On the energy spectra of photoneutrons from medium and heavy nuclei

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The results of study of the energy spectra of photoneutrons in the region of the giant dipole resonance are reviewed. It is shown that the low-energy region of the spectra can be described by a statistical theory. The nonequilibrium component of the spectrum due to decay of doorway states into the continuum is investigated. A comparison with the spectra of neutrons from heavy-particle reactions is made.

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INTRODUCTION

Since they began more than 40 years ago, about 2000 experimental and theoretical studies have been made of photonuclear reactions. Many of them have been concerned with the giant dipole resonance, which is a clearly expressed process of absorption of γ rays by nuclei in a comparatively narrow energy region (10–30 MeV). Detailed data have now been accumulated on the gross structure of the giant dipole resonance: the dependence of the position of the maximum in the photoabsorption cross section and the half-width of the resonance on the mass number A, the integrated cross section, and so forth. The theoretical investigations have led to the creation of two main models of the giant dipole resonance. These are the collective model and the shell model, and they have made it possible to describe many properties of the process of absorption of γ rays by nuclei. On the other hand, various questions associated with the giant dipole resonance, for example, the nature of the intermediate structure in the cross sections of the (γ, n) and (γ, p) reactions, the width of the resonances, and the applicability of the various models, require further study.

It should be noted that the most important results have been achieved in the study of the first phase of the photonuclear reaction, i.e., the absorption of the γ rays. The processes belonging to the stage of the reaction associated with the decay of the excited dipole states have been studied in much less detail. Information about the characteristics of the products of photonuclear reactions (the energy and angular distribution of the emitted nucleons, the final states of the nuclei to which the decay takes place, and so forth) has not been adequately systematized. The reviews on photonuclear reactions hardly consider this field of investigation. The aim of the present paper, which is devoted to an analysis of the results of measurement of the energy spectra of photoneutrons emitted by medium and heavy nuclei in the region of the giant dipole resonance, is to fill part of this gap. As the boundary between light and medium nuclei, we have chosen the value $A = 40$, at which there is a change in a number of the parameters of the giant dipole resonance. Thus, for nuclei with $Z > 20$ one observes a rapid growth of the photoneutron yield as measured by NZ/A, a quantity which varies little in the region of lighter nuclei. For $A < 40$, the cross section of the (γ, n) reaction has a complicated structure, whereas in the case of heavier nuclei it is characterized by a clearly expressed resonance or two resonances in the case of deformed nuclei. These differences may be due to the predominance for $A > 40$ nuclei of decay by evaporation of nucleons from the compound nucleus due to the high centrifugal barrier for neutrons of the $1f_{7/2}$ shell.[1]

In this paper, we consider almost all the results so far obtained, except for the photoneutron spectra measured near the threshold of the (γ, n) reaction. These data, which contain rich spectroscopic information, correspond to the region of small excitations and are therefore outside the ambit of the problems discussed below.

The study of the photoneutron energy spectra has a particular interest for the following reasons. During a nuclear reaction, nucleons can be emitted at various stages. The energy spectrum of the decay products contains a high-energy component corresponding to decay of doorway states into the continuum, a part of the spectrum due to pre-equilibrium decay from more complicated configurations, and, finally, the component due to decay of the compound nucleus.[2] The existing models of pre-equilibrium decay[3] make it possible to calculate the spectra of particles emitted during the nuclear reaction; thus, the paper of Ref. 4 is concerned with the emission of particles from the collective $1p-1h$ dipole state in the framework of the shell model, and also the emission of particles from the compound nucleus at the stage when equilibrium is established; the agreement with the spectrum of protons from the reaction $^{40}Ca(\gamma, p)^{39}K$ was found to be entirely satisfactory. Without denying the value of calculations of this type, we should like to point out a very attractive possibility of separating the components in the spectrum of emitted particles. It is associated with the existence in the photoneutron energy spectra of well-defined regions, which makes it possible to separate the equilibrium component of the spectrum.[1)] Such a possibility is realized, however, only for the (γ, n) reaction. When charged particles (protons, α particles) are emitted, the Coulomb barrier shifts the equilibrium part of the spectrum to a region of higher energies, which results in a superposition of the components of the spectrum.

[1)] The presence of an inflection in the photoneutron energy spectrum due to the direct photoeffect was noted for the first time in Ref. 6.

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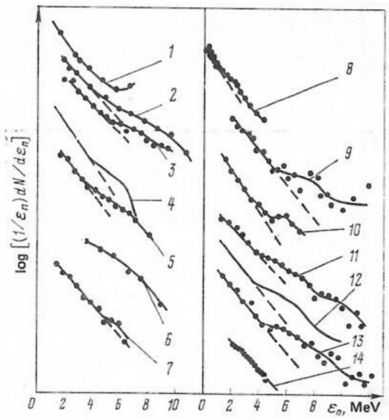

FIG. 1. Energy spectra of photoneutrons from bismuth nuclei. The numbers next to the curves correspond to the number of the experiment in Table I; 4 and 12 are extrapolations of the experimental data; the continuous curves are drawn by eye (the same applies to the curves in Figs. 2—7).

In Sec. 1, we give systematic data on the measurements of the photoneutron energy spectra made up to the present time. Section 2 is devoted to a discussion of the results, and after some general comments we analyze from the point of view of statistical theory the data for the low-energy component of the spectrum and discuss the results relating to the high-energy part of the spectra. We also compare the photoneutron spectra with the spectra of neutrons observed in reactions with heavy particles.

1. RESULTS OF MEASUREMENT OF THE PHOTONEUTRON ENERGY SPECTRA

To facilitate the comparison of data obtained in different experiments, we give all the results in the form $\log[(1/\varepsilon)dN/d\varepsilon_n]=f(\varepsilon_n)$, where ε_n is the neutron energy (Figs. 1–7). In some cases, the experimental points are extrapolated by a smooth curve. In Tables I–VII we give brief characteristics of the experiments and also some results of analysis of the spectra, namely, the effective temperatures T of the final nucleus and the quantity a, which measures the level density of the final nucleus. The results obtained for bismuth, the nucleus most frequently used as a target in the study of

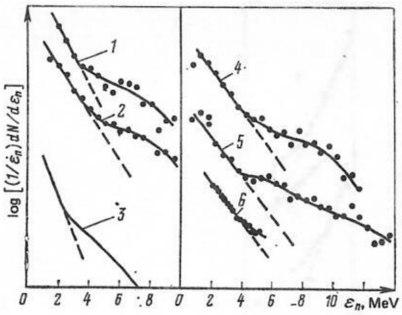

FIG. 3. Energy spectra of photoneutrons from tantalum nuclei. The numbers next to the curves correspond to the number of the experiment in Table III; 3 is an extrapolation of the experimental data.

photoneutron energy spectra, are given in Fig. 1 and Table I. In Fig. 2 and Table II we give the results obtained for gold; in Fig. 3 and Table III, for tantalum; and in Fig. 4 and Table IV, for lead. In Fig. 5 and Table V we give the results obtained for several medium and medium-to-heavy nuclei. The data for several nuclei of medium mass are given in Fig. 6 and Table VI. Separately (Fig. 7 and Table VII) we give the results of measurements of the spectra of photoneutrons emitted from chromium.

2. DISCUSSION OF RESULTS

General comments. Examination of the results shows that the spectra of photoneutrons from nuclei of medium and large mass consist, apart from rare exceptions, of two regions with a clearly defined boundary. The low-energy, exponentially decreasing part of the spectrum is due basically to neutrons emitted by the compound nucleus. The fraction of nonequilibrium neutrons in this region of the spectrum is small and rather ill defined, which makes it possible to consider an approximation in which the low-energy region of the spectrum is entirely due to statistical neutrons. Such an assumption is supported by various experimental indications discussed below.

The parameters a and T calculated from the data on the photoneutron spectra are averaged quantities. In contrast to a reaction induced by monoenergetic particles, the photoneutron spectrum obtained by means of

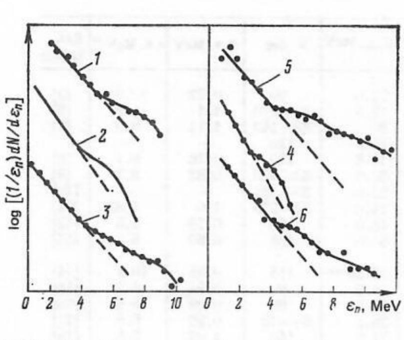

FIG. 2. Energy spectra of photoneutrons from gold nuclei. The numbers next to the curves correspond to the number of the experiment in Table II; 2 is an extrapolation of the experimental data.

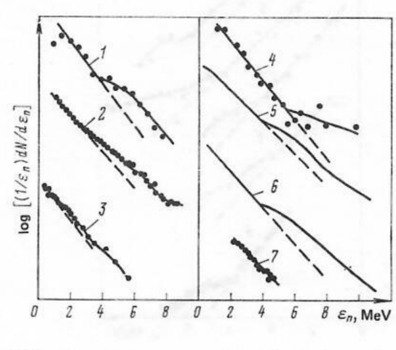

FIG. 4. Energy spectra of photoneutrons from lead nuclei. The numbers next to the curves correspond to the number of the experiment in Table IV; 5 and 6 are extrapolations of the experimental data.

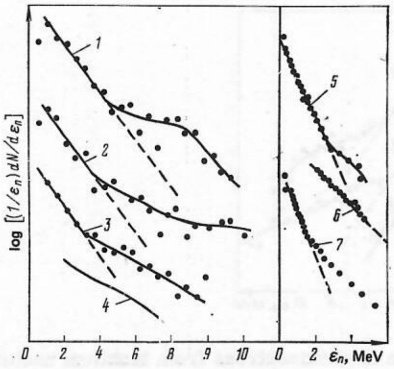

FIG. 5. Energy spectra of photoneutrons from medium-to-heavy and heavy nuclei. The numbers next to the curves correspond to the number of the experiment in Table V; 4 is an extrapolation of the experimental data.

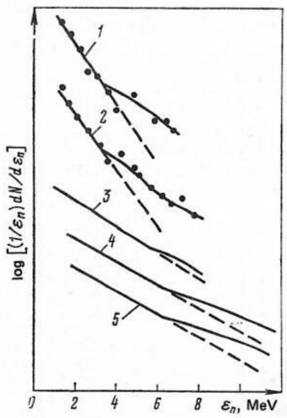

FIG. 7. Energy spectra of photoneutrons from chromium nuclei. The numbers next to the curves correspond to the number of the experiment in Table VII; 3, 4, and 5 are extrapolations of the experimental data.

bremsstrahlung γ rays is determined by their effective spectrum. Because of this, the aim of the comparison with the parameters found from the reaction with neutrons consists of establishing that these parameters have similar values, so that the low-energy component of the photoneutron spectrum can be attributed to decay of a compound nucleus.

The procedure of subtracting from the total photoneutron spectrum the exponential component extrapolated to the region of energetic neutrons permits a more detailed study of the nonequilibrium component of the photoneutron spectrum, which exceeds 15% in heavy nuclei. Such a procedure was carried out for the first time in Ref. 20 in order to separate the spectrum of "direct" neutrons from gold.

Analysis of the low-energy component of the photoneutron spectra. In accordance with the statistical theory of nuclear reactions,[32] the spectrum of nucleons emitted by the compound nucleus has the form

$$N(\varepsilon)\, d\varepsilon \sim \sigma(\varepsilon)\, \varepsilon \rho\, (E - E_0 - \varepsilon)\, d\varepsilon, \tag{1}$$

where $\rho(E - E_0 - \varepsilon)$ is the level density of the final nucleus formed after the emission of a particle with kinetic energy ε and binding energy E_0; $\sigma(\varepsilon)$ is the cross section of the inverse process. In the calculation of the spectra, $\sigma(\varepsilon)$ is usually replaced by the experimentally measured cross section for the interaction of the particle with the nucleus in the ground state. In a comparison with an experiment, one frequently introduces a further simplification, namely, that $\sigma(\varepsilon)$ is constant for all values of ε. For the level density of the final nucleus, one of two expressions is generally used. One of them follows by applying thermodynamics to the nuclear system[33] and corresponds to the well-known Maxwellian energy distribution of molecules evaporating for a liquid:

$$\rho(\varepsilon) \sim \exp(-\varepsilon/T), \tag{2}$$

where T is the effective temperature of the final nucleus. The second expression for ρ corresponds to the zeroth approximation of the Fermi-gas model[34]:

$$\rho(E) \sim (1/E^n) \exp 2\, (aE)^{1/2}, \tag{3}$$

where E is the excitation energy of the final nucleus, and it is equal to $E_\gamma - E_0 - \varepsilon$ (E_0 is the binding energy of the particle). The photoneutron spectra are usually studied by means of a bremsstrahlung spectrum; in this case, it is more convenient to use the expression (2),

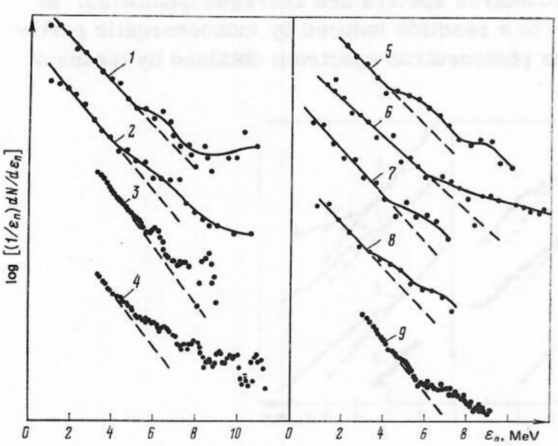

FIG. 6. Energy spectra of photoneutrons from nuclei of medium mass. The numbers next to the curves correspond to the number of the experiment in Table VI.

TABLE I. Energy spectra of photoneutrons from bismuth nuclei.

No.	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T*, MeV	a*, MeV^{-1}	Reference
1	Nuclear emulsions	22.0	90	0.72	10.9	[5]
2	The same	18.9	30–270	1.1	4.5	[6]
3		90	30–140	1.14	5.0	[7]
4	Time-of-flight method	14.3	120	—	—	
		15.8	120	0.76	9.1	[8]
5	Nuclear emulsions	30.0	60–120	0.82	8.7	[9]
6	The same	22.0	30–150	—	—	[10]
7		14.0	30–270	1.0	4.85	[11]
8	Time-of-flight method	16.0	90	0.79	8.5	[12]
9	Wilson diffusion chamber	80.0	135	0.89	8.0	[13]
10	Time-of-flight method	13.85 **	115	0.98	10.1	[14]
11	Nuclear emulsions	20.0	90	0.94	6.3	[15]
12	Time-of-flight method	33.0	90	0.99	5.9	[16]
13	Nuclear emulsions	28.5	60–75	0.92	6.8	[17]
14	Scintillation spectrometer	31.0	140	1.03	5.5	[18]

*The values of T and a in this and the following tables are calculated using the data of the quoted papers.
**The energy of monochromatic γ rays.

TABLE II. Energy spectra of photoneutrons from gold nuclei.

No.	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T, MeV	a, MeV⁻¹	Reference
1	Nuclear emulsions	30.0	90	0.98	6.2	[19]
2	Time-of-flight method	14.3	120	0.66	12.2	[8]
		15.8	120	0.66	12.2	
3	Nuclear emulsions	55.0	90	0.93	8.3	[20]
4	The same	14.0	90	0.64	10.2	[11]
5	» »	20.0	90	0.90	6.6	[17]
6	» »	28.5	60–75	0.87	7.1	[17]

TABLE III. Energy spectra of photoneutrons from tantalum nuclei.

No.	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T, MeV	a, MeV⁻¹	Reference
1	Nuclear emulsions	20	90	0.66	16.1	[21]
2	The same	30	90	0.82	11.4	[21]
3	Time-of-flight method	14.3	120	0.43	31	[8]
		15.8	120	0.43	31	
4	Nuclear emulsions	20	90	0.79	11.2	[17]
5	The same	28.5	60–75	0.82	11.4	[17]
6	Scintillation spectrometer	31	140	0.90	9.4	[18]

which does not directly contain the excitation energy. Representing the energy spectrum in the form $\log[(1/\varepsilon_n)dN/d\varepsilon_n]=f(\varepsilon)$, we obtain T from the expression $\tan\alpha = -(\log e)/T$. To analyze the spectra of neutrons from reactions with heavy particles, formula (3) is generally used, so that it is desirable to obtain not only T from the experiments but also the value of a. If the level-density parameter is assumed to be independent of E (in fact, a does depend on the excitation energy[35]), then $E = aT^2$; the effective excitation energy $\overline{E}_\gamma$ can be determined from the formula

$$\overline{E}_\gamma = \frac{\int_{E_0}^{E_{\gamma m}} E_\gamma \sigma_{\gamma n}(E_\gamma) N(E_\gamma, E_{\gamma m})\, dE}{\int_{E_0}^{E_{\gamma m}} \sigma_{\gamma n}(E_\gamma) N(E_\gamma, E_{\gamma m})\, dE}.$$

The values of a found in this way are given in Tables I–VI. The neutron spectrum from the reaction $(\gamma, 2n)$ differs in principle form the neutron spectrum from the reaction (γ, n), since the emission of the first neutron leads to a decrease in the excitation of the final nucleus. At a certain energy, the total spectrum can have an inflection [and it is in this manner that the change in the slope of the spectrum in the $(n, 2n)$ reaction observed for some nuclei is interpreted in Ref. 36]. Comparison of the photoneutron energy spectra measured at $E_{\gamma m}$ insufficient for the emission of a second neutron with the spectra obtained at $E_{\gamma m} = 28$–30 MeV (see Fig. 2) does not reveal the existence of the difference noted above, which may be due to the inadequate statistical accuracy of the results.

Let us consider the data on the low-energy part of the photoneutron spectrum from bismuth (see Fig. 1). In all measurements except those of Ref. 10, for which $\varepsilon_{\min} = 3.3$ MeV, a good extrapolation of the experimental points is a straight line corresponding to a definite value of T.[2)] The mean value of T according to the data of 12 studies is 0.93 MeV with an rms error of ±0.04 MeV. This value agrees with the value of T obtained from the spectra of neutrons scattered inelastically by bismuth in a reaction with 14-MeV neutrons ($T = 0.92 \pm 0.06$ MeV).[36] Measurements of the photoneutron spectra from bismuth have been made for different maximal energies $E_{\gamma m}$ in the bremsstrahlung spectrum (from 14 to 80 MeV). Since the cross section of the reaction ^{209}Bi$(\gamma, n)^{208}$Bi has a resonance nature with maximum E_m at $E_\gamma = 14$ MeV, a dependence of T on $E_{\gamma m}$, if it exists, may be revealed by comparing the results of measurements made at $E_{\gamma m} \gg E_m$ with results at $E_{\gamma m} \sim E_m$, i.e., at $E_{\gamma m} = 14$–17 MeV. The available data do not appear to indicate a significant difference in the values of T.

The results of measurement of the photoneutron spectra from the reaction ^{197}Au$(\gamma, n)^{196}$Au (see Fig. 2) indicate the existence of a rectilinear section until $\varepsilon_n = 3$–4 MeV, its slope corresponding to $T = 0.84 \pm 0.06$ MeV. The spectra of photoneutrons from tantalum (see Fig. 3 and Table III) give nearly equal values of the effective temperature T except for the data obtained at $E_{\gamma m} = 15.8$ MeV. The mean value (based on the data of five measurements) $T = 0.79 \pm 0.04$ MeV exceeds the value 0.67 MeV found[37] from experiments on the inelastic scattering of neutrons. In the data on the photoneutron spectra from lead, we have not included the results obtained by the time-of-flight method at $E_{\gamma m}$ from 8.8 to 12.5 MeV.[38] The shape of the photoneutron spectra measured in Ref. 38 differs very strongly from an evaporation spectrum, which confirms that the statistical treatment is not valid in a region with sparse levels of the final nucleus. An unusual nature of the neutron spectra was also found by McNeill *et al.*,[25] who investigated neutrons from the reaction ^{141}Pr$(\gamma, n)^{140}$Pr at $E_{\gamma m} = 27.5$ MeV and from lead at $E_{\gamma m} = 31$ MeV. The low-energy region of the spectra has a much shallower decay than in the spectra measured in other experiments. The reasons for these discrepancies require clarification. For lead $T = 0.91 \pm 0.04$ MeV, which is somewhat higher than T deduced from the (n, n') reaction, which is equal to 0.69 MeV.[37]

The values of T obtained from the photoneutron spectra are given in Fig. 8. As can be seen from comparison of the data with the liquid-drop model,[34] there exists satisfactory agreement for $E = 5$ MeV. The A de-

TABLE IV. Energy spectra of photoneutrons from lead nuclei.

No.	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T, MeV	a, MeV⁻¹	Reference
1	Nuclear emulsions	23	90	0.88	7.5	[22]
2	Scintillation spectrometer	32.5	90	0.97	6.3	[23]
3	Time-of-flight method	16.0	90	0.79	8.4	[12]
4	Wilson diffusion chamber	80	135	0.79	10.2	[13]
5	Time-of-flight mehtod	33	90	1.65	5.4*	[16]
6	The same	33	90	0.96	6.4**	[16]
7	Scintillation spectrometer	31	140	0.98	6.1	[18]

*The ^{208}Pb nucleus
**The ^{206}Pb nucleus.

2) The straight-line extrapolation of the data of Ref. 16 differs from the extrapolation used by the authors of the quoted paper.

TABLE V. Energy spectra of photoneutrons from medium-to-heavy and heavy nuclei.

No.	Nucleus	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T, MeV	a, MeV^{-1}	Reference
1	Rh	Nuclear emulsions	20	90	0.83	9.4	[17]
2	Rh	The same	28.5	60–75	0.80	11.7	[17]
3	In		28	30–150	0.75	15.4	[24]
4	Pr	Time-of-flight method	27.5	98	1.81	—	[25]
5	Pt	The same	16	90	0.47	30.2	[12]
6	Th	Scintillation spectrometer	31	140	1.08	5.4	[18]
7	U	Time-of-flight method	16	90	0.44	33.8	[12]

pendence of the level-density parameter a obtained from the photoneutron spectra is shown in Fig. 9. It can be seen that in the region $A \approx 180–200$ there is a discrepancy between the data. This was pointed out by Evseev *et al.*,[18] who arrived at the fundamental conclusion that the statistical theory does not describe the decay of collective nuclear states of the type of the giant dipole resonance. Evidently, the currently available data are inadequate for such a radical conclusion. Comparison of the dependence $a(A)$ for the reaction (γ, n) (measurements by Bertozzi's group of neutron spectra by the time-of-flight method) and for the reaction (n, n') (Ref. 40) does not reveal a significant difference (Fig. 10). It should also be borne in mind that different excitation energies of the final nuclei are investigated in the different experiments, so that a detailed comparison becomes difficult. In addition, features of the experiment and the methods used to analyze the data may lead to a difference (by almost a factor 2) between the a values obtained, for example, from the (n, n') and other reactions.[35]

The question of the discrepancy between the shape of the photoneutron spectra in the low-energy region and the calculation based on the statistical theory has been raised in a number of studies. For example, in Ref. 26, in which the use of a diffusion chamber made it possible to reduce the detection threshold to 0.8 MeV, it was noted that the number of neutrons with energy $\varepsilon_n < 1.5$ MeV for the nuclei ^{51}V, ^{55}Mn, and ^{59}Co is appreciably lower than the calculated value. This difference gave grounds for assuming a connection between the emission of low-energy neutrons and pre-equilibrium decay. However, the replacement in formula (1) of $\sigma(\varepsilon_n)$ by a constant in the description of the neutron spectrum in the region $\varepsilon_n \approx 1$ MeV is not justified, since

TABLE VI. Energy spectra of photoneutrons from nuclei of medium mass.

No.	Nucleus	Type of detector or detection method	$E_{\gamma m}$, MeV	θ, deg	T, MeV	a, MeV^{-1}	Reference
1	^{51}V	Wilson diffusion chamber	85	135	1.03	6.7	[26]
2	^{55}Mn	The same	85	135	0.90	10.3	[26]
3	^{54}Fe	Scintillation spectrometer	22.75	145	0.80	6.6	[27]
4	^{56}Fe	The same	25.0	145	0.82	10.9	[27]
5	^{59}Co	Wilson diffusion chamber	85	135	1.0	6.6	[26]
6	Ni	The same	85	135	1.04	5.8	[26]
7	Cu	Nuclear emulsions	24	90	1.03	5.2	[28]
8	^{59}Co		30	90	1.07	5.0	[29]
9	^{64}Zn	Scintillation spectrometer	23	145	0.89	6.4	[30]

TABLE VII. Energy spectra of photoneutrons from chromium nuclei.

No.	$E_{\gamma m}$, MeV	Detection method	θ, deg	T, MeV	Reference
1	20	Nuclear emulsions	90	0.76	[21]
2	30	The same	90	0.75	[21]
3	22.0	Time-of-flight method	—	—	[31]
4	29.4	The same	—	—	[31]
5	31.3	» »	—	—	[31]

the assumption $\sigma(\varepsilon_n) = \text{const}$ is a too crude an approximation. Allowance for variation in the penetrability for neutrons can evidently eliminate the observed discrepancy.

Thus, it can be taken as established that the values of a and T obtained by analyzing the low-energy component of the photoneutron spectra are close to the values calculated using the neutron spectra obtained from reactions with heavy particles whose energy is sufficiently low for one to be able to assume that production of a compound nucleus is the dominant process. Such a conclusion is the basis for regarding the emission of low-energy photoneutrons as a process due to decay of a compound nucleus.

Analysis of the high-energy component of the photoneutron spectra. In accordance with the conclusions of the previous section, extrapolation of the low-energy part of the neutron spectrum to the region of high-energy neutrons and subtraction of the obtained equilibrium component from the total spectrum makes it possible to determine the spectrum of neutrons emitted during the stages of the reaction preceding the formation of the compound nucleus.

The absence of a smooth transition between the two components of the neutron spectrum suggests that pre-equilibrium decay plays a small role for photonuclear reactions in the region of the giant dipole resonance. The energy spectrum of photoneutrons from medium and heavy nuclei is determined by two processes—the decay of doorway states with the emission of energetic particles, and the evaporation of neutrons from the compound nucleus.

Let us consider the main features of the spectrum of nonequilibrium photoneutrons, doing this first for heavy nuclei, for which there are more experimental data (Fig. 11), and then for medium-to-heavy and medium nuclei.

The differences in the form of the spectra in Fig. 11 are very slight if one discounts the lower threshold for the emission of neutrons in Ref. 23. All the curves are

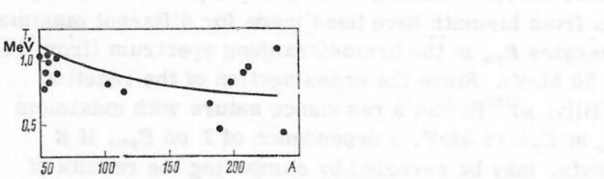

FIG. 8. Dependence of T on the mass number A. The continuous curve is calculated using the liquid-drop model.[34]

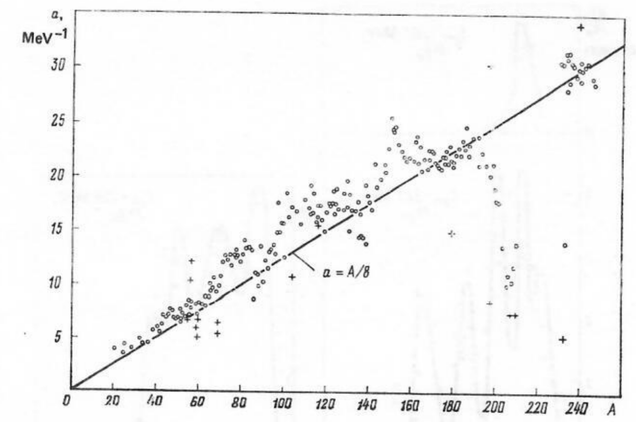

FIG. 9. Dependence of the level-density parameter a on A. The crosses are calculated using the data on the photoneutron spectra; the points are the results obtained by the method of calculating the number of resonances in the (n, γ) reaction.[39]

characterized by a maximum in the region of 5–6 MeV with half-width 2.8 MeV and a slow decrease in the region of high energies. The spectrum of nonequilibrium photoneutrons from tantalum has a similar form. For bismuth and gold, one can compare the neutron spectra measured at different energies $E_{\gamma m}$ (Fig. 12).

The form of the spectra in Fig. 12 for $E_{\gamma m} = 19–20$ and 28–55 MeV is almost the same; for $E_{\gamma m} = 14–16$ MeV, the upper limit of the distributions is at the energy $\varepsilon_n = 7–8$ MeV (the neutron binding energy is $E_0 = 7.5$ and 8.1 MeV for ^{209}Bi and ^{197}Au, respectively).

The low sensitivity of the shape of the energy spectra of the nonequilibrium neutrons to a change in $E_{\gamma m}$ indicates a proximity of the position of the cross section responsible for their emission to the giant dipole resonance for heavy nuclei.

A more definite picture of the energy dependence of the cross section of nonequilibrium neutrons can be obtained by considering their contribution to the spectrum of all neutrons (p) as a function of $E_{\gamma m}$. The dependence of p of $E_{\gamma m}$ for some heavy nuclei is shown in Fig. 13a. A correction for the angular distribution of the neutrons, which has been inadequately studied, was not introduced (a large fraction of the photoneutron energy spectra has been measured at $\theta = 90°$). The increase in p on the transition from $E_{\gamma m} \approx 15$ MeV to $E_{\gamma m} \approx 20$ MeV observed for the nuclei ^{209}Bi, ^{197}Au, and ^{181}Ta suggests a certain displacement to higher energies (relative to

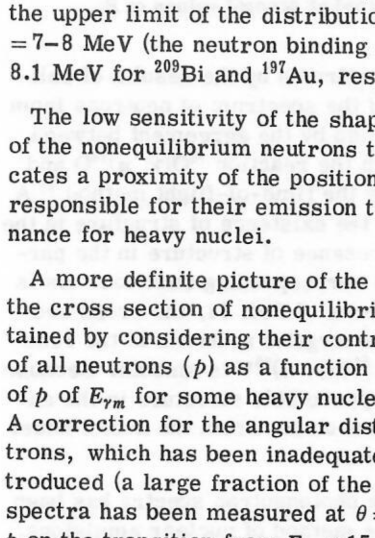

FIG. 10. Comparison of the dependence $a(A)$ for the reactions (γ, n) and (n, n'). The black circles correspond to the reaction (γ, n), the open circles to the data for the reaction (n, n').[57] The continuous curve is based on calculation in accordance with the Newton–Lang theory.[58]

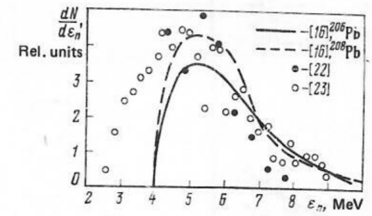

FIG. 11. Energy spectrum of nonequlibrium neutrons from lead.[16,22,23] (In the figure, the literature references are given in square brackets.)

the giant dipole resonance) of the cross section for the emission of nonequilibrium photoneutrons. This could be due, for example, to the opening of decay channels to definite states of the final nucleus. At the present time, there are no direct data on the energy dependence of this cross section.

The existence of other maxima in the spectrum of nonequilibrium neutrons besides the one observed in all nuclei at $\varepsilon_n = 5–6$ MeV remains open. It can be assumed (see Fig. 12) that in the spectrum of neutrons from Bi there are also peaks at $\varepsilon_n \approx 7$ and 9 MeV. Measurements made with natural lead and the ^{141}Pr nucleus[25] revealed the presence of structure in the neutron spectra. In experiments with chromium, a structure in the spectrum was not discovered under the same conditions,[31] which probably confirms its physical origin in the case of lead and praseodymium. The spectrum of nonequilibrium neutrons from gold also evidently contains structure.

The data on the photoneutron spectra for medium-to-heavy nuclei are too sparse for one to be able to obtain a picture of the decay of the doorway states. The spectrum of nonequilibrium neutrons from indium[24] has a shape reminiscent of the corresponding spectra from heavy nuclei. The results for rhodium, obtained at $E_{\gamma m} = 20$ and 28.5 MeV,[17] indicate an appreciable growth in the contribution of the nonequilibrium neutrons (p

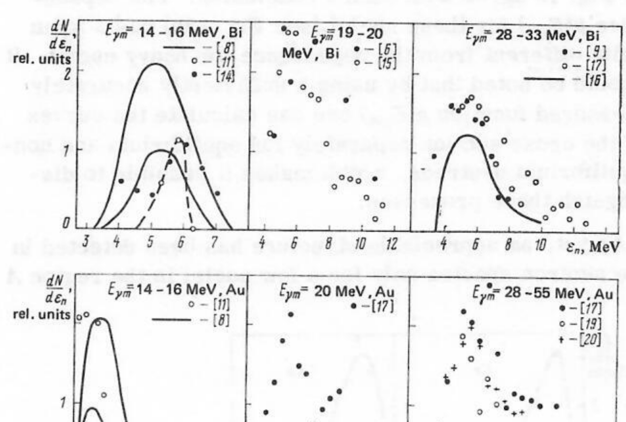

FIG. 12. Energy spectra of nonequilibrium neutrons from the nuclei ^{209}Bi and ^{197}Au. (In the figure, the literature references are given in square brackets.)

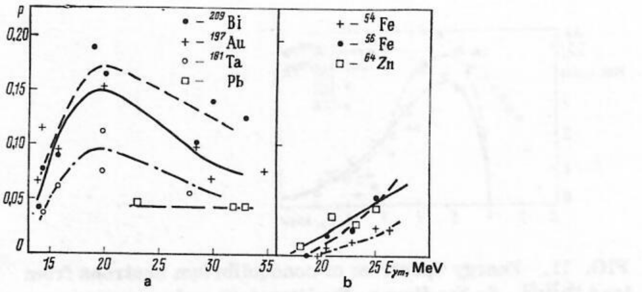

FIG. 13. Dependence of the fraction of nonequilibrium photoneutrons on $E_{\gamma m}$ for heavy (a) and medium (b) nuclei.

$=0.066$ and 0.11, respectively), which is not observed for the region of heavy nuclei. Preliminary results obtained for photoneutrons from the reaction $^{89}Y(\gamma, n)^{88}Y$ indicate the presence of structure in the energy spectra.[41]

For the nuclei of medium mass, the spectra of the nonequilibrium neutrons, calculated from the data of measurements by the method of nuclear emulsions, do not differ appreciably from the results obtained for heavy nuclei (Fig. 13b). For chromium (Fig. 14) the measurements by the time-of-flight method[31] give an appreciably higher threshold for the emission of nonequilibrium neutrons ($\varepsilon_n = 6-7$ MeV). For the nuclei ^{54}Fe, ^{56}Fe, and ^{64}Zn, the energy spectra of the photoneutrons have been measured with a relatively high statistical accuracy at several values of the energy $E_{\gamma m}$.[27,30] Figure 15 shows the spectra of the nonequilibrium neutrons from the reactions $^{54}Fe(\gamma, n)^{53}Fe$ and $^{64}Zn(\gamma, n)^{63}Zn$. Several features distinguish them from the neutron spectra from heavy nuclei considered above. There is an appreciable change in the upper limit of the spectrum with increasing excitation energy, an appreciable contribution of structure, and a smaller fraction of nonequilibrium neutrons. The first feature indicates that γ rays above the giant dipole resonance play an important part in the formation of the doorway states that decay directly into the continuum. The data of Fig. 16 agree with such a conclusion. The dependence $p(E_{\gamma m})$ for these nuclei (see Fig. 13b) has a form quite different from the dependence for heavy nuclei. It should be noted that by using a sufficiently accurately measured function $p(E_{\gamma m})$ one can calculate the curves of the cross section separately for equilibrium and nonequilibrium neutrons, which makes it possible to distinguish these processes.

As yet, an appreciable structure has been detected in the neutron spectra only for a few nuclei in the region A

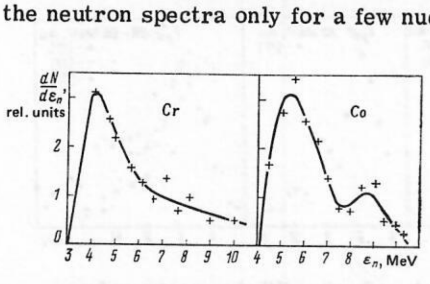

FIG. 14. Spectra of nonequilibrium photoneutrons from chromium ($E_{\gamma m} = 30$ MeV) and cobalt ($E_{\gamma m} = 30$ MeV).

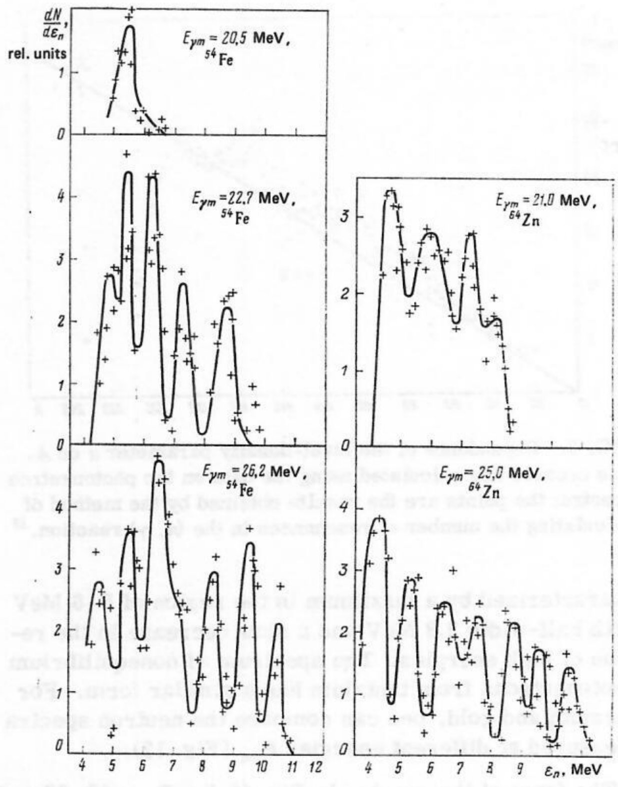

FIG. 15. Spectra of nonequilibrium photoneutrons from the nuclei ^{54}Fe and ^{64}Zn measured at several values of $E_{\gamma m}$.

≈ 60. Its existence is confirmed by the results of calibrated measurements of the spectrum of neutrons from a Pu–Be source,[42] and also by the agreement between the neutron spectra from the reaction $^{16}O(\gamma, n)^{15}O$ and the spectra measured by the time-of-flight method.[43] A necessary condition for the existence of structure in the energy spectra is the presence of structure in the partial cross section of the corresponding reaction. As is shown by the measurements of Ref. 44, the cross section for the emission of energetic neutrons in the reactions $^{52}Cr(\gamma, n)^{51}Cr$ and $^{51}V(\gamma, n)^{50}V$ is smooth. Because of this, the absence of appreciable structure in the energy spectra of the photoneutrons from the nuclei under discussion appears natural.

A large fraction of the photoneutron spectra has been obtained up to now by the method of nuclear emulsions, which, being laborious, does not ensure a high statisti-

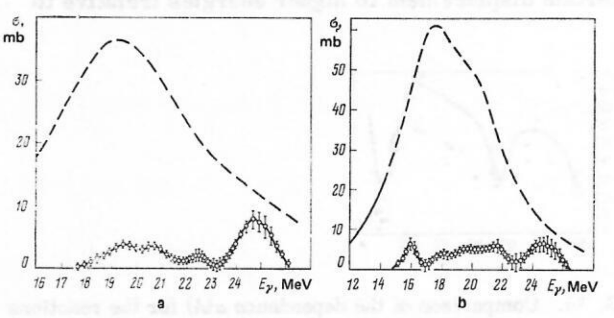

FIG. 16. Cross section of the reactions $^{54}Fe(\gamma, n)^{53}Fe$ (a) and $^{56}Fe(\gamma, n)^{55}Fe$ (b) for neutrons with energy $\varepsilon_n > 3.7$ MeV. The broken curve is the cross section for neutrons of all energies.

cal accuracy in the high-energy part of the spectrum. It is necessary to await data on the structure of the photoneutron energy spectra that can now be obtained using modern experimental techniques. The rapid growth in the yield of nonequilibrium neutrons with increasing A discovered already in Ref. 45 anticipates the yield of all neutrons, which can also be seen by comparing the curves in Figs. 13a and 13b. In part, this result can be attributed to the difference in the number of effective γ rays. Comparison of the corresponding cross sections will make it possible to establish whether the decay of doorway states to the continuum does in fact play a more important part for heavy nuclei.

Comparison of the positions of the peaks in the photoneutron energy spectra with the energies of resonances in the cross section would make it possible, for the reactions $^{54}Fe(\gamma, n)^{53}Fe$ and $^{56}Fe(\gamma, n)^{55}Fe$, to identify the levels of the final nuclei to which the individual resonance states decay. The decay takes place predominantly to levels near the ground state of a shell nature, and transitions to the ground state are hardly observed at all (Fig. 17).

A theoretical study is make of the photoneutron spectra in Ref. 46, in which an attempt is made to describe the spectra by means of pre-equilibrium decay models. It is found that neither an approximate multistep decay model with parameters chosen to achieve agreement with experiment in the (p, n) reaction nor a modified exciton model can correctly reproduce the photoneutron spectra, the discrepancy in the high-energy part of the spectrum reaching an order of magnitude. The agreement could be improved only by introducing into the expression for the density of exciton states a modulating factor leading to a relative enhancement of the channel for emission of a neutron into the continuum from the initial state of the dipole excitation. It was pointed out earlier that the presence of an inflection in the neutron spectrum suggests that the doorway states of the nuclei are responsible for the emission of the energetic neutrons. The calculations of the photoneutron spectra based on pre-equilibrium decay models lead to the same conclusion.

Let us consider the question of the shape of the spectrum of nonequilibrium neutrons in the low-energy region, which is of considerable interest for understanding the mechanism of decay of the doorway states. We

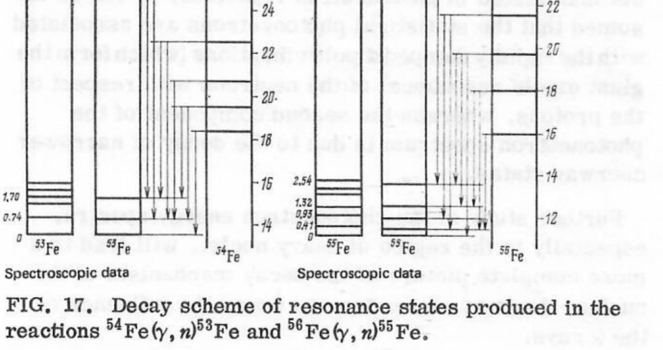

FIG. 17. Decay scheme of resonance states produced in the reactions $^{54}Fe(\gamma, n)^{53}Fe$ and $^{56}Fe(\gamma, n)^{55}Fe$.

recall that in the framework of the approximation used to analyze the results, the lower limit of the nonequilibrium spectrum coincides with the inflection which divides the two regions of the neutron spectrum. Let us consider what changes are obtained by assuming a smooth decrease to zero of the spectrum of nonequilibrium neutrons at all values of the energy $E_{\gamma m}$.

Table VIII gives the results of calculation of the temperature T of the final nucleus in both approximations on the basis of data on the spectra of the reaction $^{54}Fe(\gamma, n)^{53}Fe$. In the region $E_{\gamma m} < 20$ MeV, the photoneutron spectrum consists solely of the evaporation component, and the value $T = 0.80$ MeV is the mean of the results of three measurements at $E_{\gamma m} = 18.7$, 19.5, and 20.5 MeV. A decrease in T with increasing $E_{\gamma m}$ contradicts the statistical theory, so that the variant with T_1 appears more justified. To within the errors, the value of T_1 remains unchanged with increasing $E_{\gamma m}$, i.e., with increasing contribution of the nonequilibrium part of the neutron spectrum (the same is observed for photoneutrons from the ^{64}Zn nucleus[30]). This circumstance suggests that this contribution is slight in the region of low-energy neutrons.

Another indication of the absence of nonequilibrium low-energy nucleons is the result obtained by studying the yield near the threshold of the reaction (γ, p) for the nuclei ^{64}Ni and ^{53}Cr.[47] Because of the ratio of the neutron and proton binding energies, the evaporation of protons in the reaction $^{64}Ni(\gamma, p)^{63}Co$ is suppressed, whereas the reaction $^{53}Cr(\gamma, p)^{52}V$ proceeds through the formation of a compound nucleus. The measurements showed that in the first case the observed threshold of the reaction is 4 MeV higher than the energy threshold, whereas in the second case it is only 2 MeV higher; this last value agrees with the values of the penetrability of the Coulomb barrier and the lower limit of the observed photoneutron energy spectra for the investigated region of nuclei. The high value of the threshold of the reaction $^{64}Ni(\gamma, p)^{63}Co$ may be due to the absence of nonequilibrium low-energy protons.

Comparison of the energy spectra of photoneutrons with the spectra of neutrons from reactions with heavy particles. The photoneutron spectra considered above have various features. It is interesting to compare them with the spectra of neutrons from the reaction (n, n') and reactions induced by charged particles in the region of excitation energies near the giant dipole resonance. In contrast to the analysis of the photoneutron

TABLE VIII. Values of the nuclear temperature T under different assumptions about the shape of the nonequilibrium neutron spectrum.

$E_{\gamma m}$, MeV	18.7–20.5	22.7	26.3
T_1, MeV	0.80	0.84	0.78
T_2, MeV	—	0.77	0.71

Note. T_1 corresponds to the assumption that the lower limit of the nonequilibrium neutron spectrum coincides with the inflection in the spectrum, and T_2 to the assumption that the spectrum of nonequilibrium neutrons decreases smoothly to zero.

spectra, no attempt is made here at a complete review of the experimental material.

The spectra of energetic neutrons from the reactions (n,n') and $(n, 2n)$ have been studied comparatively little. The main aim of many investigations[48-50] was to study the density of the nuclear levels as a function of the excitation energy of the final nucleus in the framework of statistical theory. This made it necessary to adopt measures to reduce the contribution of direct processes, so that the maximal energy of the detected neutrons was restricted to the value $\varepsilon_n = 2-3$ MeV. For comparison with the photoneutron spectra, I have used the data of Ref. 36 on the inelastic scattering of 14-MeV neutrons, in which the spectra were measured up to $\varepsilon_n \doteq 5.5$ MeV.

Investigations of the reaction (α, n) for the nuclei V, Co, and Ni at $E_\alpha = 11-20$ MeV (Ref. 51) and the reaction (p, n) for the nuclei Ni, Rh, Ta, and Au at $E_p = 6-12$ MeV (Ref. 52) showed that the neutron spectra agree with the statistical theory either in the variant of the Fermi-gas model of in the variant of the evaporation model. The dependence of T on E_p and E_α found in the quoted papers and interpreted as the influence of pre-equilibrium decay[51] was explained in Ref. 53 on the basis of allowance for thermodynamic fluctuations of the temperature.

In reactions with charged particles, the contribution to the spectrum of pre-equilibrium neutrons depends strongly on the excitation energy.[54] With increasing energy of the protons, the importance of nonstatistical neutrons increases; however, because of the appreciable contribution of neutrons from pre-equilibrium decay it is only possible to separate the individual components by means of a calculation. A convincing separation of the direct and equilibrium components was achieved in Ref. 55 by analyzing the spectra of neutrons from the reaction (p, n) at different angles at proton energy $E_p = 22.2$ MeV. In contrast to the photoneutron spectra, the spectra of neutrons from the reaction $^{58}Ni(p, n)$ decreases monotonically to $\varepsilon_n = 9$ MeV, and for the reaction $^{181}Ta(p, n)$ a smooth transition from an exponential to a shallow decay is observed.

The energy spectra of neutrons from the reactions $^{209}Bi(\gamma, n)^{208}Bi$ at $E_{\gamma m} = 20$ MeV (Ref. 15), $^{209}Bi(p, n)^{209}Po$ at $E_p = 12.5$ MeV (Ref. 56), and $^{209}Bi(n, n')$ at $E_n = 14$ MeV (Ref. 36) are compared in Fig. 18 (curves 1, 3, and 2, respectively). In the region of low-energy neutrons, all three spectra, which were measured at nearly the same excitation of the nuclei, are very similar ($T = 0.93$, 0.92, and 0.76 MeV, respectively). The contribution of nonequilibrium neutrons is appreciably higher for the photoneutron reaction. One of the possible explanations is in the differing complexity of the initial configurations: $1p-1h$ for the photonuclear reaction and $2p-1h$ in the case of a bombardment of nuclei by heavy particles.

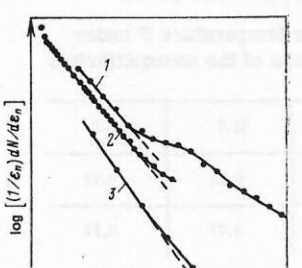

FIG. 18. Comparison of energy spectra of neutrons emitted during different reactions in bismuth.

CONCLUSIONS

Analysis of the energy spectrum of the photoneutrons makes it possible to separate the statistical component due to decay of the compound nucleus. The level-density parameter and the nuclear temperature determined from the spectra are close to the corresponding quantities for reactions with heavy particles in the same energy region.

The spectrum of the nonequilibrium neutrons is associated with the decay of doorway states directly into the continuum. For nuclei of medium mass, the cross section of the process is shifted appreciably with respect to the giant dipole resonance. The $E_{\gamma m}$ dependence of the contribution to the spectrum of nonequilibrium neutrons from nuclei of medium mass shows that the γ rays which are responsible for them have an energy exceeding the energy of the giant dipole resonance. For heavy nuclei, a displacement of the cross section for the emission of nonequilibrium neutrons relative to the giant dipole resonance is either absent or very slight. There are grounds for believing that the inflection observed in the energy spectrum of the photoneutrons corresponds to the emission threshold of nonequilibrium neutrons.

In some nuclei of medium mass ($A \approx 60$), the spectrum of nonequilibrium neutrons has an appreciable structure, which is correlated with the structure in their emission cross section.

There is a difference between the forms of the spectra of neutrons from the photonuclear reaction and from reactions induced by heavy particles. At excitation energy corresponding to the giant dipole resonance, the contribution of direct neutrons from the reactions (n, n'), (p,n), and (α, n) is appreciably less than the contribution of the energetic photoneutrons emitted on the decay of resonance states. At a high excitation energy in reactions with heavy particles, the influence of pre-equilibrium decay becomes appreciable, while it is not manifested in photoneutron reactions. It can be assumed that the statistical photoneutrons are associated with the rapidly damped dipole vibrations (which form the giant dipole resonance) of the neutrons with respect to the protons, whereas the second component of the photoneutron spectrum is due to the decay of narrower doorway states.

Further study of the photoneutron energy spectra, especially in the region of heavy nuclei, will lead to a more complete picture of the decay mechanism of the nuclear doorway states formed under the influence of the γ rays.

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