THE PROBABLE LEVEL DENSITIES AND RADIATIVE STRENGTH FUNCTIONS OF DIPOLE GAMMA-TRANSITIONS IN ^{57}Fe COMPOUND NUCLEUS

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Abstract

From the published results of experimental research of ^{56}Fe(n,2γ) reaction carried out in Budapest, the values of probable densities of cascade intermediate levels with 1/2, 3/2 spin and radiative strength functions of cascade E1 and M1 transitions in ^{57}Fe compound nucleus have been determined. These results correspond to analogous data for other nuclei studied by us and contradict to predictions of conventional models.

Introduction

The modern experiment techniques permit one to measure parameters of most nuclear reactions with error about 10% or less. Meanwhile, specific characteristics of nucleus which are important for theory and practice such as level density and radiative strength functions of cascade transitions are derived from experiment with less accuracy. The principal cause of this is insufficient volume of experimental information used in fitting process or incorrectness of its algorithms. The level density and strength functions of cascade gamma-transitions below neutron binding energy B_n are typical examples of problems to elucidate experiment results with high reliability levels. This is certainly when:

1. Setting up the best method to find unknown quantities from experimental spectra if they cannot be determined directly.

2. Collecting the experimental data as much as possible to guarantee the singularity of the desired parameters and the ability to use these quantities for complementary independent revision.

3. Evaluating all the sources of systematic error of achievable values.

Actually, the level density ρ was determined now from experimental data on:

(a) the nucleon evaporation spectra (see, for instance, [1]);

(b) the intensities of two-step gamma-cascades [2]

$$I_{\gamma\gamma} = \sum_{\lambda,f}\sum_{l}\frac{\Gamma_{\lambda l}}{\Gamma_{\lambda}}\frac{\Gamma_{lf}}{\Gamma_{l}} = \sum_{\lambda,f}\frac{\Gamma_{\lambda l}}{<\Gamma_{\lambda l}>m_{\lambda l}}n_{\lambda l}\frac{\Gamma_{lf}}{<\Gamma_{lf}>m_{lf}}, \qquad (1)$$

between compound state (neutron resonance) and a group of low-lying levels of studied nucleus determined according to algorithm [3] for all possible intervals ΔE of energy E_1 of cascade primary gamma-transitions;

(c) the gamma spectra depopulating levels with the excitation energy E_{ex} in (d,p) [4] and (^{3}He,α) [5] nuclear reactions;.

Within methods [2] and [5], ρ is determined simultaneously with strength functions of cascade gamma-transitions:

$$k = f/A^{2/3} = \Gamma_{\lambda l}/(E_\gamma^3 \times A^{2/3} \times D_\lambda). \quad (2)$$

Here E_γ is the gamma-transition energy and D_λ is the distance between initial levels λ. Such form of k provides minimal dependence of this parameter on nuclear mass and allows direct comparison of these parameters in nucleus with different masses. It is assumed that the partial radiative width $\Gamma_{\lambda l}$ of gamma transition between λ and l levels is the random average value, and the width ratio for different multipolarity transitions can be determined experimentally. It is evident that the criterion of the necessary confidence for the determination of k and ρ does not cause the difference among the results of various experiments in principle. In other words, once there are errors, explanation for these is obligatory. The results of ^{57}Fe compound nucleus [5,6] are ideal examples in this situation.

1 The basic principles to determine ρ and k from intensities of two-step cascades

Equation (1) contains more unknown parameters than measured the number of intervals in it. Nevertheless, this type of relation between ρ and k with $I_{\gamma\gamma}$ provides limitation of the region of their probable values (the simplest example for such type of function is giperellipsoid $\sum(ax_i)^2$=const with arbitrary variable number i). The interval of ρ and k possible values is rather narrow only if experimental spectra are decomposed in sole primary and sole secondary components according to [3], and ratio $\Gamma_{\lambda l}$, Γ_{lf} of primary and secondary transitions widths with equal energy and a multipolarity is set in some manner. Although the first condition is not satisfied for experimental data from [6], the use of algorithm [2] and data from files of ENDS [7] and EGAF [8] permits one to find narrow enough intervals of ρ and k values (with the accuracy $(\chi^2/f < 1)$ which provide reproduction of $I_{\gamma\gamma}$ in all 27 energy intervals of cascade gamma-transitions. In order to get this results, the current k values of iterative process [2] have to be replaced by the values which are set by experimental intensities of primary transitions 7.645, 7.279, 6.380, 6.018, 5.915, 4.217, 3.436 and 3.266 MeV. As usually, in iterative process we used values of neutron resonances, low-lying levels densities and total radiative width of s-resonances [9]. Level density of ^{57}Fe at the thermal neutron capture is very small, therefore the results of the method used to determine ρ and k are sensitive enough for parameters and decay types of low-lying levels involved in calculation of cascade intensity. Corresponding data on 10 levels with $E_f \leq 2.113$ MeV with spins $J^\pi = 1/2^- - 7/2^-$ were taken from ENDS-file. Radical discrepancy between these results and the ρ and k values from [5,6] has the simplest explanation: reliable data can be extracted from the experiment only under condition of execution of basic principles of mathematics and mathematical statistics. First of all, should be taken into account specific of errors transfer between the measured spectrum and parameters derived from it. From eq. (1), it follows, that in the first approach, the error of cascade intensity

$$\delta I_{\gamma\gamma}(E_1) = \sum(dI/d\rho \times \delta\rho + dI/dk \times \delta k) \quad (3)$$

is the incoherent nonlinear sum of errors $\delta\rho$ and δk from **whole** interval of possible energies of the cascade intermediate levels. This means, in particular, that the coincidence of the experimental and calculated cascade intensities for given ρ and k in individual intervals of nuclear excitation cannot be interpreted (as it was done in [6]) as the proof of their equality to unknown values. This fact is illustrated in Fig. 1. Here experimental intensities were obtained as superposition of graphic data in figs. 2 and 3 from [6]. They are compared with:

(a) the calculation which uses the results [5] of determination of ρ and k from the data on reaction ^{57}Fe(^{3}He,^{3}He,γ)^{57}Fe and

(b) the typical results of calculation of $I_{\gamma\gamma}$ for both obtained like in [2] random ρ and k values from the interval of their possible variation, and variant in which level density is fixed according to data [5] and only strength functions are varied (see Figs. 2 and 3).

In case of analysis of the experimental spectrum without its decomposition [3] into components corresponding to solely primary and solely secondary transitions, the total error of intensity includes in additional error related with registration of cascades with secondary transitions from the same energy interval: $\delta I^{exp}_{\gamma\gamma}(E_1) = \delta I^{prim}_{\gamma\gamma} + \delta I^{sec}_{\gamma\gamma}$. This leads to additional widening of interval of the ρ and k which reproduce experimental spectra due to false solutions. For example, fixation of level density in method [2] according to the data [5] results in the sum strength functions which, in the regions $\sim$ 3.2 and $\sim$ 4.4 MeV, are more than two times larger than the maximum experimental value of k. This means that the level density in ^{57}Fe listed in [5] contains some systematic error.

1.1 The spectrum of possible functions ρ, k and their most probable values

Values ρ and k determined within method [2] contain statistic errors. Apart from above classical errors, when calculating the unknown values, the spectra of ρ and k are stretched by the degradation of (1) equation system. This equation system is nonlinear and the correlation coefficients absolute values between their quantities are close to unit for a given χ^2 only for some part of ρ and k values. The remained cases show correlation for other pairs of parameters of (1) system.

It makes impossible situation for degrade linear equations system where interval of solution equals infinity. So, in the case considered here, the interval of all possible ρ and k values is always finite. The sign of $\delta I_{\gamma\gamma}(E_1)$ is different with equal probability at least around its zero value) and probability of random localization of iterative process [2] in vicinity of point, for example, $\sum(dI/d\rho \times \delta\rho) = -\sum(dI/dk \times \delta k)$ is inverse to the value $\sum(|dI/d\rho \times \delta\rho| + |dI/dk \times \delta k|)$.

Therefore, one can make conclusion about asymptotically convergence of found solutions to most probable values, i.e., the average values of ensemble of N realizations of iterative process [2] with corresponding standard deviation. Therefore, the ρ and k functions estimated in this way differ significantly the from data [5]. Level density (Fig. 2) has clearly expressed "step-like" structure as, in practice, in other nuclei studied by means of method [2]. The variations of the sum of radiative strength functions of dipole transitions (Fig. 3) directly testify to its dependence on the structure of cascade intermediate levels in region B_n (if only intensities of cascades [6] with transition energy less than 2.0-2.5 MeV do not have large systematic errors). First of all, it should be taken into account that the

structure in cascade intensities presented in Fig. 1 in interval $2.5 \leq E_\gamma \leq 5.5$ MeV cannot be reproduced in calculation using level densities and strength functions from [5,6]. In correspondence with [3], we could come to a conclusion that data on level densities and strength functions listed in [5,6] cannot reproduce total intensity of two-step cascades even in principal. In general case, two explanations for the disagreement between results of methods [2] and [5,6] could be accepted:

(a) the presence of serious systematic errors in extraction of ρ and k from $I_{\gamma\gamma}$ and from the total gamma-spectra corresponding to decay of ^{57}Fe levels excited in (^{3}He,^{3}He,γ) reaction;

(b) the difference of ρ and k values reproducing the spectra of these two experiments is can result by details of excited levels wave functions structures. Of course, the second possibility is to be taken into account only in case of small experimental systematic errors.

2 Main sources of systematic errors in various methods to determine ρ and k values and any ways of their reduction

So, principal differences in level densities [1,5] and [2] leads to necessity to examine data analysis algorithm and to estimate the confident level of results.

In methods [1,5], common problem at determination of ρ is the relationship between number $m = \rho \times \Delta E$ of levels excited in a given energy interval ΔE and probability T (width Γ) of measurable reaction product emission. Besides, the corresponding spectra can be reproduced by infinite number of functional dependencies $\rho = f(E_{ex})$ and $T = \phi(E_{ex})$, the intervals of possible values of level density and emission probability of reaction product T can vary from $-\infty$ to $+\infty$. It means that the type of spectra measured with methods like [1,5] always provides the result with lower confident level as compared with method [2]. The intensity measured within method [2], to the first approach, is inverse to level density and proportional to dk/dE_γ. Therefore, in all circumstances, this provides results with better confidence as compared with methods [1,5]. Again, it should be taken into account that, analysis of spectra containing [2] only from events of full energy registration of two-step cascades with fixed J^π of their initial and final levels always gives considerably better accuracy than analyses the total gamma-ray spectra measured with scintillation detector, even though owing to supplementary systematic errors caused by subtracting [13] Compton background, and due to higher stability of system with Ge detectors.

In addition, in case [1], determinetion of experimental value ρ, it required the use of theoretical value T of penetration of nucleus surface for evaporated nucleon (or light nucleus). This value should be calculated in frame of nuclear models with error being not larger than some tens percents at possible high-frequent sign-changeable variations of T relatively to average value. The existence of T gradient directly follows from results of modern method [14] to extract ρ and k from intensities of two-step cascades due to high precision of corresponding experiment. As a result, we cannot evaluate confidence of data like [1] objectively. Therefore, it is impossible to use these data to confirm [5] results.

First of all, there is no objective evidence to reject in methods [1,5] the possibility for

compensation of level density increasing (decreasing) in some excitation energy interval by the decreasing (increasing) of neutron or gamma-quantum emission probability in evaporation or primary gamma-transitions spectrum at the decay or excitation of levels close to E_{ex}. This compensation is directly observed [14] for ρ and k extracted from $I_{\gamma\gamma}$ data. The optical potentials used in method [1], most probably, cannot provide the calculation T with required details and errors of ρ at the level achieved in framework of method [14]. The evaluation [15,16] of statistical error and degree of its influence on determined in [2] values of ρ and k showed that method [2] reproduces the peculiarities of above parameters for all possible ordinary experimental systematic errors.

The situation in data analysis from (^{3}He,$\alpha\gamma$) reaction is rather worse. The simple analysis [17] of error transfer from primary transition spectra determination to the fit of this spectra by "Oslo method" [18] with some ρ and k values demonstrates that systematic errors of the desired parameters increase at least by a factor of several tens at every step. At the first step of [17], it is caused by the fact that the intensities of primary transition spectrum are much less than intensities of total gamma-spectra (Fig. 4). That is firstly related to the low energies of primary gamma-transitions. It is easy to get the lower estimation of sum of statistical errors of the primary gamma-transition spectra from the narrow energy interval in the vicinity of E_{ex}. This requires one to normalize (per 1 decay) all full energy spectra of [17] according to equation:

$$\sum I_\gamma \times E_\gamma = E_{ex}. \qquad (4)$$

The deviation of area of the primary transition spectrum [17] from unity is the part of sum of its unknown errors. The maximum of this sum deviation from unit should be very small in order to get acceptable systematic errors of ρ and k.

At the second step, because of the strong correlation [18] between ρ and k, the increase in its relative errors is practically of the same scale. For example, in order to get error of ρ and k about $\sim 50\%$, it is necessary [19] to determine (and normalize to 1) total gamma-spectra at arbitrary E_{ex} with systematic error less than $\sim 0.1 - 0.3\%$. It is possible to reject or reduce the systematic errors by using modified variant of method [17] to get spectra of primary transitions according to eq. (4) and to determine the best values ρ and k. For example, to use the Gauss method and to correct degrade matrix, this allows [20] to realize method of search for the likelihood function maximum within two main principles of mathematical statistics:

(a) to determine supplemental vector of corrections at each iteration by the Jacobean matrix without any assumption;

b) to study explicit form of maximum of ρ and k likelihood function and to select false maxima by simple variation of initial ρ and k. The method [18] does not fully satisfy two above conditions.

The situation with the confidence level of ρ and k obtained within method [2] is much better. Of course, level density and strength functions derived from experimental $I_{\gamma\gamma}$ data include both ordinary and specific systematic errors. Possible ordinary errors of ρ and k can be easily determined by estimating the propagation error of experimental cascade transition intensity to values of ρ and k. For example, comparison between the intensities of the cascade primary transitions from [8] and [21] used for normalization $I_{\gamma\gamma} = F(E_1)$ and the use of results [22] of extrapolation to zero threshold for distribution of random cascade intensities for intermediate levels energies $E_{ex} < 0.5$ MeV permits

precise determination systematic errors for both amplitude and form of $F(E_1)$ function. The variation of initial data [2] in limits of their expected errors allows to estimate [20] ordinary systematic errors of ρ and k at presence of nonlinear and ambiguous relation between $\delta F(E_1)$, $\delta\rho$ and δk. As it was shown in [15], these $\delta\rho$ and δk values obtained in this manner cannot explain "step-like" structure of ρ and k [2] by discrepancy between these parameters and conventional notions about smooth energy dependence of level density.

3 The ability to reduce special systematic errors in determination of ρ k

The left part of eq. (1) is determined by three unknown functions: the total density of the cascade intermediate levels in a given energy interval, sums of radiative strength functions of primary and secondary dipole transitions. Strong anti-correlation of these parameters causes the phenomenon that total level density with different parity and spin (this interval is determined by multipolarity selection rule), and total strength functions of E1 and M1 transitions exactly ($\chi^2/f << 1$) reproducing $I_{\gamma\gamma}$ vary in narrow enough interval. Eventually, this interval for level density with $\pi = +$, $\pi = -$, $k(E1)$ and $k(M1)$ separately is always wider than for their sums. This statement is true if the primary and secondary transitions width ratio is set on the basis of some information. Without the above information, the only way to determine ρ and k in [2] method is the use the assumption of equal energy dependencies of k for primary and secondary transitions. (Modern nuclear models clearly show incorrectness of this hypothesis at excitation energy of about several MeV [23] and, moreover, require [24] detailed accounting for nuclear structure at least up to 20 MeV excitation energy).

The partial compensation of incorrectness of assumption $k^{prim}/k^{sec} = const$ used in [2] is provided by sign-variable deviation of k for secondary transitions at various energy with respect to that for primary transitions. It means that the relative variation of total radiative width Γ_l of cascade intermediate level in method [2] really is considerably less than the relative change the energy dependence of k for secondary transition with respect to that for primary transitions. This is observed in all nuclei where experimental data permit one to use [14] method to evaluate the general trend of $k(E_\gamma, E_{ex})$ function. Furthermore, level density in all nuclei obtained within method [14] has more serious discrepancy with the predictions according to [12] than it was earlier established in [2]. The effect of change in ($k^{prim}/k^{sec} \neq const$) for different energies of decaying level on parameters to be determined according to [5] can be stronger because of the used in [18] averaging of strength functions for different energies of decaying levels.

4 Evaluation of confidence level for ρ and k parameters and possibility to improve it

The experimental data on ^{57}Fe include gamma-ray spectrum following thermal neutron radiative capture. These data are suitable, at least, to reveal the difference between the experimental and estimated ρ and k values. Comparison between the experimental and calculated spectra for different level densities and radiative strength functions is done in

Fig. 5. It confirms conclusion that models like [10-12] cannot be used for precise description of the compound nucleus cascade gamma-decay. It also testifies to the necessity of further analysis of the characters of this process, reduction and more detailed accounting for influence of all the sources of systematic errors on the parameters under search. First of all, to reduce error of $I_{\gamma\gamma} = F(E_1)$ and determine in details energy dependence of function $k = \phi(E_\gamma, E_{ex})$ directly from the experiment. This may be done after determination of intensities of two-step cascades to final levels with $E_{ex} > 0.5B_n$ in new experiment with higher quality. Otherwise, one can also to reanalyze experimental data [6].

Using numerical method [26] to improve energy resolution together with method [27] to determine quantum ordering in resolved in form of peak pairs) cascades and known decay scheme [7], one can determine function (1) with small enough systematic error. From the population of intermediate levels determined according to [14] from intensities of resolved cascades, one can get notion of general tendencies of change in strength functions as changing energy and involve these data in analysis [2]. This will allow use to reject a part of false ρ and k values obtained in analysis of row cascade intensities and, to the first approach, to take into account the change in ratio of intensities of cascade secondary transitions to final levels with different excitation energy and deeply different wave function structures.

5 Conclusions

The analysis (according to the basic principles of mathematics) of the two-step cascade intensities following thermal neutron capture in ^{56}Fe confirms conclusion obtained earlier for other nuclei that correspondence between the experimental and calculated [10-12] level densities and radiative strength functions within experimental errors cannot be achieved. The obtained level density corresponds to general trend observed in [2,14] for other nuclei. According to theoretical notions [28], this phenomenon is caused by breaking in this nucleus of at least two Cooper pairs of nucleons that results also in change in ratio of portions of quasi-particle and vibrational excitations. This phenomenon is not taken into account in the models like [10,12]. Significant increase in strength functions for $E_1 < 2$ MeV completely corresponds [14] to localization of step-like structures in energy dependence of level density for secondary transitions of cascades. In totality, the ρ and k values derived from experimental data [6] testify to the effect of nuclear structure on these quantities in wide energy ranges and some variation of this effect for different nuclei. Perhaps, from position of investigated nucleus with respect to full nucleon shells number.

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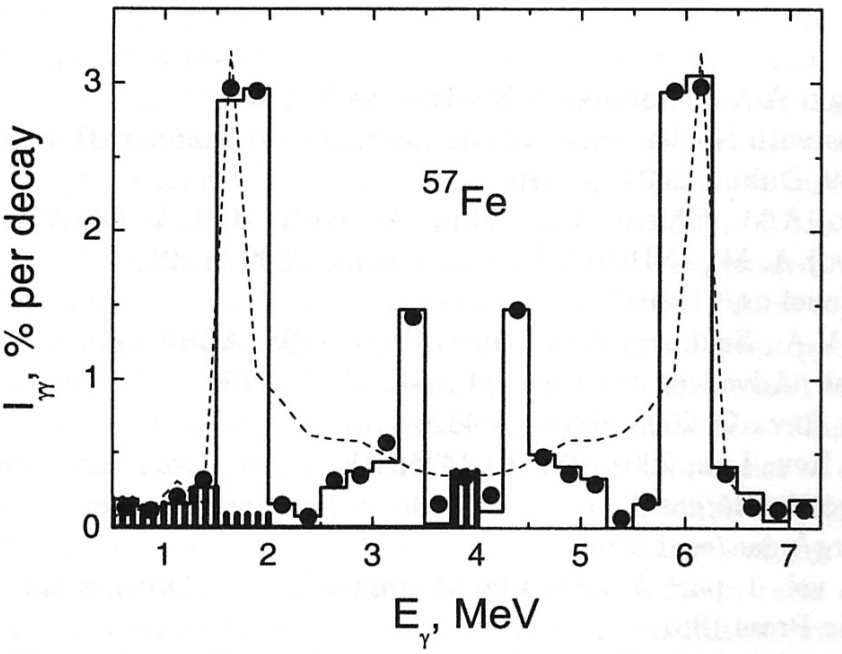

Fig. 1. The two-step cascade intensities in ^{57}Fe summed over the 0.25 MeV energy bins (histogram). Points represent an example of calculation with of ρ and k obtained according to [2]. Calculation with the data from [5,6] is shown by dashed line. The shaded area only is used in data analyses [6].

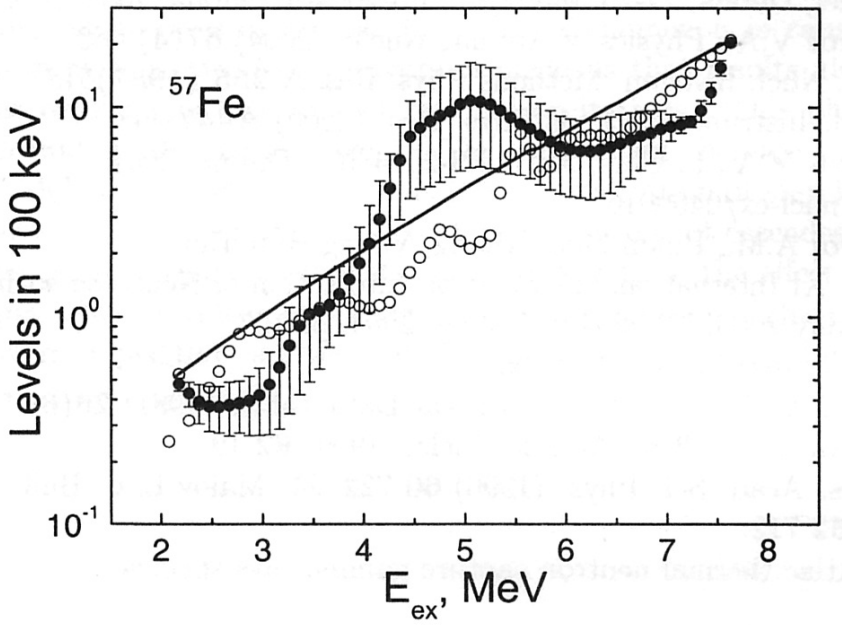

Fig. 2. The total number of intermediate levels of the two-step cascades reproducing experimental spectrum shown in Fig. 1. (points with errors). Open points show data [6] for both parities and spins 1/2 and 3/2, line represents predictions according to model [12].

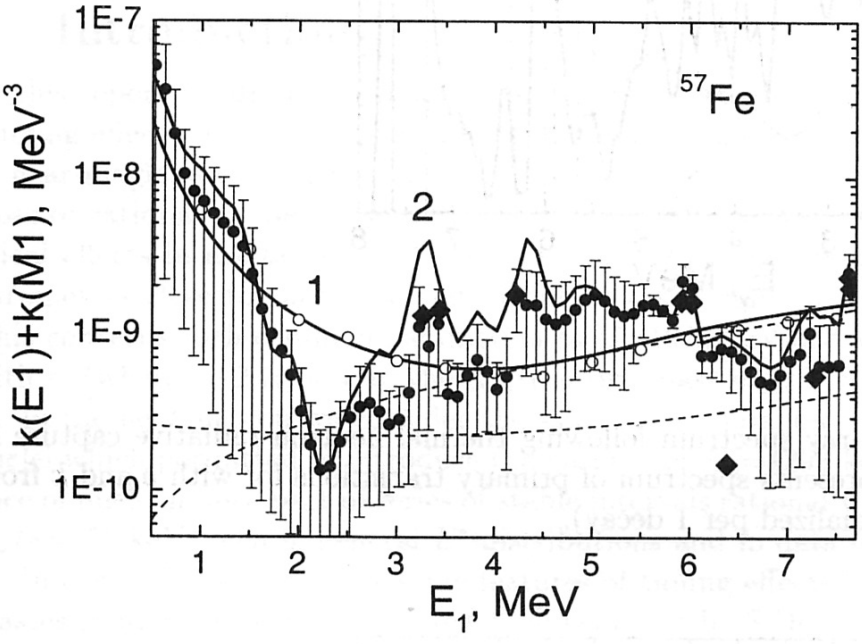

Fig. 3. The possible strength functions that together with ρ data from Fig. 2. reproduce results of [6] (points with errors). Open points show the data [6]. Curve 1 represents $k(E1)+k(M1)$ used to calculate $I_{\gamma\gamma}$ shown as dashed line in Fig. 1. Line 2 demonstrates average k values reproducing together with the fixed ρ from [5] experimental cascade intensities. Dashed line shows predictions of k(E1) according to models [10] and [11]. The lozenges show the upper estimation of k from the maximum intensities of experimentally resolved primary gamma- transitions.

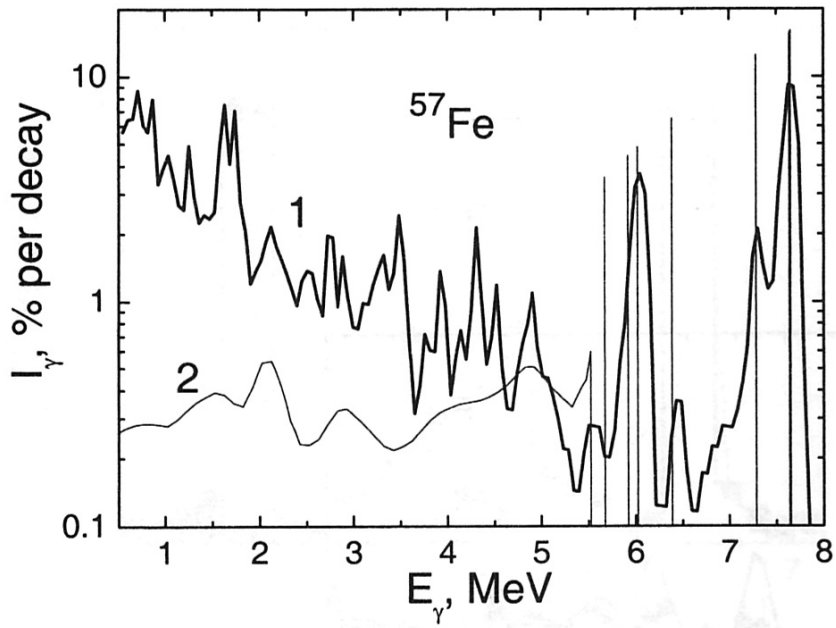

Fig. 4. The total gamma-ray spectrum following thermal neutron radiative capture in ^{56}Fe (curve 1). Curve 2 represents spectrum of primary transitions for with ρ and k from [5,6] (both spectra are normalized per 1 decay).

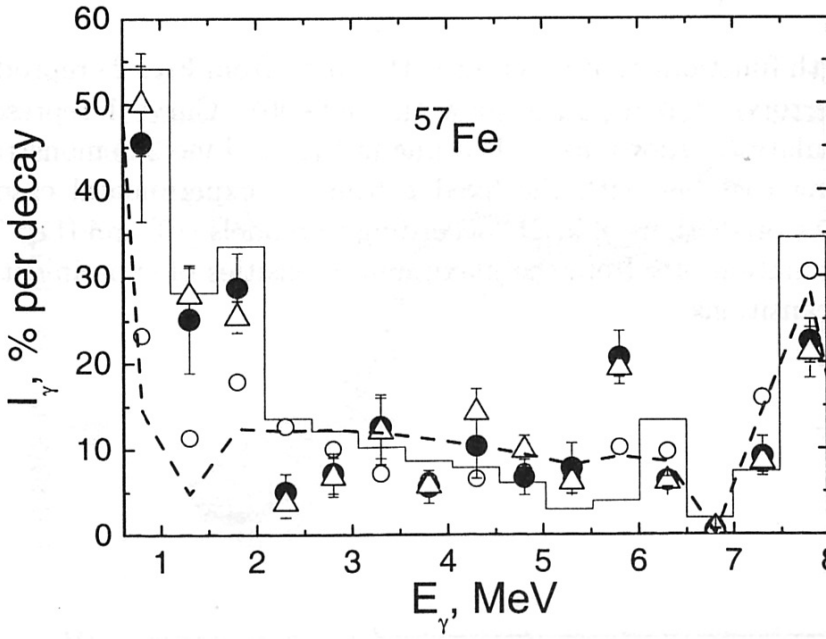

Fig. 5. The total gamma spectrum summed in the 1 MeV energy intervals (histogram) following thermal neutron capture. Points with errors show result of calculation with the our data given in figs. 2 and 3. Broken dashed curve shows predictions according to models [11,12]. Triangles show calculation with the best [2] values of k and values of ρ from [5]. Open circles are the calculation with ρ and k from [5,6] only.