AVERAGED CAPTURE CROSS SECTIONS AND RADIATIVE STRENGTH FUNCTIONS IN *pf*-SHELL NUCLEI

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The paper presents experimental results from proton capture reactions by nuclei ^{45}Sc, ^{48,50}Ti, ^{60,61,62,64}Ni, ^{63,65}Cu, ^{56,58}Fe, ^{66,68}Zn, ^{69}Ga, ^{72,74}Ge, and ^{76,78}Br, namely, partial cross sections and radiative strength functions (RSF) simulated in the framework of a statistical model and new phenomenological approaches to the description of the RSF developed by Kadmensky, Sirotkin, and Plujko. Data for the reactions ^{63,65}Cu(p,γ) ^{64,66}Zn are original. The measurements were performed in NSC KIPT using a Van de Graaf accelerator for 4.5 MeV. The RSFs were determined so as to achieve the best agreement between the measured and the calculated cross sections for fixed global parameters of the statistical model. The measured RSF values are model-dependent. As was found, the RSF is influenced by the excitation energy and final state properties of nuclei, contrary to Brink's hypothesis that denies the relationship between the RSF and the nuclear structure. These results can be extended to all *pf*-shell nuclei.

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The reactions with protons of sub-barrier energies are a convenient and widely used method of nuclear spectroscopy. For nuclei with A > 40 the density of high excited states is so great that it is justified to apply statistical methods of analysis dealing with concepts of average cross sections, level densities, statistical tensors, strength functions, etc. In these measurements and analyses statistical averaging is fulfilled that here received the name average resonance method (ARM) [1]. The successful application of the ARM was ensured by the fact that the cross sections for the final state population in capture reactions are sufficiently large for most experiments to be done. Also, the final states appeared to be aligned, despite being statistically populated, therefore angular distributions of γ-rays have significant asymmetry and thus, are well suited to spectroscopy purposes.

By the present time the statistical model has been fully developed and widely used in the analysis of particle reactions [2, 3, etc.] where the authors carried out a kinematical analysis of reactions and derived analytic expressions for nuclear reaction cross sections. The modern statistical model is combined including an optical, Fermi-gas, and evaporative models. Practically only the approach to the description of capture cross-sections remained to be developed. As distinct from particle reactions, where the role of the radiation channel was minor, the description of capture reactions came across large difficulties connected with the absence of RSF's data.

This problem is still waiting for an adequate solution. The reason is that there is no versatile and reliable method of RSF determination, especially in the resonance energy region, like the method of photonuclear reactions for higher energies. The latter permitted the RSF data to be obtained for all stable nuclei in the range of giant resonance. In the resonance energy region the most accurate is the method of isolated resonances. However, being rather time-consuming, it could not provide enough data for the systematization and analysis of the RSF. As similar but model dependent method for average and heavy mass nuclei one can regard the ARM. The application of the ARM made it possible to obtain data for many nuclei in the range A = 40…150 and make a comparison with theory. We employed this method to derive the RSF from the reaction with protons for *pf* - shell nuclei (^{45}Sc, ^{49,51}V, ^{63,65}Cu, ^{64,66}Zn, ^{57,59}-Co, ^{67,69}Ga, ^{71}Ge, ^{73}As, ^{77,79}Br etc. [5-9]). For heavier nuclei neutron capture reactions are usually used. The method is effective, though has a number of limitations on the choice of nuclei to be studied. It is capture reactions that are now the main source of information about the RSF in the resonance region of excitation energies and the data thus obtained can be related to the RSF behavior in the E1- resonance region.

This work presents for the most part original data on the partial cross sections for the ^{63,65}Cu(p,γ) ^{64,66}Zn reaction together with data and interpretation of the RSF in ^{64,66}Zn in the region of 9 … 13 MeV. With these nuclei we only demonstrate the potential of the method, while the results of these and earlier studies are extended to all *pf*-shell nuclei. So far the available information about the RSF for these nuclei and γ-quantum energies is not sufficient.

The developed method [1-3] can give the required information as it relies upon the well founded statistical model of nuclear reactions and the ARM, conditions of which are experimentally feasible for *pf*-shell nuclei. A unique pair γ - spectrometer with high energy resolution and efficiency [4] developed in the nuclear spectroscopy laboratory allows an implementation of the ARM. The pair γ - spectrometer is based on a Ge - Li detector of 63 sm^3 volume which is enclosed in the annular NaI (Tl) crystal. The measurements were fulfilled in NSC KIPT using a Van de Graaf accelerator for 4.5 MeV. The enriched targets were deposited on gold or tantalum substrates (0.7 and 1.0 μm for ^{64,66}Zn, respectively). The averaged pair γ - spectrum for ^{64}*Zn is* shown *i*n Fig. 1. The efficiency of the pair spectrometer was about 15 % as compared to a single crystal spectrometer. In the high-energy part of the spectrum we observe pronounced and resolved γ - lines corresponding to primary transitions in nuclei. The latter provide information about partial cross sections (PCS) for capture reactions which were eventually used to determine the RSF. The bell shape of the spectrum is due to the statistical character of the CN-states decay. The soft part of the spectrum is suppressed (not shown) therefore simultaneously with the pair spectrum we measured single-crystal spectra used for continuous control of the efficiency of the pair-spectrometer as well as for determination of the (p,p'γ) and (p,nγ)-cross sections from the yields of soft γ - lines.

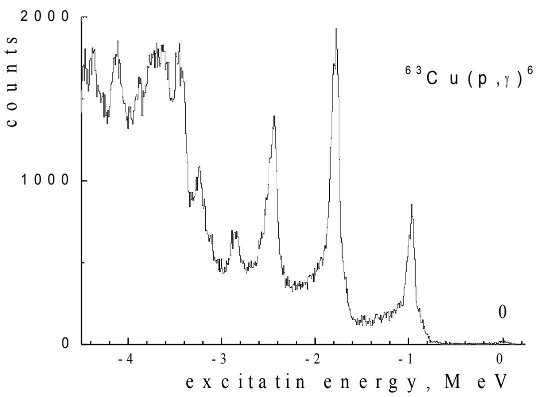

Fig. 1. *γ - spectrum from the ^{63}Cu (p,γ) ^{64}Zn reaction. Averaging over the interval Ep = 2.56...3.06 MeV. (Energy of transition to the ground state is assumed equal to zero)*

Physicists returned occasionally to proton capture reactions by ^{64,66}Zn and other *pf*-shell nuclei, as the experimental techniques were improved [5-8] and new phenomenological approaches were developed in the RSF description [10-15]. Zinc belongs to structural materials so data on the cross sections and strength functions represent significant interest from different points of view. The difficulties in the description of capture cross-sections are mostly due to the RSF being not yet elucidated sufficiently while the optical potential (OP) and the density levels (DL) for low energies are well known.

The proton capture cross sections within the statistical model can be derived through transmission coefficients /2/:

$$\sigma_{p\gamma_i}(E_p) = \pi D^2/2(2I+1) \cdot \sum_{J^\pi, l_p, L\lambda} (2J+1) \frac{T_{l_p,j_p} \langle 2\pi S_\gamma^{L\lambda}(E_{\gamma i})\rangle}{T^{tot}}, \qquad (1)$$

where D is the proton wavelength, I^π is the spin and the parity of the target nuclei, J^π is that for a composite nucleus, T^{tot} is the sum of transmission coefficients for all opened channels:

$$T^{tot} = \sum_{j'_p,l'_p} T_{j'_p,l'_p} + 2\pi \sum_{i=1}^{n_i} E_\gamma^{2L+1} S_\gamma^{L\lambda}\left(E_\gamma\right) + 2\pi \cdot \int_{E_d}^{U} \rho\left(U-E_\gamma\right) E_\gamma^{2L+1} S_\gamma^{L\lambda}\left(E_\gamma\right) dE_\gamma + \sum_{j'_n,l'_n} T_{j'_n,l'_n}, \qquad (2)$$

j_p and l_p are the spin and the orbital moment of incident protons, j'_p and l'_p are those for the exit channel, j_n, l_n (j'_n, l'_n) are for neutrons. E_d is the excitation energy of a nucleus below which it is possible to observe separate states (i), while above it the level density concept is used. T_{jp} and T_{jn} are the transmission coefficients for protons and neutrons, respectively, ρ is the density of levels with spin J for the excitation energy (U - E_γ), U = Q + E_p.

This expression also includes the radiation strength function $S_\gamma^{L\lambda}$ for the multipolarity Lλ which enters in the numerator for a particular transition for fixed excitation energy. It simultaneously enters in the denominator as analytical function and is used for calculation of averaged total radiation widths. As the RSF results from the solutions of Eq.(1), its derivation is a mathematical problem, which, in general, has no analytical solution. The RSF should be such as to fit the measured partial cross section $\sigma_{p\gamma_i}(E_\gamma)$ to the calculated one for the given transition and energy. At the same time it should be a function permitting averaged total radiation widths to be obtained satisfying the same equation. Therefore to find the RSF we had to solve the algebraic equation with respect to $S_\gamma^{L\lambda}$ using various hypotheses for the RSF in the calculation of total widths. It is either a Lorenzian or a statistical approach of Sirotkin-Plujko [11-13]. Such solution is possible in the case if the RSF is a function of photon energy only. If we confine ourselves to dipole transitions only, we can represent a cross section as a sum:

$$\sigma_{p\gamma_i}(E_p) = \sigma^{E1}_{p\gamma_i}(E_p) + \sigma^{M1}_{p\gamma_i\, p\gamma_i}(E_p) \qquad (3)$$

The measured cross sections $\sigma^{exp}_{p\gamma_i}(E_P)$ are also a sum of the magnetic and the electrical contributions, the determination of E1-RSF is only possible if the magnetic contribution to the cross section is known or estimated independently. This is quite possible since the M1-contribution is normally ~ 10 % and single-particle estimates or estimates in the framework of phenomenological models are sufficient. The statistical model parameters were taken from independent experiments [16,17]. The imaginary part of the potential was somewhat reduced with respect to global parameters reported in [17] where the energy dependence of the potential was updated. The parameters were also verified in the analysis of the (p,p'γ) and (p,nγ) - cross sections measured in our experiments.

The distribution of the radiation strength in nuclei for excitation energies approaching the nucleon binding energy is in principle poorly described by a classical Lorenzian which leads to overestimated RSFs, and hence, total radiation widths and cross sections. Though in general the mechanism of RSF formation is clear, in details it represents certain difficulties arising from a high complexity of a nuclear system at high excitation energies. The above-mentioned deviations are of systematic character [5-10], which stimulated the development of new phenomenological approaches to the description of the RSF. Those models proved successful which take into account the giant resonance spread width, temperature of a nucleus in the final state and single-particle nuclear structure [10-13]. The most advanced seems a model proposed by Sirotkin [11], and later Plujko [12,13] in which not only the above parameters are included, but also the dependence of RSF on the excitation energy is examined. Results obtained in [11-13] reveal an appreciable dependence of the RSF on the excitation energy, contradicting Brink's hypothesis. In this case the energy dependence is stronger for low than for high-energy transitions. The microscopic description of the RSF still remains inadequate for comprehensive explanation of experiment [14,15].

To describe the cross sections the RSFs were calculated by extrapolating a Lorenzian [18,19], or from expressions derived in [10-13]. The authors of [11-13] (but [10]) make use of the RSF obtained in the region of the max GDR. Data on the GDR are given in [18,19]. It is a resonance with two maxima, each giving the contribution to the strength function for low energies, however, the role of the first is dominant. The single-particle estimates for M1-transitions are based on the systematic data on the factor $k_{M1} = (3.0\pm0.4)\cdot10^{-8}$, MeV^{-3} [19]. In addition to the single-particle estimates, we used the expression proposed by Sirotkin [11]:

$$S_\gamma^{E1}/S_\gamma^{M1} = 0.03A(E_\gamma^2 + (\pi T_f)^2)/Q_n^2, \quad (4)$$

where Q_n is the neutron binding energy.

The RSFs for the E1 transitions obtained within phenomenological models in [10-13] differ only in details. Thus in [11] the influence of the nuclear structure on the RSF is considered. Here a shell structure of the single-particle level spectrum was taken into account in calculations of the particle - hole state density $\rho_{2p2h}(E_\gamma, T_f)$. The temperature dependence of the occupation numbers of the levels is also included:

$$\Gamma_{R_i}(E_\gamma) = \Gamma_i \frac{\rho_{2p2h}(E_\gamma, T_f)}{\rho_{2p2h}(E_i, T_f)}. \quad (5)$$

In the case of a constant density of single-particle states

$$\Gamma_{R_i}(E_\gamma) = 2/3\alpha\,[E_\gamma^2 + (2pT_f)^2]\cdot E_\gamma/E_o\,cth(E_\gamma/2T_f), \quad (6)$$

where $E_0 = \varepsilon_f A^{-1/3}$ is the distance between the shells, $\alpha = \varepsilon_f^{-1}$ is a constant defining widths of single-particle states, and ε_f is the Fermi energy.

Thus, the role of the nuclear structure is allowed for through densities of the particle-hole equidistant states (Eqs. (5,6)). The expression for the RSF derived in [10] allows us to describe the RSF below GDR, however, near the GDR maximum the function diverges.

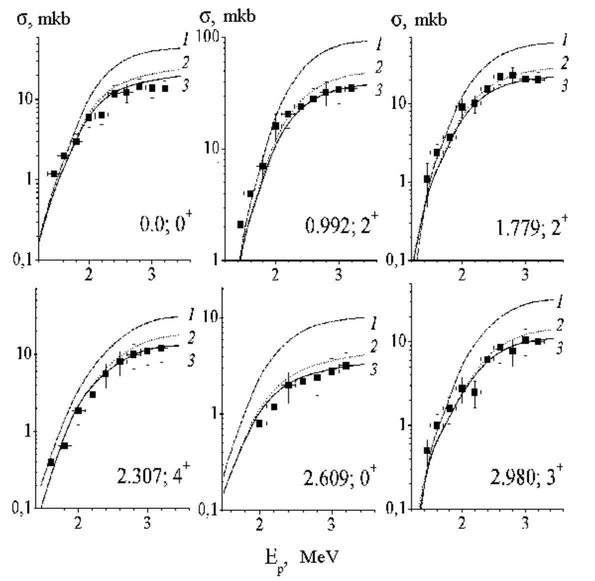

Fig. 2. *Partial cross sections for $^{63}Cu(p,\gamma)\,^{64}Zn$. Energies (keV) and quantum numbers of the states are indicated. Curves: 1- RSF as a Lorenzian, 2- RSF calculated by the model [11] (single-particle estimates of the M1 contribution), 3- calculation by the model [11] including the M1 contribution, Eq. (4)*

The expression for the RSF obtained by V. Plujko [12,13] is the following:

$$S_\gamma^{E1}(E_\gamma) = 8.674\cdot10^{-8}\frac{\sigma_o\Gamma_R}{1-\exp(-E_\gamma/T_f)}\cdot\frac{E_\gamma\Gamma(E_\gamma,T_f)}{(E_\gamma^2-E_R^2)^2+(\Gamma(E_\gamma,T_f)E_\gamma)^2},[MeV^{-3}], \quad (7)$$

where σ_o is the cross section corresponding to the maximum photoabsorption, E_R and Γ_R are the GDR energy and width, T_f is the temperature of a nucleus in the final state. In the Fermi-gas model it is related to the excitation energy of a nucleus: $T_f = \sqrt{U - E_\gamma/a}$, where *a* is the level density parameter.

A distinguishing feature of RSF calculations based on the expression (7) is the representation of Γ - spread widths of GDR, dependent on the γ - quantum energy, as a sum of a 'collisional' and a single - particle components. It results in an additional term in the expression for the strength function, leading to the non-zero limit for the RSF where the γ - quantum energy tends to zero. The second feature of the RSF is its dependence on the excitation energy of a nucleus, contrary to Brink's hypothesis. Moreover, the dependence is more pronounced for lower energies of γ - quanta.

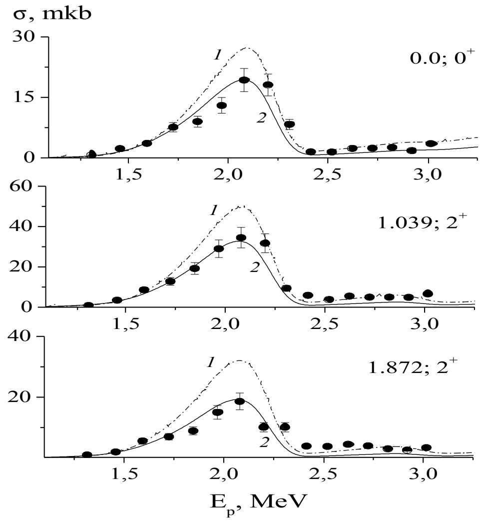

Fig. 3. *Partial cross sections for* ^{65}*Cu (p,γ)* ^{66}*Zn. Curves: 1- cross sections with Lorentzian-shaped RSF [18], 2- with RSF calculated by the models [11-13]*

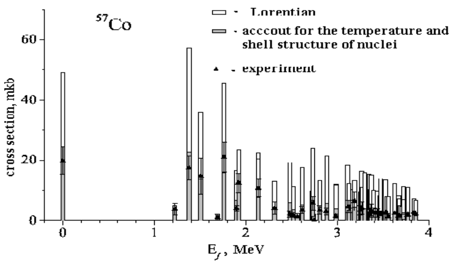

Fig. 4. *Population of the final states of* ^{57}*Co in the proton capture reaction (PCS measured at Ep=3.08 MeV).* Light *bars - Lorenzian,* ▲ *- our data, dark bars - PCS calculated with RSF from [11-13]*

In the pair spectra (Fig. 1) we observe γ - lines for transitions to low-lying states up to 3.0 MeV. Figs.2 and 3 show PCS for ^{63,65}Cu (p,γ) ^{64,66}Zn reactions measured for transitions to low-lying states for which it is possible to resolve the γ - lines. Errors in the determination of the cross sections are dependent on the number of levels over which the averaging is performed and can be reduced by extending the averaging interval.

Measurements of partial cross sections for reactions in which low-lying states are excited by primary γ - transitions, provide more than enough information about the decay mechanism of high states and within the framework of the models permit RSFs to be calculated which are necessary for the description of the capture cross-sections, with other model parameters being fixed.

The cross sections are calculated with the following Beechetti-Grenleess optical potential (in author's notation) [16]: (V_0 = 54.0, V_{RS} = 56.9, W_0 = 8.8, W_S = 8.3, W_V = 0, V_{S0} = 6.2) MeV, (r_{so} = 1.01, a_{so} = 0.75, r_R = 1.17, a_R = 0.75, r_D = 1.32, a_D = 0.57) fm.

The level densities are from [20]: Δ = 0.60 MeV, a = 7.50 MeV^{-1}. The moment of inertia is assumed equal to 0.5 of the solid state one.

Fig. 3 shows that the capture cross section for ^{65}Cu is rapidly decreasing above the neutron threshold, which is in agreement with the statistical model simulations.

The calculated cross sections for fixed model parameters are in agreement with the model for RSF [11,12] but in disagreement with the Lorenzian [18]. The latter leads to overestimated cross sections. It is evident in Fig. 4 showing the population of the ^{57}Co final states in the proton capture reaction are shown. The extrapolation of the Lorenzian results in cross sections almost 2 times greater.

The table compares measured and calculated partial cross sections for ^{63}Cu(p,γ)-reactions.

Measured and calculated cross sections for fixed parameters of the statistical mode and RSF from [11-13]. Target: ^{63}*Cu, Ep = 2.47 MeV, ΔE = 0.5 MeV*

Level energy, MeV	J^{π}	σ^{exp}(PCS), μb	$\sigma^{/11,12/}$, μb	$\sigma^{/18/}$, μb
0.000	0^+	14.4(3.6)	15.99	29.73
0.992	2^+	30.9(7.7)	30.87	58.42
1.779	2^+	18.9(4.7)	18.02	37.09
1.910	0^+	3.5(0.8)	4.38	10.21
2.307	4^+	8.2(2.0)	8.20	13.20
2.609	0^+	2.2(0.5)	2.71	6.71
2.737	4^+	6.2(1.5)	6.21	10.29
2.794	2^+	36.6(9.1)	9.20	20.51
2.980	3^+	7.8(1.9)	7.98	17.33
2.998	3^-	-	8.73	11.29
3.006	2^+	-	7.95	17.97
3.071	1^+	-	5.61	14.00
3.078	4^+	4.3(1.0)	4.96	8.39
3.095	3^+	6.9(1.7)	7.38	16.12

The discrepancy between theory and experiment was found to be independent of the energies of low-lying states. We observe a striking disagreement with a Lorenzian (the last column) but a very good agreement with the phenomenological model [11,12]. Conclusions drawn for the Zn nuclei are typical of all *pf*-shell nuclei.

Fig. 5 shows RSFs determined for six mentioned above transitions in ^{64}Zn. One can see that the best fit is achieved with a model described in [12] (Curve 2). For all transitions total radiation widths are calculated within the model of [11-13]. The contribution of the M1 - transition is taken into account by Eq. (4).

As was already pointed out, the measured cross sections can be used to obtain the RSF which would satisfy Eq. (1) in the best way. In principle, there is practically no difference in the strength functions calculated according to expressions given in [11] or [12-13] in the studied region of γ-quantum energies as the dependence on the excitation energy is poorly pronounced. The discrepancy becomes noticeable only for energies below 5 MeV. It is evident in Figs. 5 and 6 where the calculated and measured strength functions are plotted for ^{64,66}Zn. The RSF calculations were performed with GDR parameters in the ^{64}Zn nucleus borrowed from [18]: σ_1 = 41.40 mb, E_{R1} = 16.23 MeV, Γ_{R1} = 3.27 MeV, σ

$_2$ = 56.10 mb, E_{R2} = 19.19 MeV, Γ_{R2} = 5.98 MeV. For ^{66}Zn the same data were used. We can see that for ^{66}Zn above the neutron threshold all the dots are shifted upwards. This might be due to the incorrect calculation of the neutron cross section because we employed OP parameters determined for low neutron energies.

Since at low energies the choice of OP and DL parameters for these nuclei is not a problem, an adequate description of the cross sections is provided by a proper choice of a RSF. The disagreement with experiment is easily eliminated for all nuclei if in the RSF calculations a model of Sirotkin - Plujko is used [11-13].

Fig. 7 shows RSFs for ^{64}Zn nuclei which were determined from the γ - spectrum measured for fixed proton energy. The energy dependence was found using the transitions to the final states listed in Table 1. Such measurements were carried out for most of the above nuclei. Experimental RSF values were obtained within various models for total radiation widths. Experimental data are located below the Lorenzian, being grouped around curves 3 and 4 in accordance with new models.

Similar data are shown for ^{61}Cu in Fig. 8. They are normalized to Lorenzian for the ground state transition. The experimental points reveal stronger dependence on energy than the Lorenzian. Light points are our data. They are positioned much lower and coincide with calculations [11,12], but better agreement was achieved when we allowed for the spectrum of single particle states. We arbitrarily shifted the spectrum in energy to achieve this description. The same was done for the other nuclei (^{57,59}Co,^{63,65}Cu,…) in order to agree the observed and the calculated RSFs and show that there is a relation between the latter and the structure of nucleus.

The results from the studies of ^{63,65}Cu (p,γ) ^{64,66}Zn reactions correlate with those obtained earlier for A = 45-78 nuclei [6-9].

Summarizing we state that:

- The partial cross section for the proton capture reactions by ^{45}Sc, ^{48,50}Ti, ^{60,61,62,64}Ni, ^{63,65}Cu, ^{56,58}Fe, ^{66,68}Zn, ^{69}Ga, ^{72,74}Ge, and ^{76,78}Br are measured and described within the framework of a statistical model with a global set of parameters. We used the RSF that permits an adequate explanation of the observed cross sections.
- The photon strength functions in nuclei ^{46}Ti, ^{49,51}V, ^{61,62,63,65}Cu, ^{64,66}Zn, ^{57,59}Co, ^{67,69}Ga, ^{71}Ge, ^{73,75}As, and ^{77,79}Br were determined from the (p,γ) cross sections [6-9] measured using statistical averaging.
- It is shown that Lorenzian is suitable for the description of the RSF only in region of max GDR.
- In the resonance region a good description of the RSF is achieved with the phenomenological approach of Kadmensky-Sirotkin-Plujko in which the dipole resonance widths (spread widths) depend on the γ-quantum energy and the temperature of a nucleus in the final state. In this case the spread width is represented by a sum of the ‘collisional’ and the single-particle part connected with the mechanism underlying the RSF formation.

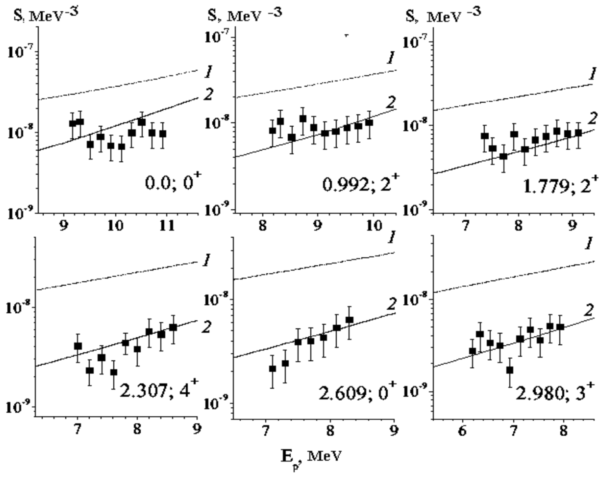

Fig. 5. *RSF measured for transitions to six low-lying states in ^{64}Zn. Curves: 1 – Lorenzian, 2 - RSF calculated according to [11,12]*

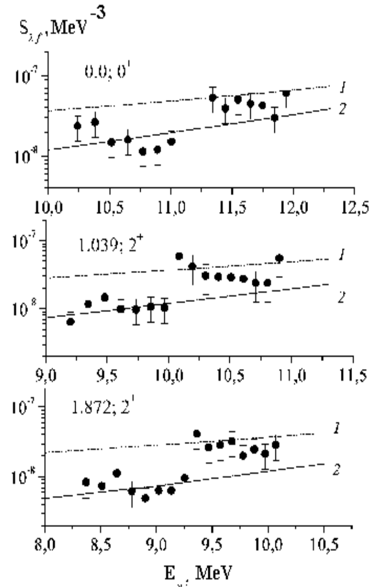

Fig. 6*. Partial radiative strength functions in ^{66}Zn. 1 - Lorenzian, 2 - [11,12]*

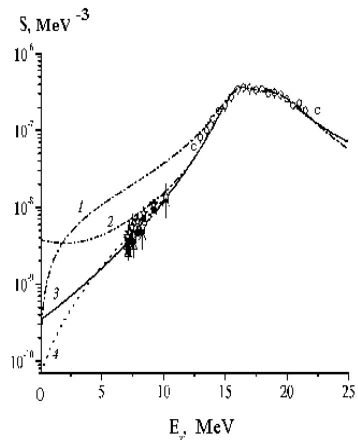

Fig. 7. *RSF in ^{64}Zn measured for the fixed excitation energy E*=10.2 MeV, ΔE = 0.5 MeV. Curves: 1 - Lorenzian [18], 2 - [10], 3 - [11], 4 - [12,13]. Points: our data with total width calculated from o - [18], Δ - [11], ÷ - [12]*

- ♦ In this description the RSF tends to be finite as E_γ tends to 0. It manifests itself in the RSF being a weak varying as a function of γ-quantum energies reaching 5-11 MeV. This RSF behavior does not follow a Lorenzian.
- ♦ The RSF was found to depend on the excitation energy, which is in conflict with Brink's hypothesis declaring that the RSF is not sensitive to the structure of nuclei.

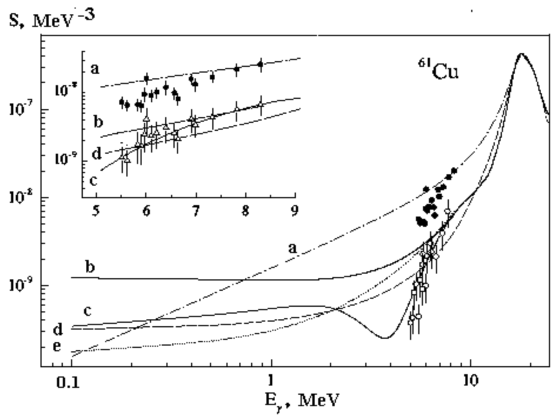

Fig. 8. *RSF in ^{61}Cu measured at E_p= 3.0 MeV, ΔEp = 230 keV. • - [21], data normalized to RSF of GDR, o - our data. Curves: a - Lorenzian [21], b - [10], c - [11], d- [11] without shell structure, e - [12]. Inset: detailed RSF in the region of 5.5 - 8.4 MeV*

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