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Giant resonances at zero and finite temperatures

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Abstract
The recent status of theoretical and experimental studies of giant dipole resonances in nuclei is presented with the emphasis on: (1) giant dipole resonances in highly excited nuclei, (2) multiple-phonon resonances and (3) pygmy dipole resonances in neutron-rich nuclei. In particular, the description of these resonances within the framework of the phonon damping model is discussed in detail.

1. Introduction

Giant resonances (GR) are fundamental modes of nuclear excitations at high frequencies. The best-known one of them is the giant dipole resonance (GDR), which was observed in photonuclear reactions almost 70 years ago and is described as the collective motion of neutrons against protons according to the simplest theoretical model by Goldhaber and Teller. The collective model of nucleus indicates that nucleus should be studied in terms of normal modes, many of which are vibrational modes. Since the GDR is a giant vibration, by studying the GDR we learn a great deal about how the single-particle motion is coupled to vibrations, hence about the nuclear structure itself. Many other types of GR were measured later. Recently the multiple-phonon GR, and the GDR in highly excited nuclei (hot GDR) were also observed. With the development of research in neutron-rich nuclei, new modes of excitations such as soft-dipole in neutron-halo nuclei, pygmy resonances in neutron-skin nuclei and their coupling to GDR were also studied. This paper presents a simple model, called the phonon-damping model (PDM), which turns out to be successful in describing simultaneously many of these resonances, including the GDR in hot nuclei, double GDR (DGDR) in β-stable nuclei, as well as pigmy dipole resonances (PDR) in neutron-rich nuclei.

2. The phonon-damping model

The PDM was proposed in 1998 in [1], and developed further in a series of papers [2, 3]. According to the PDM the propagation of the GR phonon is damped due to coupling to a

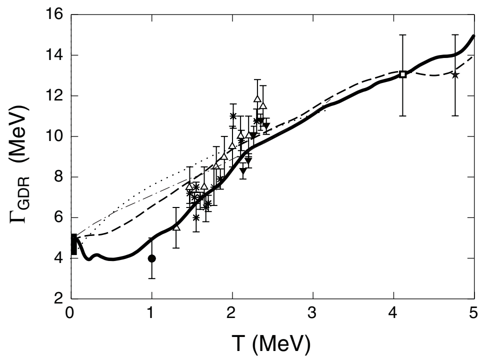

Figure 1. GDR width $\Gamma_{\rm GDR}$ as a function of temperature T for ^{120}Sn. The dashed and solid lines show the PDM results obtained neglecting and including thermal pairing gap, respectively. The predictions by two versions of the thermal shape-fluctuation model are shown as the dash-dotted [4] and thin dotted [5] lines, respectively. The experimental data are taken from [6].

quasiparticle field. The final equation of the Green function for the GR propagation has the form [3]

$$G_{\lambda i}(E) = \frac{1}{2\pi}\frac{1}{E - \omega_{\lambda i} - P_{\lambda i}(E)}\,, \tag{1}$$

where $P_{\lambda i}(E)$ is the polarization operator. The phonon damping $\gamma_{\lambda i}(\omega)$ (ω real) is obtained as the imaginary part of the analytic continuation of the polarization operator $P_{\lambda i}(E)$ into the complex energy plane $E = \omega \pm {\rm i}\varepsilon$:

$$\begin{aligned}\gamma_{\lambda i}(\omega) = \frac{\pi}{2(2\lambda+1)}\sum_{jj'}\big[f_{jj'}^{(\lambda)}\big]^2\big\{\big(u_{jj'}^{(+)}\big)^2(1-n_j-n_{j'})\\ \times[\delta(E-\epsilon_j-\epsilon_{j'})-\delta(E+\epsilon_j+\epsilon_{j'})]\\ -\big(v_{jj'}^{(-)}\big)^2(n_j-n_{j'})[\delta(E-\epsilon_j+\epsilon_{j'})-\delta(E+\epsilon_j-\epsilon_{j'})]\big\}.\end{aligned} \tag{2}$$

Here $u_{jj'}^{(+)} = u_j v_{j'} + u_{j'} v_j$, $v_{jj'}^{(-)} = u_j u_{j'} - v_j v_{j'}$ are combinations of Bogolyubov (u, v) factors, ϵ_j are quasiparticle energies and n_j are the temperature-dependent quasiparticle-occupation numbers, whose form is close to that given by the Fermi–Dirac distribution. The energy $\bar{\omega}$ of the giant resonance (damped collective phonon) is found as the pole of the Green function (1):

$$\bar{\omega} - \omega_{\lambda i} - P_{\lambda i}(\bar{\omega}) = 0. \tag{3}$$

The width Γ_λ of giant resonance is calculated as twice of the damping $\gamma_\lambda(\omega)$ at $\omega = \bar{\omega}$, i.e.

$$\Gamma_\lambda = 2\gamma_\lambda(\bar{\omega}), \tag{4}$$

where $\lambda = 1$ corresponds to the GDR. The line shape of the GDR is described by the strength function $S_{\rm GDR}(\omega)$, which is derived as

$$S_{\rm GDR}(\omega) = \frac{1}{\pi}\frac{\gamma_{\rm GDR}(\omega)}{(\omega-\bar{\omega})^2 + \gamma_{\rm GDR}^2(\omega)}. \tag{5}$$

3. Comparison with the experimental systematics

The PDM has been proved to be quite successful in the description of the width and the shape of the GDR as a function of temperature T and angular momentum J. An example is shown in figure 1. The PDM results reproduce quite well the experimental systematic of the GDR

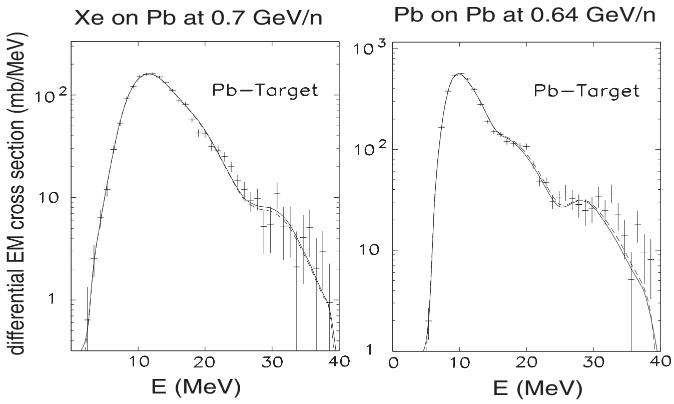

Figure 2. EM cross sections of GDR and DGDR for ^{136}Xe and ^{208}Pb. The solid lines are theoretical predictions, in which the DGDR strength functions within the PDM are used. The data points are results of the LAND collaboration [8]. The dashed lines show the best fit using χ^2. The theoretical results have been folded with the detector response by Boretzky [8].

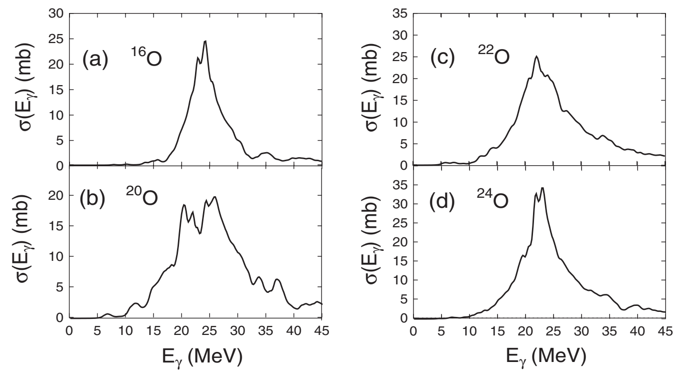

Figure 3. Photoabsorption cross sections for oxygen isotopes obtained within the PDM.

width as a function of temperature including a nearly constant width at $T \leqslant 1$ MeV, the sharp increase at $1 < T \leqslant 3$ MeV and the width saturation at $T > 3$ MeV in tin isotopes. In particular, it has been shown that the inclusion of non-vanishing thermal pairing gap is important to describe the width at $T \leqslant 1$ MeV.

The PDM has resolved the long-standing problem with the electromagnetic (EM) cross sections of the DGDR in ^{136}Xe and ^{208}Pb, in which the prediction by the non-interacting phonon picture underestimated significantly the observed DGDR cross sections measured by the LAND collaboration. The prediction using the strength functions obtained within the PDM [7] is given in figure 2 in comparison with the latest results of data analyses by LAND collaboration [8]. The agreement between the PDM prediction and the data is remarkable.

Shown in figure 3 are the photoabsorption cross sections $\sigma(E_\gamma)$, obtained within the PDM for some oxygen isotopes [3]. In the region below 10 MeV, instead of a pronounced E1 peak, only a tail is seen, which spreads towards lower energy with increasing neutron number up to $N = 14$ (^{22}O). The trend obtained within the PDM for oxygen isotopes reproduces the one observed in the recent experiments at GSI [9], which shows a clear deviation from the prediction by the cluster sum rule (CSR). The agreement between the PDM prediction and the experimental data for the photoabsorption cross sections as well as for the energy-weighted sum of PDR strength suggests that the mechanism of the damping of PDR is dictated by the coupling between the GDR phonon and noncollective *ph* excitations rather than by the oscillation of a collective neutron excess against the core. Only when the GDR is very collective so that it can be well separated from the neutron excess, the picture of PDR damping becomes closer to the prediction by the CM.

4. Conclusion

The PDM is a simple yet microscopic model, which can describe rather well various resonances and has resolved several long standing problems including the width and shape of the hot GDR as functions of temperature, and the electromagnetic cross section of the DGDR in β-stable nuclei. It also predicts an extended tail in the photoabsorption cross sections towards the low-energy region in neutron-rich nuclei.

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