6 Gamma-Ray Strength Functions

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Summary

Gamma-ray strength functions are important for description of the gamma emission channel in nuclear reactions. This is an almost universal reaction channel since gamma rays, in general, may accompany emission of any other emitted particle.

The collected data bring information on experimental data and parameterizations of giant resonaces (mainly $E1$, but also $E2$ and $M1$) and the global systematics derived from experimental strength function data.

Recommended giant resonance parameters (not only those for giant dipole resonances) are summarized in **kopecky.readme**, and a tabular form of GDR parameters for specific nuclei is given in recommended file **beijing_gdr.dat**. Other file *varlamov.dat* brings additional useful information on GDR parameters.

Information on strength functions is also in **kopecky.readme** and an extensive systematics of global strength function data is in recommended file **kopecky.dat**.

6.1 Introduction

The impact of different models for gamma-ray strength functions f_{XL} on the calculation of neutron capture related experimental quantities, such as total radiative width, cross sections and gamma-ray spectra, has been studied in Refs. [6.1–6.11] and the results and recommendations are discussed in Chapter 6.2. Traditional models, used to describe radiative $E1$, $M1$ and $E2$ strength, namely the standard Lorentzian for $E1$ and the single-particle model for $M1$ and $E2$, result in a strong overestimation of all pertinent experimental quantities.

For $M1$ and $E2$ radiation we recommend strength functions derived from a standard Lorentzian with a global set of parameters. This formulation is superior to the traditionally applied single-particle models. For the dominant $E1$ strength, however, a generalized Lorentzian, with an energy dependent width and a finite limit as the energy tends to zero, is the best representation. It reproduces data reasonably well in the mass region A=50–200 with the exception of strongly deformed targets between A=150 and 170, underestimating the experimental values. In order to obtain $E1$ strength function model for the whole mass region an "enhanced generalized Lorentzian" is proposed, with two parameters depending smoothly on the mass number.

Important quantities for calculation of the gamma-ray strength functions are Lorentzian parameters of particular giant resonances. For $E1$ and $E2$ giant resonances they are traditionally derived from the analysis of the photoabsorption cross sections. However, this experimental data base is rather scarce and no experimental data are available for many target nuclei. Therefore several global systematic parameterizations of Lorentzian parameters have been derived for all multipolarities and they are quoted and discussed in Chapter 6.3.

The calculated gamma-ray strength functions can be directly compared to experimentally determined, usually averaged, strength functions. Earlier compilations of photon-strength functions, based on experimental data from resonance- or thermal-neutron capture and photonuclear reactions, have been recently reviewed and updated with new data [6.12, 6.13, 6.14] together with their uncertainties. The individual experimental values have been used to test directly different strength function models, in particular for $E1$ radiation (see e.g. Ref. [6.15]). Further they resulted in derived global systematics of f_{E1} and f_{M1} values as a function of atomic mass A, which can be used for normalizations in statistical-model calculations. Brief description of the results is discussed in Chapter 6.4.

6.2 Models for γ-Ray Strength Functions

The gamma-ray strength function for multipole type XL is defined as the average reduced partial radiation $E_\gamma^{-(2L+1)}\langle\Gamma_{XL}(E_\gamma)\rangle$ per unit energy interval

$$f_{XL}(E_\gamma) = E_\gamma^{-(2L+1)}\langle\Gamma_{XL}(E_\gamma)\rangle/D \tag{6.1}$$

of resonances with average spacing D; E_γ is the transition energy. The corresponding gamma-ray transmission coefficient $T_{XL}(E_\gamma)$ is given by the relation

$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{(2L+1)} f_{XL}(E_\gamma). \tag{6.2}$$

Therefore gamma-ray strength functions enter as important ingredients into compound nucleus model calculations of capture cross sections, gamma-ray production spectra, isomeric state populations and into the assessment of the competition between gamma-ray and particle emission. The relevant multipolarities in this context are $E1$, $M1$ and $E2$.

On Refs. [6.1–6.11] strength function models have been tested by comparison to various experimental data related to neutron capture. Cross sections and spectra depend on the gamma-ray strength at all transition energies but do not differentiate between multipolarities; so they are mainly sensitive to the dominant El strength. Analysis of resonance transitions allows to determine the multipolarity but the resulting strength functions compose only a narrow energy region.

The simplest model for gamma-ray strength functions is the single-particle model prescribing an energy independent strength [6.16]. We used this model for $M2$-, $E3$- and $M3$ radiation with a strength of one Weisskopf unit per MeV.

Gamma-ray strength functions may be related to the photoabsorption cross section. If the latter is dominated by a giant resonance (GR) of Lorentzian shape Brink's hypothesis [6.17] leads to a strength function derived from a **standard Lorentzian**

$$f_{XL}^{SLO}(E_\gamma) = \frac{26\times 10^{-8}}{2L+1}\sigma_0\Gamma E_\gamma^{(3-2L)}\frac{\Gamma_0}{(E_\gamma^2-E_0^2)^2+E_\gamma^2\Gamma_0^2}\ \ [\mathrm{mb}^{-1}\mathrm{MeV}^{-2}], \tag{6.3}$$

where the Lorentzian parameters (σ_0, E_0, Γ_0) respectively stand for peak cross section, energy and width of the GR. We used this model for $E1$, $M1$ (spin-flip giant resonance [6.18]) and $E2$ (isoscalar giant resonance [6.19]) radiation. For $E1$ the Lorentzian parameters were taken from the analysis of the photoabsorption cross section [6.18] of the compound or a neighbouring nucleus. Global parameters were employed for $M1$ and $E2$ radiation (see Chapter 6.2). For nuclei with a split GDR we used in Eqs. (6.3), (6.5) and (6.7) the incoherent sum of two analogue terms; the same parameters (k_0, ϵ_0) for each term were used in Eqs. (6.6) and (6.7). For targets with A=175–205 and for ^{93}Nb we included a standard Lorentzian pygmy resonance [6.1] with parameters determined by fitting the high-energy end of the gamma-ray production spectrum.

For the dominant $E1$ radiation the standard Lorentzian model severely overestimates the experimental data and improvements based on microscopic approaches are needed. The theory of Fermi liquids [6.20] predicts an energy and temperature dependent width of the giant dipole resonance (GDR) $\Gamma(E_\gamma, T) = \alpha(E_\gamma^2 + 4\pi^2 T^2)$, where α is a normalization constant. The first term reflects the spreading of particle hole states into more complex configurations while the second one accounts for collision of quasiparticles. The temperature T refers to the absorbing state and can be calculated within a level density model. Kadmenskij *et al.* [6.21] suggested to choose α so as to guarantee compatibility with photoabsorption data

$$\Gamma_K(E_\gamma, T) = \frac{\Gamma_0}{E_0^2}(E_\gamma^2 + 4\pi^2 T^2). \tag{6.4}$$

Generalized Lorentzian, as proposed by Kopecky and Chrien [6.15], consists of two terms: a Lorentzian with the energy dependent width according to Eq. (6.4) and the (non-zero) $E_\gamma \to 0$ limit of the model of Kadmenskij *et al.* [6.21]

$$f_{E1}^{GLO}(E_\gamma) = 8.68\times 10^{-8}\sigma_0\Gamma_0 \left[E_\gamma \frac{\Gamma_K(E_\gamma, T)}{(E_\gamma^2 - E_0^2)^2 + E_\gamma^2 \Gamma_K^2(E_\gamma, T)} + 0.7 \frac{\Gamma_K(E_\gamma = 0, T)}{E_0^3} \right] \quad [\mathrm{mb}^{-1}\mathrm{MeV}^{-2}]. \tag{6.5}$$

Up to an energy around the neutron binding energy the $E1$ strength resulting from Eq. (6.5) and that from the model of Kadmenskij et al. [6.21] are very similar.[4] In Ref. [6.1] we showed for some selected spherical nuclei that the generalized Lorentzian model provides a reasonable simultaneous description of average resonance capture (ARC) data, capture cross sections and gamma-ray production spectra. To reproduce also data for strongly deformed nuclei we proposed in Refs. [6.3–6.5, 6.8] to use in Eq. (6.5) instead of $\Gamma_k(E_\gamma, T)$ the following *empirical* generalization of the energy dependent width

$$\Gamma_{En}(E_\gamma, T) = \left[k_0 + (1 - k_0)\frac{(E_\gamma - \epsilon_0)}{E_0 - \epsilon_0} \right] \Gamma_K(E_\gamma, T), \tag{6.6}$$

which is determined by two parameters (k_0, ϵ_0). For $k_0 > 1$ the width is enhanced compared to the result of Eq. 6.2. In that case the resulting *El* strength, obtained by replacing in Eq. 6.3 $\Gamma_K(E_\gamma, T)$ with $\Gamma_{En}(E_\gamma, T)$, is denoted as derived from an **enhanced generalized Lorentzian**

$$f_{E1}^{EGLO}(E_\gamma) = 8.68\times 10^{-8}\sigma_0\Gamma_0 \left[E_\gamma \frac{\Gamma_{E_n}(E_\gamma, T)}{(E_\gamma^2 - E_0^2)^2 + E_\gamma^2 \Gamma_{E_n}^2(E_\gamma, T)} + 0.7 \frac{\Gamma_{E_n}(E_\gamma = 0, T)}{E_0^3} \right] \quad [\mathrm{mb}^{-1}\mathrm{MeV}^{-2}]. \tag{6.7}$$

The enhancement k_0 can be used to reproduce the experimental $E1$ strength around the reference energy ϵ_0. Note, that

i) for $k_0 = 1$ the generalized Lorentzian model is obtained and

ii) $\Gamma_{En}(E_\gamma \to E_0, T \to 0) \to \Gamma_0$, i. e. compatibility with photoabsorption is maintained.

In order to study the behaviour of the k_0 enhancement factor, a large number of calculations have been performed [6.10, 6.11] in the mass region A=90–200. For these calculations of neutron capture cross sections and the resulting gamma-ray spectra the Hauser-Feshbach theory in the formulation of Moldauer [6.23] has been employed and an appropriate treatment of gamma-ray cascades. The calculations were performed with the code MAURINA [6.24].

[4] Very recently Plujko has presented a new model [6.22] for f_{E1} radiative strength function, based on microcanonical ensemble of initial states. The resulting formula has the same features as the Kadmenskij *et al.*approach [6.21], namely the energy and temperature dependence of the GDR width and the non-zero limit for $E_\gamma \to 0$. This work forms an independent theoretical support for the generalized Lorentzian formalism.

In the mass and energy region considered ($A > 100$, $E_n < 3$ MeV) charged particle emission can be neglected. Neutron optical potentials were taken from the literature and eventually slightly modified in order to improve the reproduction of total cross sections and (neutron) strength functions. For strongly deformed nuclei the neutron transmission coefficients were generated by coupled channels calculations.

For the level density, characterizing the excited states beyond the known levels, we used semi-empirical models with parameters relying on recent results for the average spacing of s-wave resonances D_0 and the number of low excited levels N_{lev}. For all nuclei calculations were performed employing the *backshifted Fermi gas model* [6.25] and the model by *Kataria, Ramamurthy and Kapoor* (KRK) [6.26] which accounts for shell effects in terms of the ground-state shell correction to the nuclear binding energy. The genuine KRK model is supplemented according to the Gilbert-Cameron prescription [6.27]: a conventional pairing shift and a constant temperature portion at lower excitation energy where the spin distribution parameter σ^2 is linearly interpolated between the value σ^2_{lev}, deduced from the levels and $\sigma^2(E_x)$, the value prescribed by the KRK model at the matching energy E_x. For comparisons we used in some cases also a more sophisticated level density model — the *generalized superfluid model* in its phenomenological version — which was developed by Ignatyuk and collaborators [6.28–6.30]. For each model the respective parameters are chosen so as to reproduce the same values D_0 and N_{lev}; in case of the generalized superfluid model this was achieved by an additional shift of the excitation energy as proposed in Ref. [6.29].

When employing a particular level density model we used the pertinent temperature T also in the expressions for the gamma-ray strength functions according to the models generalized Lorentzian and enhanced generalized Lorentzian (see Eqs. (6.4–6.7)). Under these conditions the $E1$ strength depends on the level density model employed. In case of the KRK model we use the genuine temperature prescription also in the constant temperature region.

As shown in Refs. [6.1–6.11] the generalized Lorentzian model reproduces the experimental data reasonably well in the mass region A=50–200 with the exception of targets between A=150–170. For this region a better fit of the experimental data has been obtained with the standard standard Lorentzian model. Consequently, neither the standard Lorentzian nor the generalized Lorentzian model can be used for model calculations in the whole mass region. The flexible enhanced generalized Lorentzian model could do the job if its parameters (k_0, ϵ_0) show a sufficiently smooth behaviour, so that it can be applied for cross section predictions. For a fixed reasonable value of the reference energy, namely $\epsilon_0 = 4.5$ MeV, we therefore determined for all nuclei considered in our studies the enhancement k_0, by simultaneously reproducing at least two pieces of experimental data. This was done by graphical comparisons [6.10, 6.11] between experimental data and the results obtained with different k_0. In this context we allowed for k_0, also values moderately smaller than 1. Because of the strong dependence of the results on the level density model we had to do this separately for the KRK and the backshifted Fermi gas model. The derived k_0 values only weakly depend on the reference energy ϵ_0 some test calculations indicated that a change of 1 MeV in ϵ_0 affects k_0 only by a few percent. The enhancements found in this way are displayed in Fig. 6.1 as function of the mass number of the compound nucleus. The error bars reflect uncertainties of the experimental data and the spacing D_0 as well as inconsistencies between the enhancements required for different types of data; they were found by rather rough assessments and not by detailed sensitivity studies. The trend of the enhancements can be described as a function of the mass number A by simple purely empirical expressions as e.g.

$$\begin{aligned} k_0(x) &= 1.5 && \text{for } A < 145 \\ &= 1.5 + 0.131(A-145)^2 \exp[-0.154(A-145)] && \text{for } A \geq 145 \end{aligned} \tag{6.8}$$

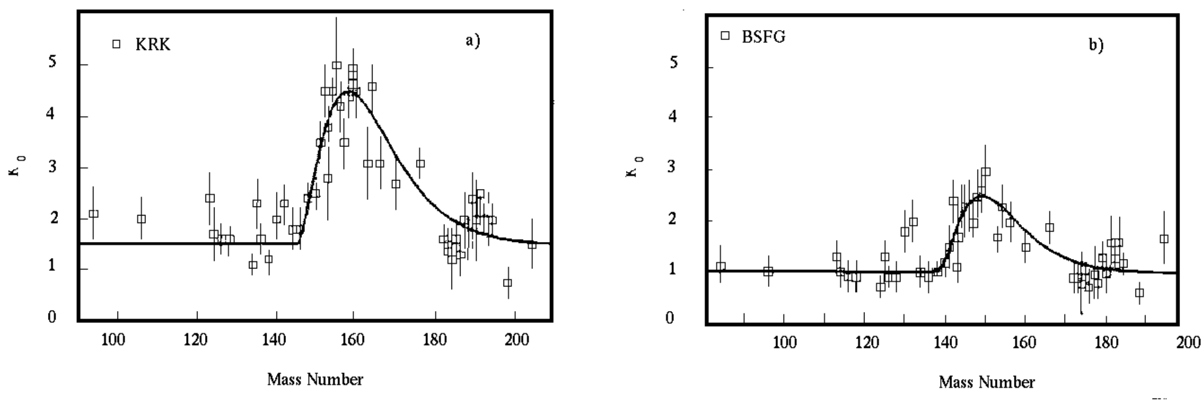

Figure 6.1: The enhancements k_0 plotted against the mass number of the compound nucleus. They are extracted from calculations employing the Kataria, Ramamurthy and Kapoor (a) and the backshifted Fermi gas model (b) for the level densities.

for the KRK model and

$$\begin{aligned} k_0(x) &= 1.0 && \text{for } A < 148 \\ &= 1.0 + 0.09(A-148)^2 \exp[-0.180(A-148)] && \text{for } A \geq 148 \end{aligned} \quad (6.9)$$

for the backshifted Fermi gas model, respectively. The expressions are actually the same as in Ref. [6.9]; the constants may change when we consider more nuclei with $A < 100$. Fig. 6.2 displays calculated average s-wave radiation width and the experimental value for the nuclei considered for the determination of k_0 and some more. For the calculations we employed the enhanced generalized Lorentzian model with the enhancement k_0 according to Eq. (6.8) or (6.9).

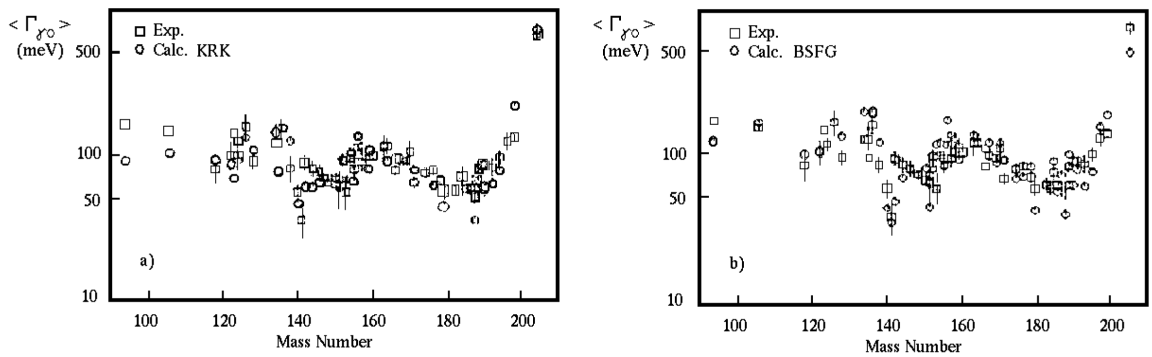

Figure 6.2: The calculated average s-wave radiation width and the corresponding experimental value. The calculations employ the enhanced generalized Lorentzian model for the *El* strength with k_0 values according to Eqs. (6.8) and (6.9), depending on the level density models employed, i.e. the Kataria, Ramamurthy and Kapoor model (a) and the backshifted Fermi gas model (b).

6.3 Giant Resonance Parameters

6.3.1 $E1$: Giant Dipole Resonance

Generally, giant resonance parameters can be obtained:
i) from the analysis of experimental photoabsorption cross sections of the compound nucleus,

ii) interpolated from experimental values of neighbouring nuclei assuming small dependence of these parameters on A,
iii) if no experimental information is available, global systematics of all parameters can be applied. It should, however, be noted, that no systematic is reliable for nuclei with $A < 50$. The shape of their excitation functions reveals quite complicated structure for every nucleus due to excitations in unbound individual $E1$ states. For more information on this subject see Ref. [6.32].

Recommended compilations of giant resonance parameters derived from experimental data are Refs. [6.31, 6.33, 6.34] and they are also quoted in **kopecky.readme** as the global trend of these parameters, and in a tabular form in the recommended file **beijing_gdr.dat**.

There is also another file, *varlamov.dat*, which contains additional useful information on giant dipole resonance parameters. The file contains 366 entries selected from the table published in [6.34]. The file provides GDR parameters deduced from photoabsorption cross sections, and also from total neutron production cross sections (total neutron production is often a good approximation to photoabsorption). In a few cases where this information is not available, GDR parameters are provided as deduced from either neutron yield, single neutron production, double neutron production or fission. It should be noted that GDR parameters given in the well known atlas by Dietrich and Berman [6.31] and included also into varlamov.dat, are based purely on total (photo)neutron production cross sections.

Global Parameterization

Spherical targets ($A > 50$)
(applied symbols have the usual meaning)

$$
\begin{array}{rcl}
E_0 &=& 31.2\ A^{-0.333} + 20.6\ A^{-0.167} \quad \text{MeV} \quad [6.19] \\
\Gamma_0 &=& 0.026\ E_r^{1.91} \quad \text{MeV} \quad [6.35] \\
\sigma_0 &=& 0.166\ A^{1.54} \quad \text{mb} \quad [6.36]\ \text{(fit to experimental data)} \\
\sigma_0 &=& 1.2 \times 120\ NZ\ /\ (A\pi\Gamma_0) \quad \text{mb} \quad [6.35]\ \text{(adjusted classical sum rule)}
\end{array}
$$

Deformed targets ($A > 50$)
($\beta =$ quadrupole deformation parameter)

$$
\begin{array}{rcl}
E_{01} &=& E_0\ /\ (1 + 0.666\beta) \quad \text{MeV} \quad [6.37] \\
E_{02} &=& E_0\ /\ (1 - 0.333\beta) \quad \text{MeV} \quad [6.37] \\
\Gamma_{01} &=& 0.026\ E_{01}^{1.91} \quad \text{MeV} \quad [6.35] \\
\Gamma_{02} &=& 0.026\ E_{02}^{1.91} \quad \text{MeV} \quad [6.35] \\
\sigma_{01} &=& 1.2 \times 120\ NZ\ /\ (A\pi\Gamma_0) \quad \text{mb} \quad [6.35] \\
\sigma_{02} &=& 1.2 \times 120\ NZ\ /\ (A\pi\Gamma_0) \quad \text{mb} \quad [6.35]
\end{array}
$$

Recently a comprehensive study (D'Arigo *et al.* [6.38]) has been completed, in which the following global expressions for all nuclei (based on the analysis of the experimental data from Dietrich and Berman [6.31]) have been derived:

Single GR hump targets ($A > 50$)

$$
\begin{array}{rcl}
E_0 &=& (49.336 + 7.34\ \beta)\ A^{0.2409} \quad \text{MeV} \\
\Gamma_0 &=& 0.3\ E_0 \quad \text{MeV} \\
\sigma_0 &=& 10.6\ A\ /\ \Gamma_0 \quad \text{mb}
\end{array}
$$

Double GR hump targets ($A > 50$)

$$
\begin{array}{ll}
E_{02} \;=\; 50\; A^{-0.232} & \text{MeV} \\
\ln\;(E_{02}/E_{01}) \;=\; 0.946\;\beta & \\
\Gamma_{01} \;=\; (0.283 - 0.263\;\beta)\; E_{01} & \text{MeV} \\
\Gamma_{02} \;=\; (0.35 - 0.14\;\beta)\; E_{02} & \text{MeV} \\
\sigma_{01} \;=\; 3.48\; A\;/\;\Gamma_{01} & \text{mb} \\
\sigma_{02} \;=\; 1.464\; A\;/\;\Gamma_{02} & \text{mb}
\end{array}
$$

Other information on systematic giant resonance parameters treatment can be found in Refs. [6.39–6.41].

6.3.2 $M1$: Spin-Flip Giant Resonance

Spin-flip giant resonance mode, as proposed by Bohr and Mottelson [6.18], is recommended (see e.g. Refs. [6.1–6.11, 6.15]).

Global parameterization

$$
\begin{array}{lll}
E_0 \;=\; 41\; A^{-1/3} & \text{MeV} & [6.18] \\
\Gamma_0 \;=\; 4 & \text{MeV} & [6.15] \\
\sigma_0 \;=\; \text{adjusted to:} & & \\
\text{1. experimental } f_{M1} \text{ value} & & \\
\text{2. } f_{M1} \;=\; 1.58\; A^{0.47} & \text{at } \pm 7 \text{ MeV} & [6.13] \\
\text{3. } f_{E1}\;/\;f_{M1} \;=\; 0.0588\; A^{0.878} & \text{at } \pm 7 \text{ MeV} & [6.36]
\end{array}
$$

6.3.3 $E2$: Isoscalar Giant Resonance

The description of $E2$ excitations in neutron capture as the isoscalar giant resonance mode are discussed in Refs. [6.10, 6.15, 6.42].

Global parameterization

$$
\begin{array}{lll}
E_0 \;=\; 63\; A^{-1/3} & \text{MeV} & [6.19] \\
\Gamma_0 \;=\; 6.11 - 0.021\; A & \text{MeV} & [6.42] \\
\sigma_0 \;=\; 0.00014\; Z^2\; E_0\;/\;(A^{1/3}\;\Gamma_0) & \text{mb} & [6.42]
\end{array}
$$

6.4 Systematics of γ-Ray Strength Functions

6.4.1 Introduction

The compound nucleus mechanism is dominant for the neutron capture process up to incident neutron energy of several MeV. Therefore, the statistical model is generally used to describe and calculate the (n,γ) cross sections and spectra for these energies. An exception to this can occur in thermal and resonance regions (thus at low neutron energies) in mass regions, where non-statistical processes (potential and valence capture) may become important.

The γ-ray transmission coefficient T_{XL}, usually used in the model calculations, is related to the γ-ray strength function f_{XL} as

$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma), \tag{6.10}$$

where E_γ is the γ-ray energy and L indicates the multipolarity of the radiation. Therefore, both theoretical and experimental knowledge of γ-ray strength functions is a very important ingredient for description and calculation of photon-production data in all reaction channels, not only for the (n,γ) reaction.

In this survey we concentrate on experimental γ-ray strength functions, collected over a period of about forty years and based on measurements of partial radiative widths $\Gamma_{\gamma i}$. Such data originate from three different experiments. Most of the data are derived from discrete resonance-capture experiments using the method of slow neutron time-of-flight spectrometry. In some cases, the thermal neutron-capture data can be used, however, with some restrictions. The last source of data is set of the photonuclear data. Common in the analysis of all these experiments is a need to average over Porter-Thomas fluctuations, which govern the distribution of partial radiative widths.

The first compilation of McCullagh *et al.* [6.43] included about 50 nuclides with absolute partial widths originating from (n_{res},γ) and (γ,n) reactions, selected from data published before 1980 and averaged over the observed resonances. These data were analyzed in the frame of model dependent (single-particle model and Brink-Axel approximation) strength functions for $E1$ and $M1$ radiation. The mean energy for this data set was about 7 MeV. From fits to these data Kopecky [6.44] derived global formulae for the additional dependence of f_{E1} and f_{M1} on the mass A compared to the above models. We prefer the model independent definition of strength functions for dipole radiation, written as

$$f_{XL}(E_{\gamma i}) = \langle \Gamma_{\gamma i}/E_{\gamma i}^3 \rangle / D_0. \tag{6.11}$$

A first update of this data set was made by Kopecky and Uhl [6.12] in 1990. In their study a few new data have been added and the general reliability of the data was addressed.

6.4.2 Selected Data

The original set of data [6.43] has been extended with data published between 1981 and 1995 with, however, no claim on completeness. The preliminary results has been published in Ref. [6.13] and the present compilation is a slightly extended and updated version. The extensions include resolved-resonance measurements [6.45–6.53], thermal-capture measurements [6.54–6.56] and photonuclear data [6.57–6.59].

Two comments should be made concerning the interpretation of thermal capture data in terms of strength functions. Firstly, Bollinger [6.60] has demonstrated that the distribution of γ-ray intensities following the thermal capture follows only approximately the Porter-Thomas distribution, and in cases that both spin components contribute in thermal region, the distribution should be intermediate between χ^2 distributions with one and two degrees of freedom. Secondly, the conversion of thermal γ-ray intensities into partial radiative widths is based on the average value of the total radiative width, as derived from all measured resonances. This quantity, especially if resonances in a wide energy region are considered, may not be a good representation of the radiative width for the thermal region. Three of such measurements have been included in our data set; we have selected only those where the authors derived the $f_{E1,M1}$ values by themselves [6.54, 6.55, 6.56]. However, it should be mentioned that a huge wealth of thermal capture data is available and it would certainly be worthwhile to consider making effort to convert well selected data into the γ-ray strength functions.

The final data sets (65 entries) of f_{E1} and f_{M1} values are listed in the electronic version of RIPL in the file **kopecky.dat**. In the original data base [6.43], only a small number of minor corrections have been carried out, most of the data have been adopted without changes. Values for two different resonance spins, treated separately in Ref. [6.43], have been combined. Given errors include statistical, normalization (assumed 20%) and Porter-Thomas uncertainties. Data posterior to Ref. [6.43] have been adopted without changes and their origin is quoted in the first column of Table 1 (see electronic version) by their reference. Further, the number of resonances and γ-rays used in evaluation of $f_{E1,M1}$ values is quoted, just to indicate the quality of averaging.

Another assessment concerned the mean energy E_γ at which $f_{E1,M1}$ values have been derived. Following Eq. (6.11) only the partial E_γ^3 reduction factor has been applied and no additional energy dependence was assumed. This is reasonably true if the energy region is narrow and the additional energy dependence which comes from the $E1$ ($M1$) giant-resonance model is negligible. The quoted $f_{E1,M1}$ value is then the mean value over all partial $f_{E1,M1}(E_{\gamma i})$ entries considered, assumed to correspond approximately to the mean value $< E_\gamma >$. This energy is quoted in Table 1 in a comment line. An inspection of these values shows, that the majority of data do not significantly deviate from earlier quoted $< E_\gamma > \approx 6 - 7$ MeV. A fraction of the $f_{E1,M1}$ scatter may, however, stem from internal differences in distributions of partial data within the $< E_\gamma >$ range. The only data outside $6 - 7$ MeV to be considered are the actinide data with $< E_\gamma > \approx 4.2$ MeV. The energy correction due to additional energy dependence (e.g. assumed E_γ^2 for $E1$ radiation) increases f_{E1} values by factor of 2.5. The global trend of $f_{E1,M1}$ data is, however, not significantly influenced due to a relatively small number of such data points, as was shown in Ref. [6.44].

6.4.3 $E1$ Radiation

All surveyed data with their original values, denoted according to their experimental origin, are displayed in Fig. 6.3 together with a least-squares fit of a power dependence on mass number A (solid curve). Data follow reasonably well the expected smooth global trend with two exceptions, where some deviations above the general scatter of data may be considered. These large deviations belong to data in mass regions with $A < 40$ and $170 < A < 210$. There is no difference detected in data trend among the three experimental methods applied. For indication how the extension and revisions of the data set have influenced the general trend in f_{E1} data, the fitted curve from 1981 [6.44] is plotted for a comparison.

Reasons for a large scatter of the low-mass data ($A < 40$) can be surely attributed to an insufficient averaging together with pronounced single-particle character of many transitions. However, it seems that their mean value reasonably represents the general trend, as expected from the other data. The situation in the mass region with $170 < A < 210$ is more complex. Several strongly enhanced data points can be explained by the presence of a non-statistical mechanism, in particular those around the double-closed shell region. However, this enhancement is not a general feature of all data, some values seem to follow the general trend, as determined by data from the mass region with $100 < A < 170$. It is noticed, that the general data scatter around the trend curve in Fig. 6.3 can be characterized by a uncertainty factor of $k = 2$, which leaves about 10% of data points outside the uncertainty band (see Fig. 6.3). This data scatter probably masks the expected enhancement of f_{E1} values in other mass regions (e.g. A=150–170).

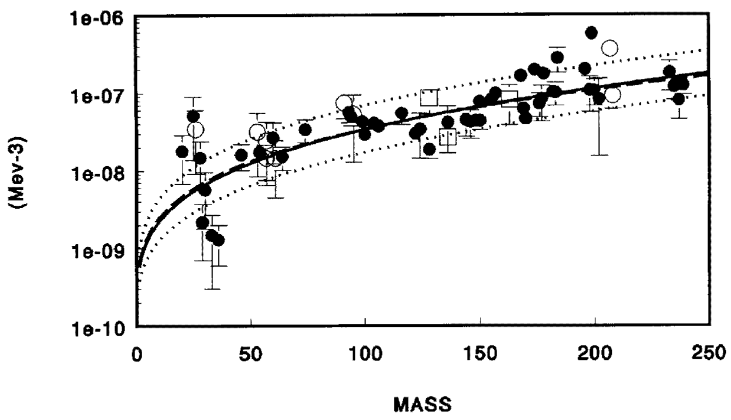

Figure 6.3: Plot of f_{E1} values [full circles (n_{res},γ), open circles (γ,n) and squares (n_{th},γ)] against the mass number. The full curve represent a LSQ fit to recent data, the fit from 1981 [6.32] is denoted by the dashed curve. Dotted curves display an uncertainty band with $k = 2$ (see Eq. (6.13)).

6.4.4 $M1$ Radiation

For $M1$ radiation, the situation is more complicated for several reasons. The systematic behaviour of the $M1$ strength function (see Fig. 6.4) shows a similar mass dependence as $E1$ radiation. These data, however, are scarce and statistically less accurate, often based on inadequate averaging. The uncertainty representing data scatter, determined in a similar way as for $E1$ radiation with about 10% data points outside, amounts to a factor of three (see Fig. 6.4). The curve fitted to data available in 1981 (Ref. [6.44]) differs very little from the present fit.

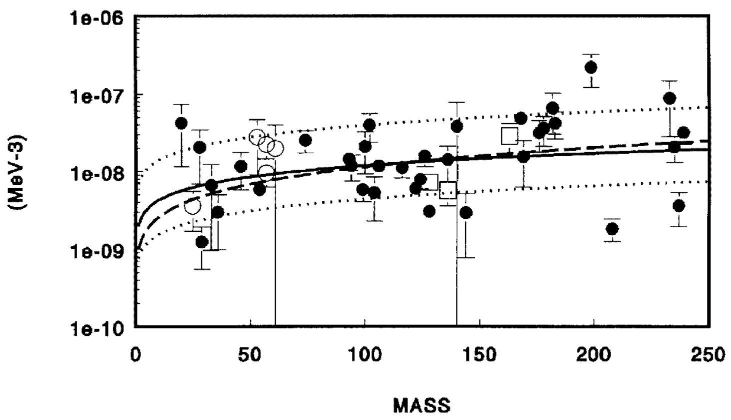

Figure 6.4: Plot of f_{M1} values, the uncertainty band has a value of $k = 3$ (used symbols are the same as in Fig. 6.1).

There is no well established general theoretical expression for f_{M1}. The frequently used single-particle estimate is at variance with a finite energy-weighted sum rule and is also ruled out by the observed mass dependence. The proposed giant resonance model [6.15], based on the Brink hypothesis [6.17] and the spin-flip $M1$ resonance, lacks a global description of the sum rule. The data display also some effects, which may be attributed to a non-statistical origin. Some of the enhanced data seem to cluster in a gross structure but a clear identification is difficult. However, their influence on the general trend is marginal, as can be seen in Fig. 6.4.

Only in two original references the nonstatistical origin of data was identified.

6.4.5 Systematics

It was shown that there has been no significant influence on the global trend of the fitted strength functions as a function of mass by updating the basis data set since 1981. It was shown further that this global trend is also not influenced by data enhanced by non-statistical effects. The general reason for this is that the associated individual errors, dominated by Porter-Thomas uncertainties, are sometimes comparable to these effects and that the number of non-statistical entries is relatively small. Therefore, we have decided to apply only corrections to the those D_0 values in the original entries, which were obviously wrong. These changes are documented in Table 1 of the file **kopecky.dat**. The least-square fit to these data resulted in a recommended experimental (trend) systematics, which reads as

$$\begin{aligned} f_{E1}(exp) &= 9.23 \times 10^{-11} A^{1.34\pm0.14}, \\ f_{M1}(exp) &= 1.58 \times 10^{-9} A^{0.47\pm0.21}. \end{aligned} \tag{6.12}$$

These expressions are recommended for estimates of f_{E1} and f_{M1} values for normalization of calculations if the neutron binding energy is not too much different from a value of 6 to 7 MeV. The associated uncertainty factor k, defined as the minimal value which satisfies the condition

$$f_{XL}^{\mathrm{calc}}/k < f_{XL}^{\mathrm{exp}} < k f_{XL}^{\mathrm{calc}}, \tag{6.13}$$

found to be $k = 2$ for $E1$ and $k = 3$ for $M1$ radiations. These, to some extent arbitrarily chosen uncertainty factors, agree reasonably with associated errors of the A power, as derived from the least-squared fit, resulting in k values 2.1 and 2.9.

6.5 Conclusions and Recommendations

A significant portion of information has been joined to **kopecky.readme** file. Summarising, we may state that the flexible enhanced generalized Lorentzian model for the $E1$ strength function is useful for the calculation of capture cross sections and related quantities as its parameters exhibit a reasonable smooth behaviour. The required enhancement depends on the level density model employed. The strong dependence of the calculated quantities (total radiative width, cross sections and gamma-ray spectra) and consequently of the extracted $E1$ enhancement parameter k_0 is not very satisfying. It probably represents the price for using too simple formulas which may fail to describe the energy dependence of the level density. Therefore a realistic level density model should always be used. It seems at present, that the backshifted Fermi gas model is the best solution for practical applications. This results also in the applicability of the enhanced generalized Lorentzian for nuclei outside the A=150–170 range, because k_0=1 in Eq. (6.9) and enhanced generalized Lorentzian = generalized Lorentzian. In view of our empirical formulation of the enhancement of the width of the generalized Lorentzian a better understanding of the effect and a subsequent theoretical description would be very helpful.

Recent experiments with Two-Step Cascade method [5.61–5.68] reveal additional information on the strength function predictions. This method is sensitive, not only to primary transitions, but also to secondary transitions via intermediate states. However, the interpretation of two-step cascade method results is complicated by its dependence on the final state parameters.

The global parametrization of the giant resonances (not only GDR) is contained in **kopecky.readme**. The recommended data file **beijing_gdr.dat** contains the giant dipole resonance parameters for the gamma-ray strength functions. These parameters of Lorentz curves are based on compilation by Dietrich and Berman [6.31] extended by the Beijing group in later years especially for light nuclei (C, N, O, Al and Si). The recent compilation of Varlamov *et al.* [6.34] has been included into RIPL as other file *varlamov.dat*. It is of similar structure, covering period 1976–95 and containing more entries than the Beijing compilation.

The main systematics of various paremeters important for the γ emission is contained in **kopecky.dat**.
1. The original experimental data set for $E1$ and $M1$ gamma-ray strength functions [6.43] has been reviewed, and extended by recent data covering the period up to 1996 and listed in **kopecky.dat**. The resulting f_{E1} and f_{M1} values show a smooth increasing dependence on mass A, different to that expected from the single-particle model. Together with an additional energy dependence above the E^3 phase-shift factor (as detected in many averaged-resonance capture experiments), it may be concluded that the use of single-particle model should be disregarded for both $E1$ and $M1$ radiation. Extended information of this survey and update can be found in Ref. [6.14].
2. The data fluctuations around the fitted systematics are dominated by a combined effect of experimental uncertainties (including the averaging properties) and uncertainties in D_0 values, their possible corrections are discussed and in several cases applied. In order to cover the uncertainty in D_0 determinations, all previous and recent D_0 evaluations are listed in **kopecky.dat**. The size of these fluctuations complicates the interpretation of individual data in terms of statistical and non-statistical components, however, a global trend of data is detected.
3. The resulting set of f_{E1} values generally underestimates the predictions by the standard Lorentzian, as expected from previous studies. This behaviour forms a global argument for the use of the generalized Lorentzian with the energy-dependent width. The enhancements of $E1$ radiation above this model in mass regions $50 < A < 60$ and $150 < A < 170$, which influences all quantities such as f_{E1}, $< \Gamma_\gamma >$, σ_γ $\mathrm{d}\sigma_\gamma/\mathrm{d}E$ may be attributed to global non-statistical effects. However, it is not excluded that some of the Γ_γ enhancements are due to experimental effects.
4. For practical applications in statistical model calculations, the experimental ratio of Γ_γ/D_0 is probably the best normalization check. The derived systematics of f_{E1} and f_{M1}, if necessary combined with the trend in $E1/M1$ ratios, can be used as a reasonable approximation of the strength functions in model calculations, if experimental values are not available.

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