Relativistic Studies of Spin-Isospin Resonances
--- Towards exotic deformed nuclei

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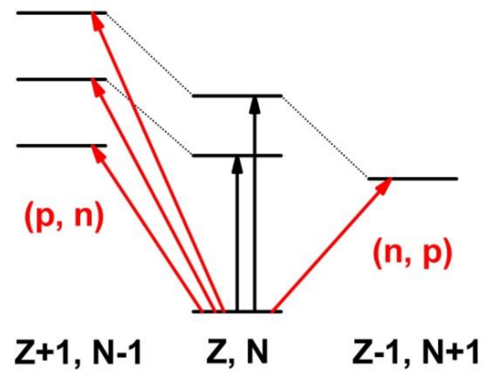
Nuclear spin-isospin excitations

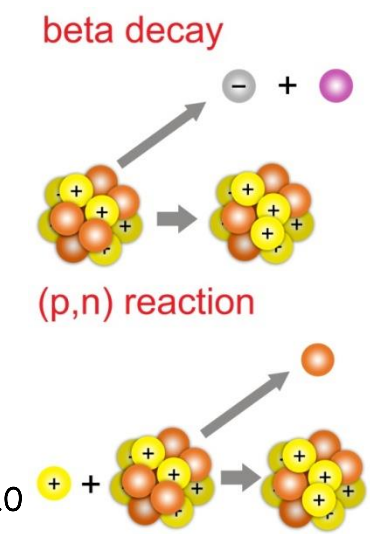
Nuclear spin-isospin excitations

- β-decays in nature
- charge-exchange reactions in lab



These excitations are important to understand

- spin and isospin properties of in-medium nuclear interaction
- effective nucleon-nucleon tensor forces Bai:2010
- neutron skin thickness Krasznahorkay:1999, Vretenar:2003, Yako:2006
- β-decay rates of r-process nuclei Engel:1999, Borzov:2006
- neutrino-nucleus cross sections Kolbe:2003, Vogel:2006, Paar:2008
- $\beta\beta$-decay rates Ejiri:2000, Avignone:2008
- unitarity of Cabibbo-Kobayashi-Maskawa matrix Towner&Hardy:2010

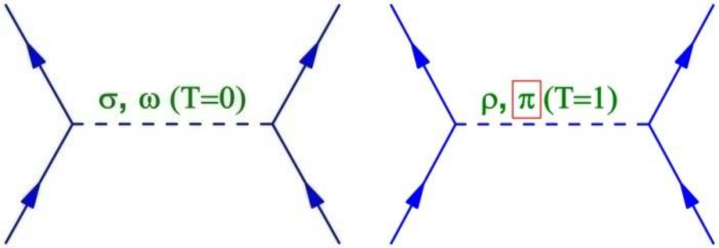


The theories achieving consistent treatment of the spin and isospin degrees of freedom are highly desired.

Covariant density functional theory

- Fundamental: Kohn-Sham Density Functional Theory
- **CDFT** starting point: effective Lagrangian density Walecka & Serot:1986, Long:2006

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



Comparing to traditional non-relativistic DFT

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

Dirac equations and RPA

- Energy functional of the system

$$E = \langle \Phi_0 | H | \Phi_0 \rangle = E_k + E_\sigma^D + E_\omega^D + E_\rho^D + E_A^D + E_\sigma^E + E_\omega^E + E_\rho^E + E_\pi^E + E_A^E + E_{\text{pair}}$$

- Dirac equations for the ground-state properties

$$\int d\boldsymbol{r}' h(\boldsymbol{r},\boldsymbol{r}')\psi(\boldsymbol{r}') = \varepsilon\psi(\boldsymbol{r}), \quad \text{with} \quad \begin{aligned} h^{\text{kin}}(\boldsymbol{r},\boldsymbol{r}') &= [\boldsymbol{\alpha}\cdot\boldsymbol{p} + \beta M]\,\delta(\boldsymbol{r}-\boldsymbol{r}'), \\ h^{\text{D}}(\boldsymbol{r},\boldsymbol{r}') &= [\Sigma_T(\boldsymbol{r})\gamma_5 + \Sigma_0(\boldsymbol{r}) + \beta\Sigma_S(\boldsymbol{r})]\,\delta(\boldsymbol{r}-\boldsymbol{r}'), \\ h^{\text{E}}(\boldsymbol{r},\boldsymbol{r}') &= \begin{pmatrix} Y_G(\boldsymbol{r},\boldsymbol{r}') & Y_F(\boldsymbol{r},\boldsymbol{r}') \\ X_G(\boldsymbol{r},\boldsymbol{r}') & X_F(\boldsymbol{r},\boldsymbol{r}') \end{pmatrix}. \end{aligned}$$

- RPA equations for the vibrational excitation properties Ring & Schuck:1980

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ -\mathcal{B} & -\mathcal{A} \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \omega_\nu \begin{pmatrix} X \\ Y \end{pmatrix}$$

- ♦ **$\delta E/\delta\rho$** → equation of motion for nucleons: **Dirac (-Bogoliubov) equations**
- ♦ **$\delta^2 E/\delta\rho^2$** → linear response equation: **(Q)RPA equations**

CDFT+RPA in charge-exchange channel

Particle-hole residual interactions **HZL**, Giai, Meng, *Phys. Rev. Lett.* **101**, 122502 (2008)

- σ-meson $$V_\sigma(1,2) = -[g_\sigma\gamma_0]_1[g_\sigma\gamma_0]_2 D_\sigma(1,2)$$
- ω-meson $$V_\omega(1,2) = [g_\omega\gamma_0\gamma^\mu]_1[g_\omega\gamma_0\gamma_\mu]_2 D_\omega(1,2)$$
- ρ-meson $$V_\rho(1,2) = [g_\rho\gamma_0\gamma^\mu\vec{\tau}]_1\cdot[g_\rho\gamma_0\gamma_\mu\vec{\tau}]_2 D_\rho(1,2)$$
- pseudovector π-N coupling

$$V_\pi(1,2) = -[\frac{f_\pi}{m_\pi}\vec{\tau}\gamma_0\gamma_5\gamma^k\partial_k]_1\cdot[\frac{f_\pi}{m_\pi}\vec{\tau}\gamma_0\gamma_5\gamma^l\partial_l]_2 D_\pi(1,2)$$

- zero-range counter-term of π-meson

$$V_{\pi\delta}(1,2) = g'[\frac{f_\pi}{m_\pi}\vec{\tau}\gamma_0\gamma_5\boldsymbol{\gamma}]_1\cdot[\frac{f_\pi}{m_\pi}\vec{\tau}\gamma_0\gamma_5\boldsymbol{\gamma}]_2\delta(\mathbf{r}_1-\mathbf{r}_2), \quad g'=1/3$$

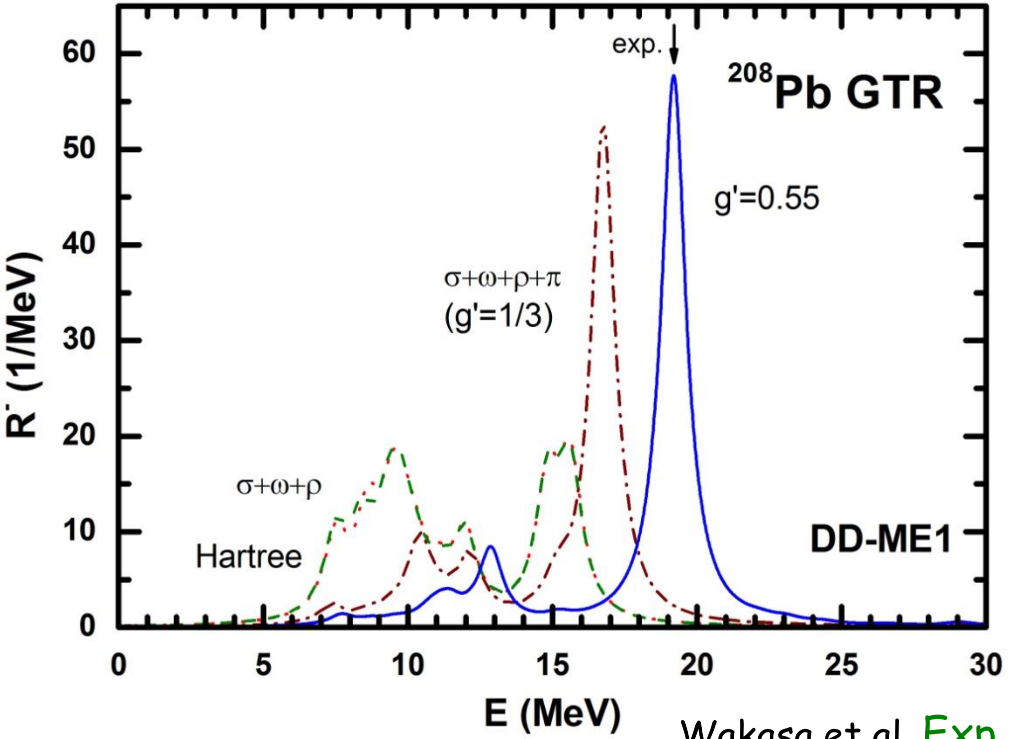
- For the correct asymptotic behavior at high q, ***g'*** is not a parameter, but must be **1/3**.

Previous results in Hartree level

CDFT+RPA for spin-isospin resonances (with only Hartree terms)

De Conti:1998, 2000, Vretenar: 2003, Ma:2004, Paar:2004, Niksic:2005

example: Gamow-Teller resonance (GTR) in ^{208}Pb ($\Delta S = 1$, $\Delta L = 0$, $J^\pi = 1^+$)

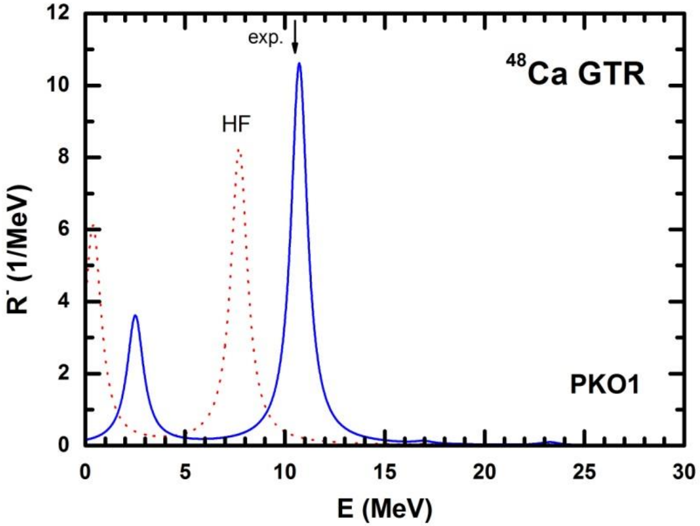


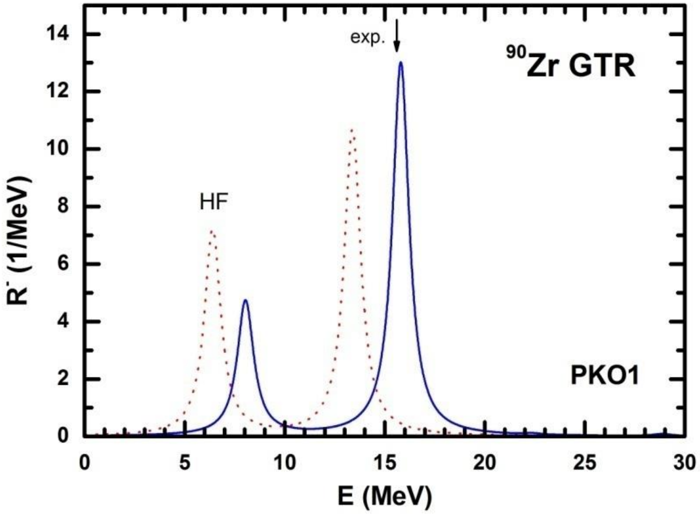
Wakasa et al. Exp. @ RCNP, Osaka U.

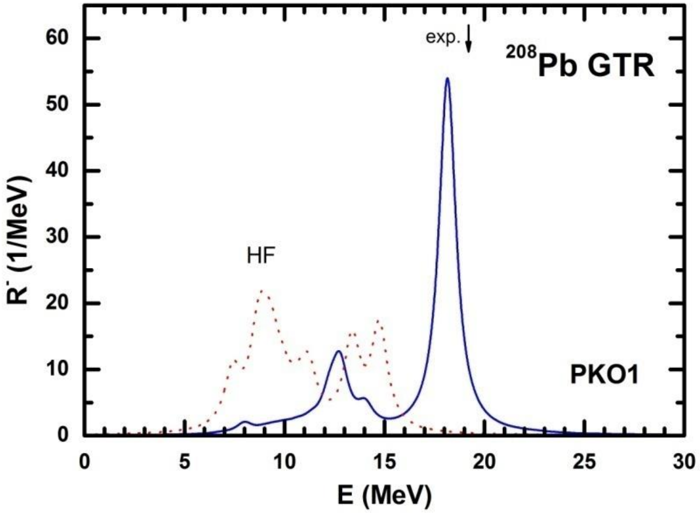
- One has to add ***π*** and fit ***g'*** → **Self-consistency is lost**

Gamow-Teller resonances

CDFT+RPA for Gamow-Teller resonances (with both Hartree & Fock terms)



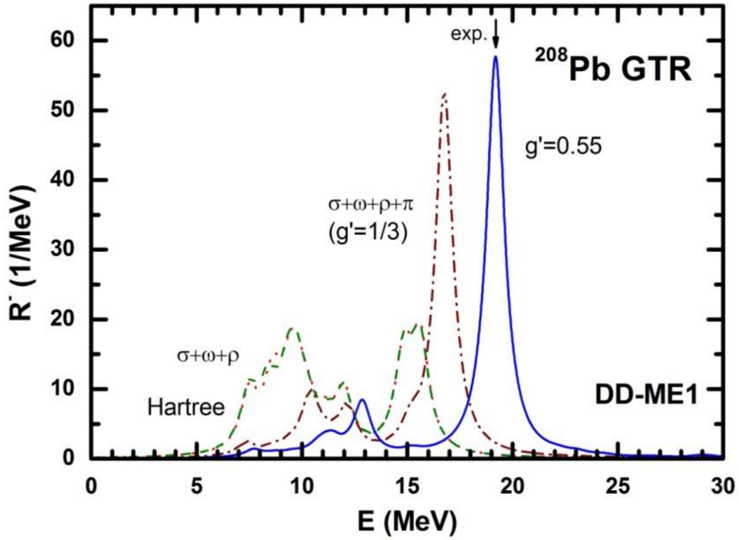




- ♦ GTR excitation energies can be reproduced in a fully self-consistent way.

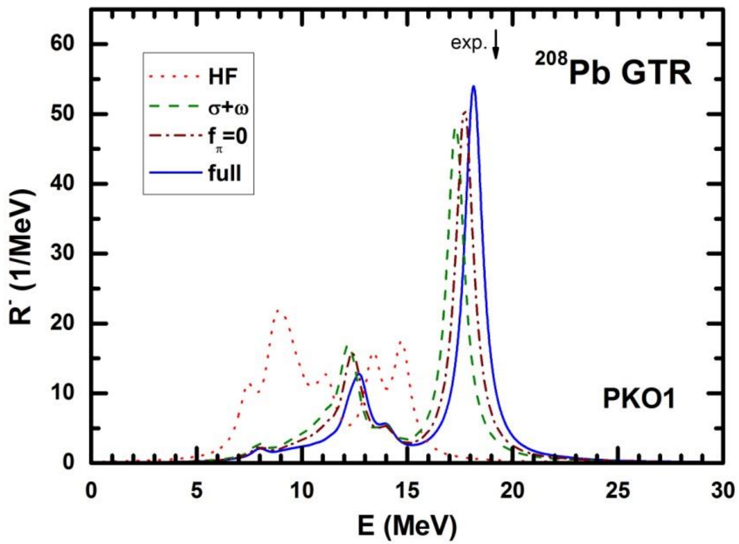
HZL, Giai, Meng, *Phys. Rev. Lett.* **101**, 122502 (2008)

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 retted to reproduce the experimental data.



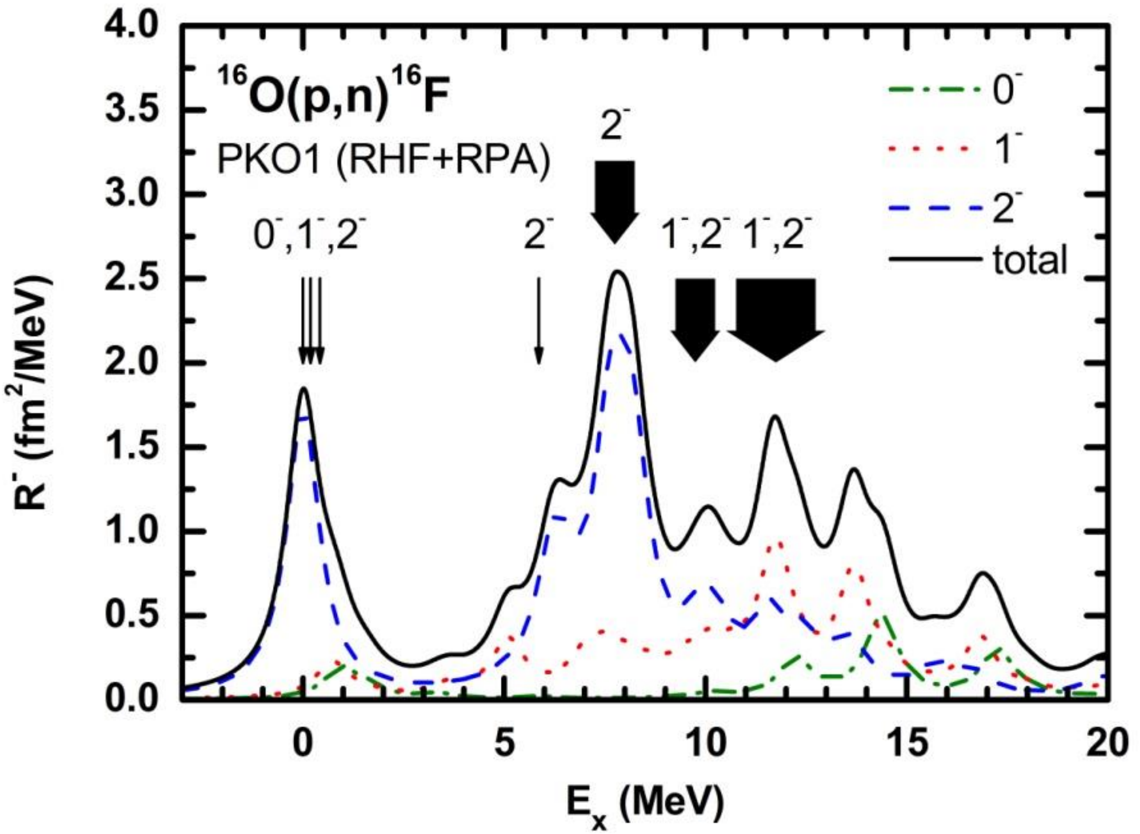
With both Hartree & Fock terms

- 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, *PRL* **101**, 122502 (2008)
HZL, Zhao, Ring, Roca-Maza, Meng, *PRC* **86**, 021302(R) (2012)

Spin-dipole resonances

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



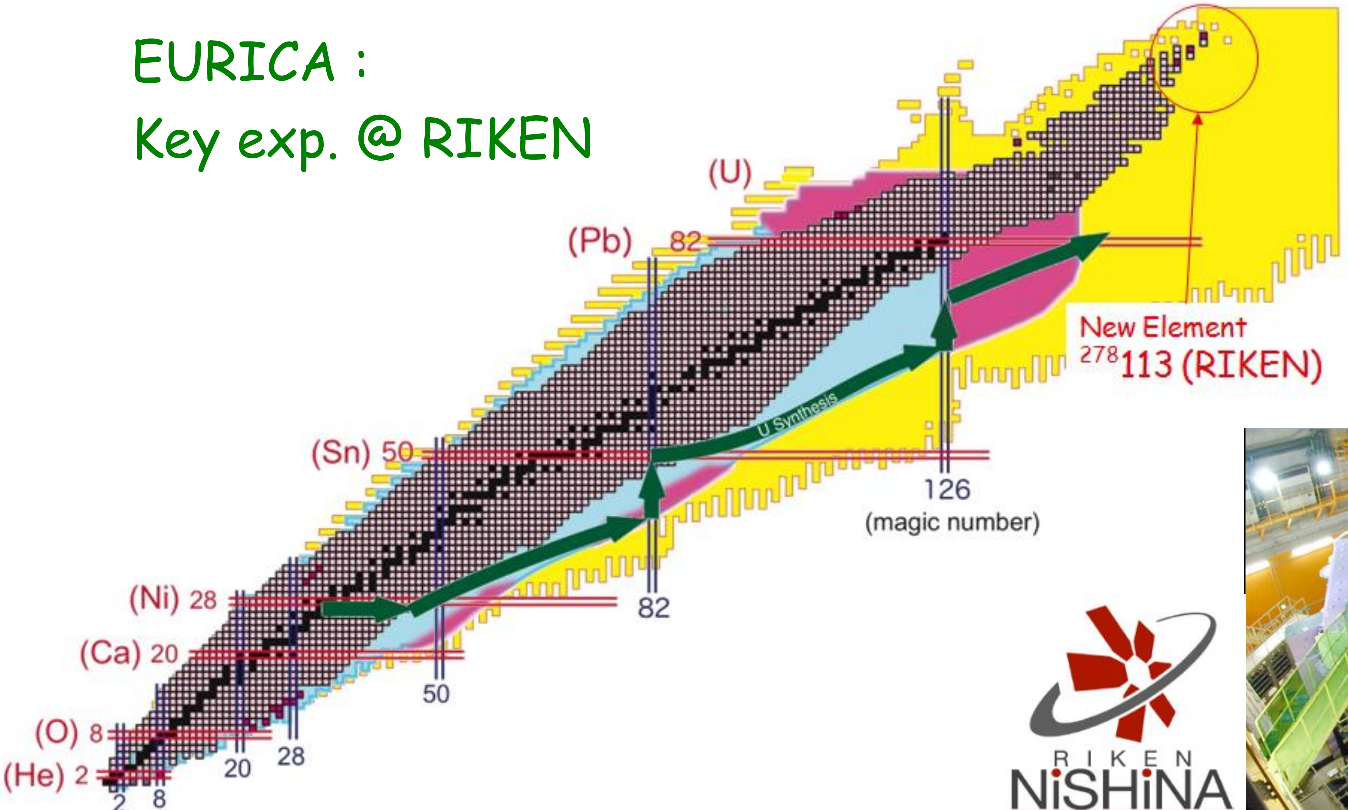
(Exp.) Wakasa et al., PRC 84, 014614 (2011); (Theory) **HZL**, Zhao, Meng, *PRC* **85**, 064302 (2012)

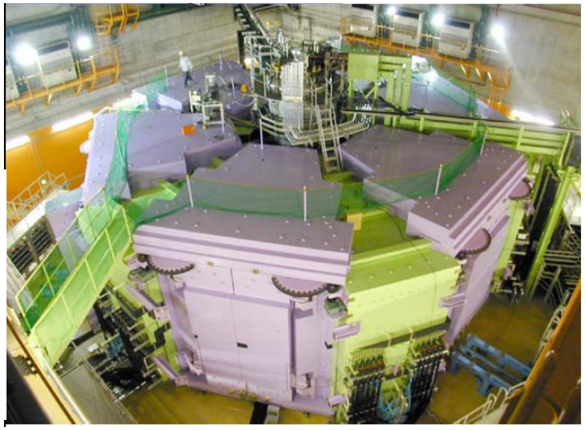
- A crucial test for the theoretical predictive power.

β decays and r-process

Nuclear β decays and r-process nucleosynthesis

EURICA :
Key exp. @ RIKEN

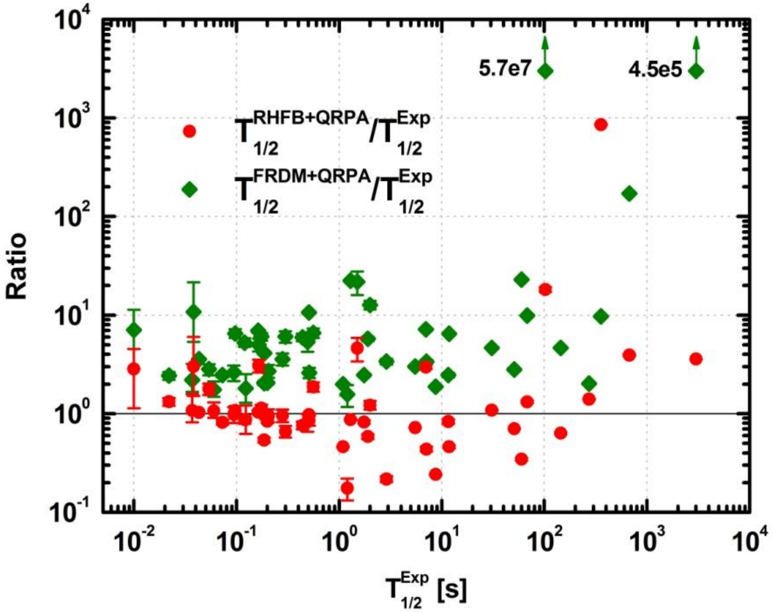


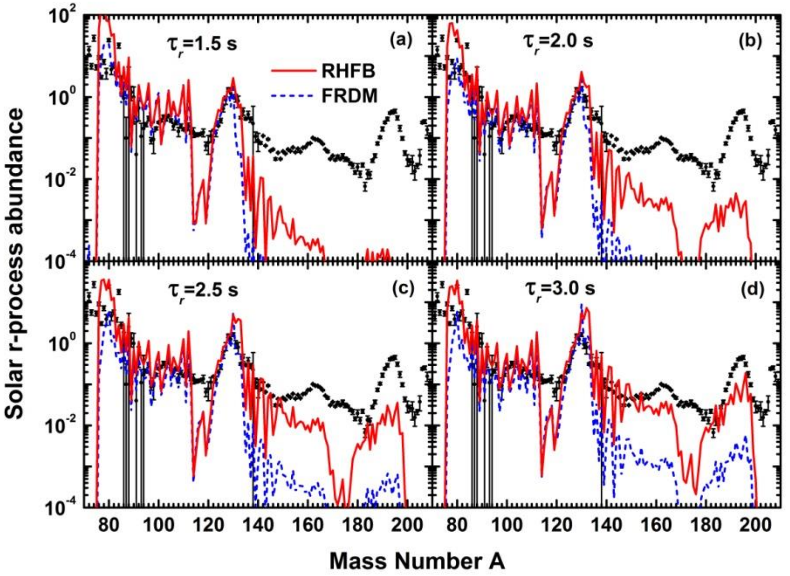


- EURICA project is providing lots of new β-decay data towards r-process path.

β decays and r-process

Nuclear *β*-decay rates and *r*-process flow (Z = 20 ~ 50 region)





FRDM: widely used nuclear input

RHFB: CDFT results with T=0 pairing

Niu, Niu, **HZL**, Long, Niksic, Vretenar, Meng, *Phys. Lett. B* **723**, 172 (2013)

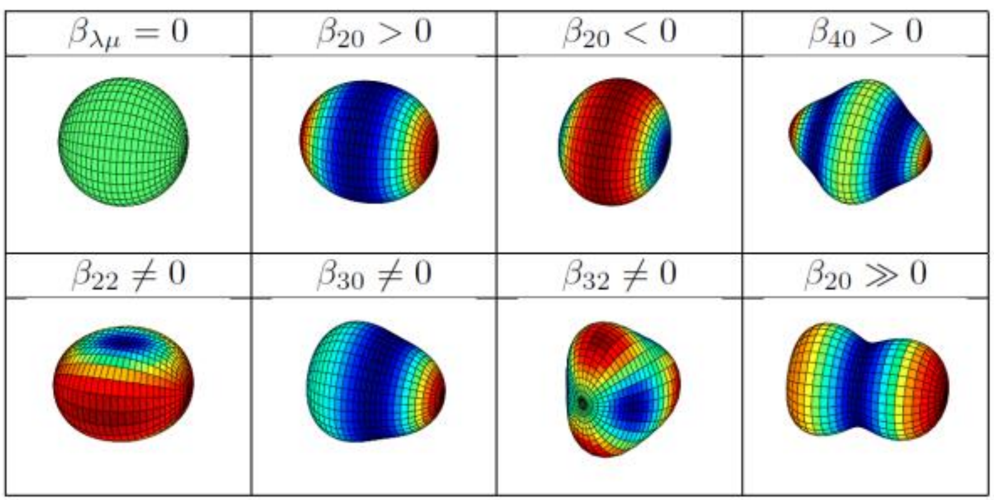
- Classical *r*-process calculation shows a faster *r*-matter flow at the N = 82 region and higher *r*-process abundances of elements with A ~ 140.

Towards deformed nuclei

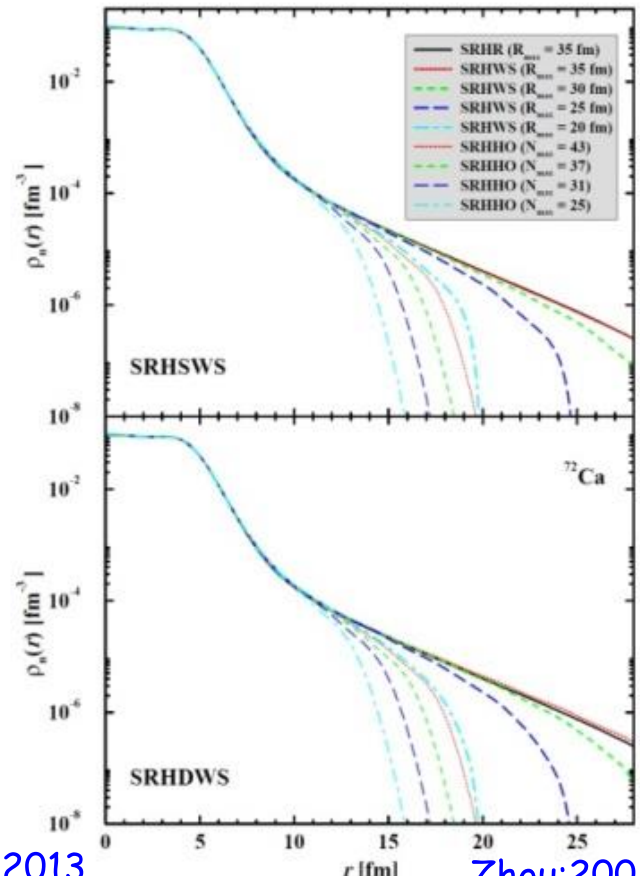
Goal: To study spin-isospin excitations in exotic deformed nuclei

- correct asymptotic behavior
- to break all geometric symmetries
- exotic shapes / exotic excitation modes
- reasonable computational time

CDFT on 3D mesh:
ground states & excitations



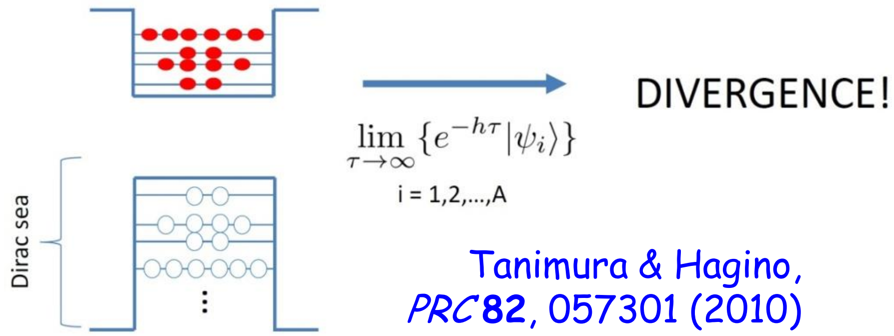
Lu:2013



Zhou:2003

CDFT on 3D mesh: ground states

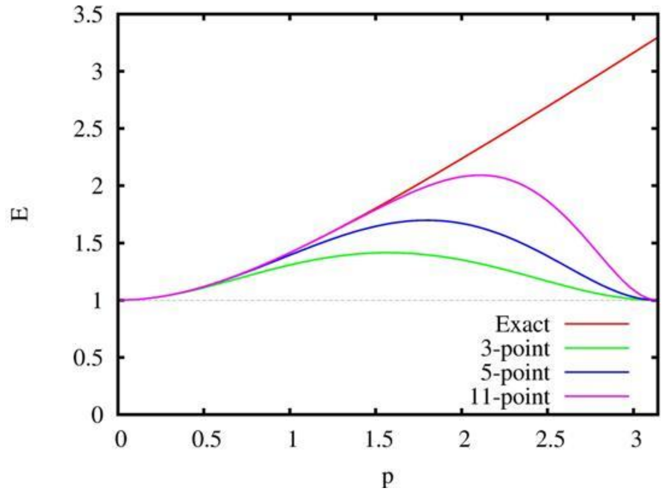
Challenge 1: Variational collapse



Tanimura & Hagino, *PRC* **82**, 057301 (2010)

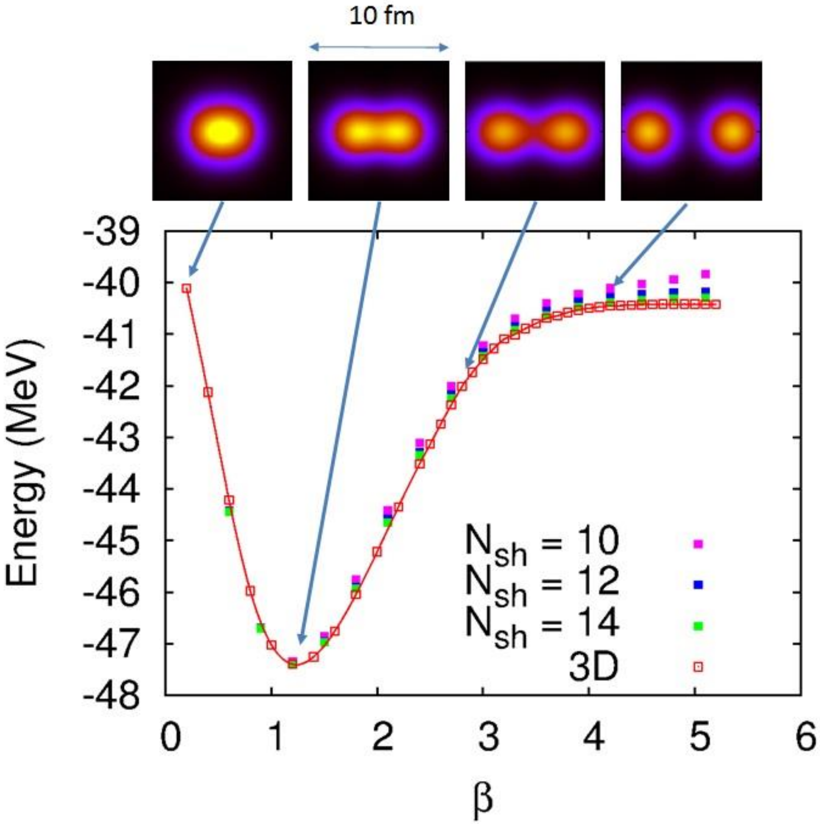
Solution: Inverse Hamiltonian method

Challenge 2: Fermion doubling



Solution: High-order Wilson terms

Preliminary results: ^{8}Be



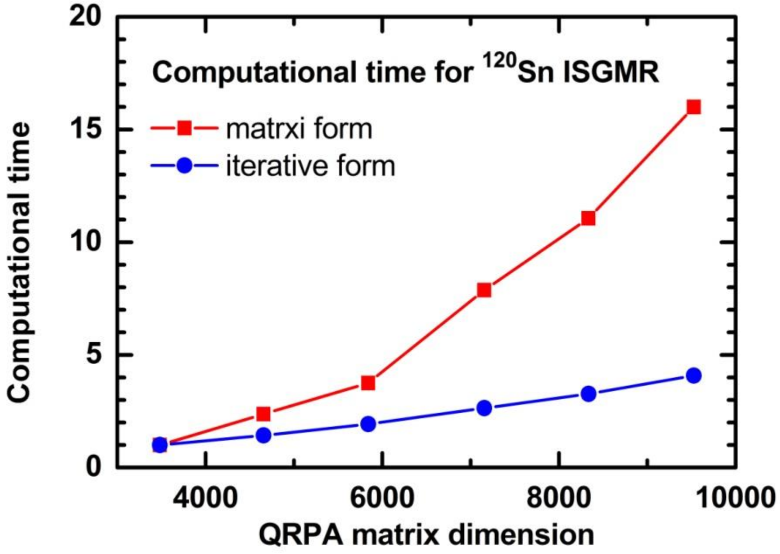
Tanimura, Hagino, **HZL**, in preparation

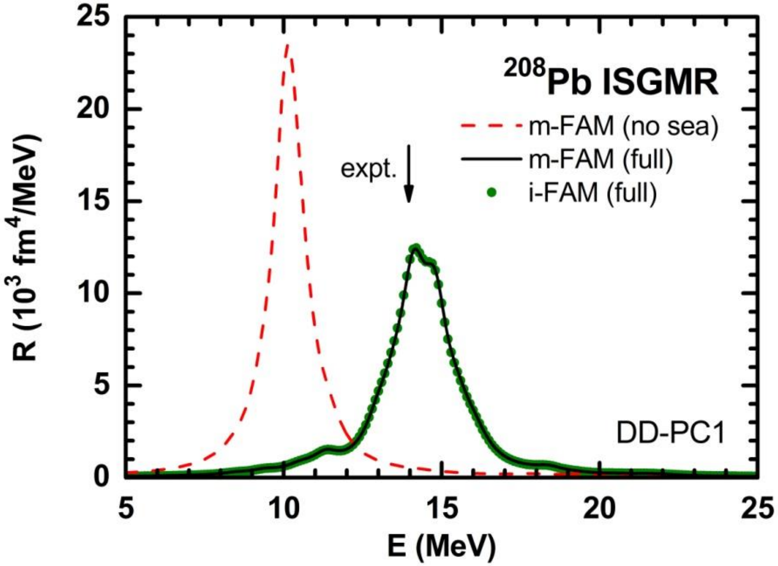
CDFT on 3D mesh: excitations

Computational challenge for the excitations in deformed systems

A promising solution:

Finite amplitude method   Nakatsukasa, Inakura, Yabana, *PRC* **76**, 024318 (2007)





(Left: data from Avogadro:2013)   **HZL**, Nakatsukasa, Niu, Meng, *PRC* **87**, 054310 (2013)

- The combination CDFT + FAM works well for the spherical and also the axially deformed systems. Niksic *et al.*, *PRC* **88**, 044327 (2013)
- To develop CDFT + FAM for the 3D deformed systems.

Summary and Perspectives

✓ **Self-consistent and covariant descriptions of nuclear spin-isospin excitations for spherical cases.**
spin-isospin resonances, *r*-process, CKM unitarity, ….

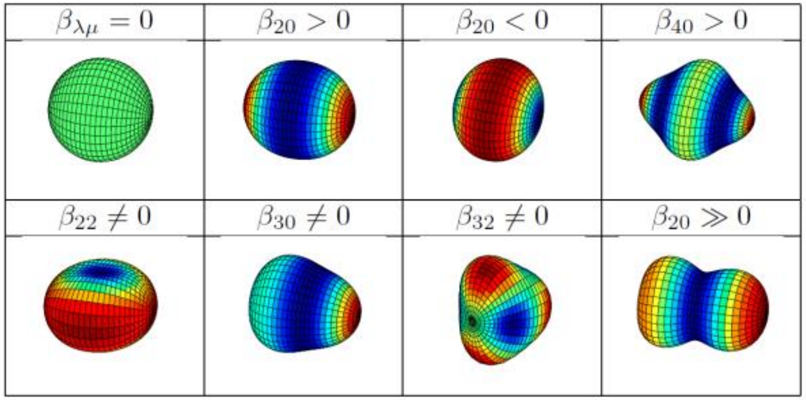
Towards deformed cases: CDFT on 3D mesh

- **Ground states: Solving Dirac equations on 3D mesh**
  inverse Hamiltonian method, high-order Wilson terms
- **Excitations: Finite amplitude method for relativistic RPA**
  In mesh representation, the effects of Dirac sea can be included implicitly and automatically.

Exotic shapes

Exotic excitation modes

……



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Thank you!