EVOLUTION OF MULTPOLE RESPONSE IN NUCLEI AT FINITE TEMPERATURE

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Giant Resonances

Giant Resonances (GR) are known as small amplitude and high frequency collective states of nucleus which typically have energies between 12-30 MeV. They can be used as a tool to probe the internal structure of nuclei. Investigation of Giant resonances under extreme conditions provides even more detailed information about the structure and properties of nuclei as well as a further challenge for theory.

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Introduction

Pygmy Dipole Resonance (PDR) is associated with the static properties of nuclei, for instance the neutron skin thickness and the nuclear symmetry energy. The PDR also plays a relevant role in astrophysics, in the r-process nucleosynthesis which takes place at finite temperatures. The strength of pygmy resonances could be able to change ($n, \gamma$) reaction rate. Investigation of this low-energy modes under extreme conditions are important in order to understand their behavior of nuclei under different circumstances.

Pygmy Dipole Resonance

The graph shows the energy [MeV] on the x-axis and strength (a.u.) on the y-axis. The PDR is indicated with a purple sphere, and the GDR with a red sphere. The graph highlights that 1-5% of EWSR is associated with the PDR, while about 100% of EWSR is associated with the GDR.
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### Overview of recent works:

What have been done up to now?

#### Derivation of FT-QRPA equations:


#### Finite Temperature RPA:


#### Finite temperature Continuum QRPA:


#### Relativistic FT-RPA:

Microscopic Model: Finite Temperature Random Phase Approximation

The creation operator can be written in a straightforward way

\[ \Gamma_{\nu}^{\dagger} = \sum_{ph} X_{ph}^{\nu} c_{p}^{\dagger} c_{h} - Y_{ph}^{\nu} c_{h}^{\dagger} c_{p} \]  \tag{1}\]

\[ \begin{pmatrix} A & B \\ -B^{*} & -A^{*} \end{pmatrix} \begin{pmatrix} X_{\nu} \\ Y_{\nu} \end{pmatrix} = \hbar \omega \begin{pmatrix} X_{\nu} \\ Y_{\nu} \end{pmatrix} \]  \tag{2}\]

defining the RPA matrices A and B

\[ A_{php'h'} \equiv \langle HF | \left[ c_{h}^{\dagger} c_{p}, \left[ H, c_{p}^{\dagger} c_{h'} \right] \right] | HF \rangle = (\varepsilon_{p} - \varepsilon_{h} ) \delta_{pp'} \delta_{hh'} + \overline{V}_{ph',hp'} \times (f_{h'} - f_{p'}) \]  \tag{3}\]

\[ B_{php'h'} \equiv - \langle HF | \left[ c_{h}^{\dagger} c_{p}, \left[ H, c_{h}^{\dagger} c_{p'} \right] \right] | HF \rangle = \overline{V}_{pp',hh'} \times (f_{h'} - f_{p'}) \]  \tag{4}\]

where temperature dependent Fermi-Dirac distribution function is given by:

\[ f_{i} = \left[ 1 + \exp(\varepsilon_{i} - \lambda)/k_{B} T \right]^{-1} \]  \tag{5}\]

we obtain RPA normality as

\[ \sum_{ab} (X_{ph}^{\nu} X_{ph}^{\nu'} - Y_{ph}^{\nu} Y_{ph}^{\nu'}) \times (f_{h} - f_{p}) = \delta_{\nu \nu'} \]  \tag{6}\]

Using RPA forward and backward amplitudes, the transition strength is calculated with

\[ B(J, E_{\nu}) = \left| \sum_{ab} (X_{ph}^{\nu} \mp (-1)^{J} Y_{ph}^{\nu}) \times \langle p||F_{J}||h \rangle \times (f_{h} - f_{p}) \right|^{2} \]  \tag{7}\]
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Goal

- We aimed to investigate the effect of temperature on the multiple response of nuclei in closed shell nuclei.
- We performed calculations in the framework of the self-consistent Finite temperature Hartree-Fock + Random Phase Approximation in matrix formalism. SGII-Skyrme energy density functional is used in the calculations.
- The single-particle continuum is discretized and spherical symmetry is assumed.

We investigated the effect of the temperature on the strength functions and excitation energies of the multipole excitations \(0^+, 1^-, 2^+\) for the selected calcium and tin nuclei. In particular, we investigated the effect of the temperature on the low-energy part of the excitation spectrum. The calculations are performed up to \(T=2.0\) MeV in order to avoid unphysical nucleon vapour.
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The calculations are performed up to \(T=2.0\) MeV in order to avoid unphysical nucleon vapour.
Temperature dependence of the occupation probabilities and single particle energies

- At finite temperature, the occupation probability of states are given by:
  \[ f_i = \left[ 1 + \exp (\varepsilon_i - \lambda) / k_B T \right]^{-1} \]

- The single particle levels are chosen around the Fermi level, which are impacted by temperature. With the increase of the temperature, nucleons are excited to higher energies and occupation probabilities are increased above the Fermi level.

- The single particle levels are sensitive to the temperature after \( T = 1 \text{ MeV} \).
Numerical Results - Dipole Spectrum

**40Ca SGII**

- B(E1:IV) (fm$^2$ MeV$^{-1}$)
- E (MeV)
- T=0.0 MeV
- T=1.0 MeV
- T=2.0 MeV

**100Sn SGII**

- B(E1:IV) (fm$^2$ MeV$^{-1}$)
- E (MeV)
- T=0.0 MeV
- T=1.0 MeV
- T=2.0 MeV

**48Ca SGII**

- B(E1:IV) (fm$^2$ MeV$^{-1}$)
- E (MeV)
- T=0.0 MeV
- T=1.0 MeV
- T=2.0 MeV

**132Sn SGII**

- B(E1:IV) (fm$^2$ MeV$^{-1}$)
- E (MeV)
- T=0.0 MeV
- T=1.0 MeV
- T=2.0 MeV
With the increase in the temperature, configuration space includes p-h, p-p and h-h pairs.

Temperature dependence can be seen considerably after \( T = 1.0 \text{MeV} \).

The low-energy part of the spectrum changes mainly due to the p-p excitations.

Table: FT+RPA transitions at \( T=2.0 \text{MeV} \) for \(^{132}\text{Sn} \) nucleus.

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>Transition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.57</td>
<td>( 3p_{3/2} \rightarrow 4s_{1/2} )</td>
<td>89.9</td>
</tr>
<tr>
<td>2.57</td>
<td>( 2f_{5/2} \rightarrow 2d_{3/2} )</td>
<td>9.7</td>
</tr>
<tr>
<td>3.26</td>
<td>( 3p_{3/2} \rightarrow 3d_{5/2} )</td>
<td>99.4</td>
</tr>
<tr>
<td>6.52</td>
<td>( 2f_{7/2} \rightarrow 2g_{9/2} )</td>
<td>98.9</td>
</tr>
<tr>
<td>6.85</td>
<td>( 2f_{5/2} \rightarrow 3g_{7/2} )</td>
<td>99.3</td>
</tr>
<tr>
<td>8.25</td>
<td>( 3s_{1/2} \rightarrow 3p_{3/2} )</td>
<td>9.94</td>
</tr>
<tr>
<td>8.25</td>
<td>( 2d_{3/2} \rightarrow 3p_{3/2} )</td>
<td>44.2</td>
</tr>
<tr>
<td>8.25</td>
<td>( 3s_{1/2} \rightarrow 3p_{1/2} )</td>
<td>7.9</td>
</tr>
</tbody>
</table>
Numerical Results - Monopole Spectrum

48Ca SGII

132Sn SGII

$\sigma_{2s} \rightarrow 3p_{\frac{3}{2}}$ (99.9% p-p exc.)

$\sigma_{2s} \rightarrow 3p_{\frac{1}{2}}$ (99.9% p-p exc.)

$\sigma_{2s} \rightarrow 4p_{\frac{3}{2}}$ (99.9% p-p exc.)

$\sigma_{3p} \rightarrow 4p_{\frac{3}{2}}$ (99.9% p-p exc.)

$\sigma_{3p} \rightarrow 5p_{\frac{1}{2}}$ (99.9% p-p exc.)

$\sigma_{2s} \rightarrow 4f_{\frac{7}{2}}$ (99.9% p-p exc.)

$\sigma_{3p} \rightarrow 5f_{\frac{7}{2}}$ (99.9% p-p exc.)

$\sigma_{3p} \rightarrow 4f_{\frac{1}{2}}$ (99.9% p-p exc.)

B(E0:IS) (fm$^{-4}$ MeV$^{-1}$)

E (MeV)

T=0.0 MeV

T=1.0 MeV

T=2.0 MeV

B(E0:IV) (fm$^{-4}$ MeV$^{-1}$)

E (MeV)

T=0.0 MeV

T=1.0 MeV

T=2.0 MeV

E. Yüksel (YTU)
With the increase of the temperature, The GMR region remains almost stable.

The new low-energy modes are formed due to the temperature effect which are mainly single particle p-p excitations.

The isovector part of the spectrum extends through the low-energy part with the formation of new these states.
Numerical Results - Quadrupole Spectrum

$^{48}\text{Ca SGII}$

$^{132}\text{Sn SGII}$

$\text{B(E2:IS) (fm}^4\text{MeV}^{-1})$

$\text{B(E2:IV) (fm}^4\text{MeV}^{-1})$
Summary and Perspectives

- Fully-self consistent Finite-temperature RPA model is used in the calculation of the monopole and dipole response of Calcium and Tin nuclei.
- At finite temperatures, the Fermi surface becomes diffuse and p-p (h-h) excitations become possible with p-h excitations.
- While Giant resonance regions (GDR, GMR and GQR) remains almost stable against temperature, the new low-energy excitations appear at finite temperatures. Temperature dependence of the responses are much more pronounced after $T > 1$ MeV.

The calculations for open shell nuclei within the FT-QRPA framework are in progress.
Thanks for your attention!