AVERAGE DESCRIPTION OF DIPOLE GAMMA-TRANSITIONS IN HOT ATOMIC NUCLEI

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Abstract

Renewed systematics for giant dipole resonance (GDR) parameters is given. New version of the modified Lorentzian approach for radiative strength function is proposed. The gamma-decay strength functions are calculated using renewed GDR parameters. The results are compared with experimental data. The calculations of the neutron induced reaction observables defined by the different RSF models were compared with experimental data. It is demonstrated that closed-form approaches with asymmetric shape of the gamma strength provide the most reliable simple method for description of gamma-decay processes.

1. Introduction

Gamma-emission is one of the most universal channels of the nuclear de-excitation which accompany any nuclear reaction. The photoabsorption and gamma-decay processes can be described by means of gamma-ray (radiative) strength functions (RSF) [1]. These functions are involved in calculations of the observed characteristics of most nuclear reactions. They are also used for investigation of nuclear structure (nuclear deformations, energies and widths of the giant dipole resonances, contribution of velocity-dependent force, shape-transitions, etc.) as well as in studies of nuclear reaction mechanisms.

Dipole electric (E1) gamma-transitions are dominant when they occur simultaneously with transitions of other multipolarities. Isovector Giant Dipole Resonances (IVGDR or GDR) are strongly displayed in E1 gamma-transitions in processes of photoabsorption and gamma-decay of the atomic nuclei [1-3]. It provides possibility to obtain GDR parameters from investigations of the E1 gamma-transitions. A comprehensive experimental database of updated values of the GDR parameters with estimations of their uncertainties (one-sigma standard deviation) was presented in [3], that is especially important for nuclear reaction codes for the reliable modelling of E1 gamma-ray cascades in highly excited nuclei as well as for the verification of different theoretical approaches used to describe GDR resonances.

In this contribution, a new version of modified Lorentzian approach for RSF [1,3] is proposed with the use of the renewed GDR width systematics. Different Lorentzian-type models of E1 strength functions [1] are tested by comparison of experimental data with theoretical calculations.

2. Renewed GDR parameter systematics

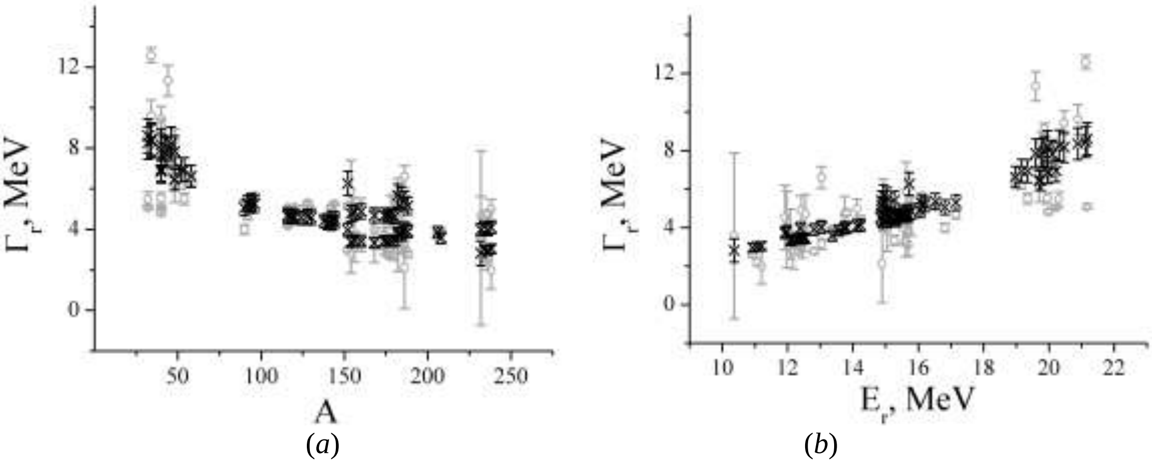
The values and corresponding uncertainties of the Lorentzian-like model parameters were presented in Ref.[3] from a fit of the theoretical photoabsorption cross sections to the experimental data for 131 isotopes from ^{10}B to ^{239}Pu nuclei (262 entries) and 9 elements of natural isotopic composition (14 entries). The GDR component of the photoabsorption cross section was calculated within standard Lorentzian (SLO) model or within simplified version (SMLO) of the modified Lorentzian approach MLO1 [1, 3]. This compilation updates and extends the RIPL-3 database contained in files "gamma/gdr-parameters&errors-exp-SLO.dat" and "gamma/gdr-parameters&errors-exp-MLO.dat" [1].

In this contribution, the values of GDR parameters and their uncertainties from [3] are used to obtain renewed systematics of GDR parameters. The expression for new systematics for GDR width are taken in the following form (in units of MeV):

$$\Gamma_{r,j} \equiv \Gamma_{r,j}^{(sys)} = a_1 \cdot E_{r,j} + a_2 \cdot \beta_{dyn} \cdot E_{r,j} \cdot \gamma_j \, , \quad (1)$$

where a_1, a_2 are constants, $E_{r,j}$ and $\Gamma_{r,j}$ are GDR energy and width for vibration along j-axis respectively, $\gamma_j = {R_0 / R_j}^{1.6}$, with R_j, R_0 for nuclear radiuses along j axis and for radius of equivalent spherical nuclei. Parameters of quadrupole dynamical deformation β_{dyn} were determined from systematics [5]: $\beta_{dyn} = \sqrt{1224 A^{-7/3} / E_{2_1^+}}$, where $E_{2_1^+}$ is energy of the first collective 2^+ state. The systematics $E_{2_1^+} = 65 A^{-5/6} / (1 + 0.05 E_{shell})$ was used in the absent of experimental data on $E_{2_1^+}$ with E_{shell} for shell correction energy calculated by the Myers-Swiatecki mass formula [1]. The χ^2 method was used to fit parameters for spherical and axially deformed nuclei. The value $\Delta\Gamma_{r,j} = 1$ (MeV) was taken as GDR width uncertainty. The values of constant and their uncertainties $a_1 = 0.255(20)$, $a_2 = 0.370(83)$ were obtained by the fitting within SLO model. Similar systematics is obtained also for the SMLO model.

The comparisons of the GDR widths with systematics (1) are presented in figure 1.

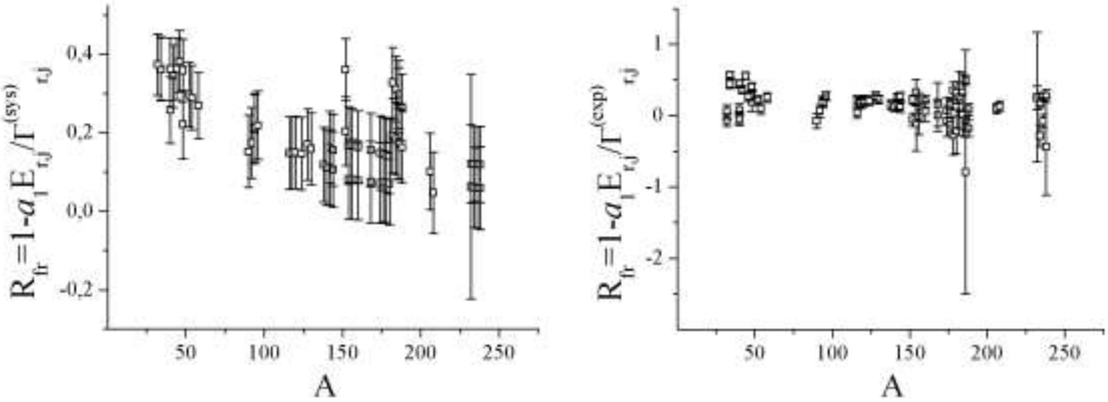


(*a*) (*b*)

Fig. 1. Mean GDR widths as a function of mass number (*a*) and GDR energies (*b*) calculated by the use of SLO model: open circles - renewed GDR parameters [3]; crosses - parameters obtained by the systematics (1).

As one can see from fig. 1, the values of GDR widths within renewed systematics are in good agreement with experimental GDR parameters for the middle-weight and heavy atomic nuclei. Figure 2 demonstrates contribution of the fragmentation component

$R_{fr,j} = 1 - a_1 E_{r,j} / \Gamma_{r,j}$ into the full GDR width. It can be seen that the contribution of the fragmentation component to the full width value can be up to 40 percent.



(*a*) (*b*)

Fig. 2. Ratio $R_{fr,j} = 1 - a_1 E_{r,j} / \Gamma_{r,j}$ of fragmentation component to the total GDR width for different nuclei. Panel (*a*) - $\Gamma_{r,j}$ defined by eq.(1), panel (*b*) - $\Gamma_{r,j}$ experimental GDR width from[3].

3. Test of simplified RSF models

In order to test simplified RSF models [1], the gamma-decay radiative strength functions are calculated and compared with experimental data. The renewed GDR parameters were used: the SMLO parameters [3] were taken for calculations within MLO models (MLO1, MLO2, MLO3), and parameters of SLO model were applied for other models (SLO, the enhanced generalized Lorentzian, EGLO, and generalized Fermi-Liquid model, GFL). Variants 1-3 of MLO model give similar trend for photoabsorption cross sections and, therefore, only the MLO1 calculations are shown in the figures.

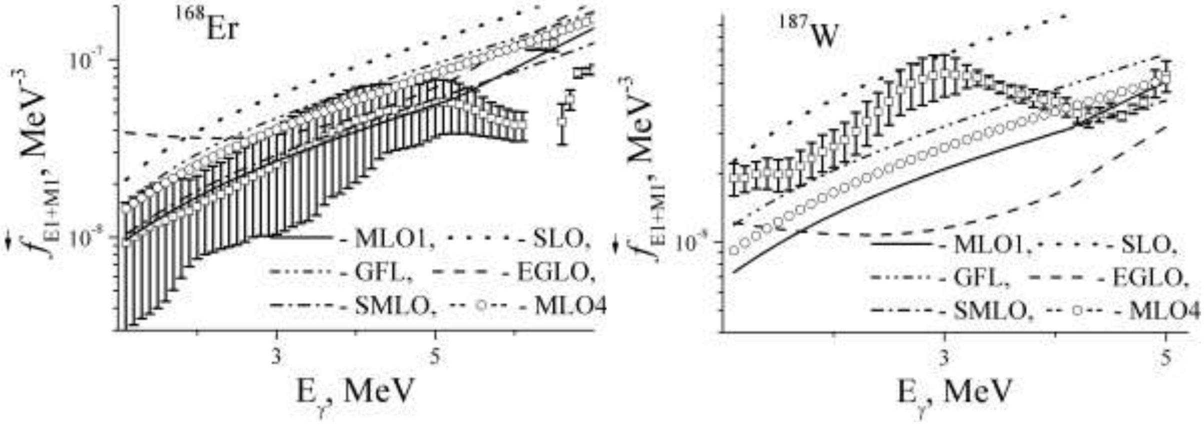
On a base of the systematic (1) for the GDR width, we propose new expression for description of the energy dependent width:

$$\Gamma_j(E_\gamma, U) = b_j \; a_1 \cdot (E_\gamma + U) + a_2 \cdot \beta_{dyn} \cdot E_{r,j} \cdot \gamma_j \;, \tag{2}$$

where E_γ and U - energy of the gamma-rays and excitation energy respectively. Parameters $b_j = 1$ in the absence of experimental data on GDR width $\Gamma_{r,j}$ and they are found from the condition $\Gamma(E_\gamma = E_{r,j}, U = 0) = \Gamma_{r,j}$ in the opposite cases. The calculations of the MLO model with this expression for energy dependent width are named below as MLO4.

The comparison of the calculations of the E1 RSF of different forms with the experimental data is shown in Figs. 3 - 6. Experimental data and calculations correspond to the sum of the E1 and M1 transitions. The M1 strength functions were calculated by the methods described in the RIPL[1] with the use of the Lorentzian shape for the M1 RSF $\overleftarrow{f}_{M1}$ with the magnitude that was adjusted to the ratio $\overleftarrow{f}_{M1} / \overleftarrow{f}_{E1}$ at neutron separation energy.

Fig. 3 shows the dipole gamma-decay strength functions for ^{168}Er and ^{187}W within different RSF models in comparison with experimental data from [6, 7]. The calculations were performed for excitation energy $U = S_n$.



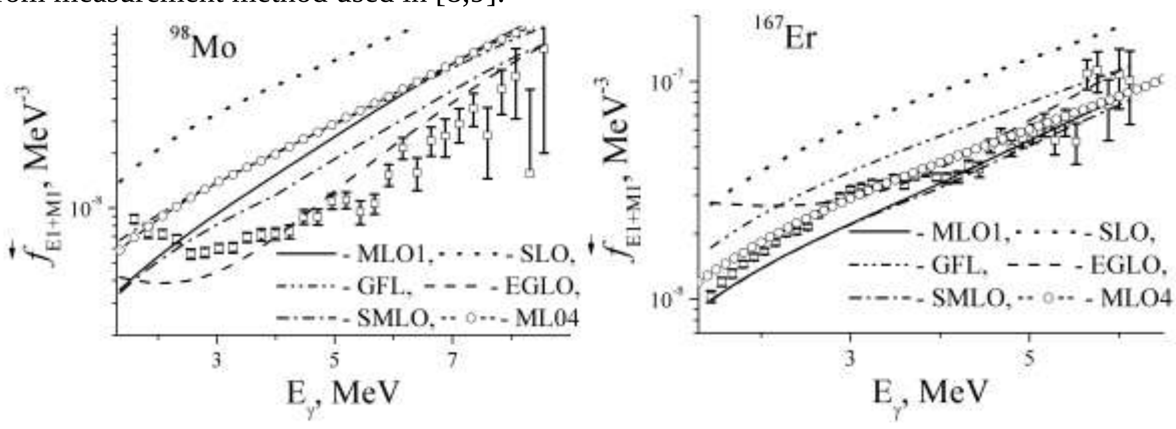
(*a*) (*b*)

Fig. 3. The gamma-decay strength functions within different RSF models for ^{168}Er (*a*) and ^{187}W (*b*): $U = S_n$. Experimental data are taken from [6, 7]

The fig.4 shows dipole gamma-decay strength functions for ^{98}Mo and ^{167}Er within different RSF models in comparison with experimental data from [8,9]. The experimental data from [8, 9] are averaged with the excitation energy U by the following form:

$$f_{aver}(E_\gamma) = \begin{cases} \dfrac{1}{U_{\mathrm{m}} - 4} \displaystyle\int_4^{U_{\mathrm{m}}} \overleftarrow{f}(E_\gamma, U_f = U_i - E_\gamma) dU_i, & 1 < E_\gamma \le 4, \\ \dfrac{1}{U_{\mathrm{m}} - E_\gamma} \displaystyle\int_{E_\gamma}^{U_{\mathrm{m}}} \overleftarrow{f}(E_\gamma, U_f = U_i - E_\gamma) dU_i, & 4 < E_\gamma \le U_{\mathrm{m}}, \end{cases}$$

where $U_{\mathrm{m}} = 8\ MeV \approx S_n$, S_n-neutron separation energy. This averaging on U is resulted from measurement method used in [8,9].



(*a*) (*b*)

Fig. 4. The gamma-decay strength functions within different RSF models for ^{98}Mo (*a*) and for ^{167}Er (*b*). The experimental data are taken from [8, 9]

In fig. 5 results of the calculations for the ^{92}Mo and ^{96}Mo nuclei are compared with experimental data from [10]. The calculations were performed for excitation energy $U = S_n$.

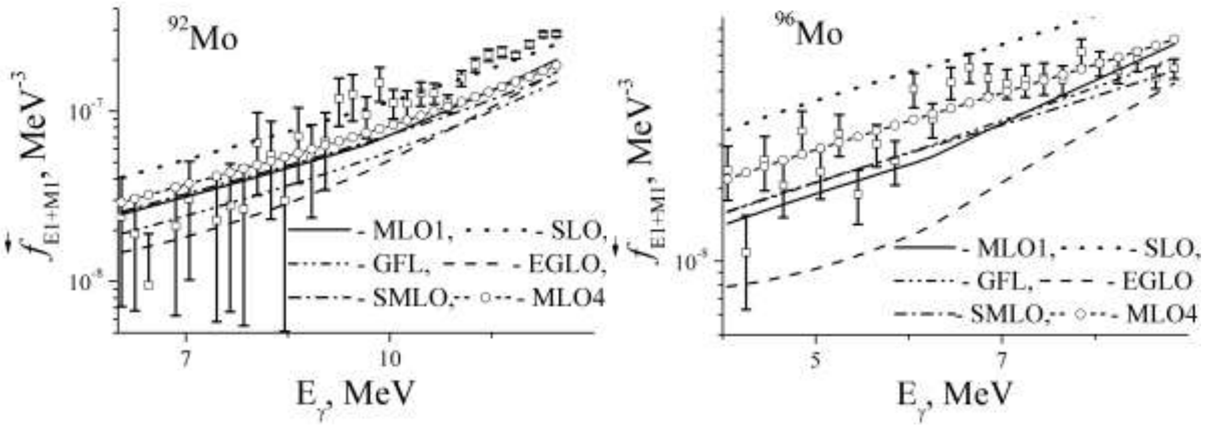


Fig. 5. The gamma-decay strength functions within different RSF models for ^{92}Mo (*a*) and ^{96}Mo (*b*): $U = S_n$. Experimental data are taken from [10]

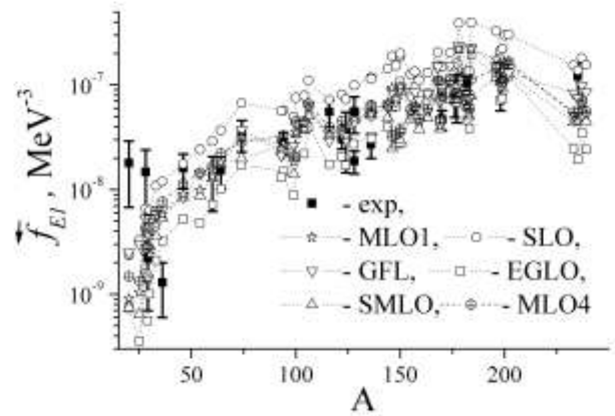


Fig. 6. The gamma-decay strength functions within different RSF models: $U = S_n$. Experimental data are taken from [11].

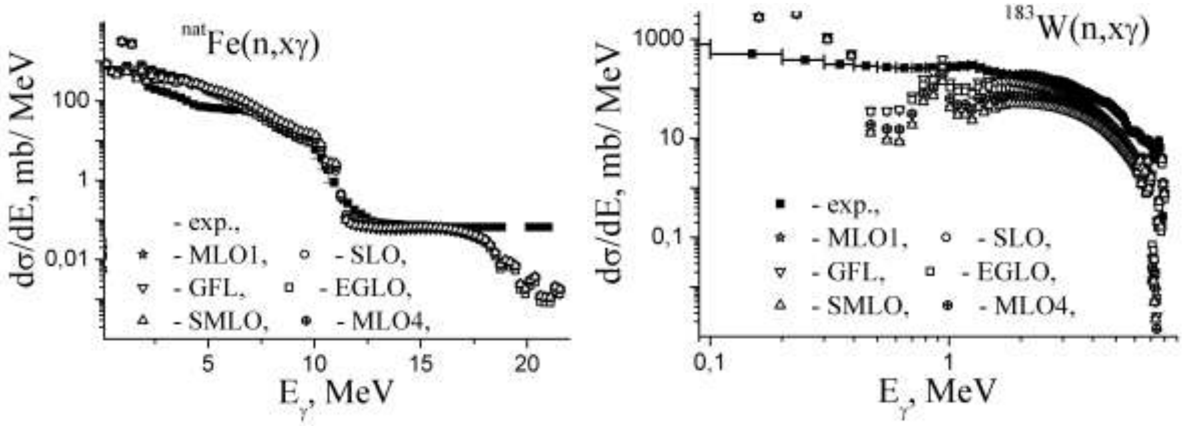
Fig. 6 demonstrates comparison of the calculations for gamma-decay strength functions within different RSF models with experimental data from [11] for different nuclei. The calculations were performed for excitation energy $U = S_n$.

We see from these figures that RSF models with asymmetric shape (EGLO, GFL, MLO1, SMLO, MLO4) give better description of the experimental data than the SLO model in the low-energy region, which predict a vanishing strength function at zero gamma-ray energy. The results of the calculations of gamma-decay RSF within EGLO, GFL, MLO1, MLO4 and SMLO models are all characterized by a non-zero limit. It can be also noted that different variants of the MLO (MLO1, MLO4, SMLO) approach are based on general relations between the RSF and the nuclear response function [12]. Therefore, they can potentially lead to more reliable predictions among different simple models.

Table 1 presents the ratio $\chi^2(model)/\chi^2(\text{SLO})$ of chi-square deviations of the theoretical RSF of gamma-decay from experimental data. The average values of the ratio for approximately 40 nuclei with $25 < A < 200$ were obtained. As one can see from this table and figures, asymmetric RSF gives better agreement with the experimental data at least in approximation of axially-deformed nuclei which is adopted in presented calculations. On the whole, proposed variant of the MLO model (MLO4) leads to the best description of the experimental data. It should be noted that experimental data compilation [11] was made by the different group measurements and χ^2_i for some nuclei may strongly effect on full sum $\sum_{i=1}^{n} \chi_i^2(model)/\chi_i^2(\text{SLO})$.

Table 1. The average $\sum_{i=1}^{n} \chi_i^2(model)/\chi_i^2(\text{SLO})\ /n$ ratio of chi-square deviations of the theoretical RSF of γ-decay from experimental data. n - cumulative number of nuclei ([6,7]: $n = 38$, [8,9]: $n = 41$, [10]: $n = 7$, [11]: $n = 53$).

Exp.Data	n	Model				
		EGLO	GFL	MLO1	SMLO	MLO4
[6,7]	38	1,22	0,91	0,98	1,01	0,89
[8,9]	41	0,18	0,17	0,11	0,11	0,13
[10]	7	2,22	2,11	1,16	1,71	1,20
[11]	53	9,38	2,76	8,75	13,81	6,97



(*a*) (*b*)

Fig. 7. Gamma-ray spectra from $^{nat}Fe(n,x\gamma)$ and $^{183}W(n,x\gamma)$ reactions calculated with EMPIRE code using different models for the RSF. The experimental data are taken from [13] for panel *a* ($E_n = 14.1$ MeV) and from [14] for panel *b* ($E_n = 0.5$ MeV).

Figure 7 shows gamma-ray spectra from $^{nat}Fe(n,x\gamma)$ and $^{183}W(n,x\gamma)$ reactions at $E_n = 14.1$ MeV for panel *a* and at $E_n = 0.5$ MeV for panel *b*. Excitation functions of the $^{nat}Fe(n,\gamma)$, $^{183}W(n,\gamma)^{184}W$ reactions are demonstrated on fig.8. The cross section calculations were performed by the use of EMPIRE 3.1 Rivoli code [16]. It should be mentioned that in these calculations, gamma-decay widths were normalized on their experimental values at the neutron binding energy. The difference in the calculations of gamma-ray spectra and excitation functions within the different RSF models is growing for heavy nuclei.

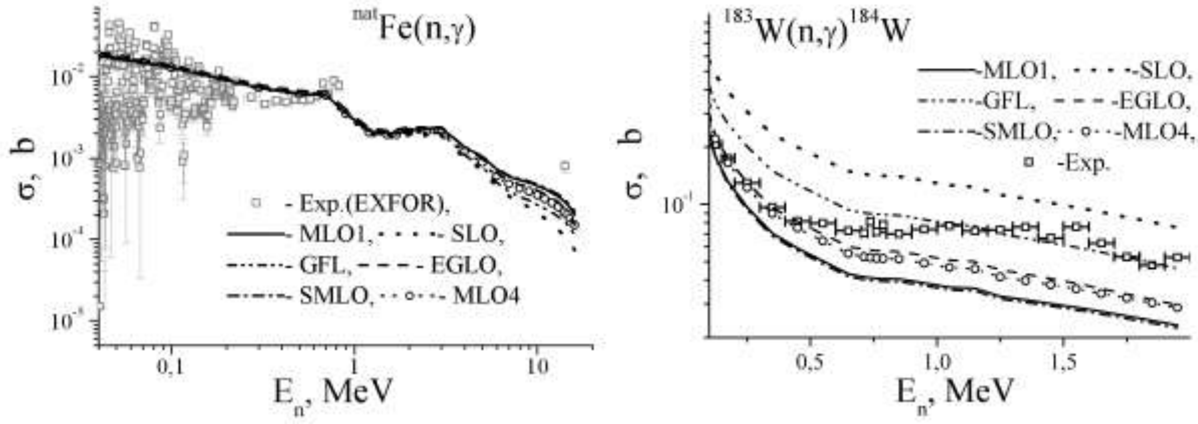


Fig. 8. The excitation functions of ${}^{nat}Fe(n,\gamma)$ and ${}^{183}W(n,\gamma)^{184}W$ reactions using different RSF models. The experimental data are taken from EXFOR data library for panel *a* and from [15] for panel *b*.

It can be seen from fig. 7,8 that calculations within the RSF models with asymmetric shape in general give better agreement with the experimental data for middle-weighted and heavy nuclei.

4. Conclusions

The overall comparison of the calculations within different simple models and experimental data shows that the EGLO and MLO (SMLO) approaches with asymmetric shape of the RSF provide a universal and rather reliable simple method for estimation of the dipole RSF over a relatively wide energy interval ranging from zero to slightly above the GDR peak. In generally, new version of MLO model (MLO4) leads to best description of the experimental data as for gamma-decay and for photoexcitation functions.

Reliable experimental information is needed for more accurate determination of the temperature and energy dependence of the RSF. It would give possibility to investigate the contributions of the different mechanisms responsible for the damping of the collective states and provide more reliable test of the closed-form models of the E1 RSF.

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