# EVOLUTION OF MULTIPOLE RESPONSE IN NUCLEI AT FINITE TEMPERATURE

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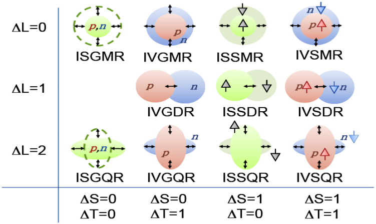
# Outline

# Introduction




- P.F. Bortignon, A. Bracco, R.A. Broglia, 1998
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## Giant Resonances

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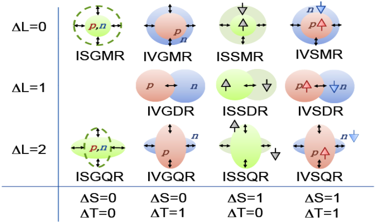


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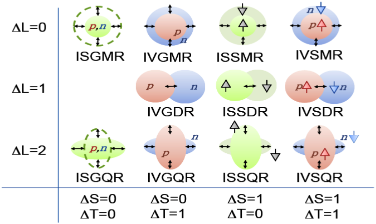


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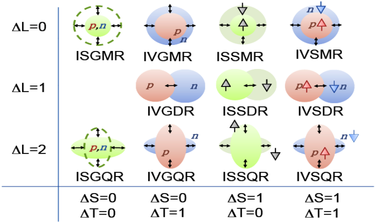


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## Giant Resonances

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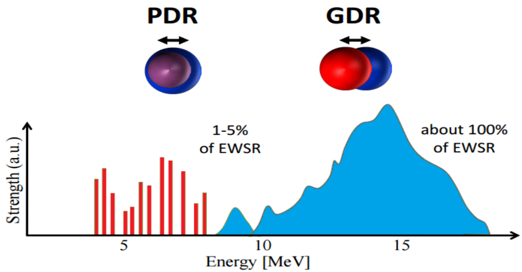
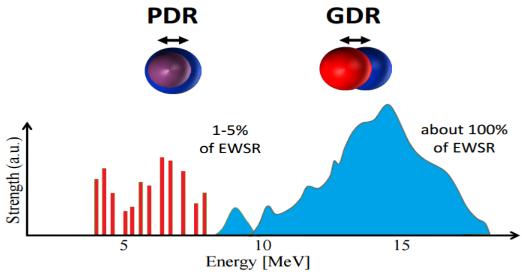
- They can be used as a tool to probe the internal structure of nuclei.
- Investigation of Giant resonances under extreme conditions provides even more detailed information about the structure and properties of nuclei as well as a further challenge for theory.




## Pygmy Dipole Resonance

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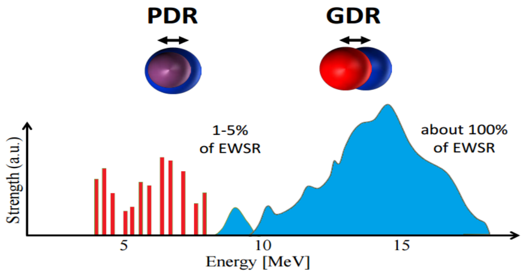


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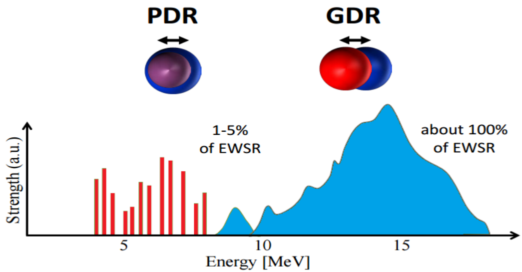


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- Investigation of this low-energy modes under extreme conditions are important in order to understand their behavior of nuclei under different circumstances.

# Overview of recent works: What have been done up to now?

**Derivation of FT-QRPA equations:**
H. M. Sommermann, Ann. Phys. (NY) 151, 163 (1983).

**Finite Temperature RPA:**
H. Sagawa and G. F. Bertsch, Phys. Lett. B 146, 138 (1984).
F. Alasia and O. Civitarese, Phys. Rev. C 42, 1335 (1990).
O. Civitarese and M. Reboiro, Phys. Rev. C 63, 034323 (2001).
D. Lacroix, P. Chomaz, and S. Ayik, Phys. Rev. C 58, 2154 (1998).
N. Dinh Dang and A. Arima, Phys. Rev. C 68, 044303 (2003).

**Finite temperature Continuum QRPA:**
E. Khan, N. Van Giai, and M. Grasso, Nucl. Phys. A731, 311 (2004).

**Relativistic FT-RPA:**
Y.F. Niu, N. Paar, D. Vretenar, J. Meng, Physics Letters B 681 315319 (2009).

# 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:

$$f_i = [1 + exp(\varepsilon_i - \lambda)/k_B T]^{-1} \tag{5}$$

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

$$B(J, E_\nu) = \left| \sum_{ab} (X_{ph}^\nu + (-1)^J Y_{ph}^\nu) \times \langle p||F_J||h\rangle \times (f_h - f_p) \right|^2 \tag{7}$$

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- The single-particle continuum is discretized and spherical symmetry is assumed.
- The effect of the temperature on the strength functions and excitation energies of the multipole excitations $(0^+, 1^-, 2^+)$ are investigated 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.

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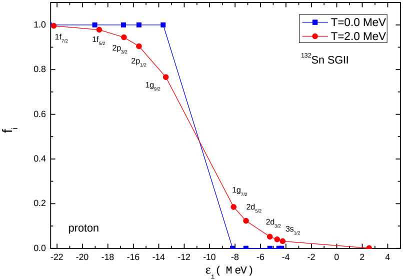
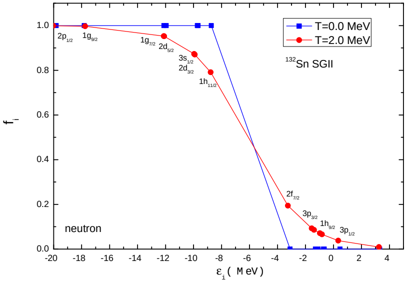
- The calculations are performed up to T=2.0 MeV in order to avoid unphysical nucleon vapour.

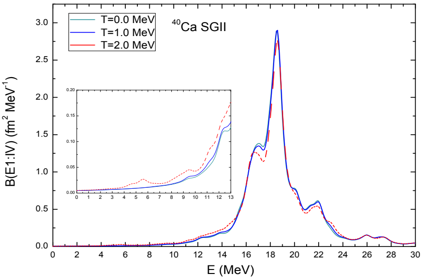
# Temperature dependence of the occupation probabilities and single particle energies

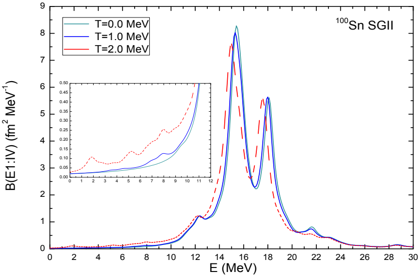
- At finite temperature, the occupation probability of states are given by:
  $f_i = [1 + exp(\varepsilon_i - \lambda)/k_B T]^{-1}$

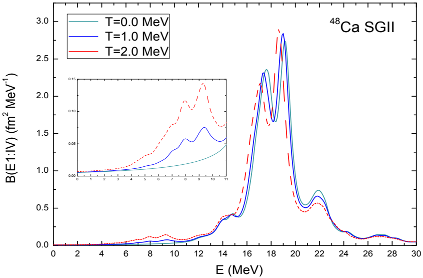


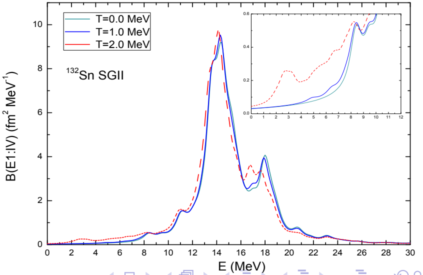




- The single particle levels are chosen around the Fermi level, which are impacted by temperature. With the increase of the temperature, nucleons are excited to higher energies and occupation probabilities are increased above the Fermi level.
- The single particle levels are sensitive to the temperature after $T = 1$ MeV.

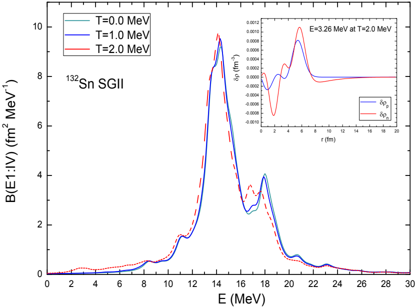

T=0.0 MeV
T=1.0 MeV
T=2.0 MeV
40Ca SGII
B(E1:IV) (fm2 MeV-1)
E (MeV)


T=0.0 MeV
T=1.0 MeV
T=2.0 MeV
100Sn SGII
B(E1:IV) (fm2 MeV-1)
E (MeV)


T=0.0 MeV
T=1.0 MeV
T=2.0 MeV
48Ca SGII
B(E1:IV) (fm2 MeV-1)
E (MeV)


T=0.0 MeV
T=1.0 MeV
T=2.0 MeV
132Sn SGII
B(E1:IV) (fm2 MeV-1)
E (MeV)

# Numerical Results - Dipole Spectrum

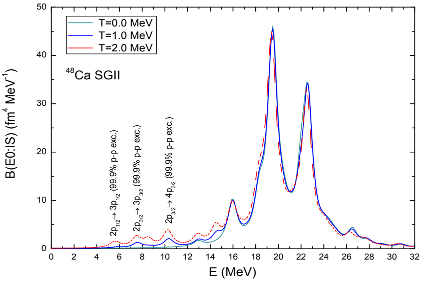


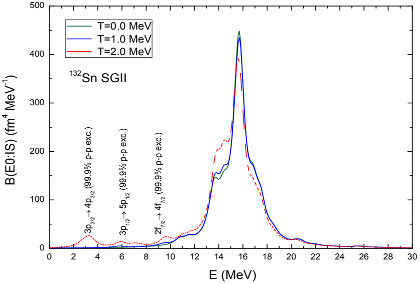

- With the increase in the temperature, configuration space includes p-h, p-p and h-h pairs.
- Temperature dependence can be seen considerably after $T = 1.0 MeV$.
- The low-energy part of the spectrum changes mainly due to the p-p excitations.

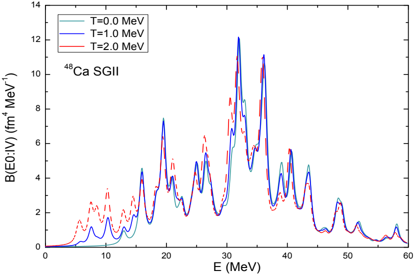
Table: FT+RPA transitions at T=2.0 MeV for $^{132}$Sn nucleus.

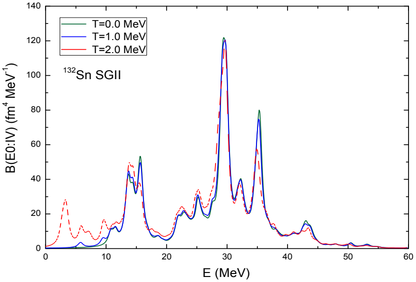
| E (MeV) | Transition | % |
|---|---|---|
| 2.57 | $3p_{3/2} \rightarrow 4s_{1/2}$ | 89.9 |
| 2.57 | $2f_{5/2} \rightarrow 2d_{3/2}$ | 9.7 |
| 3.26 | $3p_{3/2} \rightarrow 3d_{5/2}$ | 99.4 |
| 6.52 | $2f_{7/2} \rightarrow 2g_{9/2}$ | 98.9 |
| 6.85 | $2f_{5/2} \rightarrow 3g_{7/2}$ | 99.3 |
| 8.25 | $3s_{1/2} \rightarrow 3p_{3/2}$ | 9.94 |
| 8.25 | $2d_{3/2} \rightarrow 3p_{3/2}$ | 44.2 |
| 8.25 | $3s_{1/2} \rightarrow 3p_{1/2}$ | 7.9 |

# Numerical Results - Monopole Spectrum



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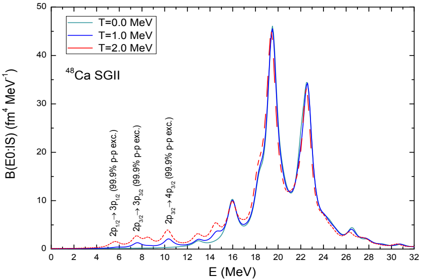
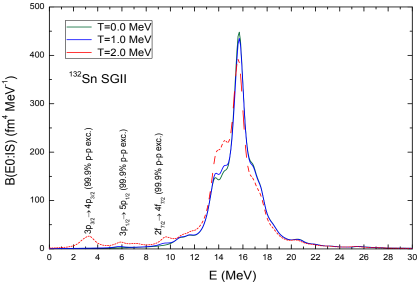
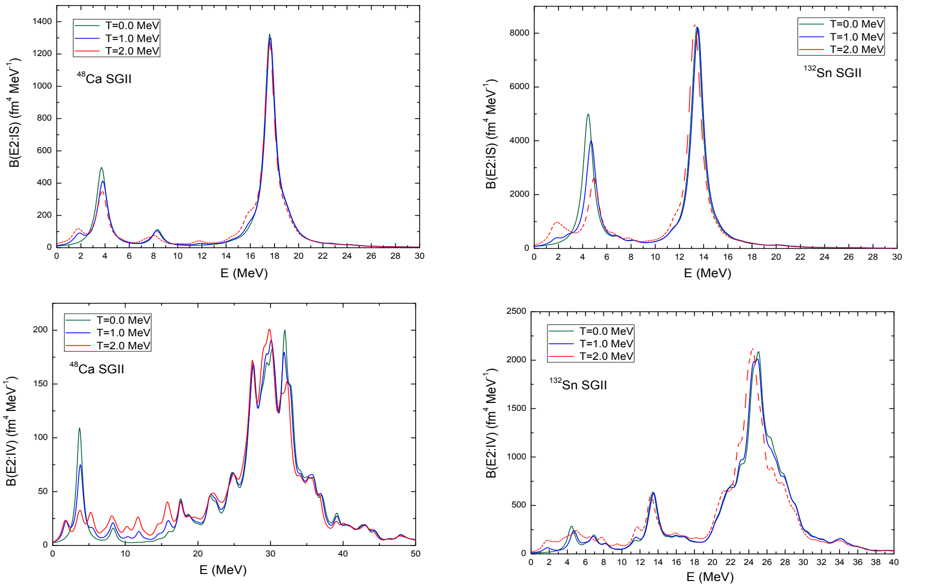



- With the increase of the temperature, The GMR region remains almost stable.
- The new low-energy modes are formed due to the temperature effect which are mainly single particle p-p excitations.
- The isovector part of the spectrum extends through the low-energy part with the formation of new these states.

# Numerical Results - Quadrupole Spectrum



## 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!*