

ON PROBLEMS OF EXPERIMENTAL DETERMINATION OF RELIABLE VALUES OF NUCLEUS PARAMETERS AT LOW EXCITATION ENERGY – ^{60}Ni AS AN EXAMPLE

A.M. Sukhovoj, V.A. Khitrov

Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The reanalysis of the published experimental data from reaction $^{59}\text{Co}(p,2\gamma)^{60}\text{Ni}$ was performed. The region of the most probable values of level density and radiative strength functions of cascade gamma-transitions was determined. The obtained data were rather precisely approximated by the V.M. Strutinsky model and semi-phenomenological model – for strength functions. The region of appearance and magnitude of maximal errors of the calculated cross-section of nucleon emission in evaporation spectra in traditional methods of their analysis were determined as well. There was for the first time obtained methodically correct information on the radiation strength function of primary gamma-transitions in diapason of neutron binding energy with averaging over large set of initial levels.

1 Introduction

The only goal of an experiment is to get new experimental information. But, for the further development of science, especially fundamental one, this information must be more reliable than that obtained earlier. Accounting for inevitability of appearance of different errors and mistakes in this process, the most importance is their revealing and rejection. This process requires one to perform new experiments by the methods not used earlier and to reveal obvious errors in the performed earlier analysis of experimental data, for example.

This problem appears itself most sharply in low energy nuclear physics. Development of this branch of fundamental science is impossible without using different hypotheses and notions of nuclear properties determined, with the rare exception, only experimentally. Moreover - only in the form which requires mathematical treatment of different extent of complexity, the following physics interpretation and model description.

To the all enumerated above completely corresponds the situation with investigation of nucleus properties at small (up to ≈ 10 MeV) excitation energy of arbitrary nucleus. Physically it is set by nucleon binding energy B_n in a nucleus. Complete and correct understanding of properties and parameters of a process appeared by this requires one to determine with good precision the level density of a nucleus $\rho = D^{-1}$ with given quantum parameters at any excitation energy and probability (width) Γ of the reaction products emission (strength function $k = \Gamma/(DE_\gamma^3 A^{2/3})$ for gamma-quanta).

There are no ways for complete achievement of this goal – resolution of existing spectrometers does not allow one to distinguish fixed nuclear levels lying by several MeV above the ground state and, for example, by several keV above B_n .

Therefore, the values ρ and k can be obtained only from solution of reverse task of mathematical analysis – determination of corresponding parameters from the experimentally measured function S (spectrum or cross-section). This solution in most cases is badly stipulated and ambiguous. *Id est*, the errors $\delta\rho$, δk cannot be equal to zero even at zero experimental uncertainty of function δS . Moreover, the shape of their functional relation is set a priori on the basis of existing notions. As a result, the determined parameters of function $S = f(\rho, \Gamma)$ contain usually more or less not removable systematical error.

Intensity of spectra of nuclear reaction products measured without coincidences with other products (one-step reactions) is determined by product of ρ and Γ . This circumstance increases relative error of determination of any of these parameters in case if another parameter was set independently, for example, by means of some nuclear model. Really, at present this possibility can be realized only with unknown systematical error. A lack of further progress in development of the methods for experimental determination of ρ and Γ in one-step reactions means, in practice, that the potential of their possibilities is exhausted.

At the same time, real progress in experimental determination of ρ and Γ can be achieved only from comparison of the data of independent experiments. This can be made by analysis of results of multi-step reactions (registration in coincidence of intensity of cascades from two and more successive nuclear reaction products). Just study of these cascades terminating at one or several final levels allowed one to realize independent model-free method for determination of maximum reliable values of ρ and k . As it was shown in [1], only registration of cascade gamma-quanta in such variant provides maximal sensitivity of experiment to sought parameters of a nucleus.

And, accordingly – guaranties their lowest systematical uncertainty with respect to alternative methods for determination of level density and emission probability of reaction products.

2 Dubna method for determination of ρ and k

The main and absolutely necessary condition for obtaining of reliable information from two-step reactions is maximally possible test of existing information used in analysis of experiment. Just practical realization of this condition allowed one to create the method for simultaneous model-free determination of ρ and k [2, 3] from experimental spectra by use of only algorithms, rules and principles of mathematic and mathematical statistics. Non-observance of these theses guaranties appearance of principle discrepancies between the data obtained by different groups from the one hand and circulation of earlier appeared systematical errors - from the other hand.

The latest example of this kind is the analysis of the two-step cascade intensities

measured by authors [4] in reaction $^{59}\text{Co}(p, 2\gamma)^{60}\text{Ni}$. Experimental spectrum in this as well as in some tens of analogous cases has the following peculiarities:

(a) it is the sum of two unknown functions corresponding to near by energy primary and secondary gamma-transitions in any interval of their values;

(b) the sum of intensities of all the possible two-step cascades (plus primary transition to the ground state) always equals 100%;

(c) the experimental spectra can be reproduced with the $\chi^2/f \ll 1$ value by infinite number of different functions ρ and Γ from limited interval of their values;

(d) the relation between change in cascade intensity $\delta I_{\gamma\gamma}$ and changes in $\delta\rho$ and $\delta\Gamma$ is non-linear and strongly different for various energies of cascade gamma-quanta;

(e) the confidence interval for the ρ and k values, reproducing $I_{\gamma\gamma}^{exp}$, has practically acceptable width only by use of the procedure [5] in analysis of experiment.

Potential possibility to account for enumerated above specifics of the analysis of the two-step cascade intensities takes place and in the case [4].

1. Level scheme of ^{60}Ni below excitation energy of 5 MeV includes [6] less than 40 secondary transitions to level $E_f = 1.332$ MeV and, correspondingly, the spectrum – narrow peaks. The use of method [5] in this case would allow one to determine two-step cascade intensities in function on their primary transition energy with the error caused, in practice, only by the total error of approximation of peak areas.

2. Rather essential discrepancies between the experimental and calculated by authors [4] spectra of cascade intensities (for example, for $1.5 < E_\gamma < 3$) MeV guarantee, by conditions (b) and (d), their undoubted difference of unknown amplitude in any other points of the spectrum.

3. According to [3], from combination of the individual cascade intensities and intensities of their primary and secondary gamma-transitions, authors of [4] could additionally estimate to the first approach the dependence of radiative strength functions on energy of levels excited by the primary gamma-transitions.

The presence of these errors unambiguously requires reanalysis of the experimental data on the two-step cascade intensities in ^{60}Ni . Analogous reanalysis accounting for the mentioned above specific of the experiment was earlier performed for ^{57}Fe , [7], ^{96}Mo [8], ^{172}Yb [9] and for some other nuclei. In all these cases real systematical errors of the values of level densities and radiative strength functions cited in original articles are maximally large.

3 Conditions of reanalysis

Systematical error in determination of ρ and Γ from cascade intensities are caused, first of all, by systematical error of determination of absolute value of cascade intensity. According to [10], if its value is small enough ($\delta I_{\gamma\gamma}/I_{\gamma\gamma} < 50\%$), then distortions of ob-

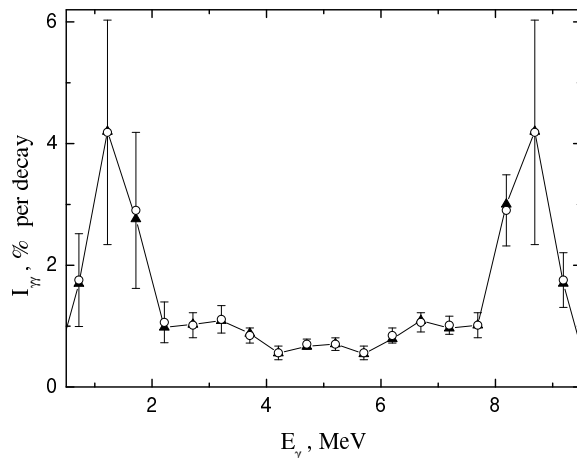


Fig. 1. Typical approximation of intensities of two-step cascades to the first excited state of ^{60}Ni . Points with errors – from [4], curve with triangles – the best fit.

tained parameters are also comparatively small. Their further reduction can be provided by careful choice of additional experimental data involved in analysis.

The total intensity of two-step cascades was renormalized from the data [4] and accepted to be equal to 33 events per 100 decays for $0.5 < E_\gamma < 9.5$ MeV. (For example, a portion of the most intense cascades in near-magic nuclei ^{144}Nd and ^{200}Hg equals accordingly 32% and 35% [11, 12]). By this, intensity of cascades in interval about $E_\gamma = 8.75$ MeV was changed by us to intensity in interval $E_\gamma = 1.25$ MeV because of presence of undoubted error in [4].

The distribution of number of decaying initial cascade levels was taken in accordance with [4] equal to 39.6; 3.7 and 4.5% for spins $J^\pi = 3, 4^-; 1, 2^-; 2, 3, 4^+$ correspondingly (for orbital moment of captured protons $l = 0 - 2$). In analysis below $E_{ex} = 4.02$ MeV were used known scheme of level density and modes of their decay. Parameters of the Fermi-gas model – one of the variants of initial level density in random iteration process [2, 3] for determination of ρ and Γ – were taken from [13]. Typical example of the best fit of cascade intensity is shown in Fig. 1.

The total radiative width for initial levels with enumerated above spins and parity was taken equal to 1.6 eV in accordance with [14]. The value of spacing D between s-resonances for ^{59}Ni was taken from the same compilation. The part of levels of negative parity was additionally varied in iterative process with respect of initial one (it linearly decreases from 50% for B_n to 0 – at $E_{ex} = 4.02$ MeV at the first step of calculations). All existing now experimental data on intensities of two-step cascades in more than 50 nuclei from ^{28}Al to ^{200}Hg demonstrate negligibly small role of pure quadruple transitions. Therefore, only dipole gamma-quanta are taken into account in calculation what does not exclude possibility of presence of mixture of multipoles $M1 + E2$ and $E1 + M2$.

Unlike [4] (determinate by authors variation of subjectively chosen strength functions), we used the described in [2, 3] procedure of multiple distortion of the initial ρ and Γ values

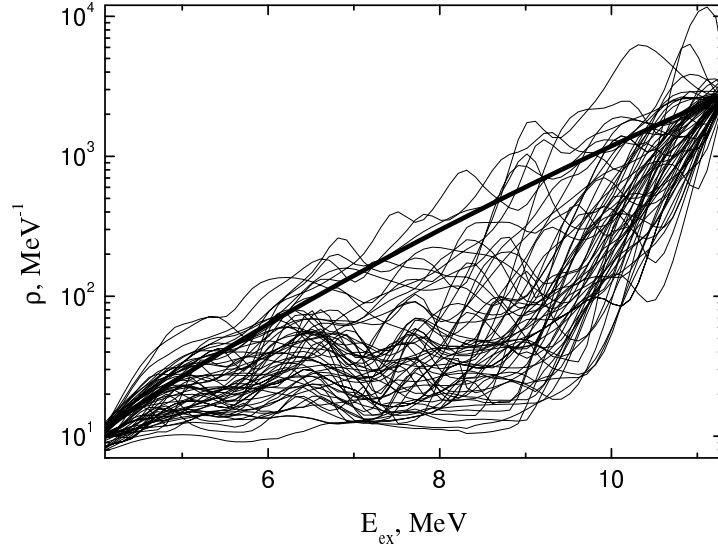


Fig. 2. Thin curves – the spectrum of random values of the level density function ($1 \leq J \leq 5$), reproducing the data [4] with $\chi^2/f < 0.05$. Thick curve – model [15].

by small-amplitude random functions with accumulation of changes decreasing χ^2 . The sets of ρ and k providing such quality of approximation are given in figures 2 and 3.

The dispersion of strength functions and level density for any cascade quantum and excitation energies is very large (by one or two orders more than the data [2, 3]). Its mean-squared value in some energy intervals exceeds the average ρ and k . In these cases, the errors “down” in figures 4 and 5 are absent. Of course, each of random functions ρ and k has errors caused by uncertainty of experimental data and different reasons for appearance of fluctuations of widths of primary and secondary transitions. But, in difference of principle from [4], the best values of ρ and Γ include the dependence of ρ and k on nuclear structure at $E_{ex} \leq B_n$ to the maximum extent. Such possibility is completely absent in data treatment [4].

The data presented in Fig. 3 show that obligatory accounting for the obtained in Oslo low energy “tail” of strength functions is not required for description of cascade intensity. But, it must be noted that the errors of the data presented in figures 2 and 3 are maximal for the region of excitations lying above $E_{ex} \sim 9 - 10$ MeV owing to small statistics and use of the least informative experimental spectrum (relatively to possible cascade intensities in function on their primary transition energy [5]). Due to this reason they are of small efficiency for determination of the ρ and k values corresponding to this energy.

Enormous dispersion of the data in figures 2 and 3 is unambiguously caused by the fact that the calculated by use of these data cascade intensity with primary and secondary gamma-transitions with energies from the same interval really correspond to combinations of analogous unknown experimental functions I_{exp} and arbitrary unknown error δI :

$$\begin{aligned} I_{cal}^{prim} &= I_{exp}^{prim} + \delta I \\ I_{cal}^{sec} &= I_{exp}^{sec} - \delta I. \end{aligned} \quad (1)$$

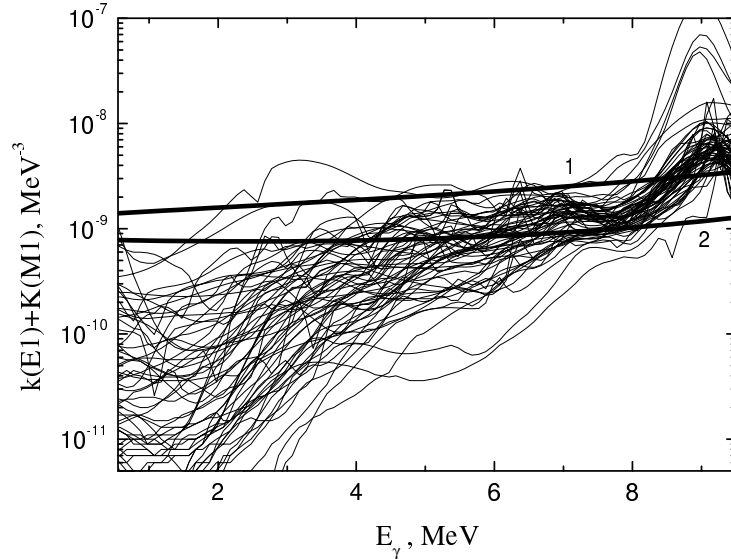


Fig. 3. The same, as in Fig. 2, for $k(E1) + k(M1)$. Curve 1 – model [16], curve 2 – [17] in sum with $k(M1)=\text{const}$.

As a result, this brings to deviations of ρ and k with different sign and maximal by module for $I_{exp} = \delta I$. Conclusions about parameters ρ and k in this situation inevitably have essential uncertainty. Nevertheless, concrete conclusions on gamma-decay process and its parameters can be made from model approximation of obtained here ρ and k and for this nucleus.

4 Model approximation of ρ and k

Model approximation of functional dependences $\rho = \phi(E_{ex})$ and $k = \psi(E_\gamma, E_{exp})$ was performed below for the averages of random functions Figs. 2 and 3 and, therefore, its concrete results are to be considered as rough enough. That is why, approximation of $\rho = \phi(E_{ex})$ was performed in the simplest variant $K_{coll} = \text{const}$, but with accounting for influence of shell inhomogeneities of one-particle spectrum on parameter g .

In some cases, as a minimum it is possible to determine a sign of corresponding uncertainty. So, a lack of the data on extent of dependence of $k = \psi(E_\gamma, E_{ex})$ on excitation energy rather essentially increases error in determination of ρ and Γ . However, it follows from comparison of variants for their determination [2] and [3] that the obtained for nickel and presented in figures 4 and 5 ρ values are overestimated and k – underestimated.

Approximation of $k = \psi(E_\gamma)$ was performed within frameworks of semi-phenomenological model [18]. The results are shown in figures 4 and 5.

As a result, one can accept that the analysis described above allowed one to determine main properties of nucleus ^{60}Ni . The discrepancies of the ρ and k values with the Dubna data for this nuclei are to high extent caused by systematical errors of used here

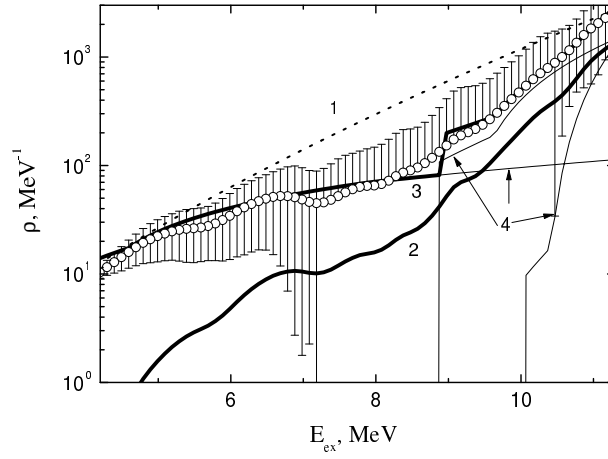


Fig. 4. Approximation of the mean level density from Fig. 2 by model [19]. Points with errors – mean value with the mean squared deviation. (The mean squared distribution of the data of Fig. 2 is given only if it does not exceed the average). Curve 1 – model [15], curve 2 – fitted value of negative parity level density, curve 3 – the best fit, curve 4 – partial densities of 2-, 4- and 6-quasi-particle excitations.

“alternative” methods of determination of the same parameters.

Table 1.

Parameters of approximation of level density and radiative strength functions for different nuclei: the coefficient of change of square of nuclear temperature κ and contribution w of model [17] in the summed strength function. E_1 – position of local peak and its amplitude P_1 (multiplied by 10^{-7}), α - velocity of decrease of amplitude as primary transition energy decreases. Parameter of level density a , coefficient of collective enhancement of level density K_{coll} and thresholds U of break of the second and third Cooper pairs obtained in variant [20] accounting for shell inhomogeneities of one-particle spectrum.

Parameter	^{60}Ni	^{74}Ge	^{96}Mo	^{114}Cd	^{118}Sn	^{124}Te
κ	0.0002	0.14(6)	0.41(16)	0.18(9)	0.04(25)	0.18(3)
w	0.011	0.25(4)	0.16(3)	0.10(4)	0.01(4)	0.56(6)
E_1 , MeV	5.10(2)	5.4(1)	5.8(2)	5.7(1)	5.0(1)	7.3(1)
P_1	0.37(2)	5.3(2)	4.0(6)	9.6(36)	8.2(6)	7.2(7)
α , MeV^{-1}	1.03(2)	0.59(35)	0.74(21)	0.89(6)	0.90(8)	0.80(9)
a , MeV^{-1}	6.16	9.96	11.	13.	13.3	15.6
K_{coll}	12	17	6.7	13	4.5	15
U_2 , MeV	8.9	5.9	3.7	3.8	4.7	2.8
U_3 , MeV	10.	8.8	6.5	5.9	4.3	6.6

Unlike the data on k derived from two-step cascade intensities, reproduction of form of energy dependence in case under consideration by model [18] requires one to take into account not less than four local peaks (or corresponding continuous distribution, exponentially decreasing when primary gamma-transition energy decreases). Large values of K_{coll} and break threshold of the second Cooper pair U_2 allow one to relate the observed

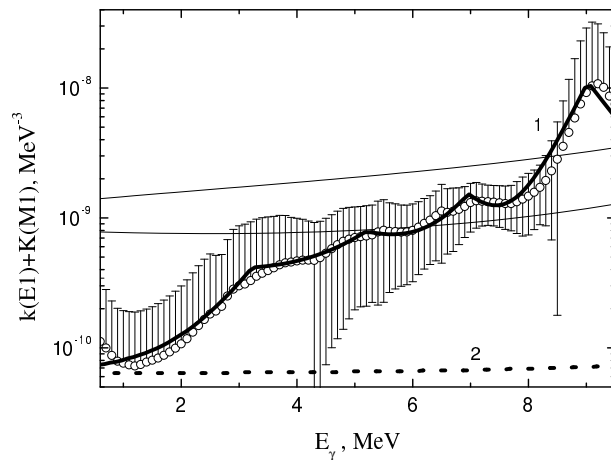


Fig. 5. The same, as in Fig. 4, for $k(E1) + k(M1)$. Curve 1 – the best fit, curve 2 – contribution of model [17].

dependence and its parameters with gamma-transitions between levels with large phonon components of wave functions. The main difference of the data for ^{60}Ni from the data [18] consists in significant averaging [4] of strength functions over large set of initial cascade levels. The distribution shown in Fig. 5 can be combined from some peaks with exponentially decreasing tails. This result can be interpreted as enhancement of gamma-transitions at decay of fixed resonance with primary excitation of some intermediate level groups in different energy intervals. Test of this hypothesis needs in both additional experiments, analogous to [4], and correct from the point of view of principles of mathematics and mathematical statistics treatment of their results. I. e., adequate by these conditions to [3].

5 Sources of systematical errors of different methods

1. Large volume of the experimental ρ and k values was obtained from analysis of the total gamma-spectra and presented in publications by Norwegian collaboration. There are two different of principle differences between their data and Dubna data:

(a) absolute absence of a something essential deviation of ρ from “smooth” dependence and

(b) absolute absence of some estimations of systematical error of the ρ and $f = kA^{2/3}$ values presented by authors [21]. In particular, the authors did not show a precision of determination of systematical uncertainty of absolute intensity of the total gamma-spectra measured by them for different excitation energies.

But, as it was shown in [22], obtaining of the reliable ρ and f values requires lesser (most probably, much lesser) their total uncertainty (for example, 1%) for any gamma-

quanta energy. Without such proof, the observed discrepancy of ρ and k between [3] and [21] can be relate, first of all, with the systematical errors of using the method [21] for experimental total gamma-spectra data treatment.

2. Level density in ^{60}Ni , obtained from the spectra of evaporation nucleons in [13], very strongly differs from function ρ precisely reproducing cascade intensities (Fig. 2). Most probably, the source of error is the error of calculation of differential cross section of product emission $\frac{d\sigma}{d\varepsilon}$ in reaction with non-zero residual excitation energy of final nucleus.

Up to now it is calculated only by optical model of a nucleus and only in the frameworks of unverified hypothesis on independence of partial width Γ of emission of the nuclear reaction product on nuclear structure. Id est, the known parameters of interaction of reaction product with non-excited nucleus are extrapolated to the region where occurs sharp change of its properties [13, 23].

In this region, according to quasi-particle-phonon model of nucleus, nucleon does not interact with nucleus being in the state of quasi-particle vacuum excitations, but interacts with nucleus in the state, for example, “quasi-particles \otimes quadrupole phonon” or more complicated structure. Moreover – with different fragmentations at different nuclear excitation energy [24].

Conclusion about dependence of Γ on nuclear structure (id est, excitation energy of final nucleus) unambiguously follows, for example, from [25]. And it fully agrees with the obvious axiom that any extrapolation of theoretical model in unstudied region of excitations has an error which can be determined only experimentally.

According to Hauser-Feshbach notion, the cross-section under consideration is determined by sum over initial and final levels of products of type $\Gamma_b(U, J, \pi, E, I, \pi)\rho_b(E, I, \pi)$ for the final reaction product b [13, 23]:

$$\frac{d\sigma}{d\varepsilon_b}(\varepsilon_a, \varepsilon_b) = \sum_{J\pi} \sigma^{\text{CN}}(\varepsilon_a) \frac{\sum_{I\pi} \Gamma_b(U, J, \pi, E, I, \pi)\rho_b(E, I, \pi)}{\Gamma(U, J, \pi)} \quad (2)$$

where

$$\Gamma(U, J, \pi) = \sum_{b'} \left(\sum_k \Gamma_{b'}(U, J, \pi, E_k, I_k, \pi_k) + \sum_{I'\pi'} \int_{E_c}^{U-B_{b'}} dE' \Gamma_{b'}(U, J, \pi, E', I', \pi') \rho_{b'}(E', I', \pi') \right). \quad (3)$$

It follows from (2) and (3) that at presence of unknown error δ of the calculated Γ width value, experimental cross-section $\frac{d\sigma}{d\varepsilon}$ can be precisely reproduced only by using level density with adequate systematical error.

If the calculated partial Γ_{cal} and experimental Γ_{exp} widths obey to correlation $\Gamma_{cal} = \Gamma_{exp}(1 + \delta)$, then the level density $\rho_{cal} = \rho_{exp}/(1 + \delta)$ must be used in calculation for reproduction of cross-section (2). Of course, unknown relative error δ of calculated width depends on excitation energy of final nucleus and can depend on spin of levels which are connected each to other at b reaction product emission. In this case, the error δ is the

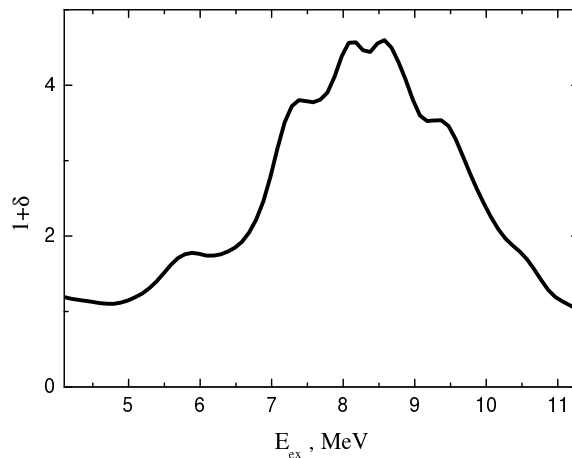


Fig. 6. The degree of enhancement of differential cross-section of nucleon emission in ^{60}Ni for different excitation energy of final nucleus.

weight average. If one determines it using relation: $(1 + \delta) = \rho_{es}/\rho_{2\gamma}$, which connects level density ρ_{es} determined from evaporation spectrum [13, 23] with density $\rho_{2\gamma}$, derived from cascade intensity (fig. 4), then the error of the calculated cross-section $\frac{d\sigma}{d\varepsilon}$ can be directly estimated at any excitation energy of final nucleus. The result is presented in Fig. 6. The main error of the presented in this figure data is related to the fact that the ρ value was determined directly from two-step experimental spectrum, but not from cascade intensities for given energy of their primary transition and because of lack of information on function $k(E_\gamma, E_{ex})$. However, there are no principle differences with analogous data for ^{181}W [26].

3. The any ordinary errors of the expected amplitude cannot even in principle distort the form of energy dependence of ρ and k determined in correspondence with [2, 3]. Serious systematical error in this case can have only more fundamental character. For instance, connected with lack of the model of gamma-decay of highly excited levels accounting in available (for analysis of experimental data) form for coexistence and interaction of excitations of fermion and boson type and so on.

6 Conclusion

1. Confirmation of the data on level density derived from the spectra of evaporation nucleons by analogous data from the two-step cascade intensities is achieved only subjectively at serious violations of statements of mathematics and mathematical statistics at analysis of $I_{\gamma\gamma}$.

2. As in the other spherical even-even nuclei, taking into consideration, break of three

Cooper pairs of nucleons is quite enough for model description [19] of level density in ^{60}Ni below B_n . Collective effects increase level density by order of magnitude.

3. High degree of averaging of cascade intensities over their initial levels allows one to expect considerable averaging of strength functions. In particular, the strength function of the primary gamma-transitions to the first two-phonon state $E_f = 2.505$ MeV of this nucleus is increased, as a minimum, by order of magnitude with respect to the model [16, 17] predicted values. It is possible also that the increased gamma-transitions following decay of different initial cascade levels selectively excite groups of levels of collective structure at different excitation energy. Id est, the parameters of model approximation of the strength function determined from “averaged resonances” can strongly differ from analogous strength functions of decay of the only initial cascade level.

4. Precise description of the two-step gamma-cascade intensities does not require increase of strength functions at decrease of gamma-transitions energy. This effect is easily quantitatively explained even by small errors [27] at normalization of the total gamma-spectra at different excitation energy of spherical nucleus.

5. The notion of authors, for instance, [13] that the approximate equality of level densities derived by them from the spectra of evaporation nucleons in different nuclear reactions is a proof of absence of systematical errors is obviously mistaken. In practice, these very big errors of the calculated value of cross-section are completely correlated. Id est, they are caused by strong influence of structure of excited levels of final nucleus but not – by any errors of the used optical potentials.

6. Because dominant proton capture occurs [4] to the level $\pi = -$, then this strongest increase of strength function is first observed for the primary $E1$ -transitions of the compound-state decay to final two-phonon level.

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