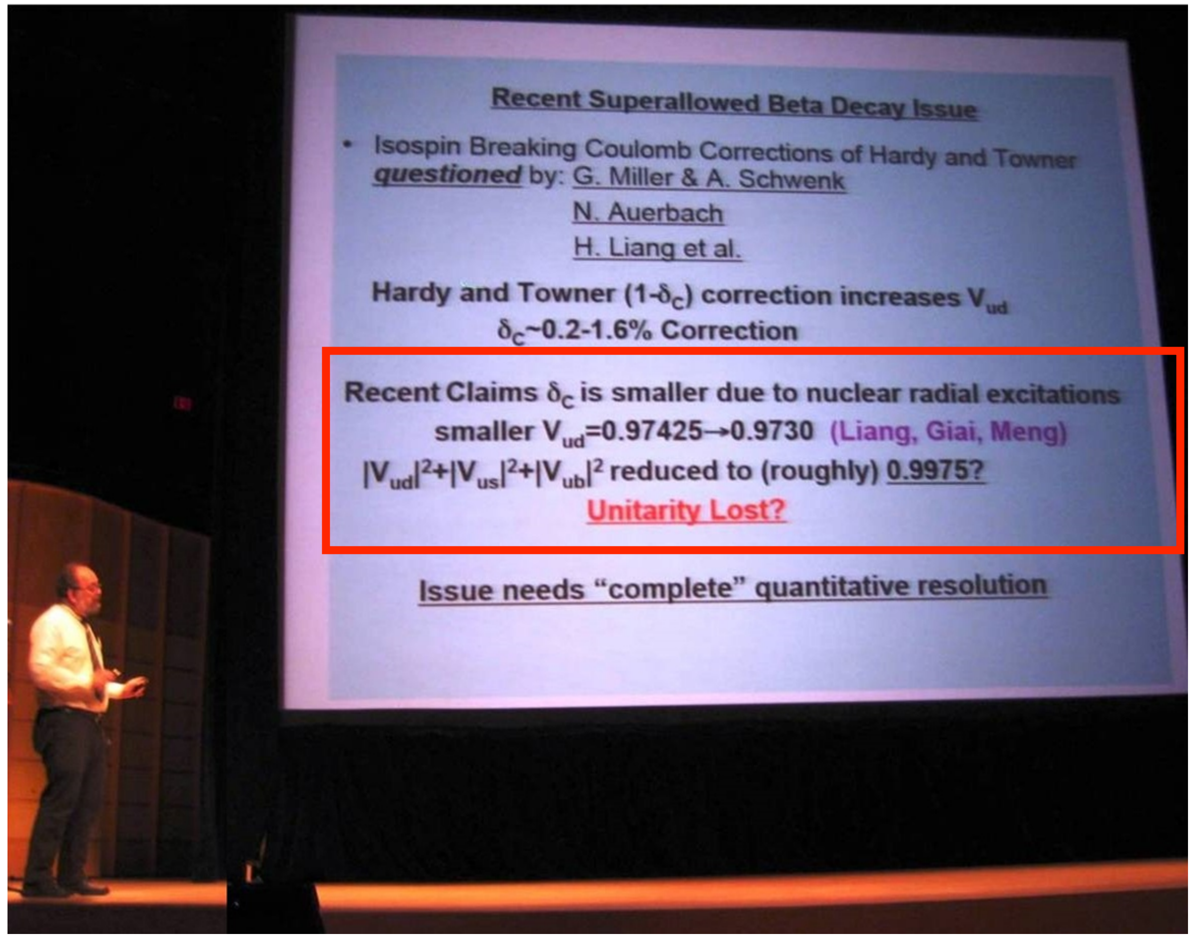
CKM matrix and its unitarity test

Cabibbo-Kobayashi-Maskawa matrix

Nobel Prize 2008

"There exist *at least* three families of quarks in nature."
"Only three?"





Plenary talk in INPC2010 "Precision Electroweak Tests of the Standard Model" by Professor William Marciano

CKM matrix and its unitarity test

Cabibbo-Kobayashi-Maskawa matrix

- quark eigenstates of weak interaction ⟺ quark mass eigenstates
- unitarity of CKM matrix ⟺ test of Standard Model

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2252 \pm 0.0009 & 0.00415 \pm 0.00049 \\ 0.230 \pm 0.011 & 1.006 \pm 0.023 & 0.0409 \pm 0.0011 \\ 0.0084 \pm 0.0006 & 0.0429 \pm 0.0026 & 0.89 \pm 0.07 \end{pmatrix}$$

Unitarity test   Particle Data Group 2014

- the most precise test comes from $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$
- the most precise $|V_{ud}|$ comes from nuclear $0^+ \rightarrow 0^+$ superallowed β transitions

Nuclear superallowed β transitions

$$|M_F|^2 = |\langle f|\, T_+ \,|i\rangle|^2 = |M_0|^2(1-\delta_c)$$

- experimental measurements
- theoretical corrections (isospin symmetry-breaking corrections)

"Only three families of quarks in nature?"

Isospin symmetry-breaking corrections δ_c

- Isospin symmetry-breaking corrections δ_c. All values are expressed in %.

	with Fock terms			w/o Fock terms			
	PKO1	PKO2	PKO3	DD-ME1	DD-ME2	NL3	TM1
$^{10}C \longrightarrow {}^{10}B$	0.082	0.083	0.088	0.149	0.150	0.124	0.133
$^{14}O \longrightarrow {}^{14}N$	0.114	0.134	0.110	0.189	0.197	0.181	0.159
$^{18}Ne \longrightarrow {}^{18}F$	0.270	0.277	0.288	0.424	0.430	0.344	0.373
$^{26}Si \longrightarrow {}^{26}Al$	0.176	0.176	0.184	0.252	0.252	0.213	0.226
$^{30}S \longrightarrow {}^{30}P$	0.497	0.550	0.507	0.612	0.633	0.551	0.648
$^{34}Ar \longrightarrow {}^{34}Cl$	0.268	0.281	0.267	0.368	0.376	0.438	0.320
$^{38}Ca \longrightarrow {}^{38}K$	0.313	0.330	0.313	0.431	0.441	0.390	0.572
$^{42}Ti \longrightarrow {}^{42}Sc$	0.384	0.387	0.390	0.515	0.523	0.436	0.443
$^{26}Al \longrightarrow {}^{26}Mg$	0.139	0.138	0.144	0.198	0.198	0.172	0.179
$^{34}Cl \longrightarrow {}^{34}S$	0.234	0.242	0.231	0.302	0.307	0.289	0.267
$^{38}K \longrightarrow {}^{38}Ar$	0.278	0.290	0.276	0.363	0.371	0.334	0.484
$^{42}Sc \longrightarrow {}^{42}Ca$	0.333	0.334	0.336	0.442	0.448	0.377	0.383
$^{54}Co \longrightarrow {}^{54}Fe$	0.319	0.317	0.321	0.395	0.393	0.355	0.368
$^{66}As \longrightarrow {}^{66}Ge$	0.475	0.475	0.469	0.568	0.572	0.560	0.524
$^{70}Br \longrightarrow {}^{70}Se$	1.140	1.118	1.107	1.232	1.268	1.230	1.226
$^{74}Rb \longrightarrow {}^{74}Kr$	1.088	1.091	1.071	1.233	1.258	1.191	1.234

HZL, Giai, Meng, *Phys. Rev. C* **79**, 064316 (2009)

Isospin corrections & V_{ud}

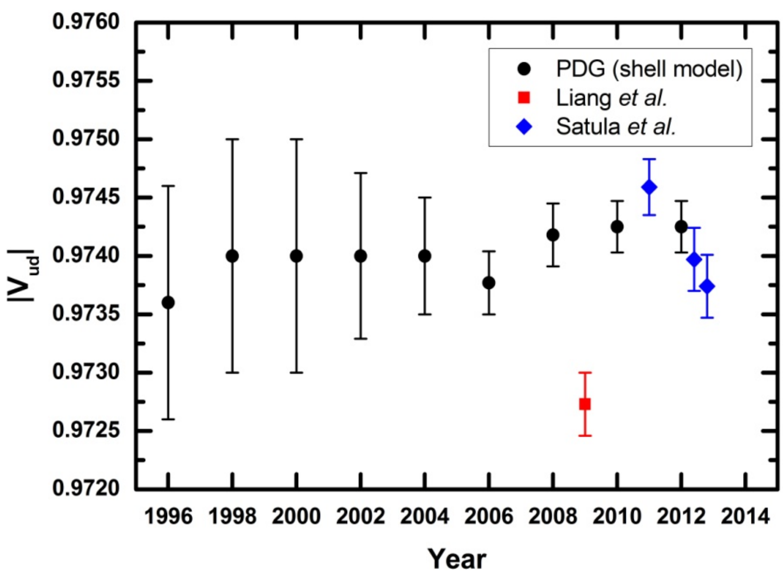
PHYSICAL REVIEW C **79**, 064316 (2009)

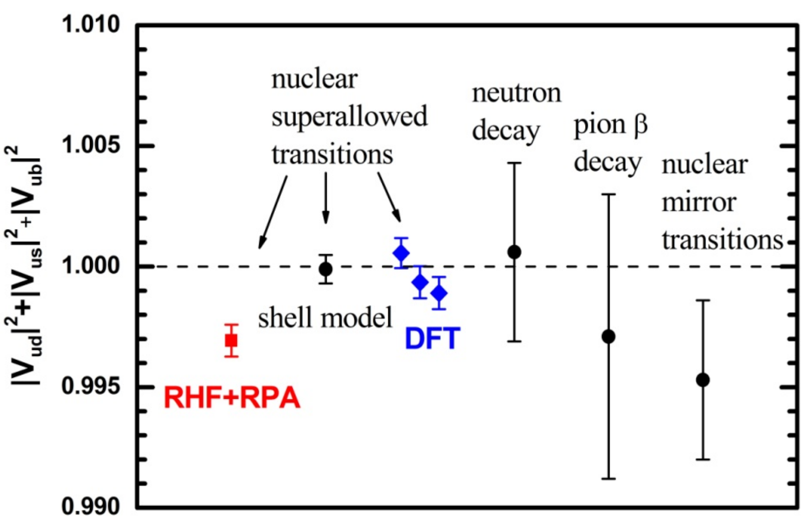
Isospin corrections for superallowed Fermi β decay in self-consistent relativistic random-phase approximation approaches

Haozhao Liang (梁豪兆),[1,2] Nguyen Van Giai,[2] and Jie Meng (孟杰)[1,3]

cited by PDG 2010, 2012, 2014, ...

Isospin corrections by self-consistent CDFT



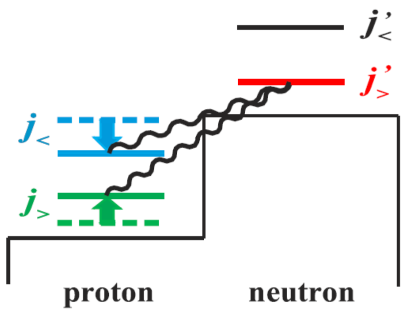


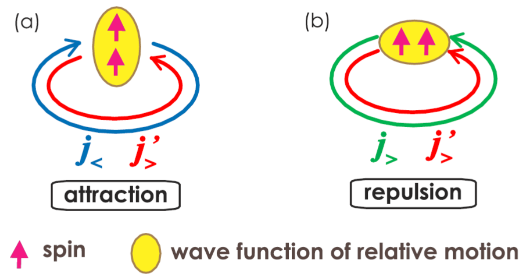
HZL, Giai, Meng, *PRC* **79**, 064316 (2009); Satula *et al.*, *PRL* **106**, 132502 (2011); *PRC* **86**, 054316 (2012)

- To our best knowledge: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$: **0.997 ~ 1.000** (**the 4th family?**)
- ongoing studies ……

Tensor effects in CDFT?

Tensor effects are crucial, in particular, for properties of exotic nuclei



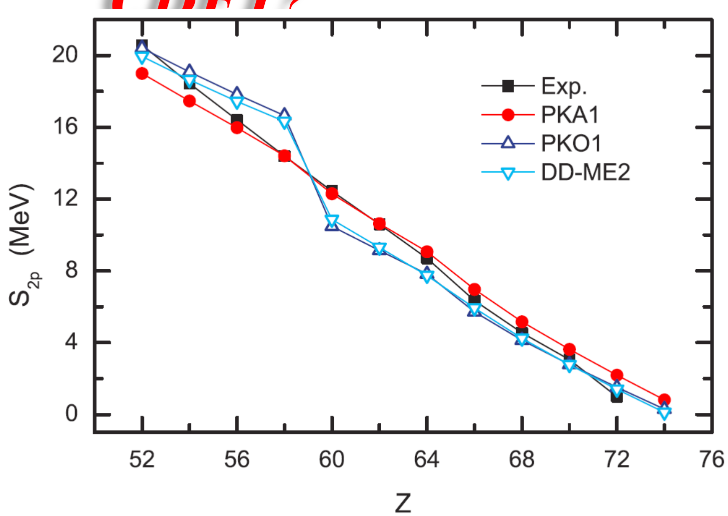


Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005)

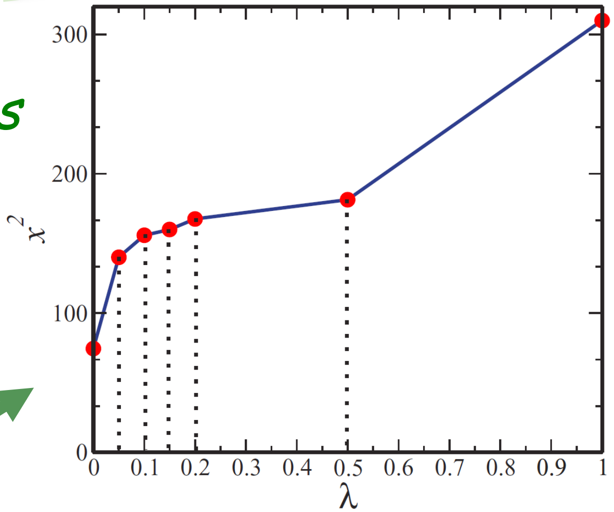
new magic numbers

What are the tensor effects in CDFT?

Ab initio for CDFT



some fingerprints



π meson (tensor) is not welcomed in CDFT

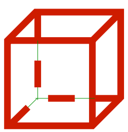
Long et al., *Phys. Rev. C* **76**, 034314 (2007)

Lalazissis et al., *Phys. Rev. C* **80**, 041301(R) (2009)

CDFT from lattice QCD?

2010 2011 2012 2013 2014 2015 2016

HPCI Program

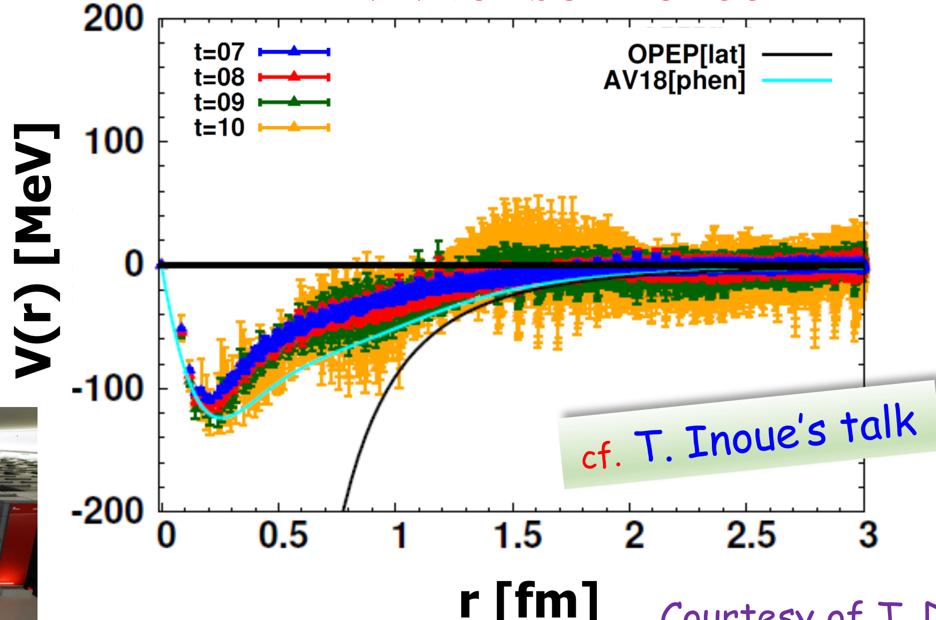


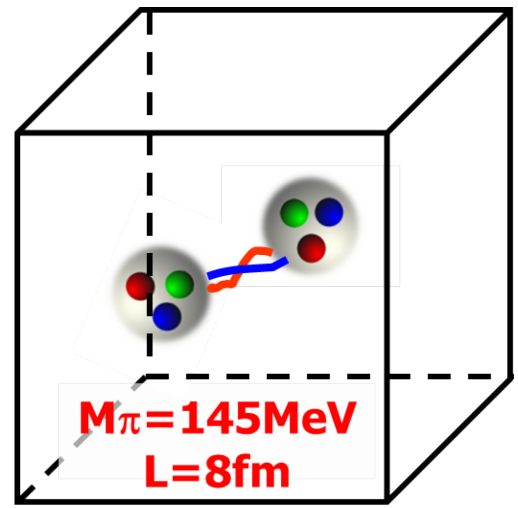
Mπ=800 MeV
L=2fm

"Unphysical" QCD

The world's 1st calculation of Baryon Forces in "Real"

NN tensor force





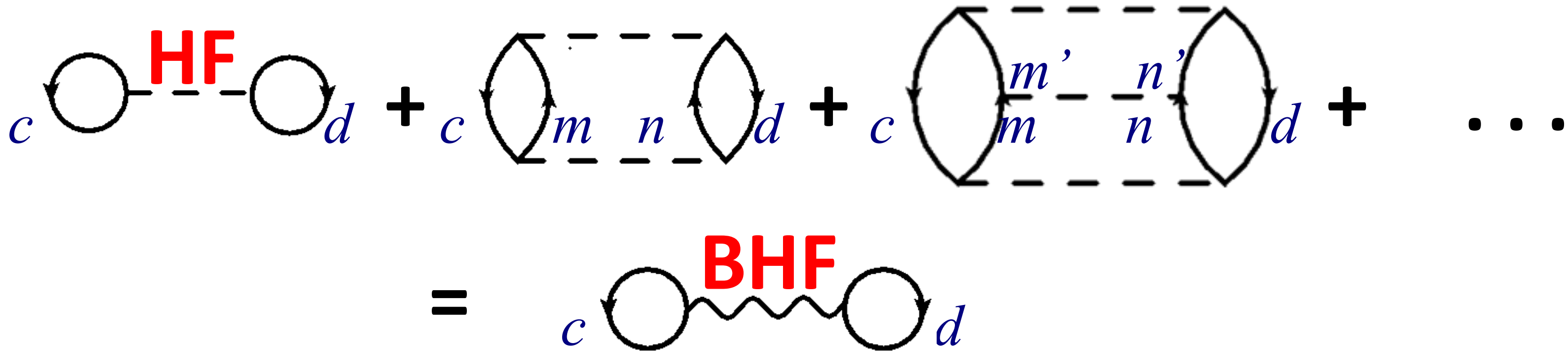
Courtesy of T. Doi

Hadrons to Atomic nuclei
HAL
from Lattice QCD

Ab initio for CDFT

- Brueckner-Hartree-Fock theory (*ladder diagrams to all order*)

(with exchange terms as well)



- Bethe-Goldstone equation → **finite nuclei**

$$\langle ab|G(W)|cd\rangle = \langle ab|V|cd\rangle + \sum_{mn} \langle ab|V|mn\rangle \frac{Q(m,n)}{W - \varepsilon_m - \varepsilon_n} \langle mn|G(W)|cd\rangle$$

where the starting energy $W = \varepsilon_c + \varepsilon_d$

For the first time, **Bethe-Goldstone equation** is solved **self-consistently**

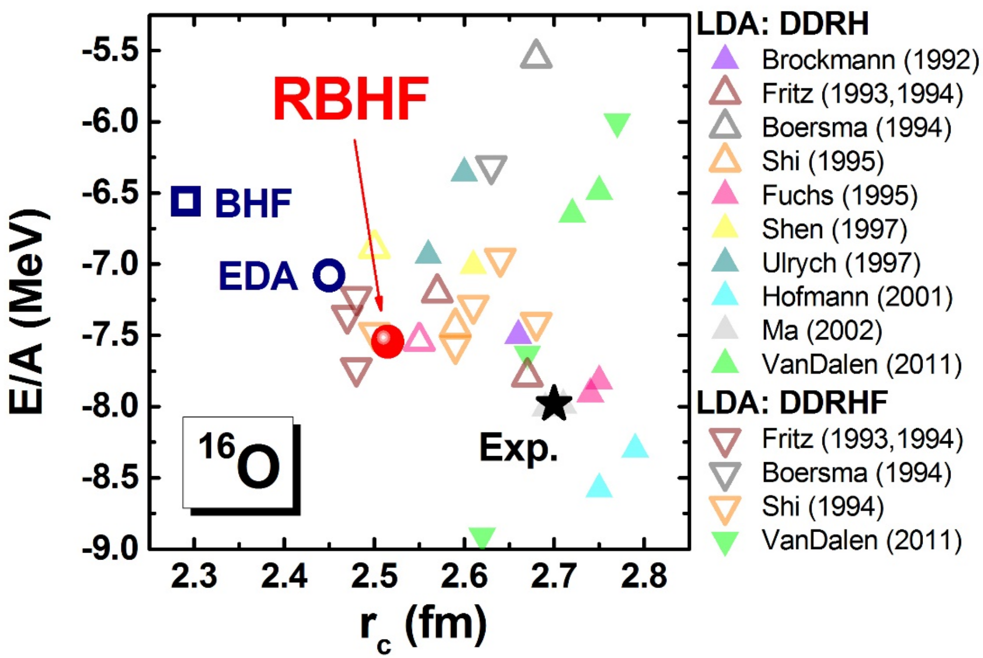
- in the **two-body** frame
- in pure **relativistic** scheme

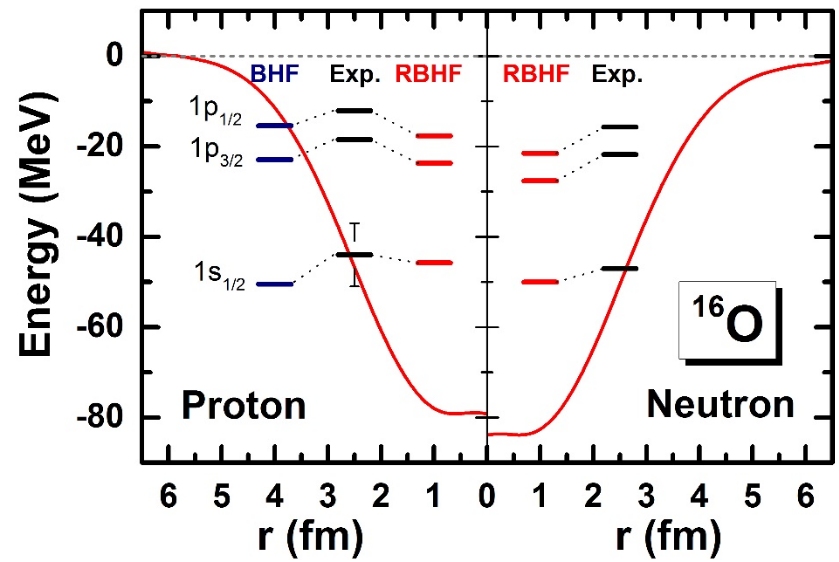
RIKEN IPA project

Shen, Hu, HZL, Meng, Ring, Zhang, arXiv:1609.01866

Relativistic BHF for finite nuclei

- Relativistic BHF calculations for ^{16}O with Bonn A interaction





EDA = effective density approximation [Müther(1990)]
LDA = local density approximation

RIKEN IPA project
Shen, Hu, HZL, Meng, Ring, Zhang, arXiv:1609.01866

- a first *ab initio* calculations for finite nuclei in **relativistic** scheme
- **Spin-orbit** splitting is reproduced well from the bare interaction.
- benchmark for various LDA calculations

A dream for another 10 years

quantum-field-theory oriented DFT

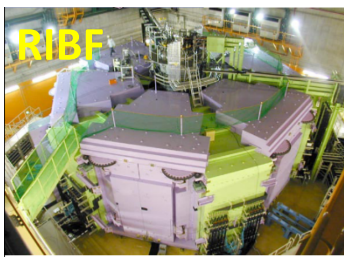
EDF from
effective action
$E_{\mathrm{HK}}[\rho] \sim \Gamma[\rho]/\beta$
(Legendre transform)

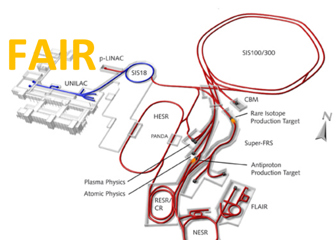
non-perturbative nature by
renormalization group
$\partial_k \Gamma_k[\rho] = \mathrm{Tr}\{\ldots\}$
(flow eq.)

theoretical uncertainties
from **EFT**
$\Gamma^{(2)}, \Gamma^{(3)}, \Gamma^{(4)} \ldots$
(power counting)

Interdisciplinary:
(lattice) QCD
hadron
cold atom
condensed matter
quantum chemistry
……

Exp. facilities:





Supercomputers:

also cf. Nazarewicz' talk
Schwenk & Polonyi, arXiv:0403011 [nucl-th]
Kutzelnigg, JMS 768, 163 (2006)
Drut, Furnstahl, Platter, PPNP 64, 120 (2010)
Braun, JPG 39, 033001 (2012)
Metzner et al., RMP 84, 299 (2012)

Acknowledgments

To Jun & our first baby

(~in a month)

Acknowledgments

Thank you very much for your encouragement and supports!