

DIPOLE PHOTON STRENGTH FUNCTIONS FROM NEUTRON INDUCED REACTIONS

Walter Furman¹

Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research

141980 Dubna Moscow region

E-mail: furman@nf.jinr.ru

Abstract

It will be reviewed a current status of theoretical and phenomenological approaches to investigation of dipole photon strength functions. The model of electric dipole photon strength functions (EDPSF) depending on the temperature of gamma-transition final state is compared with the phenomenological EDPSFs recently obtained by various methods. Special accent is put on the results derived by a “model-less” analysis of two-step gamma decay of compound-states created after thermal neutron capture by heavy nuclei. The conclusion on the dependence of these strength functions on characteristic of final states is made. A necessity for development of the consistent theoretical approach for description the dipole strength functions in the case of deformed nuclei is discussed.

¹ Speaker

Workshop on Photon Strength Functions and Related Topics
Prague, Czech Republic
17-20 June 2007

1. Introduction

Slow neutron induced reaction (n,γ) provides very detailed information on photon strength functions (PSF) with $E_\gamma \leq B_n$. In many cases it is possible to study gamma-decay of individual excited (compound) induced reaction (n,γ) provides very detailed information on photon strength functions (PSF) with E_γ nuclear states with known $J\pi$ values leading to final states with very limited range of $J\pi$ quantum numbers. In addition study of two-step ($n, \gamma\alpha$)-reaction [1,2] and ($n, \gamma\gamma$)-decay [3-6] gives unique possibility to extract the information on PSF for γ -transitions between excited nuclear states important for verification of theoretical models and many practical applications. During last decade very useful the results on the sum of mainly dipole PSF were obtained with aid of two step reactions (${}^3\text{He}, {}^3\text{He}'\gamma$) and (${}^3\text{He}, {}^4\text{He}'\gamma$).

Below we consider mainly dipole γ -transitions dominated in gamma-decay of compound states created by slow neutron capture.

2. Gamma-transitions from compound states

Gamma-transitions from highly excited nuclear states could be analyzed on the basis of statistical model. We use below the approach proposed in ref. [7].

Wave function of compound nuclear state after neutron capture (neutron resonance – NR) could be expressed in form [7]

$$\Psi^{J\pi} = \sum_{i=1}^N x_i g_i^{J\pi} + \sum_{j=1}^{\tilde{N}} \tilde{x}_j \tilde{g}_j^{J\pi} \quad , \quad (1)$$

where $g_i^{J\pi}$ and $\tilde{g}_j^{J\pi}$ are quasi-particle-phonon basic functions, the *principal* and *small* components respectively.

$$\sum_{i=1}^N x_i^2 \cong 1 \quad (x_i \gg \tilde{x}_j) \quad (2)$$

For an ensemble of NR the distribution of principal components has a form

$$P(x_1, \dots, x_N) = \frac{2N(\pi)^{N/2}}{\Gamma(N/2 + 1)} \delta(1 - \sum_{i=1}^N x_i^2) \quad (3)$$

In the limit of $N=1$ this formula describes a pure ensemble. So we can hope that for $N \geq 1$ the distribution (3) gives reasonable results. To estimate a number of principal components consider a spreading of basic state $g_i^{J\pi}$ over compound states λ with the same quantum numbers $J\pi$

$$P(E_\lambda) dE_\lambda = \frac{\Gamma_i dE_\lambda}{2\pi[(E_i - E_\lambda)^2 + \Gamma_i^2/4]} \quad (4)$$

here Γ_i is a spread width of the basic state $g_i^{J\pi}$.

$$\text{So } \langle x_i^2 \rangle = \frac{\Gamma_i \langle D^{J\pi}(E_\lambda) \rangle}{2\pi[(E_i - E_\lambda)^2 + \Gamma_i^2/4]} \quad (5)$$

Taking into account normalization condition for x_i and natural assumption $\rho_0^{J\pi} \Gamma_i \gg 1$ we can derive that

$$\rho^{J\pi} \approx \rho_0^{J\pi} \quad (6)$$

The last condition used really for all combinatorial calculations of level density. The Soloviev quasi-particle-phonon model [8] reproduces in general experimental level density. It means that Γ_i is comparatively small and a variation of level density within Γ_i is small too. So we can obtain

$$N \approx \langle \Gamma_i \rangle \rho^{J\pi}(U) \quad (7)$$

Main contribution into normalization condition of $\Psi^{J\pi}$ (2) goes from basic states with the mean number of quasi-particles

$$n \approx \bar{n} \cong (2gU)^{1/2} \quad (8)$$

So it's possible to show [7] that $\langle \Gamma_i \rangle \approx 1$ MeV and N is the number of compound states at spreading interval $\langle \Gamma_i \rangle$.

As it's follow from quasi-particle-phonon model a main contribution into normalization condition of $\Psi^{J\pi}$ gives basic states formed by combinations of shell model states from last unfilled shell near Fermi surfaces for neutron and proton systems (*principal* components) in the energy interval:

$$\Delta E \approx \Gamma_i \ll \hbar\omega_0 \cong 41A^{-1/3} \quad (9)$$

A creation of quasi-particle with transition to adjacent shell needs in an additional energy more than $\hbar\omega_0$ and a number of quasi-particles of respective basic states became much lower ($n \approx 2$) than a mean number (8). So the density of such (*small*) components will be much lower than for abovementioned principal components and its contribution to the normalization of compound state $\Psi^{J\pi}$ will be very small.

There is evident difference [7] between γ -transition from compound state c to low lying highly excited state c' and γ -transition from the same state c to ground state or to other comparatively "simple" (s) excited states lying above the ground one.

In case of (cc') dipole γ -transitions the operators of electromagnetic interaction $E1$ or $M1$ should match two very complicated many component wave functions (WF).

In contrary for (cs) γ -transitions the same operators have to ensure an overlapping of compound state c wave function and much more simple WF of low lying (ground) state s . Due to different structure of WFs of the states c and s PSF for (cs) γ -transitions has to be different from PSF for (cc') transitions.

3. Dipole strength functions in slow neutron induced reactions

The reduced width amplitude of γ -transition of (λI) type ($\lambda=E$ or M) from NR c to final state f could be expressed as [7]:

$$\gamma_{cf} = \langle \Psi_c^{J\pi} | \widehat{m}(I, \lambda) | \Psi_f^{J_f \pi_f} \rangle \quad (10)$$

Inserting in this formula WFs of states c and f one has

$$\gamma_{cf} = \sum_{i=1}^N \sum_{j=1}^{N_f} x_i y_j m_{ij} \quad , \quad (11)$$

where matrix element

$$m_{ij} = \langle g_i^{J\pi} | \widehat{m}(\lambda I) | g_j^{J_f \pi_f} \rangle \quad (12)$$

If (**assumption 1**) each basic function $g_j^{J_f \pi_f}$ of final state f could be linked by the operator $\widehat{m}(\lambda I)$ with r ($r \gg 1$) (in average) functions $g_i^{J\pi}$ when each function $g_i^{J\pi}$ is connected by the same operator with in average k functions $g_j^{J_f \pi_f}$ so number of total links is

$$R = N_f r = N k \quad (13)$$

where $N \ll N$ is number of basic functions $g_i^{J\pi}$ satisfying of the respective selection rules.

So one can derives [7]

$$\langle \gamma_{cf}^2 \rangle = \langle m_{ij}^2 \rangle \langle x_i^2 \rangle \langle y_j^2 \rangle R = \langle m_{ij}^2 \rangle r / N \quad (14)$$

We see that the reduced width γ_{cf}^2 does not depend on number N_f so it is valid as for complicated states (c type) ($N_f \gg 1$) as well as for extremely simple states s ($N_f = 1$). Of course the approach [7] reproduces the dispersions of γ_{cf}^2 and its other statistical properties.

Up to now we considered only γ -transitions related to links between principal components of WFs of initial and final states. It's true for MI transitions because the respective operator is able to connect most basic functions $g_i^{J\pi}$ obtained by combination of $p-h$ -configurations from last unfilled proton and neutron shells.

The estimation of PSF(M1) made in [7] is

$$S_{\gamma}^{cf}(M1) \equiv \frac{\langle \Gamma_{\gamma_{cf}}^{J\pi} \rangle}{\langle D_c^{J\pi} \rangle E_{\gamma}^3} \sim (1 \div 2) \times 10^{-8} \text{ MeV}^{-3} \quad (15)$$

But for $E1$ γ -transitions a situation is essentially different. The **assumption 1** is not true. (cc') γ -transitions connect excited states with opposite parity. The structure of such states are rather different. Note that in the last unfilled proton (or neutron) shell there is only one state with “abnormal” parity opposite to ones of all rest shell states and the difference ΔJ of its spin value from spins of all rest shell states is $\Delta J \geq 2$.

Then NRs with parity of ground state π_0 contain the principle components $g_i^{J\pi}$ formed by $p-h$ -configurations of shell states of “normal” parity and even $p-h$ -combinations of shell states of opposite parities. In contrary the basic components $g_i^{J\pi}$ states c or c' with parity ($-\pi_0$) include odd number of $p-h$ -configurations connecting shell states of opposite parities.

So $E1$ operator with symmetry I could not realize links between most principle components of states c and c' . In this case $E1$ γ -transitions could go only through small components of WFs related with $p-h$ -transitions to adjacent shell.

It is convenient to account for the effect of most contributing small components of WFs in terms of GDR formed on the final state c' (Brink hypothesis [9]).

In the standard approach the cross-section EI photo-absorption for nuclear state f has a form [10]:

$$\sigma_{E1}(E_\gamma)_{AB} = \frac{4\pi e^2 \hbar NZ}{mcA} (1 + \xi) \frac{E_\gamma^2 \Gamma_G}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_G^2}, \quad (16)$$

where E_G and Γ_G are the position and spread width of GDR. The PSF(EI) could be expressed as

$$S_\gamma^{cf}(E1) = \frac{1}{3\pi^2 c^2 E_\gamma} \sigma_{E1}^{fc}(E_\gamma). \quad (17)$$

And finally

$$S_\gamma^{cf}(E1)_{AB} = \frac{4e^2 NZ}{3\pi mc^3 \hbar A} (1 + \xi) \frac{E_\gamma \Gamma_G}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_G^2} \quad (18)$$

In this approach there is no difference between (cc') and (cs) γ -transitions.

In the paper [11] there was made an attempt to account for PSF $_c(EI)$ a dependence on structure of final state f .

In general
$$\sigma_{E1}(E_\gamma) = -4\pi e^2 E_\gamma \text{Im} P(E_\gamma), \quad (19)$$

where $P(E_\gamma)$ is a dipole response. By definition

$$\text{Im} P(E_\gamma) = \text{Im} P(-E_\gamma) \quad (20)$$

If one use the response $P^n(E_\gamma)$ related to the dielectric nuclear penetrability $n(E_\gamma)$

$$n(E_\gamma) = 1 + 4\pi P^n(E_\gamma), \quad (21)$$

and the analytic properties of this response are different:

$$\text{Im} P^n(E_\gamma) = -\text{Im} P^n(-E_\gamma) \quad (22)$$

The standard expansion of $P(E_\gamma)$ is

$$\text{Im} P(E_\gamma) = -\pi \sum_c |d_{0c}|^2 \{ \delta(E_c - E_0 - E_\gamma) + \delta(E_c - E_0 + E_\gamma) \} \quad (23)$$

For $P^n(E_\gamma)$ the same expansion has an opposite sign before the second term in figure brackets.

In the last formula the dipole operator has standard shape

$$d = \frac{N}{A} \sum_{p=1}^Z x_p - \frac{Z}{A} \sum_{n=1}^N x_n \quad (24)$$

and $E_0(E_c)$ is an energy of ground θ (excited c) state. If using technique of strength function to average the expansion (23) over the energy interval $\Delta E \ll E_\gamma, \Delta E \rho c \gg I$ so one can obtain

$$\rho_c |d_{0c}|^2 dE_\gamma = |d_{0G}|^2 \frac{\Gamma_G(E_c) dE_c}{2\pi [(E_c - E_G)^2 + \Gamma_G^2 / 4]} \quad (25)$$

If (25) insert into expansion (23) and account for only term with $E_\gamma > 0$ we have:

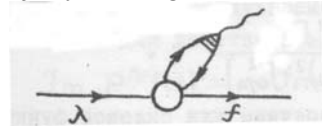
$$\text{Im} P(E_\gamma) = -\frac{\pi |d_{0G}|^2 \Gamma_G}{2\pi [(E_\gamma - E_G)^2 + \Gamma_G^2 / 4]} \quad (26)$$

But if for $P^n(E_\gamma)$ one takes into account both terms in (23) so the following result could be obtained [11]:

$$\text{Im} P^n(E_\gamma) = -\frac{\pi |d_{0G}|^2 \Gamma_G E_\gamma E_G}{(E_\gamma^2 - E_G^2)^2 + \Gamma_G^2 (E_\gamma^2 + E_G^2) / 2} \quad (27)$$

The last formula provides explanation of E_γ dependence in numerator of $S_\gamma^{cf}(E1)_{AB}$ [10].

Follow approach [11] represent the amplitude of reduced width of $E1$ γ -transition from NR c to final state f by the diagram:



$$(28)$$

Here the solid lines correspond to initial and final states, the circle shows a fragmentation amplitude of p-h-state formed on the state f to decaying state c . Analytically the amplitude (28) has a form:

$$M_{cf}(E_\gamma) = \sum_{\nu, \nu'} V_{c, f\nu\nu'}(E_\gamma) A_{\nu\nu'}(E_\gamma) X_{\nu\nu'}(E_\gamma) \quad (29)$$

Here $A_{\nu\nu'}(E_\gamma)$ is a p-h propagator

$$A_{\nu\nu'}(E_\gamma) = \frac{n_\nu - n_{\nu'}}{E_\gamma + \varepsilon_\nu - \varepsilon_{\nu'} + i\delta(n_\nu - n_{\nu'})} \quad (30)$$

where ν denotes a shell state with energy ε_ν . The equation for vertex $X_{\nu\nu'}(E_\gamma)$

$$X_{\nu\nu'}(E_\gamma) = d_{\nu\nu'}^* + \sum_{\nu\nu''} (V_{ph})_{\nu\nu', \nu_1\nu_2} A_{\nu_1\nu_2}(E_\gamma) X_{\nu_1\nu_2}(E_\gamma) \quad (31)$$

includes the effective interaction in p-h-channel V_{ph} and the matrix element of dipole operator. The fragmentation amplitude could be linked to the width of composite state $\{f\nu\nu'\}$:

$$\text{if} \quad \Gamma_{f\nu\nu'}(E_\gamma) = \frac{2\pi}{\langle D^{J\pi} \rangle} |V_{c, f\nu\nu'}|^2 \quad (32)$$

$$\Gamma_{f\nu\nu'}(E_\gamma) \approx \Gamma_f(E_\gamma) \quad (33)$$

so

$$V_{c, f\nu\nu'} = \left(\frac{\Gamma_f(E_\gamma) \langle D^{J\pi} \rangle}{2\pi} \right)^{1/2} e^{i\delta_{c, f\nu\nu'}} \quad (34)$$

The equation for $X_{\nu\nu'}(E_\gamma)$ has a solution [12]:

$$X_{\nu\nu'}(E_\gamma) \approx d_{\nu\nu'}^* C(E_\gamma) \quad (35)$$

where

$$C(E_\gamma) \approx \frac{E_\gamma^2 - \varepsilon_0^2}{E_\gamma^2 - E_G^2} \quad (36)$$

with $\varepsilon_0 \approx E_G$. So

$$M_{cf}(E_\gamma) = \left(\frac{\Gamma_f(E_\gamma) \langle D^{J\pi} \rangle}{2\pi} \right)^{1/2} \frac{2\varepsilon_0}{E_\gamma^2 - E_G^2} \sum_{\nu\nu'} e^{i\delta_{c, f\nu\nu'}} d_{\nu\nu'}^* n_\nu (1 - n_{\nu'}) \quad (37)$$

and the average width has a form:

$$\langle \Gamma_{\gamma ef}(E1) \rangle = \frac{4e^2 E}{3c^3} \langle M_{cf}^2 \rangle \quad (38)$$

Using the sum rule

we obtain
$$\sum_{\nu\nu'} |d_{\nu\nu'}|^2 (\varepsilon_\nu - \varepsilon_{\nu'}) (n_\nu - n_{\nu'}) = \frac{NZ}{\hbar Am} \quad (39)$$

$$S_\gamma^{ef}(E_\gamma) = Const \frac{NZ}{A} \frac{\Gamma_f(E_\gamma) \varepsilon_0}{(E_\gamma^2 - E_G^2)^2} \quad (40)$$

In Landau-Migdal approach [12] $\Gamma_f(E_\gamma)$ has a form

$$\Gamma_f(E_\gamma) \approx \frac{\Gamma_G}{E_G} (E_\gamma^2 - 4\pi^2 T_f^2) \quad (41)$$

so finally we have

$$S_\gamma^{ef}(E_\gamma)_{KMF} = 3 \times 10^{-6} \frac{NZ}{A} \frac{\Gamma_G (E_\gamma^2 - 4\pi^2 T_f^2 (U_f))}{E_G (E_\gamma^2 - E_G^2)^2} \quad (42)$$

Sometimes it is more convenient to use another form:

$$S_\gamma^{ef}(E_\gamma)_{KMF} = \frac{0,7}{3\pi^2 \hbar^2 c^2} \frac{\sigma_{E1}^{tot} \Gamma_G^2 (E_\gamma^2 - 4\pi^2 T_f^2)}{E_G (E_\gamma^2 - E_G^2)^2} \quad (43)$$

The formulas (42-43) were derived for $E_\gamma \leq B_n$. In this energy range the ratio

$$S_\gamma^{ef}(E_\gamma)_{KMF} / S_\gamma^{ef}(E_\gamma)_{AB} \approx 0,7 \frac{E_\gamma^2 - 4\pi^2 T_f^2}{E_G E_\gamma} \quad (44)$$

depends on E_γ and excitation energy U_f .

It should be stressed that the formula for $S_\gamma^{ef}(E_\gamma)_{KMF}$ was obtained with some approximations such as a reduction of *ph*-poles in the equation for vertex $X_{\nu\nu'}(E_\gamma)$ to one effective pole ε_0 and an use for all indicated poles one spread width $\Gamma_f(E_\gamma)$.

These approximations allow one to describe some integral behavior of PSF and could not pretend to reproduce a fine structure of the tail of *E1* GDR such as for instance the pygmy resonances or other weakly collective phenomena. But for analysis of primary *E1* γ -transitions and total radiation widths this approach could be effective. It was confirmed in course of following extensive investigations. (See, for more detail the contribution of F. Bechvar at this conference). It should be noted that the formula (42) was obtained for spherical nuclei and its modifications for deformed nuclei has semi-phenomenological character.

3. Comparison with experiment

Here we have to confess that theoretical study of *E1* PSF has been initiated by experimental results [1,2] of Dubna group on investigation of the two step (*n,γ*α)-reaction for target nucleus ^{143}Nd . The total width of this reaction could be expressed in form [2]:

$$\Gamma_{\gamma\alpha}^c = \sum_{EI, MI, J_c^z} \frac{\Delta}{2\pi\rho_c} \sum_{\Delta_i} S_\gamma^{cc'} [EI(MI), E_\gamma] (E_\gamma^i)^{2I+1} \sum_{\kappa_\alpha} \frac{T_{\kappa_\alpha}^{c'}(Q_{\kappa_\alpha}^i)}{\Gamma_{c'\gamma}^i} \quad (45)$$

Schematically the spectrum of emitted α -particles is shown in left figure below

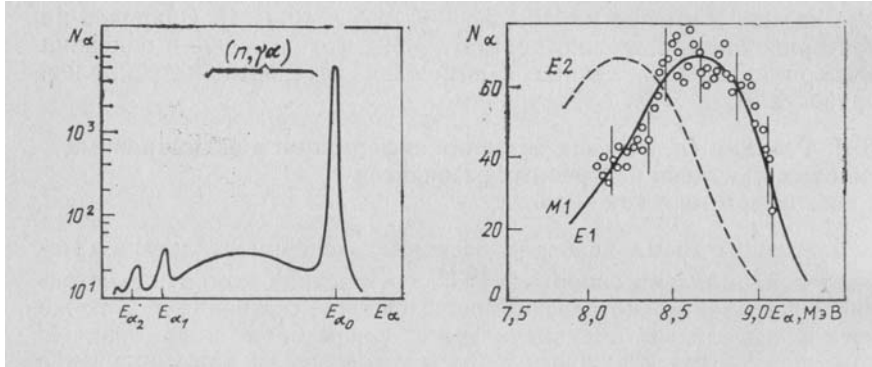


Fig. 1 Alpha spectra from $^{143}\text{Nd} (n, \gamma) ^{140}\text{Ce}$ reaction

In the right part of fig. 1 the fit of α -spectrum measured in ref. [13] is shown. The fit gives evidence of dominating the dipole (cc') γ -transitions in this reaction.

It was very important to study this reaction for different $J\pi$ states of compound nucleus ^{144}Nd . The ratio of $\Gamma_{\gamma\alpha}^3 / \Gamma_{\gamma\alpha}^4 \equiv \omega(\Lambda 1)$ depends strongly on type of dipole (cc') γ -transitions.

For $E1$ γ -transitions $\omega(E1) = T_{\alpha 2} / (T_{\alpha 2} + T_{\alpha 4}) \approx 4$ (46)

and for $M1$ γ -transitions

$$\omega(M1) = T_{\alpha 3} / (T_{\alpha 3} + T_{\alpha 5}) \approx 0.8 \quad (47)$$

In experiment [2] the value of $\omega(\Lambda 1)$ was in between of these two numbers so with accuracy of 30% for (cc') primary γ -transitions with $E_\gamma \leq 2.5\text{MeV}$

$$S_\gamma^{cc'}(E1) \approx S_\gamma^{cc'}(M1) \approx 0.8 \times 10^{-8} \text{ MeV}^{-3} \quad (48)$$

This result revealed for the first time a strong dependence of dipole PSF on structure of the state to which γ -transition goes.

Using the formula (45) for $\Gamma_{\gamma\alpha}^c$ and calculating the transmission coefficients $T_{\kappa\alpha}^c(Q_{\kappa\alpha}^i)$ for α -emission by standard method [14] it could be obtained [2] PSF_{E1} shown below together with other experimental data for ^{144}Nd .

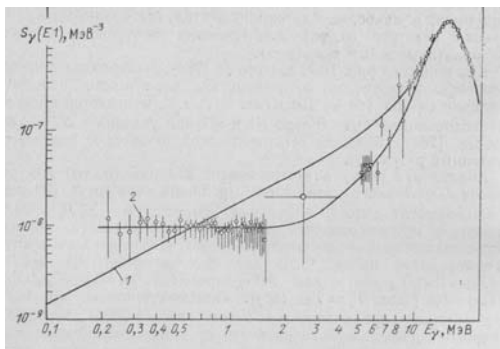


Fig. 2. Comparison experimental (points with error bars) and theoretical PSF (E1)

Here the curve 1 corresponds to $S_\gamma^{cf}(E1)_{AB}$ while the curve 2 relates to $S_\gamma^{cf}(E1)_{KMF}$.

It should be stressed that $S_{\gamma}^{cf}(E1)_{KMF}$ reproduces here the experimental data without any normalization. Due to rather good averaging over intermediate states c' the experimental PSF could serve as some kind of benchmark for this value.

Compare PSF $S_{\gamma}^{cs}(E1)_{KMF}$ for $E_{\gamma} \leq B_n$ [15]

$$\tilde{S}_{\gamma}^{cs}(E_{\gamma} \leq B_n) \equiv \frac{\langle \Gamma_{\gamma cs}^{J\pi} \rangle}{\langle D_c^{J\pi} \rangle E_{\gamma}^5 A^{8/3}} \approx 10^{-15} \frac{\Gamma_G}{4\{1 - (E_{\gamma} / E_G)^2\}^2} \quad (49)$$

with the experimental data on PSF_{E1} ($E_{\gamma} \leq B_n$) compiled in ref. [16]. The results presented in fig. 3 show that $S_{\gamma}^{cs}(E1)_{KMF}$ reproduces in general respective experimental values.

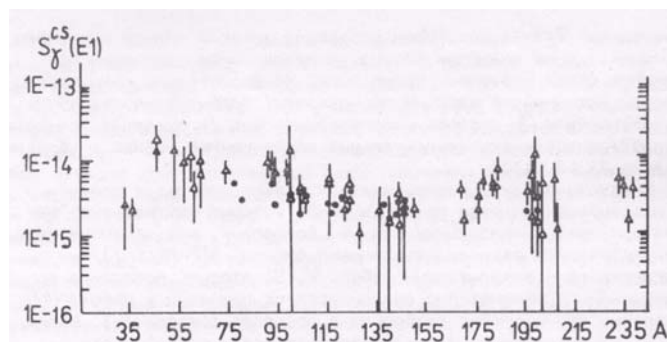


Fig. 3 Comparison of experimental (triangles) and theoretical(dots) PSF_{E1}. No normalization used.

The same has been done for $S_{\gamma}^{cs}(M1, E_{\gamma} \leq B_n) \equiv \frac{\langle \Gamma_{\gamma cs}^{J\pi} \rangle}{\langle D_c^{J\pi} \rangle E_{\gamma}^3}$. Note that in the approach [7] $S_{\gamma}^{cc'}(M1) \approx S_{\gamma}^{cs}(M1) \approx (1 \div 2) \times 10^{-8} \text{ MeV}^{-3}$ (50)

In figure below experimental data from [16] is compare with $S_{\gamma}^{cs}(M1)$ normalized to the ¹⁴⁴Nd data [2,17].

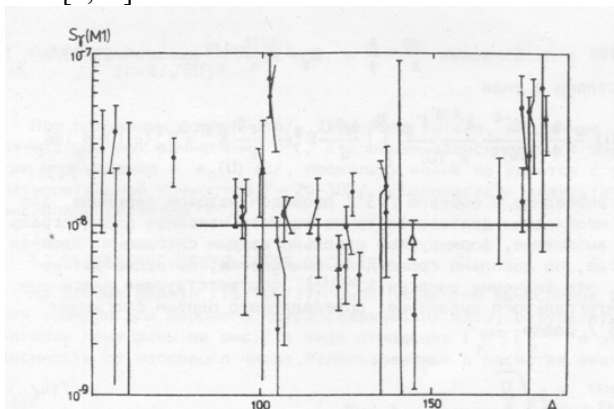


Fig. 4. Comparison the experimental [16] PSF_{M1} ($E_{\gamma} \leq B_n$) with the estimation from [7]

An overall agreement for $A > 90$ is reasonable. It is clear that modern more precise data could show some variations near the estimation (50) especially due presence of M1 GDR and a closeness to magic shell numbers.

Using the theoretical strength functions [7,11] with above mentioned fixed parameters there were calculated total gamma-widths [15] for some middle mass and heavy nuclei . The results are shown in fig.5 below.

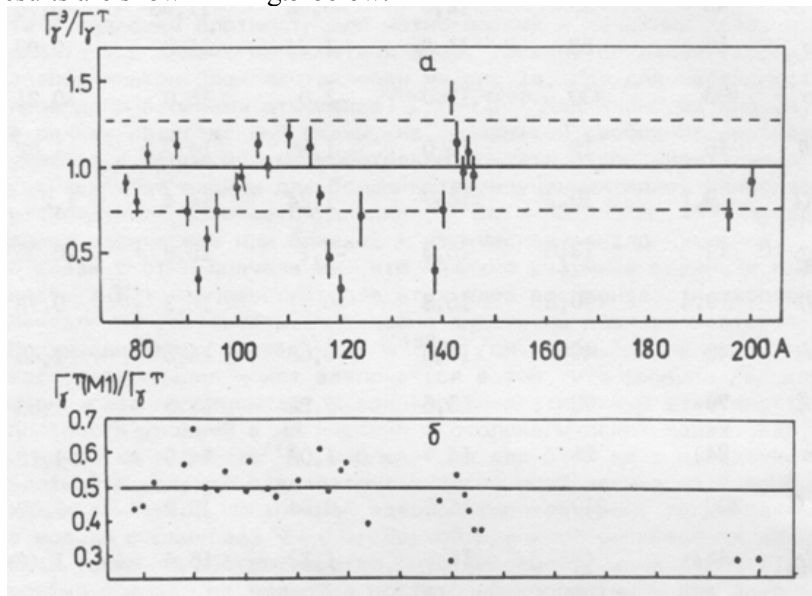


Fig. 5 The ratios $(\Gamma_\gamma)^{exp}/(\Gamma_\gamma)^{theor}$ –(upper part) and a relative contribution to $(\Gamma_\gamma)^{theor}$ of M1 γ -transitions (lower part).

An overall agreement is satisfactory excluding some near magic nuclei. One can see that the M1 γ -transition contribution to $(\Gamma_\gamma)^{theor}$ is essential one.

It is easy to derive the simple analytical formula for averaged total radiative widths of NR using the same theoretical PSFs . Defining $\Gamma_\gamma = \Gamma_\gamma(E1) + \Gamma_\gamma(M1)$ one can obtain [17]

$$\Gamma_\gamma(E1) = 2.9 \times 10^{-5} \Gamma_G \left\{ 5 \left[\frac{3}{4(1-3/\sqrt{aU_c})^2} - \frac{2.3}{(1-4/\sqrt{aU_c})^2 \sqrt{aU_c}} \right] + \frac{1}{(1-5/\sqrt{aU_c})^2} \right\} \left(\frac{U_c}{a} \right)^3 \text{ meV} \quad (51)$$

$$\Gamma_\gamma(M1) = 91 \frac{1}{(1-3/\sqrt{aU_c})^2} (U/a)^2 \text{ meV} \quad (52)$$

These formulas give correct enough results for all middle mass and heavy nuclei with standard values of parameter a from the paper [18].

With the same PSFs many total γ -ray spectra after thermal neutron capture were calculated [19]. Some examples of the results obtained without any normalization to experimental data are shown below in fig. 6.

It is appropriate to note here that the same approach to the dipole PSFs and in general to gamma-decay of compound states near neutron binding energy permits one to describe successfully parity violation effects in total gamma-spectra [B91].

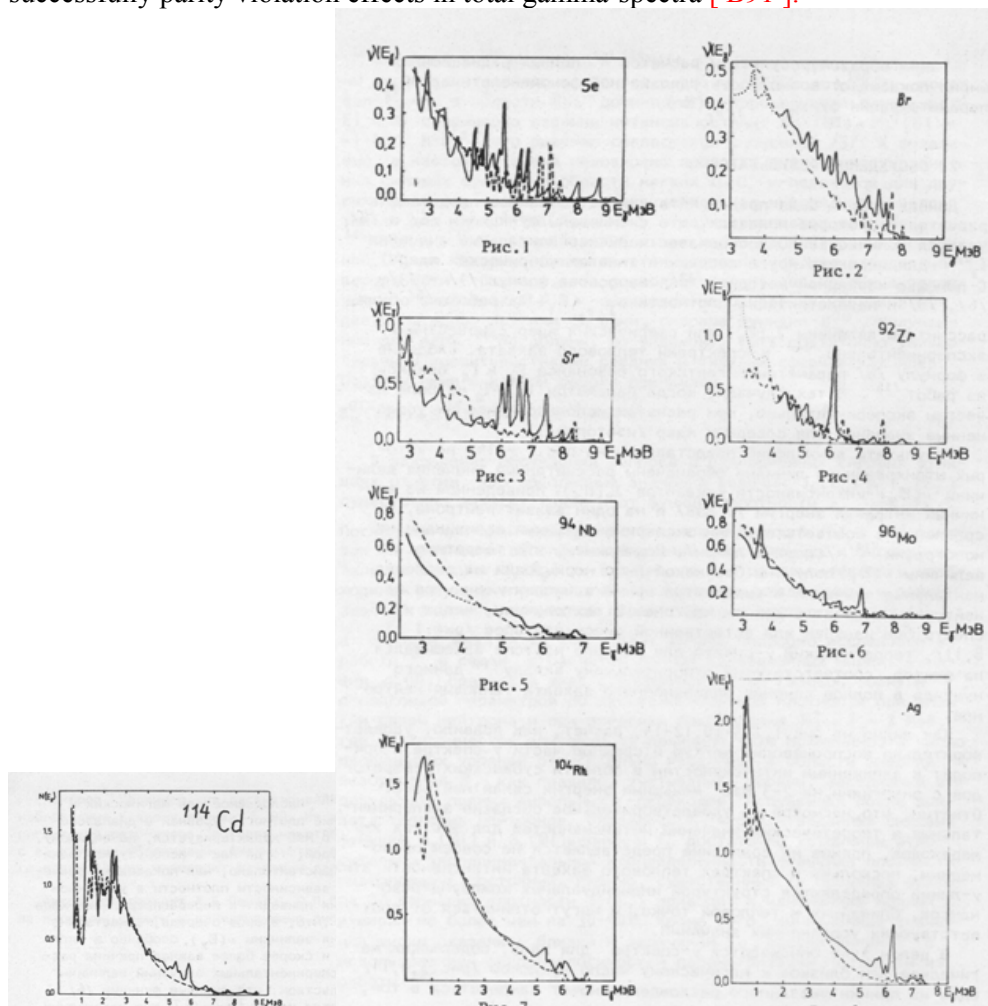


Fig. 6. Total γ -ray spectra: experiment -solid lines, calculations – dashed ones

During last two decades a lot of new information for primary dipole PSF was obtained via studying of two step gamma cascades (TSCs) by Sukhvoi (Dubna) [3,4] and Bečář (Prague) [5,6] groups. These relatively “simple” experiments need very cumbersome and sophisticated analysis for extraction of phenomenological PSFs. The results of both groups obtained in framework of different data analysis methods are different too.

In the papers F. Bečář and I. Tomandl a comprehensive description of TSC experiment and their method of data processing is presented as well as the results obtained. Here we outline schematically main ideas of TSC experiment and show very selective recent results of Dubna group.

After applying some corrections the TSC raw spectra could be converted into the spectra expressed via absolute intensities of respective γ -transitions.

POS (P S F 0 7) 0 1 3

So
$$I_{c\gamma f} = \frac{\Gamma_{\gamma ci} \Gamma_{\gamma f}}{\Gamma_{c\gamma} \Gamma_{i\gamma}}, \quad (53)$$

Really due to a finite energy resolution of used γ -detectors there exists some averaging over intermediate states i that results in additional ambiguities of data analysis. But it was created some methods [6, 21-22] for extraction from TSC data a sum of

$$S_{\gamma}^{ci}(E1) + S_{\gamma}^{cic}(M1) \quad (54)$$

In the approach of Dubna group one manages to extract simultaneously [22] the level density (LD) $\rho(E^*)$ and the sum (54) of dipole PSFs. Some results from ref. [4] averaged over many middle mass and heavy nuclei are represented below in figs. 7 and 8.

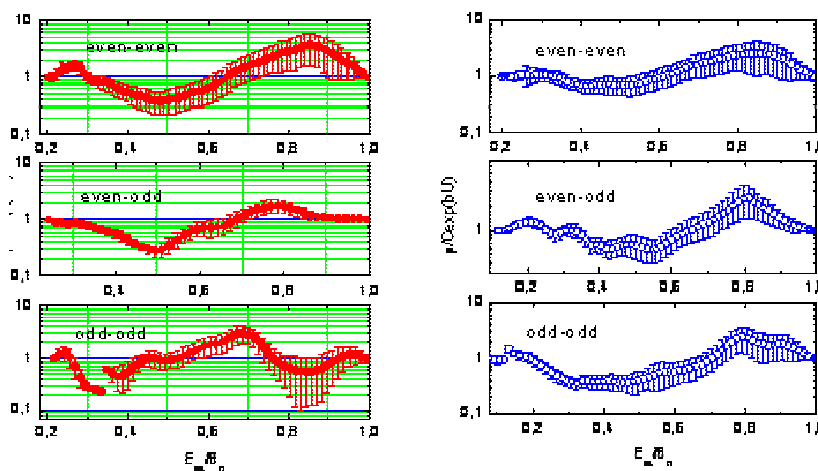


Fig.7. The ratios $\rho(E^*)/\exp(aE^*)$ from [4] in function of E_{γ}/B_n averaged over all nuclei under investigation.

The right part of this fig. (empty circles) corresponds the assumption of data analysis when there is no difference in an energy dependence of PSFs for primary and secondary γ -transitions. In the right part of fig. 7 such difference is taken in account (full circles). One can see that the details of LD irregularities (step-like behavior) depend strongly on the type of nuclei (compare for example the results for even-even and odd-odd nuclei). Of course this dependence of LD could be the result of the specific method data treating. But it is appropriate to note that the results obtained with aid of very different method used by Oslo group show also some step-like LD energy dependence (see respective papers presented at this conference).

The results for the sums of dipole PSFs (54) shown in fig. 8 could reflect in some extent the step-like behavior of LD but in general they give definite indications on dependence of on temperature of an intermediate level i in accordance with ref. [11]. It is more convincing for even-even and even-odd nuclei.

Many arguments for similar conclusion were obtained by Prague and Oslo groups (see respective contributions to this conference).

In fig. 9 it is presented one example of such results

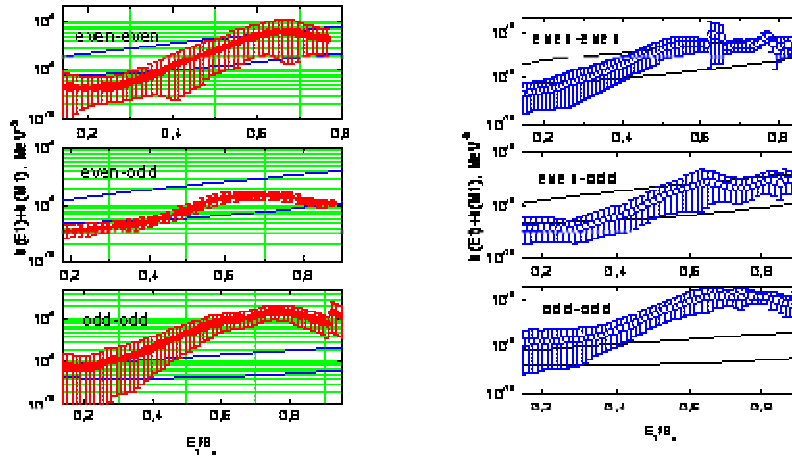


Fig. 8. The averaged sums of dipole RSF from [4]. The legends are the same as in fig. 7. The lower curves correspond to $S_{\gamma}^{ci}(E1)$ from [11] and the upper ones relate to the standard Lorentzian shape [10]. Both curves obtained with $S_{\gamma}^{ci}(M1) = Const$.

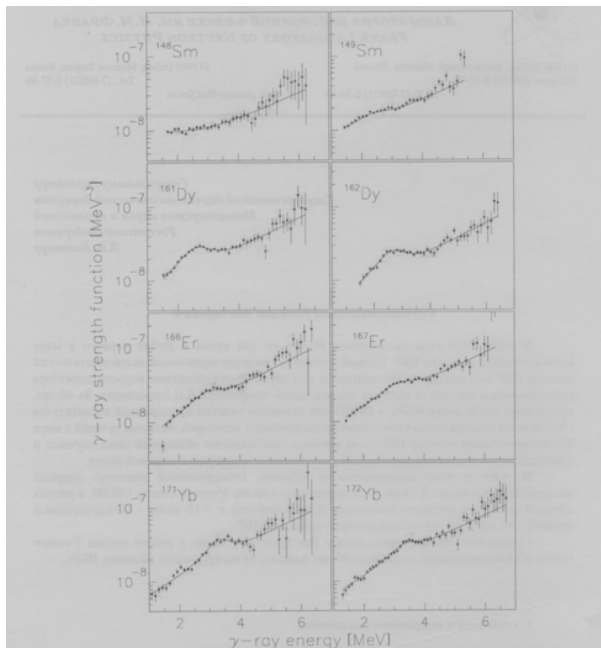


Fig.9. PSFs for $^{148,149}\text{Sm}$, $^{141,142}\text{Dy}$, $^{146,147}\text{Er}$ and $^{171,172}\text{Yb}$. The full circles are experimental data. The solid lines are a fit to the data using $S_{\gamma}^{ci}(E1)$ from [11] and as $S_{\gamma}^{ci}(M1)$ a spin-flip GMDR plus a pygmy resonance.

4. Conclusion

Slow neutron induced reactions (n, γ), ($n, \gamma \gamma$), ($n, \gamma \alpha$) are the effective tool for study of dipole PSFs that are in turn very essential as for deeper understanding of nuclear structure as well as for many important applications.

The present theoretical models are unable to describe in detail all existing experimental data on dipole RSFs. But the experimental data itself are in many cases non-selfconsistent and need in essential improvement.

Taking into account all uncertainties of experimental data and theoretical models it is possible to conclude that the statistical approaches are able to reproduce basic features of phenomenological dipole PSFs. But detailed description of most precise experimental data obtained with aid of modern powerful experimental facilities requires a further development of very sophisticated microscopic theoretical approaches realizing at present in leading research laboratories.

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