Energy-density functional plus multi-phonon theory as a powerful tool for nuclear structure and astrophysics

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The Theoretical Model

The Nuclear Energy-Density Functional: a Functional of Neutron and Proton Densities

\[ \mathcal{E}(\rho_n, \rho_p) = \sum_q \tau_q (\rho_q) + \mathcal{E}_{\text{int}}(\rho_n, \rho_p) \]

\[ \tau_q, \rho_q \quad - \text{kinetic and number densities; } q \text{ denotes neutrons or protons} \]

\[ \mathcal{E}_{\text{int}}(\rho_n, \rho_p) = \mathcal{E}_{\text{int}}(\rho_n^{(0)}, \rho_p^{(0)}) + \sum_q U_q \delta\rho_q + \frac{1}{2} \sum_{q_1,q_2} f_{q_1,q_2} \delta\rho_{q_1} \delta\rho_{q_2} \]

\[ U_q = \frac{\delta\mathcal{E}_{\text{int}}}{\delta\rho_q} \quad \text{MF interaction} \]

\[ f_{q_1,q_2} = \frac{\delta^2 \mathcal{E}_{\text{int}}}{\delta\rho_{q_1} \delta\rho_{q_2}} \quad \text{residual interaction} \& \text{nuclear excitations} \]

**Phenomenological EDF approach** based on a fully microscopic self-consistent Skyrme HFB theory


**Quasiparticle-Phonon Model**

(N. G. Soloviev: *Theory of Atomic Nuclei: Quasiparticles and Phonons* (Bristol, 1992).)

- Multipole- and spin- multipole interactions in p-h and p-p channels;
- Model basis built of phonons solved by QRPA equations.
- Wave functions of the excited states built of up to three-phonon configurations.
Theory of Nuclear Excitations

QPM phonons: commute as fermions and thus obey the Pauli principle. Structure properties: obtained by solving of QRPA equations.

\[ Q^+_{\lambda \mu i} = \frac{1}{2} \sum \sum \left\{ \psi^{\lambda i}_{jj'} [\alpha^+_j \alpha^+_j] \lambda_\mu - (-1)^{\lambda-\mu} \varphi^{\lambda i}_{jj'} [\alpha_j \alpha_j] \lambda-\mu \right\} , \]

\( i \) — labels the number of the QRPA state

QPM wave functions are a mixture of one-, two- and three-phonon components: anharmonicities included.

\[ \psi_\nu(JM) = \left\{ \sum_i R_i(J\nu) Q^+_{JM_i} \right\} + \sum_{\lambda_1 i_1, \lambda_2 i_2} P^{\lambda i_1}_{\lambda_1 i_1}(J\nu) \left[ Q^+_{\lambda_1 i_1} \otimes Q^+_{\lambda_2 i_2} \right] \]

\[ + \sum_{\lambda_1 i_1, \lambda_2 i_2, \lambda_3 i_3} T^{\lambda i_1 \lambda_2 i_2 \lambda_3 i_3}_{\lambda_1 i_1 \lambda_2 i_2}(J\nu) \left[ Q^+_{\lambda_1 i_1} \otimes Q^+_{\lambda_2 i_2} \otimes Q^+_{\lambda_3 i_3} \right] \]

\[ \psi_0 \]

\( \nu \) — labels the number of the QPM excited state

Exploratory investigations of new modes of nuclear excitations in stable and exotic nuclei within the EDF+QPM approach

\[ \delta r = \sqrt{<r^2>_n} - \sqrt{<r^2>_p} \]

\[ \delta r_{\text{EDF}} = 0.15 \text{fm} \]

PDR is independent of the type of nucleon excess (neutron or proton) and closely connected with the thickness of the nuclear skin.

\[ \text{PDR} \leq 1\% \text{ of the TRK sum rule } (S_{\text{TRK}} \sim N/Z/A) \]

\[ \Rightarrow \text{Generic mode of excitation} \]

Transition densities

\[ \delta \rho^T(\vec{r}) = \sum_{j_1j_2;\lambda \mu} [i^\lambda Y_{\lambda \mu}(\hat{r})]^\dagger \rho_{j_1j_2}^{\lambda T}(r)[a_{j_1}^+a_{j_2}]_{\lambda \mu} \]

Dipole polarizability

\[ \alpha_D = \frac{\sigma_{-2}}{2\pi^2 \alpha^2} \]

\[ \sigma_{-2} = \int \frac{\sigma(E)}{E^2} d(E) \]

and \( \alpha \) is the fine structure constant

\[ \text{ground state} \]

\[ \text{neutron skin} \]

\[ \text{nucleus } ^{206}_{\text{Pb}} \]

\[ \text{N/Z=1.51} \]

\[ \text{transition densities} \]

\[ \text{electric dipole response} \]

\[ \text{A. Tonchev et al., B. to be submitted} \]
Presently, this is the only existing method allowing for self consistent determination of nuclear ground state and unified description of low-energy single-particle, multi-phonon states and giant resonances in a large multi-particle-multi-hole configuration space.

Spectral structure of the pygmy dipole resonance

Fine structure of the giant M1 resonance in $^{90}$Zr

Polarized photon scattering off $^{52}$Cr: Determining the parity of J=1 states
Krishichayan, Megha Bhike, W. Tornow, G. Rusev, A. P. Tonchev, N. Tsoneva, and H. Lenske,
Exp: R. Schwengner et al., First systematic photon-scattering experiments in N=50 nuclei: using bremsstrahlung produced with electron beams at the linear accelerator ELBE, Rossendorf and quasi-monoenergetic $\gamma$-rays at HI\'S facility, Duke university.

A way to investigate $^{85}\text{Kr}$ branching point and the s-process:

$^{85}\text{Kr}$ (t \sim 10.57 Y) ground state is a branching point and thus a bridge for the production of $^{86}\text{Kr}$ at low neutron densities.

- At stellar temperature of kT = 30 keV we obtain MACS of $83^{(+23,-38)}$ mb which is about 50% higher than the value of Z.Y. Bao et al., At. Data Nucl. Data Tables 76, 70 (2000).

- The new MACS value explains the higher $^{86}\text{Kr}$:$^{82}\text{Kr}$ ratios measured in large star dust SiC grains.

- The experimental uncertainty is improved by a factor of \sim 3 to 50%.
**NEUTRON CAPTURE CROSS SECTIONS**

of the $^{85}\text{Kr}(n,\gamma)^{86}\text{Kr}$, $^{87}\text{Sr}(n,\gamma)^{88}\text{Sr}$, $^{89}\text{Zr}(n,\gamma)^{90}\text{Zr}$ and $^{91}\text{Mo}(n,\gamma)^{92}\text{Mo}$ reactions calculated with TALYS using EDF+QRPA, HFB+QRPA and EDF+three-phonon QPM.

$^{85}\text{Kr}(n,\gamma)^{86}\text{Kr}$ cross sections, the hashed area corresponds to the cross section determined with the experimental strength as derived in R. Raut et al., Phys. Rev. Lett. 111, 112501 (2013).

$^{87}\text{Sr}(n,\gamma)^{88}\text{Sr}$, TALYS cross sections are compared with experimental data G. Walter, Kernforschungszentrum Karlsruhe Reports No.3706 (1984); R.L. Macklin and J.H. Gibbons, Phys. Rev. 159, 1007 (1967).
Theoretical prediction of Pygmy Quadrupole Resonance

The pygmy quadrupole resonance and neutron skin modes: First experimental evidences of the existence PQR in $^{124}$Sn

$^{124}$Sn($\alpha, \alpha' \gamma$)

$\gamma$-decay branching ratios

EDF+QPM


N. Tsoneva, NS2016
Thank you!

H. Lenske

S. Goriely

R. Schwengner


A. Zilges, V. Derya, M. Spieker et al.

N. Pietralla, P. von Neumann-Cosel, A. Richter, D. Savran et al.

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