Vol. 31 (2000) ACTA PHYSICA POLONICA B No 2

A NEW CLOSED-FORM THERMODYNAMIC APPROACH FOR RADIATIVE STRENGTH FUNCTIONS *

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(Received January 7, 2000)

A closed-form approach for average description of the $E1$ radiative strength functions is examined. It gives simple and rather accurate method of simultaneous description of the γ-decay and photoabsorption dipole strength functions in the medium and heavy nuclei. The approach is able to cover a relatively wide gamma-ray energy interval, ranging from zero to values above GDR peak energy.

PACS numbers: 21.60.–n, 21.60.Ev, 24.30.Cz

1. Introduction

Gamma-emission is one of the most universal channel of the nuclear de-excitation processes which can accompany any nuclear reaction. It can be described by the radiative strength functions [1, 2]. These functions are also auxiliary quantities involved in calculations of the observed characteristics of the nuclear structure and many different nuclear processes ([3–8]). The calculations, as a rule, are very time consuming and simple closed-form expressions are preferable in evaluation of the γ-ray strengths. The theory-based approaches are also needed in improving the reliability and accuracy of the strength estimations. Below a model of this type is considered with statistical description of the radiative strengths of excited states.

2. Gamma-ray strengths in heated nuclei

We shall consider the radiative strength functions averaged over spins of initial states for γ-transitions of the electric dipole type with the energy ε_γ in

* Presented at the XXVI Mazurian Lakes School of Physics, Krzyże, Poland September 1–11, 1999.

heated nuclei at fixed initial excitation energy U (the temperature T). The emission and absorption processes for γ-rays are generally connected with different radiative strengths [1, 2]. The gamma-decay (downward) strength function $\overleftarrow{f}_{E1}$ determines the γ-emission of heated nuclei. It is associated with the average radiative width $\Gamma_{E1}(\varepsilon_\gamma)$ per unit of the γ-ray energy interval. The photoexcitation (upward) strength function $\overrightarrow{f}_{E1}$ is connected with photoabsorption cross-section $\sigma_{E1}(\varepsilon_\gamma, T)$. Both of these strengths are determined by spectral function $\mathcal{F}(\varepsilon_\gamma, \mathcal{T})$:

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma, T) \equiv \frac{\Gamma_{E1}(\varepsilon_\gamma)}{3\varepsilon_\gamma^3} \frac{\rho(U, Z, N)}{\rho(U - \varepsilon_\gamma, Z, N)} = \mathcal{F}(\varepsilon_\gamma, T_f) \tag{1}$$

and

$$\overrightarrow{f}_{E1}(\varepsilon_\gamma, T) \equiv \frac{\sigma_{E1}(\varepsilon_\gamma, T)}{3\varepsilon_\gamma (\pi\hbar c)^2} = \mathcal{F}(\varepsilon_\gamma, T), \tag{2}$$

where $\rho(U, Z, N)$ is the total density of the initial states. The γ-decay strength function depends on temperature T_f of the final states. This temperature is a function of the γ-ray energy in contrast to the initial states temperature T.

The spectral function $\mathcal{F}(\varepsilon_\gamma, \mathcal{T})$ is proportional to the imaginary part of the nuclear response function on the electromagnetic field [8, 9]. For description of the neutrons and protons motion in the nucleus we use the semiclassical Landau–Vlasov equations with a source term for relaxation processes [10, 11]. The Fermi sphere distortions are truncated by the layers of monopole and dipole multipolarities [12] and the hydrodynamic boundary condition is adopted that the radial component of the nucleon current vanishes at the nuclear surface. This approach leads to the same equations for particle density and velocity as they are in the hydrodynamic Steinwedel–Jensen model with friction force between the proton and neutron fluids [13] (extended SJ model) but provides implicit expression for damping width of the velocity. Using the dipole mode approximation for response function (dipole polarizability) within the extended SJ model (see, §14.4 of Ref. [13]) together with general expression between the spectral function $\mathcal{F}(\varepsilon_\gamma, \mathcal{T})$ and the nuclear response function from [8, 9], we find for $E1$ dipole transitions in spherical nuclei

$$\mathcal{F}(\varepsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \mathcal{L}(\varepsilon_\gamma, \mathcal{T}) \sigma_r \Gamma_r \frac{\varepsilon_\gamma \Gamma}{(\varepsilon_\gamma^2 - E_r^2)^2 + (\Gamma \varepsilon_\gamma)^2}, \quad \mathrm{MeV}^{-3}, \tag{3}$$

where E_r is the giant dipole resonance (GDR) energy. The quantities σ_r and Γ_r are the peak value and the width of the $E1$ photoabsorption cross-section at zero temperature. Here, σ_r is taken in mb and E_r, Γ_r, ε_γ in MeV.

The scaling factor $\mathcal{L}(\varepsilon_\gamma, \mathcal{T})$ defines the enhancement of magnitude of the radiative strength functions in heated nuclei with temperature $\mathcal{T}$ as compared to the cold nuclei. This factor can be interpreted as average number of the $1p$–$1h$ excited states in heated system placed in an external field with frequency $\omega \equiv \varepsilon_\gamma/\hbar$,

$$\mathcal{L}(\varepsilon_\gamma, \mathcal{T}) \equiv \frac{1}{1-\exp(-\varepsilon_\gamma/\mathcal{T})} = \frac{1}{\varepsilon_\gamma}\int\limits_0^{+\infty} d\varepsilon_1 d\varepsilon_2 n(\varepsilon_1)(1-n(\varepsilon_2))\delta(\varepsilon_1-\varepsilon_2+\varepsilon_\gamma), \tag{4}$$

where $n(\varepsilon) = 1/[1-\exp((\varepsilon-\mu)/\mathcal{T})]$ is the Fermi distribution function for occupation of the single-particle states.

In the case of cold nuclei the photoexcitation strength function is only defined and it is given by Eqs. (2), (3) with factor $\mathcal{L} \equiv 1$.

The damping width Γ in Eqs. (3) determines the reduced friction force for isovector velocity (Eq. (14.60) from Ref. [13]). It is calculated by a source term $J(\boldsymbol{p}, \boldsymbol{r}, t)$ of relaxation processes in Landau–Vlasov equation for dipole isovector mode [10, 11] as $\Gamma \equiv 2\hbar \int d\boldsymbol{p}(\boldsymbol{p}/m)J(\boldsymbol{p}, \boldsymbol{r}, t)/((2\pi\hbar)^3(\boldsymbol{v}_p - \boldsymbol{v}_n))$ with $\boldsymbol{v}_p$ and $\boldsymbol{v}_n$ for the velocities of the proton and neutron fluids. We take into account two main relaxation mechanisms: *(i)* The two-body collisional damping; *(ii)* The fragmentation width caused by the interaction of particles with the time-dependent self-consistent mean field which is imitated by the isovector one-body relaxation mechanisms in the relaxation time approximation. We use non-Markovian collisional integral with retardation effects as the source term of the collisional damping. The isovector one-body relaxation time is expressed by corresponding fragmentation width, which is taken as to be equal to the wall formula value [14] but scaled with an coefficient obtained by fitting the total width at $\varepsilon_\gamma = E_r$ and $\mathcal{T} = 0$ to the GDR width. As a result, we have

$$\Gamma \equiv \Gamma(\varepsilon_\gamma, \mathcal{T}) = B_c \frac{\Gamma_r}{E_r^2}\left[\varepsilon_\gamma^2 + (2\pi\mathcal{T})^2\right] + \Gamma_r(1-B_c), \tag{5}$$

where $B_c = 1.08 \cdot 10^{-3}\sigma_{\rm in}E_r^2/\Gamma_r = 5.39 \cdot 10^{-3} F \cdot E_r^2/\Gamma_r$ is two-body contribution to the GDR damping width $\Gamma_r \equiv \Gamma(\varepsilon_\gamma = E_r, \mathcal{T} = 0)$ at zero temperature with the $\sigma_{\rm in}$ for in-medium neutron–proton cross section near the Fermi surface; $F = \sigma_{\rm in}/\sigma_{\rm free}$ is scaling factor between the values of the in-media and free space cross sections ($\sigma_{\rm free} = 5\text{fm}^2$).

The dependence of the width on the energy and temperature is due to two-body component of the width described by the first term on the right-hand side of Eq. (5). The energy dependence results from memory effects in the collision integral and agrees with Landau's prescription. The temperature dependence results from the smeared out behavior of the equilibrium distribution function near the Fermi momentum in the heated nuclei. The second term on the right-hand side of Eq. (5) is the fragmentation component of the width.

The expression (3) with (4)–(5) is named below as the thermodynamic pole approximation [8] (TPA model) and the denotation $\mathcal{F}_{\mathrm{TPA}}$ is used for corresponding spectral function. This function has the temperature-dependent finite value for vanishing gamma-ray energy. As a result, the γ-decay and photoexcitation dipole strength functions within this model have the same non-zero value at $\varepsilon_\gamma = 0$:

$$\overleftarrow{f}_{E1}(0, T_f \equiv T) = \overrightarrow{f}_{E1}(0, T) = 8.674 \cdot 10^{-8} \sigma_r \Gamma_r T \Gamma(0, T)/E_r^4\,. \quad (6)$$

3. Comparison of the closed-form $E1$ strength models

Here, the comparison of the calculations of the $E1$ radiative strength functions is given within the framework of TPA-approach and others closed-form models. The results are also compared with the experimental data. Two other simple models are the following:

(i) Standard Lorentzian (SLO) model [1, 2] with Lorentzian line shape and the energy-independent width. The SLO spectral function, $\mathcal{F}_{\mathrm{SLO}}$, has the form of Eq. (3) but with $\mathcal{L} \equiv 1$ and $\Gamma \equiv \Gamma_r$.

(ii) An enhanced generalized Lorentzian (EGLO) model [15, 16] with radiative strength function consisting of two components, namely, a Lorentzian with the energy and temperature dependent width and finite value term [17] for zero value of γ-ray energy:

$$\mathcal{F}_{\mathrm{EGLO}}(\varepsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \sigma_r \Gamma_r \left[\frac{\varepsilon_\gamma \Gamma_k}{(\varepsilon_\gamma^2 - E_r^2)^2 + (\varepsilon_\gamma \Gamma_k)^2} + 0.7 \frac{\Gamma_{k,0}}{E_r^3} \right], \quad (7)$$

where the energy-dependent width Γ_k is taken as proportional to the collisional component of the width with an empirical function $Q(\varepsilon_\gamma) = \kappa + (1 - \kappa)(\varepsilon_\gamma - 4.5)/(E_r - 4.5)$:

$$\Gamma_k(\varepsilon_\gamma, \mathcal{T}) = Q(\varepsilon_\gamma) \frac{\Gamma_r}{E_r^2} \left[\varepsilon_\gamma^2 + (2\pi \mathcal{T})^2 \right], \quad (8)$$

$\Gamma_{k,0} \equiv \Gamma_k(0, \mathcal{T})$. The factor κ was obtained by fitting the average resonance capture data and it depends on the model used for level density. In the case of the backshifted Fermi gas model [18] the κ is given by [16]: $\kappa = 1$ if $A < 148$ and $\kappa = 1 + 0.09(A - 148)^2 \exp(-0.18(A - 148))$ when$A \geq 148$. We use this model, so that the temperatures T, T_f relate to one another and to the initial excitation energy U as $T_f = (1+\sqrt{1+4a(aT^2-T-\varepsilon_\gamma)})/2a$, $T = (1+\sqrt{1+4a(U-\Delta)})/2a$, where Δ the energy shift parameter and a the level density parameter.

The foregoing expressions for spectral functions are only applicable to spherical nuclei. In the case of the axially symmetric deformed nuclei any spectral function is the sum of two components of the form (3) or (7) with GDR parameters $E_{r,1}$, $\Gamma_{r,1}$, $\sigma_{r,1}$ and $E_{r,2}$, $\Gamma_{r,2}$, $\sigma_{r,2}$ corresponding to the collective motion along two principal axes.

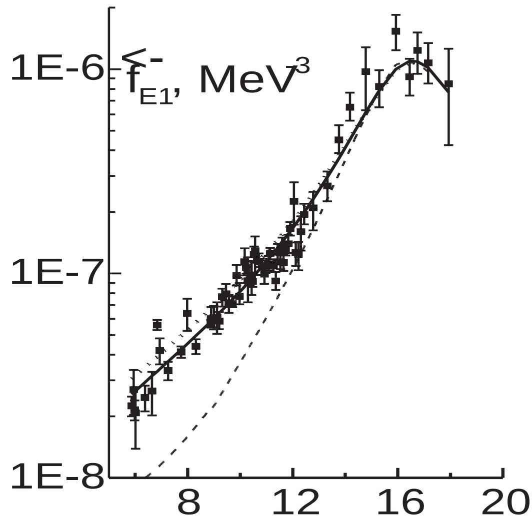

Fig. 1.

In Fig. 1 the results of the calculations of the gamma-decay strengths $\overleftarrow{f}_{E1}$ in ^{90}Zr are shown: solid line — TPA; dot — SLO; dash — EGLO. The experimental data are taken from Refs. [19, 20]. The TPA and EGLO strengths are calculated at the initial excitation energies U corresponding to the experimental ones. The curves connect the calculated values and they are drawn only for a vivid presentation of the results. The values of the GDR parameters are taken from photonuclear data [16, 21]. The level density parameters are used from [16]. The contribution of collisional damping to the GDR width was taken in TPA calculations as $B_c = 0.2$ in agreement with Refs. [10, 11].

As it can be seen from this figure, the TPA and SLO models describe experimental data better than the EGLO for this nucleus and energy range. The calculations by TPA model lie also more close to the experimental data than within SLO method. For example, the values of the least-squares deviations per one degree of freedom from experimental data are equal to 2.8

and 5.2 for the TPA and SLO models, respectively. Note that the SLO model leads to incorrect zeroth value of the gamma-decay strength function at vanishing gamma-ray energy, contrary to EGLO and TPA approaches.

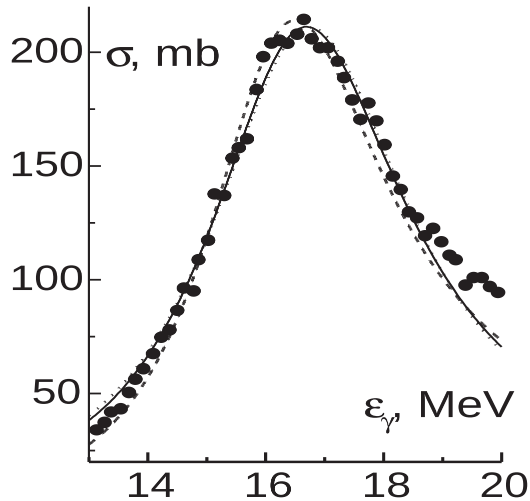

Fig. 2.

In Fig. 2 the comparison is shown between different approaches in the case of the photoabsorption cross-section on ^{90}Zr. The notations are the same as in Fig. 1. The experimental data are taken from Ref. [21]. The behaviour of the $E1$ strength functions calculated by the TPA method is almost in coincidence with SLO model in the vicinity of the GDR peak energy for cold nuclei. It is mainly resulted from account of the one-body relaxation width, which is independent of the gamma-ray energy.

The comparison between calculations within TPA, EGLO and SLO models and experimental data demonstrates usefulness and reliability of the TPA approach for unified description of the γ-decay and photoabsorption strength functions in a relatively wide energy interval, ranging from zeroth gamma-ray energy to the values above GDR peak energy. This is important for prediction of the downward and upward radiative strength functions in cold and heated nuclei as well as for extraction of the GDR parameters of heated nuclei with small errors from γ-emission data.

I am very grateful to Profs. A.V. Ignatyuk, P. Oblozinsky, M.G. Urin and J. Kopecky for valuable discussions and comments. This work was supported in part by the IAEA under Contract No. 10308/RO.

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