Microscopic description of pygmy and giant resonances within EDF plus QPM approach

Nadia Tsoneva

Extreme Light Infrastructure - Nuclear Physics (ELI-NP)
Agenda

- Pygmy modes: new low-energy modes of excitation in stable and exotic nuclei
- Microscopic theory of nuclear excitations
- Dipole and Quadrupole pygmy modes
- Pygmy modes, Dipole polarizability, Giant resonances,
- \((n,\gamma), (p,\gamma)\) cross sections and nuclear reaction rates of stellar nucleosynthesis.

Our Goals

- Microscopic approach to infinite matter and finite nuclei
- Ground states and nuclear excitations
- Astrophysical investigations
The Richness of Nuclear Spectra...

- Orbital “Scissors” mode: $E_x \sim 3$ MeV, $B(M1) \sim 3 \mu_N^2$
- Two Phonon Excitation: $E_x \sim 4$ MeV, $B(E1) \sim 10^{-3}$ W.u.
- Pygmy Quadrupole Resonance: $E_x \sim 2 - 5$ MeV, $B(E2) \sim 0.5$ W.u.
- Pygmy Dipole Resonance: $E_x \sim 6 - 9$ MeV, $B(E1) \sim 0.5$ W.u.
- Spin-flip M1 excitations: $E_x \sim 4 - 12$ MeV, $B(E2) \sim 6 \mu_N^2$
- Giant Dipole Resonance: $E_x \sim 10 - 20$ MeV, $B(E1) \sim 5 - 12$ W.u.

Moderate and Heavy nuclei:

Microscopic theory of nuclear excitations
The Model Hamiltonian

\[ H = H_{MF} + H_{res} \]

\[ H_{MF} = H_{sp} + H_{pair} \]

\[ H_{res} = H_{M}^{ph} + H_{SM}^{ph} + H_{M}^{pp} \]

Nuclear Ground State

Single-Particle States
Phenomenological density functional approach based on a fully microscopic self-consistent Skyrme Hartree-Fock-Bogoljubov (HFB) theory

Pairing and Quasiparticle States

\[ a_{jm} = u_{j} \alpha_{jm} + (-)^{j-m} v_{j} \alpha^{+}_{j-m} \]

Excited states

\[ H_{M}^{ph} \text{ - multipole interaction in the particle-hole channel;} \]
\[ H_{SM}^{ph} \text{ - spin-multipole interaction in the particle-hole channel;} \]
\[ H_{M}^{pp} \text{ - multipole interaction in the particle-particle channel} \]

\[ V(r - r') \approx \sum_{\lambda \mu} (-)^{\mu} R_{\tau}^{\lambda}(r, r') Y_{\lambda \mu}(\theta, \phi) Y_{\lambda \mu}(\theta', \phi') \]

\[ R_{\tau}^{\lambda}(r, r') = \kappa_{\tau}^{\lambda} R^{\lambda}(r) R^{\lambda}(r') \]

\[ \tau = 0 \text{ isoscalar interaction} \]
\[ \tau = 1 \text{ isovector interaction} \]
The QPM basis is built of phonons:

\[
Q_{\lambda \mu i}^+ = \frac{1}{2} \sum_{\tau} \sum_{jj'} \left\{ \psi_{jj'}^{\lambda i} [\alpha_j^+ \alpha_{j'}^+]_{\lambda \mu} - (-1)^{\lambda-\mu} \psi_{jj'}^{\lambda i} [\alpha_{j'}^+ \alpha_j^+]_{\lambda-i} \right\}
\]

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

The phonons are not 'pure' bosons:

\[
\left[ Q_{\lambda \mu i}, Q_{\lambda' \mu' i'}^+ \right] = \delta_{\lambda \lambda'} \delta_{\mu \mu'} \delta_{ii'} + \text{fermionic corrections} \sim \alpha_{j_1 m_1}^+ \alpha_{j_2 m_2}^+
\]

QRPA equations are solved:

\[
\left[ H, Q_{\lambda \mu i}^+ \right] = E_{\lambda \mu i} Q_{\lambda \mu i}^+
\]
Beyond QRPA: Including Anharmonicities. Expansions up to 6-QP Components

\[ \psi_{\nu}(JM) = \left\{ \sum_i R_i(J\nu)Q_{JM}^i + \sum_{\lambda_1 \lambda_2} P_{\lambda_1 \lambda_2} Q_{\lambda_1 \lambda_2}^i, J\nu \right\} \quad \text{with basis of QRPA phonons}\]

- "ph" and "pp"-type configurations
- Pauli principle, orthogonality
- Core polarization effects
- Large multi-particle-multi-hole configuration space
- SPECTRAL FRAGMENTATION
- SPECTRAL SHIFTS


\[ |\Psi\rangle = \sum_{abc} X_a + X_{ab} + X_{abc} \]

\[ B(E1) (\text{e}^2 \text{fm}^2) \]

\[ \begin{align*}
\mathbf{112}^{\text{Sn}} & \quad \text{QRPA(1ph)} \\
N/Z=1.24 & \quad \text{QPM(1ph+2ph)} \\
\text{QPM(1ph+2ph+3ph)} & \quad \text{QPM(1ph+2ph+3ph)}
\end{align*} \]

N.Tsoneva, Hirschegg18
Multi-phonon nuclear excitations
Two-phonon states

The Pygmy Dipole Resonance
Observation of Pygmy Dipole Resonance in stable nuclei with moderate neutron excess \((N > Z)\)

Neutron PDR strength increases with the N/Z ratio!

- PDR

  - Generic mode of excitation;
  - Below particle threshold;
  - Independent of the type of nucleon excess
  - Depending on the size of N/Z;
  - \(\approx 1\%\) of the Thomas-Reiche-Kuhn sum rule \((S_{TRK} \approx NZ/A)\)
Binding Energy, Skin Thickness and PDR


- **Binding Energy**
  \[ B_A(N, Z) = \int d^3 r E(\rho_0(r), \rho_1(r)) \]
  \[ = \int d^3 r (E_{\text{kin}}(r) + E_{\text{int}}(r)). \]

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

- **PDR Strength**
  \[ B(E\lambda) \approx \left[ \sum_{T=1}^{1} e_T^\lambda \int_0^\infty r^2 \rho^T_{\lambda i}(r) r^2 dr \right]^2 \]
Identifying the Skin Mode: Dipole Transition Densities in Sn Isotopes


Neutron PDR

Proton PDR

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

N.Tsoneva, Hirschegg18
Parity assignment of the PDR
Parity Measurements of Low-Energy Dipole Excitations in $^{138}\text{Ba}$

First experiment on parity assignment of PDR in $^{138}\text{Ba}$ at Hi$\gamma$S: $E_\gamma$=4-8.5 MeV


\[ \sigma_{\gamma\gamma}(M1)/\sigma_{\gamma\gamma}(E1) \sim 3\% \]

- verified for the first time that the PDR is predominantly E1 in nature.
- The fine structure of the M1 spin-flip mode is explained.
- Low-energy E1 strength fragmentation: Interplay between PDR, multi-phonon excitations and core polarization related to the GDR

**TABLE I.** $E1$ and $M1$ parameters deduced in $^{138}\text{Ba}$ below the neutron-separation energy in comparison with the QPM calculations.

<table>
<thead>
<tr>
<th></th>
<th>$\langle E_{E1} \rangle$ [MeV]</th>
<th>$\Sigma B(E1) \uparrow [e^2\text{fm}^2]$</th>
<th>$\langle E_{M1} \rangle$ [MeV]</th>
<th>$\Sigma B(M1) \uparrow [\mu_N^2]$</th>
<th>EWSR$_{E1}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>6.7</td>
<td>0.96(18)</td>
<td>6.9</td>
<td>2.5(6)</td>
<td>1.3</td>
</tr>
<tr>
<td>QPM</td>
<td>7.3</td>
<td>1.22</td>
<td>6.9$^a$</td>
<td>2.9$^a$</td>
<td>1.8</td>
</tr>
</tbody>
</table>

$^a$4.1 MeV $< E^* < 8.5$ MeV.
Fine Structure Measurements of the Giant M1 Resonance in $^{90}$Zr at HI$\gamma$S


- Explaining the fragmentation pattern and the dynamics of the 'quenching'.
- Multi-particle multi-hole effects increase strongly the orbital part of the magnetic moment.
- QPM prediction of M1 strength at and above the neutron threshold.

Polarized photon scattering off $^{52}$Cr:
Determining the parity of $J=1$ states.

Fine structure of the low-energy dipole strength in the $\gamma$-soft $^{196}$Pt

Research Proposal: approved

Physical Sciences Research Program 2018, SSC Facility
iThemba Laboratory for Accelerator Based Sciences,
Republic of South Africa
Distinguishment of the Pygmy Dipole Resonance from Other Modes
Complementary \((\alpha, \alpha'\gamma)\) and \((\gamma, \gamma')\) experiments: PDR splits to two parts with different structure

- **KVI**
  - Coincident experiment
  - \(E_{\alpha} = 130\) MeV
  - High energy resolution

- **TUD**
  - NRF experiment
  - Real photons
  - \(E_{\gamma} = 4 - 8\) MeV
  - High energy resolution

---

D. Savran et al. PRL, 97 172505 (2006)

D. Savran et al. NIMA 564 267 (2006)

J. Endres et al. PRL 105, 212503 (2010)
GiEDF+QPM: Separation of the PDR from the low-energy GDR in $^{206}$Pb

New evidences on the existence of pygmy quadrupole resonance
QRPA Isoscalar and Isovector Quadrupole States up to 35 MeV in Sn Isotopes

\[ M_1(2^+) \approx \langle 2^+ \| \sum_k r_k^2 Y_{2\mu} (\Omega_k)(\tau_3)^I \| \text{g.s.} \rangle \]

PQR – pygmy quadripole resonance
ISGQR – isoscalar giant quadrupole resonance
IVGQR – isovector giant quadrupole resonance
Quadrupole Transition Densities in Sn Isotopes
A Signature of Pygmy Quadrupole Resonance

PQR – pygmy quadripole resonance
ISGQR – isoscalar giant quadrupole resonance
IVGQR – isovector giant quadrupole resonance

N. Tsonева, Hirschegg18
Pygmy quadrupole resonance is a genuine mode!

B(M1) to the first symmetric $2_1^+ \sim 10^{-2} \mu_N N^2$ and $B(E2) \sim 1/\varepsilon_b^2$

B(E2) increases with the neutron number

A change in the $E_b$ of the $g_{9/2}$ which is the proton Fermi level in Sn isotopes when approaching the N=Z limit. $E_b = -12.88$ MeV in $^{134}$Sn; $E_b = -7.20$ MeV in $^{104}$Sn
The PQR mode—Quadrupole Oscillations of the Neutron Skin

PQR ...theoretically predicted in 2011

...experimentally confirmed in 2015/2016

L. Pellegrin, A. Bracca, NT et al., PRC 92, 014330 (2015).

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

$^{124}\text{Sn}(^{17}\text{O},^{17}\text{O'}\gamma)$

$\gamma$-decay branching ratios

N. Tsoneva, Hirschegg18
First Systematic Data on PQR in Tin Isotopes

From the $\gamma$-decay behavior

- Large $b_0$ values are observed in all stable even-even Sn isotopes
- At least two different modes are present!

Both observations are consistent with earlier QPM predictions for the PQR!

From the summed E2 strength

- Strength increases with increasing neutron number
- ... strength seems to be increasing when passing $^{114}$Sn
- Is $^{120}$Sn a special nucleus?

... shell-structure changes?

M. Spieler – The origin of low-lying collective $E1$ and $E2$ strength in atomic nuclei
NUCLEON CAPTURE CROSS SECTIONS
Nuclear Structure and Astrophysical (n,γ) Capture Cross Sections

- Compound Nucleus Capture: **Hauser-Feshbach Theory** → Statistical Approach at High level densities

- Direct Capture: Population of Identifiable Nuclear States → Microscopic Reaction Theory

- Investigations by Detailed Balance: (n,γ) ↔ (γ,n)

**Total Capture Cross Section: Incoherent Superposition of Electric (E) and Magnetic (M) Multipoles**

\[
\sigma(E_{c.m.}) = \sum_{LSJ_i J_f \ell} \frac{8\pi}{2J_f + 1} \frac{\alpha}{v_{rel}} \frac{q}{1 + q/m_f} \left[ \left| E^{LSJ_i J_f}_{\ell}(q) \right|^2 + \left| M^{LSJ_i J_f}_{\ell}(q) \right|^2 \right]
\]

\[
E^{LSJ_i J_f}_{\ell}(q) \xrightarrow{q \to 0} \frac{q^L}{(2L+1)^{!!}} \sqrt{B_{J_i J_f} (EL)} \delta_{S0} \text{ etc.}
\]
Exp: R. Schwengner et al., First systematic photon-scattering experiments in \( \text{N}=50 \) nuclei: using bremsstrahlung produced with electron beams at the linear accelerator ELBE, Rossendorf and quasi-monoenergetic \( \gamma \) - rays at Hi\( \gamma \)S facility, Duke university.

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

$^{87}\text{Sr}(n,\gamma)^{88}\text{Sr}$

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

$^{85}\text{Kr}$ ( $\tau \sim 10.57$ $\text{Y}$) 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 $\text{MACS}$ 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 $\text{MACS}$ 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 ~3 to 50%.
Nuclear Pygmy Modes as Doorways to Nucleosynthesis: Destruction of the s-process $^{205}$Pb nuclide by n-capture via the PDR?

- At stellar temperature of $kT = 30$ keV
  - MACS of $130(+25,-25)$ mb

⇒ The combined PDR plus core polarization contribution is crucial!

⇒ M1 contribution small, less than 5%.

Collection of Observables Probing the n-p Matter

**Neutron skin thickness**

$$\delta r = \sqrt{r_n^2} - \sqrt{r_p^2}$$

**Symmetry Energy**

$$S(\rho) \equiv \frac{1}{2} \left( \frac{\partial^2 E(\rho, \delta)}{\partial \delta^2} \right)_{\delta=0} \approx E(\rho, \delta = 1) - E(\rho, \delta = 0) ; \delta \equiv (N - Z)/A$$

**Density Dependence of the Symmetry Energy**

$$S(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \ldots \quad \text{with} \quad x \equiv \frac{\rho - \rho_0}{3\rho_0}$$

**Nuclear Dipole Polarizability and Photoabsorption**

$$\alpha_p = \frac{1}{2\pi^2\alpha} \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE = \frac{\sigma_{-2}}{2\pi^2\alpha} = 6.942 \sigma_{-2}$$
### Summary of a few moments of the photoabsorption cross section of $^{206}$Pb and $^{208}$Pb

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_{\text{max}}$ (MeV)</th>
<th>$60NZ/A$ (mb MeV)</th>
<th>$\sigma_0$ (mb MeV)</th>
<th>$\sigma_{-1}$ (mb)</th>
<th>$\sigma_{-2}$ (mb/MeV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{206}$Pb</td>
<td>26</td>
<td>2962</td>
<td>3544±294</td>
<td>241±17</td>
<td>18±1</td>
<td>Present+[46,49] [ENDF]</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>25</td>
<td>2980</td>
<td>3981±331</td>
<td>287±18</td>
<td>20±1</td>
<td>[50] [ENDF]</td>
</tr>
</tbody>
</table>

### Photoabsorption cross sections & moments and Nuclear Matter

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$ (mb MeV)</th>
<th>$\sigma_{-1}$ (mb)</th>
<th>$\sigma_{-2}$ (mb/MeV)</th>
<th>$R_{\text{skin}}$ (fm)</th>
<th>$J$ (MeV)</th>
<th>$L$ (MeV)</th>
<th>$K_{\text{sym}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMF012</td>
<td>3653</td>
<td>237</td>
<td>17</td>
<td>0.12 [0.13]</td>
<td>29.8</td>
<td>48.3</td>
<td>98.7</td>
</tr>
<tr>
<td>FSUGarnet</td>
<td>3689</td>
<td>243</td>
<td>18</td>
<td>0.15 [0.16]</td>
<td>30.9</td>
<td>51.0</td>
<td>59.5</td>
</tr>
<tr>
<td>FSUGold</td>
<td>3638</td>
<td>251</td>
<td>19</td>
<td>0.19 [0.21]</td>
<td>32.6</td>
<td>60.5</td>
<td>51.3</td>
</tr>
<tr>
<td>RMF028</td>
<td>3711</td>
<td>265</td>
<td>21</td>
<td>0.26 [0.29]</td>
<td>37.5</td>
<td>112.6</td>
<td>26.2</td>
</tr>
<tr>
<td>RMF032</td>
<td>3812</td>
<td>262</td>
<td>21</td>
<td>0.30 [0.32]</td>
<td>41.3</td>
<td>125.6</td>
<td>28.6</td>
</tr>
<tr>
<td>GIEFD</td>
<td>3060</td>
<td>230</td>
<td>18</td>
<td>0.15 [0.16]</td>
<td>33.4</td>
<td>53.9</td>
<td>188.4</td>
</tr>
</tbody>
</table>
Summary and Outlook

- New low-energy modes: PDR, PQR ...
- GiEDF+QPM: an extended DFT plus multi-phonon approach to nuclear spectra and astrophysics
- Subthreshold pygmy modes, multi-phonon excitations, GDR and capture cross sections
- Correlations: PDR → skin thickness ↔ polarizability ↔ slope L ↔ ...
- Predictions of s- and r-process nucleosynthesis rates

In collaboration with:

H. Lenske, V. Derya, S. Goriely, J. Piekarewicz, R. Schwengner, M. Spieker, A. Tonchev, W. Tornow ...