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E1 RADIATIVE STRENGTH FUNCTION FOR GAMMA-DECAY AND PHOTOABSORPTION

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Photoabsorption cross sections and γ-decay strength function are calculated and compared with experimental data to test the existing models of dipole radiative strength functions (RSF) for the middle-weight and heavy atomic nuclei. Ready-to-use tables of giant dipole resonance parameters with their errors are prepared. Systematics for GDR energy and width are given. It is shown that the phenomenological closed-form models with asymmetric shape can be used for overall estimates of the dipole RSF in the γ-ray energy region up to about 20 MeV, when GDR parameters are known or their systematics can be adopted.

1. Introduction

Gamma-emission is one of the most universal channels among the nuclear de-excitation processes which accompanies any nuclear reaction. The average probability for a γ-transition can be described through the use of the radiative strength functions [1 - 4].

Dipole electric γ-transitions (E1) are dominant, when they occur simultaneously with transitions of other multipolarities and types. Therefore we focus here on the dipole RSF. The average dipole radiative width $\overline{\Gamma}_{E1}$ per unit of the gamma-ray energy interval is determined by dipole γ-decay (downward) strength function $\overleftarrow{f}_{E1}$ in the following way

$$\overleftarrow{f}_{E1}\left(E_\gamma\right)=\frac{\overline{\Gamma}_{E1}\left(E_\gamma\right)}{3E_\gamma^3}\frac{\rho(U)}{\rho\left(U-E_\gamma\right)}, \qquad (1)$$

where $\rho(U)$ is the total density of the excited states in heated nuclei at initial excitation energy U (initial temperature T); E_γ is the γ-ray energy.

The dipole photoexcitation (upward) strength function $\vec{f}_{E1}$ and the total photoabsorption cross-section σ_{E1} are related by the following equation

$$\sigma_{E1}\left(E_\gamma\right)=3E_\gamma\left(\pi\hbar c\right)^2\vec{f}_{E1}\left(E_\gamma\right). \qquad (2)$$

In this contribution, some phenomenological and semiclassical models of E1 RSF [3, 4, 5] are investigated. For this purpose, experimental photoabsorption and gamma-decay data are compared with theoretical calculations.

2. Main features of the tested RSF models

Different models are used to describe the dipole RSF. Tested semiclassical approach with moving surface MSA [5] is based on solving the kinetic Landau - Vlasov equation for finite system with a moving surface [6]. In this case, the nuclear response function (and the RSF) consists of two terms, namely a volume component that is related to the shift of proton and neutron fluids in the nuclear interior and a surface component due to vibrations of mutually non-penetrating neutron and proton spheres.

The absorption of dipole gamma-rays in the $E_\gamma \le 20$ MeV energy region is mainly governed by excitation of the isovector giant dipole resonance (GDR). Therefore the phenomenological expressions of the RSF for nuclei in this energy range (see [2, 3] and reference therein) have a Lorentzian-like shape. The different phenomenological expressions of dipole RSF for photoabsorption and gamma-decay are presented [2 - 4]. Specifically, dipole RSF $\vec{f}_{E1}$ for photoexcitation of cold nuclei within standard Lorentzian model (SLO) and the modified Lorentzian model (MLO) can be presented in the following form (in units of MeV^{-3})

$$\vec{f}_{E1}\left(E_\gamma\right)=8.674\cdot10^{-8}\sum_{r=1}^{n}\sigma_r\Gamma_r\times$$
$$\times\frac{E_\gamma\overline{\Gamma}_r(E_\gamma)}{\left(E_\gamma^2-E_r^2\right)^2+\left[\overline{\Gamma}_r(E_\gamma)\cdot E_\gamma\right]^2}, \qquad (3)$$

where $n=1$ in spherical nuclei and $n=2$ in axially deformed nuclei; Γ_r and E_r are width and energy of the GDR (in MeV); σ_r is the peak photoabsorption cross section (in mb); $\overline{\Gamma}_r\left(E_\gamma\right)$ is an energy-dependent "width" that is equal to the GDR width at $E_\gamma=E_r$ and $\Gamma_r=\overline{\Gamma}_r\left(E_\gamma=E_r\right)$;.

The phenomenological models of the RSF are different in the expressions for $\overline{\Gamma}_r\left(E_\gamma\right)$, which reflects the description of the collective state damping. In the SLO model, the width $\bar{\Gamma}_r(E_\gamma)$ is taken as an energy-independent quantity equal to the GDR width Γ_r. The width shape is similar to the fragmentation component of the collective excitation width (one-body dissipation) and corresponds to the nucleon collisions with a moving surface of the self-consistent mean-field. In this case, the contribution of nucleon collisions in the nuclear interior is not included [7]. If the excitation energy is not too high and E_γ ranges from zero up to the GDR energy, the width $\bar{\Gamma}_r(E_\gamma)$ within MLO1 approach has the following form [4]

$$\bar{\Gamma}_r(E_\gamma) = \begin{cases} a(E_\gamma + U_f) = aU, & \text{for } \gamma-\text{decay}, \\ a\,E_\gamma, & \text{for photoabsorption}, \end{cases} \quad (4)$$

where $a = \Gamma_r / E_r$, if the normalization condition $\Gamma_r = \bar{\Gamma}_r(E_\gamma = E_r)$ is adopted.

3. Calculations and discussion

In this section, we compare results of the calculations within SLO, MLO and MSA approach with experimental data. The expressions for the phenomenological RSF both photoabsorption and gamma-decay within SLO and MLO1 depend on GDR parameters E_r, Γ_r and σ_r. We obtain these parameters from a fit of the theoretical photoabsorption cross sections within the MLO1 and SLO models to the experimental and evaluated data, and then we use the GDR characteristics for calculation of the RSF for gamma-decay.

In line with Refs. [4, 8, 9], dipole photo-absorption cross-section σ_{E1} is taken to be equal to the total photoabsorption cross-section $\sigma(\gamma,\ abs)$. If experimental or evaluated data on $\sigma(\gamma,\ abs)$ for given nuclei is absent in data base, then the total cross section is approximated by the total photoneutron cross section $\sigma(\gamma,\ sn)$

$$\sigma_{E1} \cong \sigma(\gamma,\ abs) \cong \sigma(\gamma,\ sn) = \\ = \sigma(\gamma,\ 1nx) + \sigma(\gamma,\ 2nx) + \sigma(\gamma,\ 3nx) + ... + \sigma(\gamma,\ F), \quad (5)$$

where $\sigma(\gamma,\ F)$ is the total photofission cross section and $\sigma(\gamma,\ Nnx)$ the a sum of all cross sections leading to the ejection of N neutrons, i.e. $\sigma(\gamma,\ Nnx) = \sigma(\gamma,\ Nn) + \sigma(\gamma,\ Nn\,p) + \sigma(\gamma,\ Nn\alpha) + ...$.

The relationship (5) is realized with a good accuracy in rather heavy nuclei due to small contributions of the photo-charged-particle reaction cross sections to $\sigma(\gamma,\ abs)$. Experimental data on total photoneutron, $\sigma(\gamma,\ sn)$, and total photoabsorption, $\sigma(\gamma,\ abs)$, cross sections are taken from the international nuclear data library EXFOR (http://www-nds.iaea.org/exfor/).

For some nuclei the EXFOR data base does not contain experimental information on photoneutron cross section, therefore $\sigma(\gamma,\ sn)$ is estimated by using the total photofission cross section $\sigma(\gamma,\ F)$, photoneutron cross sections $\sigma(\gamma,\ 1nx)$, $\sigma(\gamma,\ 2nx)$, $\sigma(\gamma,\ 3nx)$ and the inclusive photoneutron yield cross section $\sigma(\gamma,\ xn)$ which includes the multiplicity of neutrons emitted in each reaction event: $\sigma(\gamma,\ xn) = \sigma(\gamma,\ 1nx) + +2\sigma(\gamma,\ 2nx) + 3\sigma(\gamma,\ 3nx) + ... + \bar{\nu}\sigma(\gamma,\ F)$, with $\bar{\nu}$ for the average multiplicity of photofission neutron. Errors of estimated cross are found with help of the procedure that is similar to one described in ref. [4].

In order to obtain more reliable GDR parameters, the deuteron photodisintegration cross section, $\sigma_{QD}(E_\gamma)$, is extracted from total photoabsorption cross section $\sigma(\gamma,\ abs)$. The component, $\sigma_{QD}(E_\gamma)$, is taken according to Ref. [10].

An adjustment is performed by the least square method minimizing the χ^2 - value:

$$\chi^2 = \frac{1}{N - N_{par}} \sum_{i=1}^{N} \left(\frac{\sigma_{theor}(E_{\gamma,i}) - \sigma_{\exp}(E_{\gamma,i})}{\Delta\sigma_{\exp}(E_{\gamma,i})} \right)^2 , \quad (6)$$

where $\sigma_{theor}(E_{\gamma,i})$ is the theoretical cross sections calculated with eq. (2), (3) at γ-ray energy $E_{\gamma,i}$, $\sigma_{\exp}(E_{\gamma,i})$ the experimental cross section and $\Delta\sigma_{\exp}(E_{\gamma,i})$ the corresponding statistical error, and N the total number of data points; N_{par} is the number of parameters deduced from the fit (the value $N_{par} = 3$ or $N_{par} = 6$ is used for spherical or deformed nuclei respectively). Note, two types of errors are used for estimated and evaluated data. The first type errors equal to ten percent of the cross section: $\Delta\sigma_{\exp}(E_{\gamma,i}) = 0.1 \cdot \sigma_{\exp}(E_{\gamma,i})$. The second type errors are linearly dependent on energy: $\Delta\sigma_{\exp}(E_{\gamma,i}) = \delta(E_{\gamma,i}) \cdot \sigma_{\exp}(E_{\gamma,i})$, where $\delta(E_{\gamma,i})$ is the relative error. We assumed that relative errors should be minimum near the resonance energy and maximum near tails, and we take the energy dependence of the relative error in spherical nuclei in the triangular shape

$$\delta\left(E_\gamma\right) = \delta_{\min} + b\left|E_r - E_\gamma\right|, \qquad (7)$$

and trapezoidal shape for deformed nuclei

$$\delta\left(E_\gamma\right) = \begin{cases} \delta_{\min} + b\left(E_{r1} - E_\gamma\right), \; E_\gamma < E_{r1}, \\ \delta_{\min}, \; E_{r1} \le E_\gamma \le E_{r2}, \\ \delta_{\min} + b\left(E_\gamma - E_{r2}\right), \; E_\gamma > E_{r2}. \end{cases} \qquad (8)$$

Hear, $\delta_{\min} = 0.1$, E_{r1}, E_{r2} are energies of first and second resonance, $b = \left(\delta_{\max} - \delta_{\min}\right) / \left(E_{r1} - E_{\gamma,1}\right)$, where relative error at the first presented value of experimental gamma-ray energy $\delta_{\max} = 0.5$.

The best least square minimization was performed using the MINUIT package (http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html). Errors (standard deviations) of GDR parameters are calculated by the use of MINOS procedure of the MINUIT code.

With the use of the obtained GDR energies and widths, we looked for their systematic in the forms

$$\bar{E}_r = a_1 A^{-1/3} + a_2 A^{-1/6} \text{ (MeV)}, \; \Gamma_r = a_3 E_r^{1.91} \text{ (MeV)}, \qquad (9)$$

where a_1, a_2, a_3 are parameters of systematic, A is a mass number and $\bar{E}_r$ is defined by the equestion

$$\bar{E}_r = \begin{cases} E_r, \; |\beta_2| \le 0.1, \\ \left(E_{r1} + 2E_{r2}\right)/3, \; \beta_2 < 1, \\ \left(2E_{r1} + E_{r2}\right)/3, \; \beta_2 > 1. \end{cases} \qquad (10)$$

Here, $\bar{E}_r$ equal to energy of resonance peak for spherical nuclei and mean energy in deformed nuclei with quadrupole deformation parameter β_2. The results of the fitting and χ^2-values renormalized on χ^2-values for parameters obtained in [8] are presented in epy Table.

Parameters and χ^2 deviations for width and energy systematic within SLO and SMLO models

Model	a_1	a_2	a_3	$\chi^2_{\bar{E}_r}/\chi^2_{[8]}, \chi^2_{\Gamma_r}/\chi^2_{[8]}$
SLO	27.469 ± 0.009	22.063 ± 0.004	0.02691 ± 0.00004	0.82, 0.93
$SLO_{[8]}$	31.2	20.6	0.026 ± 0.005	1
MLO	28.690 ± 0.010	21.731 ± 0.004	0.02769 ± 0.00003	0.99, 0.79

Comparisons of GDR energies and widths with systematic are presented in Fig. 1

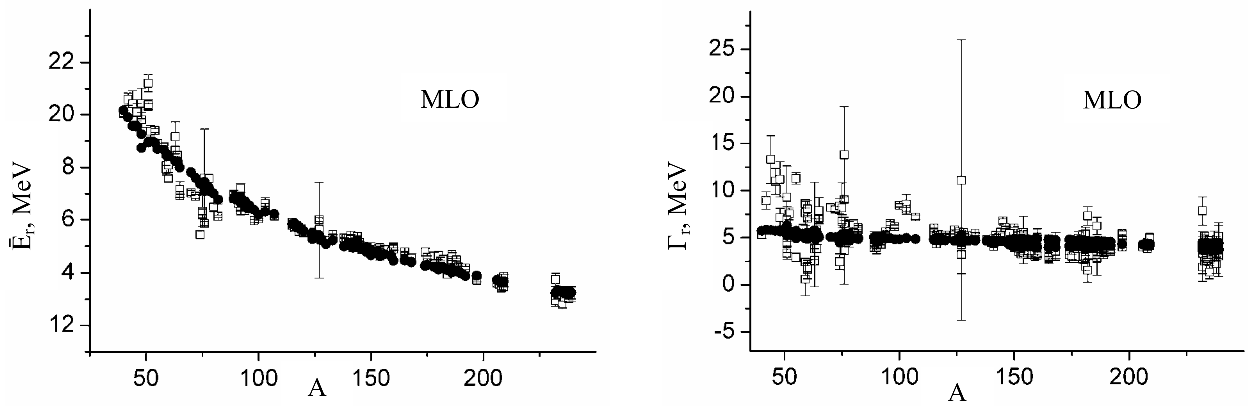
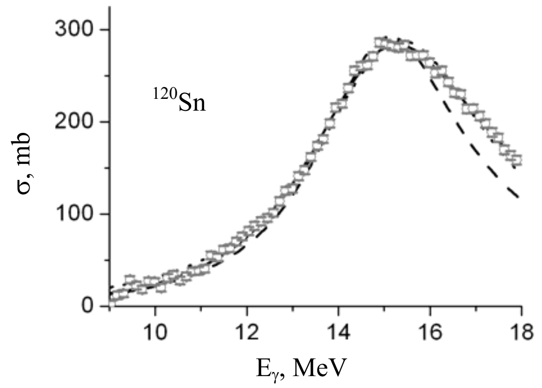


Fig. 1. Comparisons of energy (left panel) and width (right panel) within MLO1 (SMLO) model with systematics: circles – systimatics; squares – results of fitting with estimated errors.

The calculations were done for 120 nuclei. For example, the results for photoabsorption cross section on ^{120,124}Sn as well as their comparison with experimental data are shown in Fig. 2. Gamma-decay E1 + M1 strength function on ^{118}Sn as well as its comparison with experimental data is shown in Fig. 3. For calculation of the M1 RSF, the method from [3] was used.



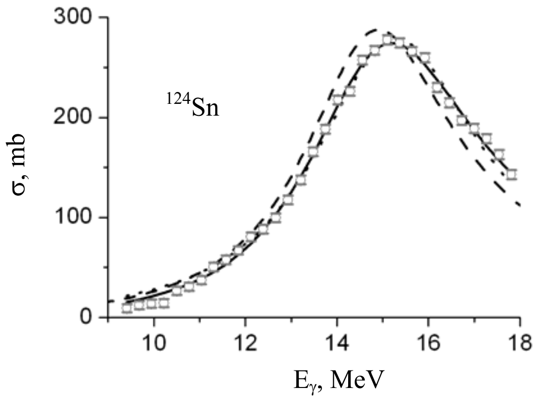


Fig. 2. Photoabsorption cross section for ^{120}Sn, left panel, and ^{124}Sn, right panel. Curves: solid line – MLO; dot line – SLO; dash line – MSA; points – experimental data. Experimental data is taken from [11].

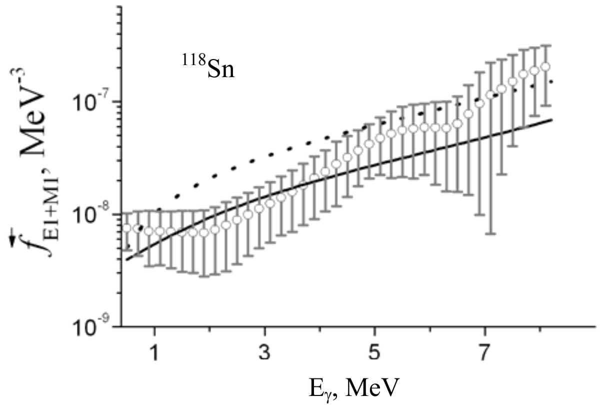


Fig. 3. Gamma-decay strength function RSF for ^{118}Sn. Curves: solid line – MLO; dot line – SLO; open points – experimental data. Experimental data is taken form [12].

It can be seen that the different predictions are in rather close agreement in a range of γ-ray energies around the GDR peak. Overall comparison of the calculations within different simple models and experimental data shows that MLO1 approach with asymmetric shape of the RSF provides a unified and rather reliable simple method to estimate the dipole RSF both for γ-decay and for photoabsorption over a relatively wide energy interval ranging from zero to slightly above the GDR peak, at least, when GDR parameters are known or GDR systematics can be safely applied to. Otherwise, the semi-classical MSA seem to be more adequate to describe the dipole photoabsorption RSF in spherical nuclei of medium mass.

It can be noted that different variants of the MLO1 approach are based on general relations between the RSF and the nuclear response function. Therefore they can potentially lead to more reliable predictions among simple models. However, the energy dependence of the width is governed by complex mechanisms of nuclear dissipation and is still an open problem.

Reliable experimental information is needed to better determine the temperature and energy dependence of the RSF, so that the contributions of the different mechanisms responsible for the damping of the collective states can be further investigated.

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E1 РАДІАЦІЙНІ СИЛОВІ ФУНКЦІЇ ГАММА-РОЗПАДУ ТА ФОТОПОГЛИНАННЯ

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За допомогою порівняння розрахунків перерізів фотопоглинання та радіаційних силових функцій гамма-розпаду з експериментальними даними опротестовано прості моделі опису дипольних радіаційних силових функцій для середніх та важких атомних ядер. Визначено значення параметрів гігантських дипольних резонансів (ГДР) та їх похибки. Отримано систематику для енергій та ширин ГДР. Показано, що феноменологічні моделі асиметричного вигляду для опису дипольних радіаційних силових функцій є найбільш надійними для оцінки дипольних радіаційних силових функцій в інтервалі енергій гамма-квантів до 20 МеВ, якщо відомі параметри ГДР чи систематики для них.

E1 РАДИАЦИОННЫЕ СИЛОВЫЕ ФУНКЦИИ ГАММА-РАСПАДА И ФОТОПОГЛОЩЕНИЯ

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С помощью сравнения расчетов сечений фотопоглощения и радиационных силовых функций гамма-распада с экспериментальными данными протестированы простые модели описания дипольных радиационных силовых функций в средних и тяжелых атомных ядрах. Найдены параметры гигантских дипольных резонансов (ГДР) и их погрешности. Получена систематика энергий и ширин гигантских дипольных резонансов. Показано, что феноменологические модели асимметричного вида для описания дипольных радиационных силовых функций являются наиболее надежными при оценке дипольных радиационных силовых функций в интервале энергий гамма-квантов до 20 МэВ, если известны параметры ГДР или их систематики.

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