Tensor effects on the isospin excitation with random phase approximation based on relativistic Hartree-Fock approach

Zhiheng Wang (王之恒)

Lanzhou University 1909 兰州大学

筑波大学 University of Tsukuba

Supervisors: W. H. Long, T. Nakatsukasa

Collaborators: H. Z. Liang, Z. M. Niu

Outline

Outline

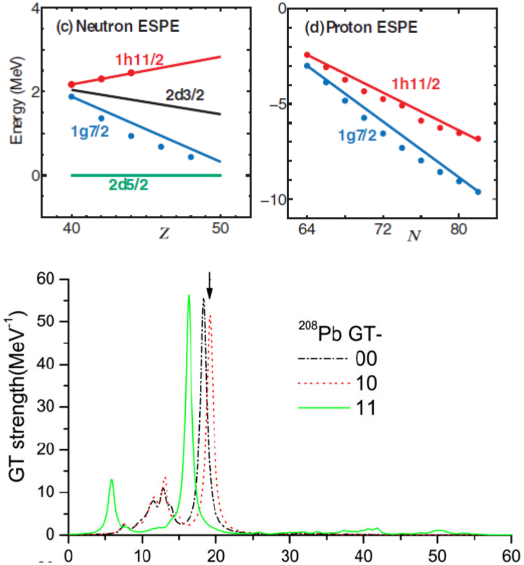
Effects of tensor force and its uncertainty

- Tensor force is an important noncentral ingredient of nuclear force.

Nonrelativistic form:

$$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{q})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{q}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 q^2$$

- ☞ variational procedure
- ☞ perturbative method



Otsuka (2005), Bai (2009)

- It is still difficult to reliably constrain the magnitude and sign of the tensor force. Further exploration of tensor effects and more efficient constrain are necessary.
- The spin-isospin excitations are better candidates than the ground-state quantities to constrain the tensor force.

Bai (2010)

Relativistic representation of tensor force

- Relativistic representation of the nuclear tensor interaction based on Relativistic Hatree-Fock (RHF) approach
  - Unified and self-consistent treatment of both tensor and spin-orbit interactions
  - New origin associated with the Fock diagrams of Lorentz scalar (σ and δ) and vector (ω and ρ) couplings

  Long (2006), Jiang (2015)
- Random phase approximation (RPA) based on the RHF and the quasiparticle random phase approximation (QRPA) based on the relativistic Hatree-Fock Bogoliubov (RHFB) approach
  - The π-meson is included in both the ground-state description and the particle-hole residual interaction.
  - The zero-range pionic counter-term with $g' = \frac{1}{3}$ is maintained self-consistently.

  Liang (2008), Niu (2013)

Goal

- **To investigate the effects of the tensor force on the nuclear isospin excitation in covariant framework**

Outline

Relativistic Hartree-Fock equation

- Solving the RHF equation : $\int dr' h(r,r')\psi(r') = \varepsilon_a \psi(r)$
  - h concludes the kinetic energy, local and nonlocal self energies,

$$h^k = \begin{pmatrix} 0 & -\frac{d}{dr} + \frac{\kappa_a}{r} \\ \frac{d}{dr} + \frac{\kappa_a}{r} & 0 \end{pmatrix} \delta(r,r'),$$

$$h^D = \begin{pmatrix} \Sigma_0(r) + \Sigma_S(r) & \Sigma_T \\ \Sigma_T & \Sigma_0(r) - \Sigma_S(r) - 2M \end{pmatrix} \delta(r,r'),$$

$$h^E = \begin{pmatrix} Y_{G_a}(r,r') & Y_{F_a}(r,r') \\ X_{G_a}(r,r') & X_{G_a}(r,r') \end{pmatrix}$$

  - Expanding the single-particle wave function on the Dirac Woods-Saxon Basis as

$$\psi(r) = \sum_p a_p g_p(r) + \sum_d a_d g_d(r),$$

  then the RHF equation was transformed to a problem of diagonalization.

- Inputs for the RPA equation : single-particle energy ε_a and wave function $\psi_a(r)$

Long (2006, 2009), Liang (2010)

RPA equation

- Based on the static RHF equation

$$H_0[f]f_a(1) = Tf_a(1) + \sum_b \langle b(2)|V(1,2)|b(2)\rangle f_a(1) - \sum_b \langle b(2)|V(1,2)|a(2)\rangle f_b(1),$$

one can derive the RPA equation using the linear response method. The RPA equation for the charge-exchange excitation reads

$$\begin{pmatrix} \mathcal{A}^J_{p\bar{n}p'\bar{n}'} & \mathcal{B}^J_{p\bar{n}n'\bar{p}'} \\ -\mathcal{B}^J_{n\bar{p}p'\bar{n}'} & -\mathcal{A}^J_{n\bar{p}n'\bar{p}'} \end{pmatrix} \begin{pmatrix} U^J_{p'\bar{n}'} \\ V^J_{n'\bar{p}'} \end{pmatrix} = \omega \begin{pmatrix} U^J_{p\bar{n}} \\ V^J_{n\bar{p}} \end{pmatrix}$$

with

$$\mathcal{A}^J_{Aa,Bb} = (E_A - E_a)\delta_{Aa,Bb} + \sum_{i=1}^{14} H^J_i(AaBb),$$

$$\mathcal{B}^J_{Aa,Bb} = (-1)^{j_B+j_b} \sum_{i=1}^{14} H^J_i(AabB).$$

- The two-body interaction contains those from all the coupling channels: $\phi = \sigma^{\mathrm{S}}, \omega^{\mathrm{V}}, \rho^{\mathrm{V}}, \rho^{\mathrm{VT}}, \rho^{\mathrm{T}}, \pi^{\mathrm{PV}}$ and A^{V}

  Ring (1980), Liang (2010)

Excited states and transition probabilities

- The excited states are constructed as

$$|\nu\rangle = Q_\nu^\dagger |RPA\rangle,$$

with $Q_\nu^\dagger = \sum_{pm_phm_h} X_{ph}^\nu c_p^\dagger c_h + \sum_{pm_phm_h} Y_{ph}^\nu c_h^\dagger c_p$ and $Q_\nu |RPA\rangle = 0$.

- The transition probability caused by the single-particle operator $\hat{F}_{JM}$ is

$$\begin{aligned} B_\nu =& |\langle \nu_{JM} | \hat{F}_{JM} | RPA\rangle|^2 \\ =& \hat{J}^2 \sum_{ph} \left\{ X_{ph}^{J\nu} \langle p || F_J || h\rangle + (-1)^{j_p+j_h} Y_{ph}^{J\nu} \langle h || F_J || p\rangle \right\} \end{aligned}$$

- The T_- $(n \to p)$ and T_+ $(p \to n)$ channels are calculated simultaneously, and they will be separated naturally with the following principle:

$$\begin{cases} \sum_{p\bar{n}} (U_{p\bar{n}}^J)^2 - \sum_{n\bar{p}} (V_{n\bar{p}})^2 = +1, & \text{for } T_- \text{ channel;} \\ \sum_{p\bar{n}} (U_{p\bar{n}}^J)^2 - \sum_{n\bar{p}} (V_{n\bar{p}})^2 = -1, & \text{for } T_+ \text{ channel.} \end{cases}$$

The excited energies and X, Y amplitudes are determined as

$$\begin{cases} \Omega = +\omega, \quad X_{p\bar{n}}^J = U_{p\bar{n}}^J, \quad Y_{n\bar{p}}^J = V_{n\bar{p}}^J, & \text{for } T_- \text{ channel;} \\ \Omega = -\omega, \quad X_{n\bar{p}}^J = V_{n\bar{p}}^J, \quad Y_{p\bar{n}}^J = U_{p\bar{n}}^J, & \text{for } T_+ \text{ channel.} \end{cases}$$

Two-body interaction caused by ρ-tensor

- The RHF+RPA published bofore, using the parameter sets PKOi (i=1,2,3), didn't consider the contributions from the ρ-tensor couplings.
- ρ-tensor couplings is included in the effective parameter set PKA1.
  - The two-body interactions of ρ-tensor couplings and the zero-range counter-term read

$$V^{\rho-T}(1,2) = \frac{1}{4M^2}[f_\rho\gamma_0\sigma_{\nu k}\vec{\tau}\partial^k]_1 \cdot [f_\rho\gamma_0\sigma^{\nu l}\vec{\tau}\partial]_2 v(m_\rho;\boldsymbol{r}_1,\boldsymbol{r}_2),$$

and

$$V^{\rho-T\delta}(1,2) = \frac{1}{12M^2}[f_\rho\gamma_0\sigma_{\mu\nu}\vec{\tau}]_1 \cdot [f_\rho\gamma_0\sigma^{\mu\nu}\vec{\tau}]_2\delta(\boldsymbol{r}_1-\boldsymbol{r}_2).$$

  - The inclusion of ρ-tensor couplings at the same time gives rise to the ρ-vector-tensor and ρ-tensor-vector couplings:

$$V^{\rho-VT}(1,2) = -[g_\rho(1)\gamma_0\gamma_\nu\vec{\tau}]_1 \cdot [\frac{f_\rho(2)}{2M}\gamma_0\sigma^{\nu l}\partial_l\vec{\tau}]_2 v(m_\rho;\boldsymbol{r}_1,\boldsymbol{r}_2),$$

$$V^{\rho-TV}(1,2) = -[\frac{f_\rho}{2M}\gamma_0\sigma^{\nu l}\vec{\tau}\partial_l]_1 \cdot [g_\rho\gamma_0\gamma_\nu\vec{\tau}]_2 v(m_\rho;\boldsymbol{r}_1,\boldsymbol{r}_2).$$

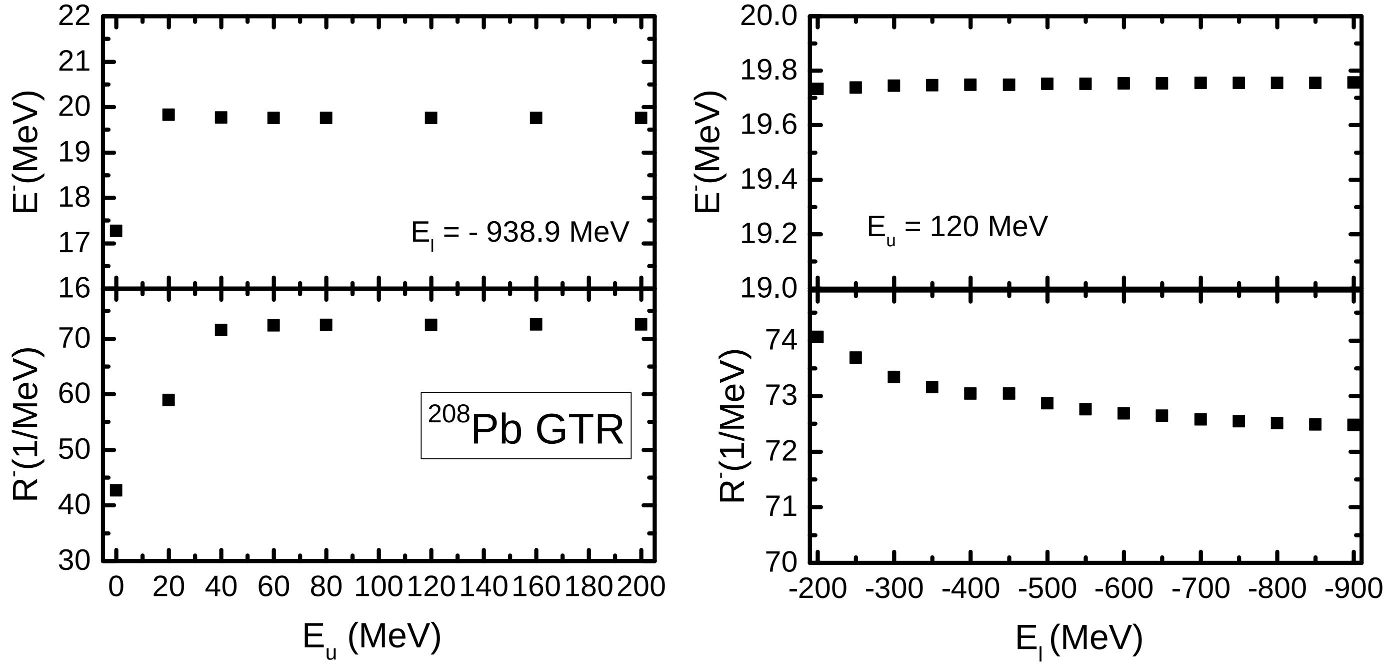
Outline

Self-consistency and convergence test

- Checking the isobaric analog states (IAS) without the coulomb interaction

	^{48}Ca	^{90}Zr	^{132}Sn	^{208}Pb
E_{IAS}(keV)	4.25	4.36	-36.9	-32.9

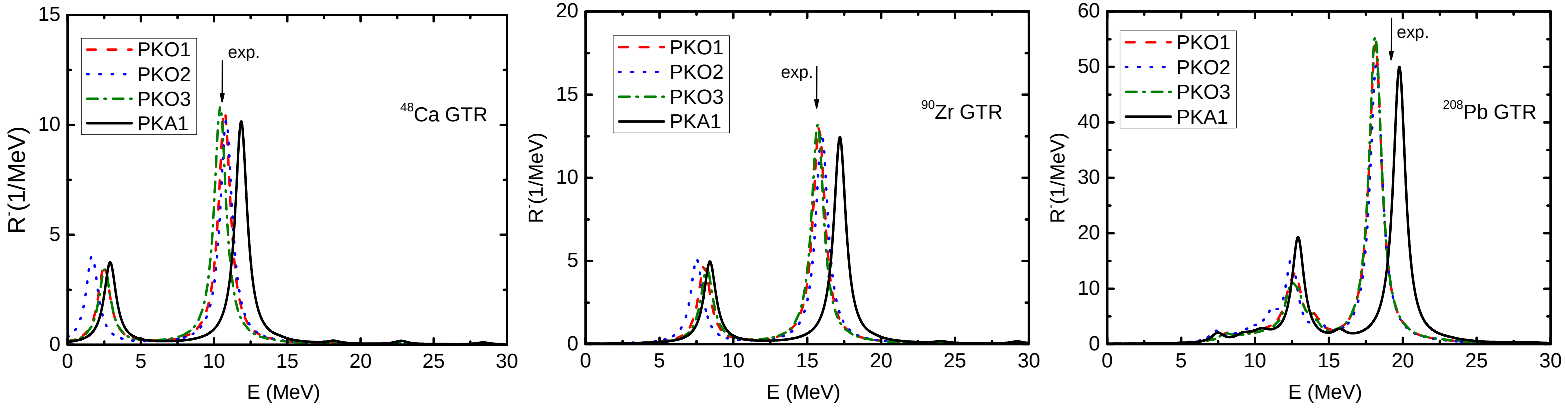
- Convergence test



☞ The single-particle energy truncation is chosen as $[-M\ ,\ M+120$ MeV].

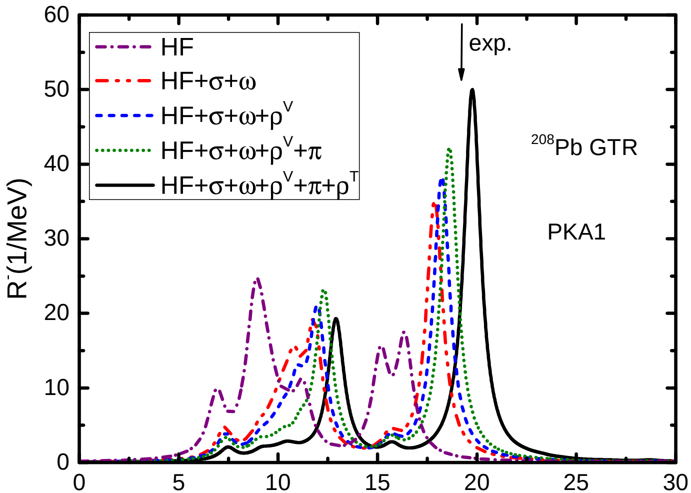
Some results of RPA using PKA1

The Gamow-Teller resonance (GTR) by RHF+RPA



☞ The PKA1 remarkably pulls upwards the position of the dominate peak.

Contributions from different channels



☞ The isoscalar σ- and ω-mesons play a very important role in determining the GTR strength distribution.

☞ The ρ-T coupling pulls upwards the GTR energy most remarkably.

☞ What is the role of the tensor force?

Outline

Plans

- To derive the contributions of the covariant tensor force to the RPA matrix elements.
- To develop the RPA codes which can exclude the contributions of the tensor force.
- To clarify the effects of tensor force on the isospin excitation through the calculations with and without the tensor force.

Plans

- To derive the contributions of the covariant tensor force to the RPA matrix elements.
- To develop the RPA codes which can exclude the contributions of the tensor force.
- To clarify the effects of tensor force on the isospin excitation through the calculations with and without the tensor force.

Thank you for your attention!