First Tsukuba-CCS-RIKEN joint workshop on microscopic theories of nuclear structure and dynamics

Microscopic description of nuclear β-decay half-lives

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Outline

1. Introduction
2. Theoretical framework
3. Results and discussion
4. Summary and perspectives

Introduction

- The nuclear β-decay plays an important role not only in the nuclear physics, but also in other branches of science, such as astrophysics.
- Since majority of neutron-rich nuclei relevant to the r-process are still out of the reach of experimental capabilities, theoretical predictions have to be used.
- Theoretical models:
  - ★ Phenomenological formula; Zhang2006PRC, Zhang2007JPG
  - ★ Gross theory; Takahashi1973ADNDT, Takahashi1990PTP, Nakata1997NPA

    the reliability of the extrapolation is questionable
  - ★ The shell model; Pinedo1999PRL, Caurier2002PRC, Langanke2003RMP

    large configuration spaces ➔ mainly for nuclei with A<60 or near magic nums
  - ★ The proton-neutron quasiparticle random phase approximation (PN-QRPA);

    can treat arbitrarily heavy systems; Möller1997ADNDT, Sarriguren2011PRC

Introduction

- Self-consistent QRPA (the residual interactions in the QRPA calculations are self-consistently derived with the effective interactions used in the g.s. calculations):

  ⋆ Traditional (non-relativistic) density functional:

  DF (Fayans)+CQRPA: Borzov1996ZPA, Borzov2003,2005PRC, Borzov2008NPA

  ETFSI (Skyrme)+CQRPA: Borzov1997NPA, Borzov2000PRC

  SHF BCS+QRPA: Minato2009PRC, Sarriguren2010PRC

  SHFB+QRPA: Engel1999PRC

  ⋆ Covariant (relativistic) density functional:

  RHB+QRPA: Paar2004PRC, Nikšić2005PRC, Marketin2007PRC

  In present RHB+QRPA model, π meson field is absent in the g.s. description and the strength parameter of counter-term of π meson field (g') in QRPA calculation is treated as an adjustable parameter.

Introduction

- The fully consistent RHF+RPA model has achieved great success in the description of both nuclear ground state and charge-exchange excitations. Liang2008PRL
  - ⋆ π is included in both the g.s. description and the p-h residual interaction;
  - ⋆ the exact zero-range counter-term with g'=1/3 is maintained.
- The RHF model has been extended to the RHFB, which gives a unified and self-consistent description of both mean field and pairing correlations.

  Long2010PRC, Long2010PRC(R)
- Based on the RHFB approach, we have developed the fully consistent QRPA (RHFB+QRPA) model recently. Niu2013PLB

Present talk:

- employ the RHFB+QRPA model to calculate the nuclear β-decay rates and investigate the influence of Fock terms and pairing correlations.

Outline

1. Introduction
2. Theoretical framework
   - ⋆ Relativistic Hartree-Fock-Bogoliubov theory
   - ⋆ Quasiparticle random phase approximation
   - ⋆ Nuclear β-decay half-lives
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Relativistic Hartree-Fock-Bogoliubov theory

- Effective Lagrangian density:

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

- RHFB equation: Kucharek1991ZPA, Long2010PRC

$$\int dr'\begin{pmatrix} h(\mathbf{r},\mathbf{r}')-\lambda & \Delta(\mathbf{r},\mathbf{r}') \\ \Delta(\mathbf{r},\mathbf{r}') & -h(\mathbf{r},\mathbf{r}')+\lambda \end{pmatrix}\begin{pmatrix}\psi_U(\mathbf{r}') \\ \psi_V(\mathbf{r}')\end{pmatrix} = E\begin{pmatrix}\psi_U(\mathbf{r}) \\ \psi_V(\mathbf{r})\end{pmatrix},$$

where $h(\mathbf{r},\mathbf{r}')$ and $\Delta_\alpha(\mathbf{r},\mathbf{r}')$ are the mean field and paring potential

$$h(\mathbf{r},\mathbf{r}') = h^{\rm kin}(\mathbf{r},\mathbf{r}') + h^{\rm D}(\mathbf{r},\mathbf{r}') + h^{\rm E}(\mathbf{r},\mathbf{r}'), \qquad \Delta_\alpha(\mathbf{r},\mathbf{r}') = -\frac{1}{2}\sum_\beta V_{\alpha\beta}^{pp}(\mathbf{r},\mathbf{r}')\kappa_\beta(\mathbf{r},\mathbf{r}').$$

★ $h^{\rm kin}$, $h^{\rm D}$, and $h^{\rm E}$: PKO1. Long2006PLB

★ V^{pp}: Gogny pairing force with D1S parameter set. Berger1991CPC

Quasiparticle random phase approximation

- QRPA equations: Ring1995Springer

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

where ω_{ν} is the excitation energy, X_{ν} and Y_{ν} denote the 2qp amplitudes. The QRPA matrices A and B read:

$$A_{kk'll'} = (E_k + E_{k'})\delta_{kl}\delta_{k'l'} + \frac{\delta^2 E}{\delta R^*_{kk'}\delta R_{ll'}}, \qquad B_{kk'll'} = \frac{\delta^2 E}{\delta R^*_{kk'}\delta R^*_{ll'}}.$$

- In the canonical basis, the matrices A and B for the charge-exchange channel read:

$$\begin{aligned} A_{pnp'n'} &= H^{11}_{pp'}\delta_{nn'} + H^{11}_{nn'}\delta_{pp'} \\ &\quad + V^{ph}_{pnp'n'}(u_p v_n u_{p'} v_{n'} + v_p u_n v_{p'} u_{n'}) \\ &\quad + V^{pp}_{pnp'n'}(u_p u_n u_{p'} u_{n'} + v_p v_n v_{p'} v_{n'}), \\ B_{pnp'n'} &= V^{ph}_{pnp'n'}(u_p v_n v_{p'} u_{n'} + v_p u_n u_{p'} v_{n'}) \\ &\quad - V^{pp}_{pnp'n'}(u_p u_n v_{p'} v_{n'} + v_p v_n u_{p'} u_{n'}). \end{aligned}$$

RPA QRPA

$E \rightarrow H^{11}$

$u,v = 0,1 \rightarrow u,v = [0,1]$

$V^{pp} = 0 \rightarrow V^{pp} \neq 0$

where $H^{11}_{kl} = (u_k u_l - v_k v_l)h_{kl} - (u_k v_l - v_k u_l)\Delta_{kl}$. Paar2003, 2004PRC

Nuclear β-decay half-lives

- The nuclear β-decay half-life in the allowed Gamow-Teller approximation reads as follows:

$$T_{1/2} = \frac{\ln 2}{\lambda_\beta} = \frac{D}{g_A^2 \sum_m \left| \sum_{pn} \langle 1_m^+ | \sigma\tau | 0^+ \rangle \right|^2 f(Z,A,E_m)},$$

where $D = \frac{\hbar^7 2\pi^3 \ln 2}{g^2 m_e^5 c^4} = 6163.4$ s, $g_A = 1$. The transition probability $\langle 1_m^+ | \sigma\tau | 0^+ \rangle$ can be directly taken from the QRPA calculations.

★ The integrated $(e, \bar{\nu}_e)$ phase volume $f(Z,A,E_m)$:

$$f(Z,A,E_m) = \frac{1}{m_e^5} \int_{m_e}^{E_m} p_e E_e (E_m - E_e)^2 F(Z,A,E_m) dE_e,$$

★ The maximum value of β-decay energy E_m:

$$E_m = E_i - E_f = (m_n - m_p) - E_{\mathrm{QRPA}} = \Delta_{np} - E_{\mathrm{QRPA}}.$$

Due to $E_m > m_e$, the sum on m runs over all final states with E_{QRPA} smaller than $\Delta_{nH} = \Delta_{np} - m_e = 0.782$ MeV.

Outline

β-decay rates in QRPA calculations

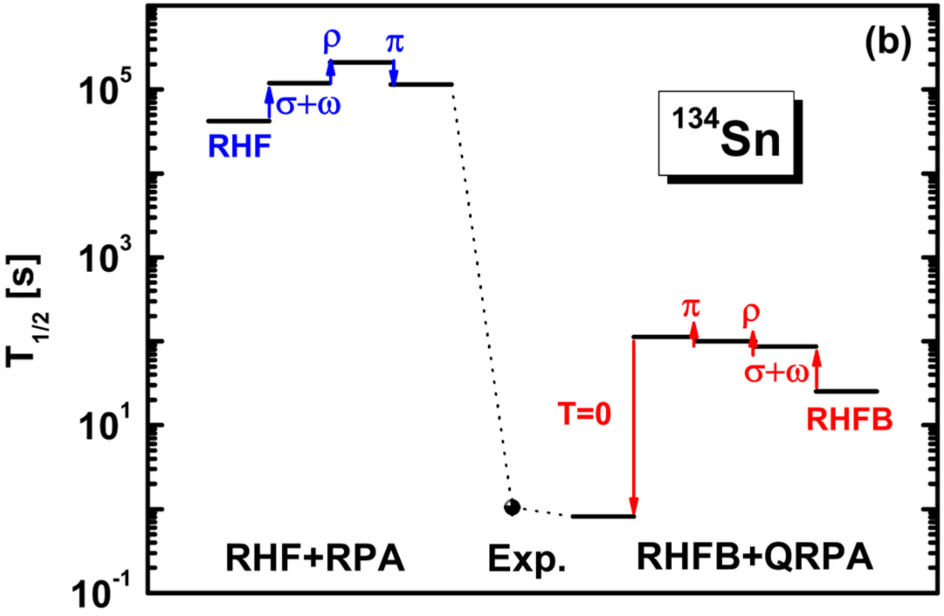

Figure: β-decay half-lives of ^{134}Sn. The results based on the (Q)RPA calculations without any residual interactions and the calculations gradually including the residual interactions of σ and ω fields, ρ field, π field, and $T = 0$ pairing are presented.

- **ph residual interactions**: increase the calculated β-decay half-lives. RHF(B)+(Q)RPA: σ- and ω-mesons play an important role via exchange terms.

- **pp interactions**: T=1: are necessary to reproduce data. T=0: can reduce the calculated β-decay half-lives significantly.

The influence of T=0 pairing

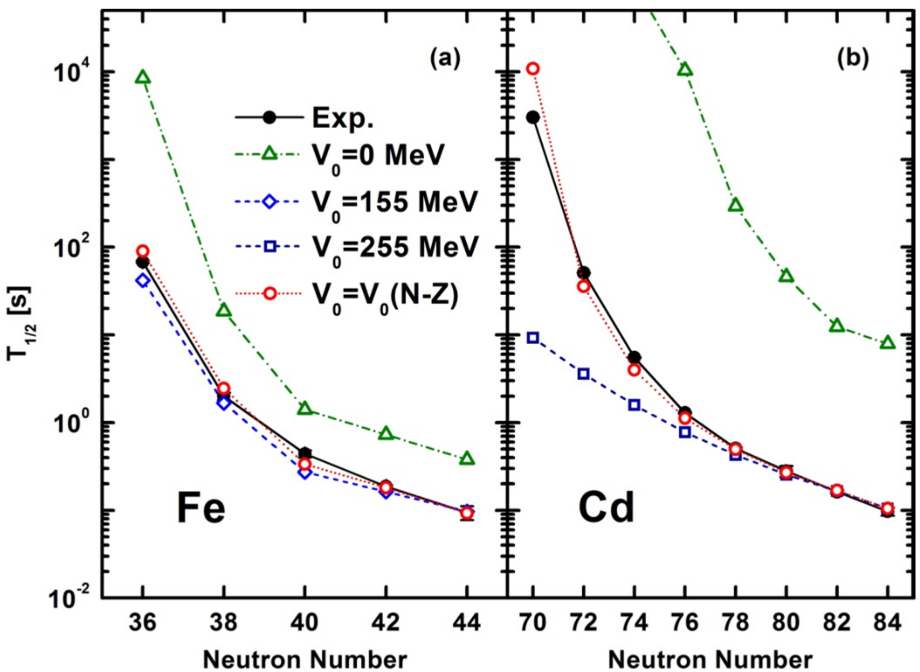

Figure: β-decay half-lives for Fe and Cd isotopes calculated in RHFB+QRPA model with the PKO1 parameter set.

Z. M. Niu, Y. F. Niu, H. Z. Liang, W. H. Long, T. Niksic, D. Vretenar, and J. Meng, PLB 723, 172 (2013).

- The V_0 fitted to the β-decay half-lives of ^{70}Fe and ^{130}Cd are significantly different. With the V_0 fitted to the β-decay half-lives of ^{130}Cd, the calculated results underestimated the β-decay half-lives of ^{118,120,122}Cd. ➔ This may point out a possible isospin-dependence of V_0.

- By fitting to the experimental half-lives of Ca-Sn nuclei, an isospin-dependent function similar to the Woods-Saxon potential is proposed:

$$V_0 = V_1 + \frac{V_2}{1+e^{a+b(N-Z)}},$$

V_1=134 MeV, V_2=121 MeV, a=8.5, b=-0.4.

β-decay rates of Ca-Sn isotopes

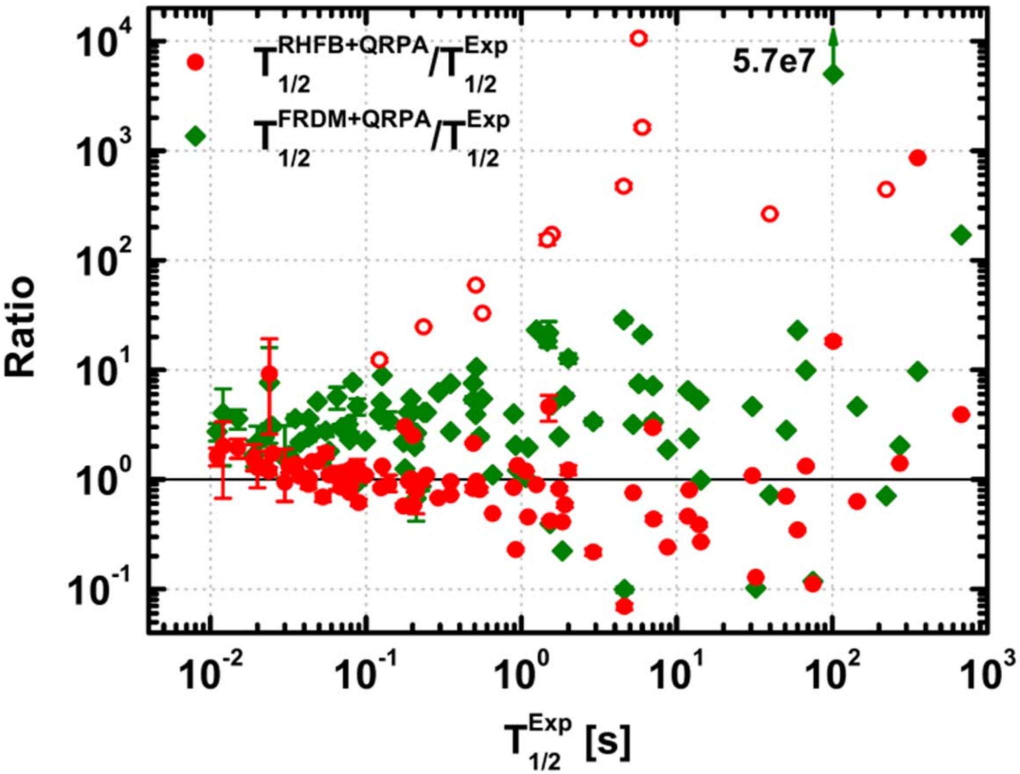

Figure: The ratios of theoretical half-lives to the experimental values as a function of the experimental half-lives for Ca-Sn isotopes. The circles and diamonds represent the results calculated by the RHFB+QRPA and FRDM+QRPA approaches, respectively.

- RHFB+QRPA: well reproduces the experimental half-lives of these neutron-rich nuclei except for some magic nuclei, such as the Ni isotopes.
- FRDM+QRPA: generally overestimates the nuclear half-lives, which can be attributed partially to the neglect of the isoscalar pn pairing.

Influence of Q_β values

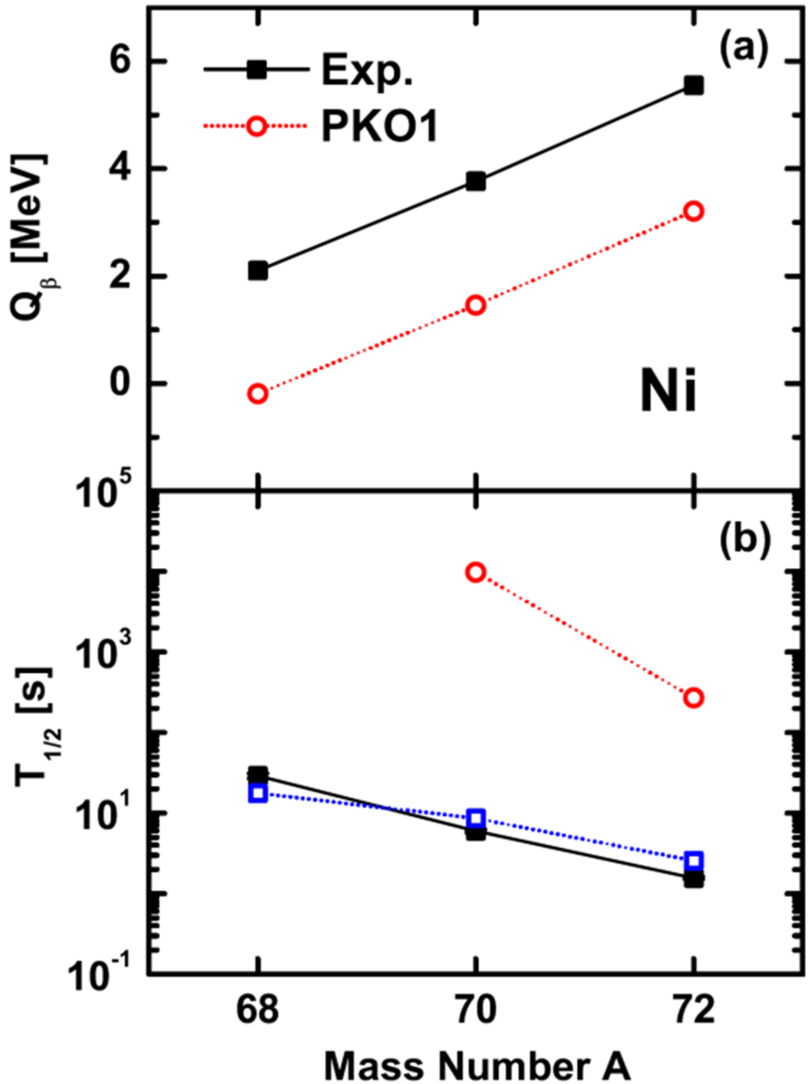

Figure: Q_β values and its influence on β-decay half-lives of Ni isotopes.

- The experimental Q_β values are systematically underestimated by the RHFB theory.
- The new results are in excellent agreement with the experimental data, which reflects the importance of accurate nuclear mass predictions in half-life calculations.
- This modification of Q_β is not self-consistent in the predictions of nuclear β-decay half-lives.

 Results and discussion

PVC effect on β-decay half-life

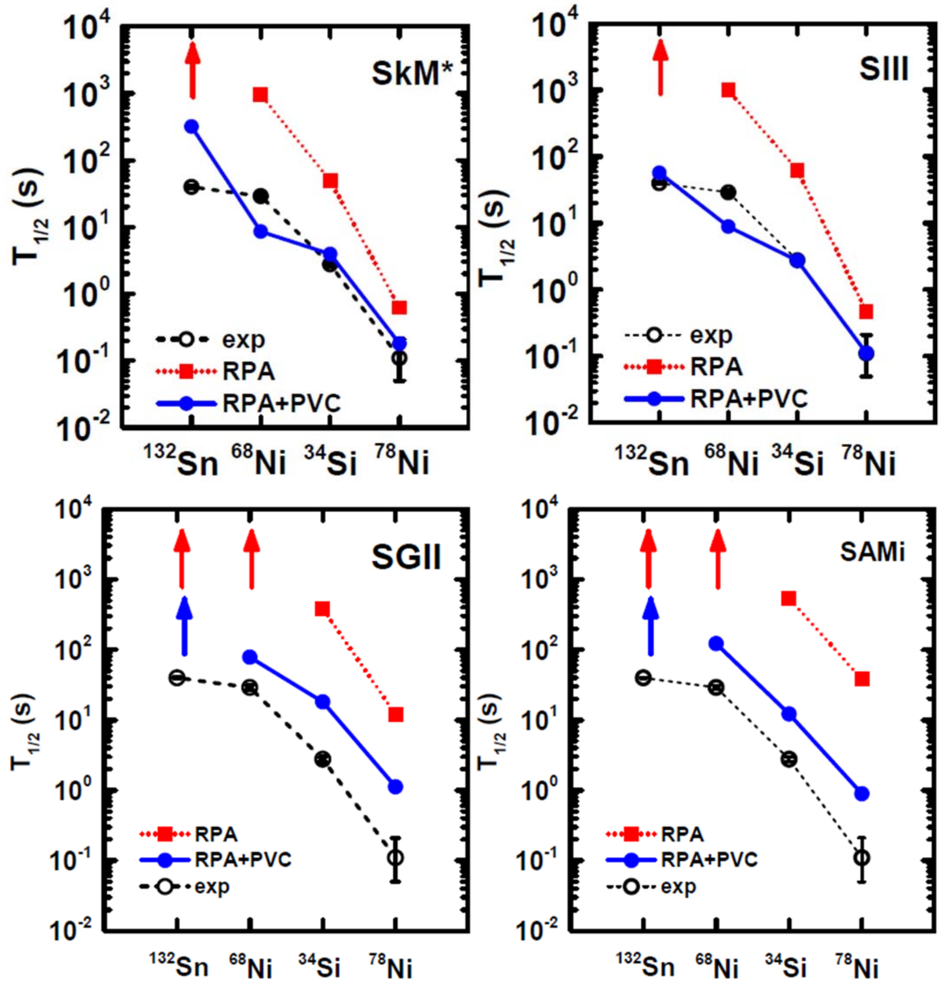

Figure: The β-decay half-lives of 132Sn, 68Ni,34Si, and 78Ni, calculated by RPA and RPA+PVC approaches, respectively, in comparison with experimental values.

- The effect of the PVC decreases the half-lives by large factors compared to RPA, substantially improving the agreement with experimental data.

Y. F. Niu, **Z. M. Niu**, G. Colò, and E. Vigezzi, PRL 114, 142501 (2015)

Outline

Summary and perspectives

- **Summary**:
  - ★ The nuclear β-decay half-lives are sensitive to the pp residual interactions and that in the T=0 channel can significantly reduce the β-decay half-lives.
  - ★ The self-consistent RHFB+QRPA calculations well reproduce the experimental half-lives of Ca-Sn isotopes with an isospin-dependent T=0 pairing except for some magic nuclei.
  - ★ The effect of the PVC decreases the half-lives by large factors compared to RPA, substantially improving the agreement with experimental data for magic nuclei.
- **Perspectives**:
  - ★ QRPA → QRPA+QPVC
  - ★ Deformation degree
  - ★ Other applications: 2β decay and neutrino-nucleus scattering

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Thank you!