An investigation of interplay between dissipation mechanisms in heated Fermi systems by means of radiative strength functions

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Abstract

A simple analytical expression for the $\gamma$-decay strength function is derived with microcanonical ensemble for initial excited states. The approach leads to both a non-zero limit of the strength function for vanishing gamma-ray energy and a partial breakdown of Brink hypothesis. It is shown that the low energy behaviour of the $\gamma$ - decay strength functions is governed by the energy behavior of the damping width. It may provides a new tool for study of the interplay between different relaxation mechanisms of the collective excitations.

I. INTRODUCTION

The emission and absorption of the gamma-rays as well as electron - positron decay are described in the many-body systems by the radiative strength functions. These functions are very useful for study nuclear models, mechanisms of the $\gamma$- processes, widths of the collective excitations and nuclear deformations [1–3]. Besides fundamental importance from a theoretical point of view, the strength functions are needed to generate data for the energy and non- energy applications [4]. It is critically important to have the simple closed-form expression for the $\gamma$ - ray strength function because in the most cases this function is auxiliary quantity used in calculations of different nuclear characteristics and processes.
II. GAMMA-DECAY STRENGTH FUNCTION IN HEATED NUCLEI

The gamma-decay strength function $E_1(\epsilon_\gamma)$ determines the $\gamma$-emission from heated nuclei [8]. It is connected with the average $\gamma$-width $\bar{\Gamma}(\epsilon_\gamma)$ for radiation of the energy $\epsilon_\gamma$ as

$$\bar{\Gamma}(\epsilon_\gamma) = \frac{3\epsilon_\gamma^3}{\frac{\omega_i}{\Omega_f(E_f - \epsilon_\gamma)/\Omega_i(E)}} \Omega_f(E)$$

where $\Omega_i$ and $\Omega_f$ are the total density of the initial and final states, respectively. The dipole transitions is considered for reasons of importance in applications. We find the expression for the function $E_1(\epsilon_\gamma)$ by use of the relation for average radiative width from [9]. The latter expression was obtained with the microcanonical distribution for excited states. We have in the case of the spherical nuclei

$$E_1(\epsilon_\gamma) = -6e^2 \frac{NZ}{A} \left( \frac{2}{3hc} \right)^3 \frac{Im\chi(-)(\omega,T_f)}{1 - \exp(-\epsilon_\gamma/T_f)}$$

where $\chi(-)(\omega,T_f) = Sp(rY_{10}(\hat{r})\delta n(-))/q_\omega(t)$ is the linear response function of the heated nucleus to the external dipole field $q_\omega(t) r Y_{10}(\hat{r})$, $q_\omega(t) = q_0 \exp[-i(\omega + i\eta)t], \eta \to +0, \ q_0 \ll 1$, and $\delta n(-)(t) \equiv \delta n_p(t) - \delta n_n(t)$ is the perturbation of the isovector single-particle density induced by this field. The function $\chi(-)$ is proportional to the polarizability of the nucleus in the electric dipole field.

Note that the $\gamma$-decay strength function depends on temperature $T_f$ of the final states. This temperature is a function of the $\gamma$-ray energy in contrast to the initial states temperature $T$.

We use the hydrodynamic model with the friction [10] to provide a simple closed-form expression for the response function. This approach is the extension of the Steinwedel-Jensen (SJ) hydrodynamic model and gives a simple description of the giant dipole resonance (GDR) excitation as well as its damping. The standard hydrodynamics corresponds to the Vlasov-Landau kinetic approach when only the monopole and dipole distortions of the Fermi sphere are taken into account [11]. Because of this, we apply the Vlasov-Landau kinetic equation completed by a source term for relaxation processes in order to obtain the friction coefficient of the isovector velocity. The SJ-mode plays the most important role in heavy nuclei [12]. It corresponds to a volume density oscillation which is almost unaffected by the dynamical
distortion of the Fermi surface with multipolarities more than quadrupole \[13\]. Next we follow the approach from \[14\] and do not use a normalization of the damping width to that magnitude which corresponds to the infinite matter value \[15,16\].

One finally gets for the damping width of the isovector velocity

\[
\Gamma(\epsilon, T_f) = \Gamma_c(\epsilon, T_f) + \Gamma_s, \quad \Gamma_c(\epsilon, T_f) = \hbar/\tau_c(\epsilon, T_f), \quad \Gamma_s = k_s\hbar \bar{v} R_0. \tag{2}
\]

Here, \(\Gamma_c\) and \(\Gamma_s\) are the two-body and one-body (fragmentation) contributions to the total width respectively. The quantity \(\tau_c(\epsilon, T_f)\) is the collisional relaxation time for the isovector dipole distortion of the Fermi surface. It is associated with two-body collisions in the heated nucleus which is subjected to the electric field oscillating with the frequency \(\omega = \epsilon / \hbar\). For the isotropic collision probabilities it is given by \[14,15,17\]

\[
\tau_c(\epsilon, T_f) \simeq 0.9\hbar\alpha T_f^{-2}/[1 + (\epsilon / 2\pi T_f)^2]. \tag{3}
\]

The dependence of the relaxation time \(\tau_c\) on the energy \(\epsilon\) results from memory effects in the collision integral and follows Landau’s prescription. The temperature dependence arises from the smeared out behavior of the equilibrium distribution function near the Fermi momentum in the heated nuclei. The one-body relaxation width \(\Gamma_c\) is taken similar to the wall formula \[18,12\] but with scaled coefficient \(k_s\) \[15\]. The quantities \(R_0\) and \(\bar{v} \approx (3v_F/4)\) are the nuclear radius and the average velocity of the nucleon, respectively.

Using the expression for the polarizability of the nucleus in the dipole mode approximation from \[10\] and Eq.\((1)\) we get for the dipole strength function

\[
\tilde{f}_{E1}(\epsilon) = 8.674 \cdot 10^{-8} \frac{\sigma_0 \Gamma_G}{1 - \exp(-\epsilon / T_f)} \frac{\epsilon \Gamma_\gamma(\epsilon, T_f)}{(\epsilon^2 - E_G^2)^2 + (\Gamma_\gamma(\epsilon, T_f)\epsilon)^2}, \quad (MeV^{-3}), \tag{4}
\]

where \(E_G\) and \(\Gamma_G\) are the GDR energy and width, respectively, in \(MeV\); the quantity \(\sigma_0\) is the peak of the photoabsorption cross-section in \(mb\).

This approach takes into account various damping mechanisms as well as thermal energy of the electromagnetic field in heated nuclei. The imaginary part of the dipole response function associated with Eq.\((1)\) has a Lorentzian shape with frequency-dependent width.
In the cold nuclei this form of the $Im \chi^{(-)}$ was obtained within the random-phase approximation \[19\]. This term is also in close agreement with the imaginary part of the response function of the heated Fermi-liquid drop to an external pressure, when approximation of the dissipative nuclear fluid-dynamics is used for description of the system \[16\].

**III. NUMERICAL RESULTS AND DISCUSSIONS**

In Fig.1 results of the calculations of the strength functions $\tilde{f}_{E1}$ in $^{144}Nd$ with the initial states energy $E$ equal to the neutron binding energy $B_n = 7.82$ MeV are shown. The GDR parameters were taken from photonuclear data \[20\]. We used the Fermi gas model to get the temperature $T_f$ of the final states, $T_f = \sqrt{T^2 - \epsilon_\gamma/a}, E = aT^2$, where $a$ is the level density parameter, $a = A/8$. The value of the scaled coefficient $k_s$ was found to fit the quantity $\Gamma_\gamma(\epsilon_\gamma = E_G, T = 0)$ to the GDR width $\Gamma_G$. The experimental data are taken from \[21\]. All solid curves were obtained by use of the Eq.(4) with $\alpha = 9.2 MeV$. This value $\alpha$ corresponds to the magnitude of the in-medium nucleon-nucleon cross section which is smaller than the cross section in free space by a factor of 2 (see \[15\] for comments). The dashed line in the Fig.1a was calculated within the framework of the EGLO model as presented in \[22\]:

$$\tilde{f}_{E1} = 8.674 \cdot 10^{-8} \sigma_0 \Gamma_G \left[ \frac{\epsilon_\gamma \Gamma_{EL}(\epsilon_\gamma, T)}{(\epsilon^2_\gamma - E_G^2)^2 + (\Gamma_{EL}(\epsilon_\gamma, T)\epsilon_\gamma)^2} + 0.7 \frac{\Gamma_{EL}(\epsilon_\gamma = 0, T)}{E_G^3} \right],$$

(5)

where $\Gamma_{EL}(\epsilon_\gamma, T) = [k_0 + (1 - k_0)(\epsilon_\gamma - \epsilon_0^\gamma)/(E_G - \epsilon_0^\gamma)] \Gamma_{0}(\epsilon_\gamma, T)$ is the empirical width, and $\Gamma_{0}(\epsilon_\gamma, T) \equiv (\epsilon^2_\gamma + (2\pi T)^2)\Gamma_G/E_G^2$ is the collisional width reproducing the GDR width data at $\epsilon_\gamma = E_G$ and $T = 0$. The parameters $k_0$ and $\epsilon_0^\gamma = 4.5 MeV$ are adjusted to reproduce the averaged resonance capture data; $k_0 = 1$ for the $^{144}Nd$.

The dotted line presents the approximation of the $\gamma$-decay strength function by the Lorentzian with the energy independent width $\Gamma_G$ (SLO model). In the Fig.1b the dot-dashed and dotted lines show the calculations when damping width $\Gamma_\gamma$ is determined only by the two-body and one-body dissipation mechanisms, respectively. The curve 3 gives the evaluations with the quantity $\alpha = 4.6 MeV$ which corresponds to the nucleon-nucleon cross section in free space.
The results obtained by our approach and EGLO model are in good agreement at low energies. They describe experimental data in this range much better than the SLO model and give a nonzero temperature-dependent limit of the strength function for vanishing gamma-ray energy.

When compared to EGLO approach in the range of the GDR peak energy, the behaviour of the E1 strength functions calculated by the proposed method is almost in coincidence with SLO model. It is resulted mainly of taking into account the one-body component of width which is practically independent of the gamma-ray energy. The EGLO model also includes an additional term; it is second component on the right-hand side of Eq. (3). Recall that the SLO approach is probably the most appropriate simple method for the estimation of the \( \gamma \)-strength in the range of giant resonance peak energy.

As seen it is from this figure, the values \( \hat{f}_{E1} \) are sensitive to the magnitude of \( \alpha \) which defines the contributions one-body and two-body components to the GDR damping width. A rather good description of experimental data is obtained at \( \alpha \approx 9.2 \text{ MeV} \). In this case the contribution of the collisional damping to the GDR width is about 15\%; the latter is in agreement with the results of the direct fitting of experimental data for the GDR widths [14].

Figure 2 demonstrates the dependence of the dipole \( \gamma \)-decay strength functions on the excitation energy \( E \), i.e. a partial breakdown of Brink hypothesis. For the solid curve \( E = B_n \) and \( E = 50 \text{ MeV} \) in the case of the dashed line. The violation of Brink hypothesis is growing with increasing excitation energy. The difference of the E1 strength function values calculated at different \( E \) increases with decreasing \( \gamma \)-energies and these deviations are more important for the \( \gamma \)-transitions with energies under or of the order of the nuclear temperature.

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REFERENCES

[1] K. Snover, Ann.Rev.Nucl.Part.Sci. 36(1) (1986) 545.

[2] Y. Alhassid, B. Bush, Phys. Rev. Lett. 61 (1988) 1926; Report No YCTP-N16-88. Yale University. 1988. 55 P.

[3] J.J. Gaardhoje, Ann.Rev.Nucl.Part.Sci. 42 (1992) 483.

[4] A. Bracco, F. Camera, M. Mattiuzzi, B. Million, M. Pignanelli, J.J. Gaardhoje, A. Maj, T. Ramsoy, T. Tveter, Z. Zelazny, Phys. Rev. Lett. 74 (1995) 3748.

[5] T. Baumann, E. Ramakrishnan, M. Thoennessen, Acta Phys. Pol. B28 (1997) 197.

[6] M. Mattiuzzi, A. Bracco, F. Camera, W.E. Ormand, J.J. Gaardhoje, A. Maj, B. Million, M. Pignanelli, T. Tveter, Nucl. Phys. A612 (1997) 262.

[7] Reference Input Parameter Library (RIPL). Handbook for calculations of nuclear reaction data. Sci.Ed. P. Oblozinsky. IAEA - TECDOC, 1998. The directory GAMMA (Coordinator: J. Kopecky) on the Web site - http://www-nds.iaea.or.at/ripl/.

[8] G.A. Bartholomew, E.D. Earle, A.J. Fergusson, J.W. Knowles, A.M. Lone, Adv. Nucl. Phys. 7 (1973) 229.

[9] V.A. Plyuiko, Yad. Fiz. 52 (1990) 1004 [Sov.J. Nucl. Phys. 52 (1990) 639].

[10] J.M. Eisenberg, W. Greiner, Nuclear Theory. V.1: Nuclear Models, Collective and Single-Particle Phenomena, North-Holl., Amsterdam, 1987. Ch. 14, §§3-5.

[11] T. Yukawa, G. Holzwarth, Nucl. Phys. A364 (1981) 29.

[12] W. D. Myers, W. J. Swiatecki, T. Kodama, L. J. El-Jaick, E. R. Hilf, Phys. Rev. C15 (1977) 2032.

[13] S. Nishizaki, K. Ando, Prog. Theor. Phys. 71 (1984) 1263.

[14] V.A. Plyuiko, Abstracts of Intern. Conf. Nucl. Phys. Close to Barrier. Warsaw. Poland.
[15] V.M. Kolomietz, V.A. Plujko, S. Shlomo, Phys. Rev. C54 (1996) 3014.

[16] V.A. Plujko, Ital. Phys. Soc. Conf. Proc. v.59.Part1. Int. Conf. Nucl.Data Sci. Techn.
   Eds. G. Reffo, A. Ventura, C. Grandi. Trieste, 19-24 May, 1997, Trieste, Italy. P.705.

[17] S. Ayik, D. Boiley, Phys. Lett. B276 (1992) 263; B284 (1992) 482E.

[18] C. Yannouleas, R. A. Broglia, Ann. Phys. (NY) 217 (1992) 105.

[19] C.B. Dover, R.H. Lemmer, F.J.W. Hahne, Ann. Phys. (NY) 70 (1972) 458.

[20] S.S.Dietrich, B.L.Berman, Atom. Data and Nucl. Data Tabl. 38 (1988) 199.

[21] T.S.Belanova, A.V. Ignatyuk, A.B. Pashchenko, V.I. Plyaskin, The resonance capture
   of neutrons. Handbook (In Russian), Energoatomizdat, Moscow, 1986. Fig.1.12.

[22] J. Kopecky, M.Uhl, R.E. Chrien, Phys. Rev. C47 (1993) 312.
Fig. 1. The gamma-decay strength functions $\tilde{f}_{E1}$ in $^{144}Nd$. 
Fig. 2. The dependence of the dipole $\gamma$-decay strength functions on the excitation energy.