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(γ,n) REACTIONS NEAR THE THRESHOLD AND THE RADIATIVE CAPTURE OF NEUTRONS

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ABSTRACT

The author discusses the possibilities of obtaining information about the properties of the atomic nucleus and nuclear interactions by comparing the results of investigations of photoneutron reactions near the threshold with those of investigations of the reverse reactions - namely, radiative neutron capture.

1. Introduction

As is well known, radiative capture is one of the basic processes in the interaction of neutrons with atomic nuclei at energies ranging from zero to several mega-electron-volts. A detailed knowledge of the quantitative characteristics of this process is necessary when one is performing reactor and shielding calculations, trying to solve certain astrophysics problems or working in various other scientific fields. During several decades of intensive study - at many laboratories in a number of countries - of the radiative capture of neutrons, extensive information has been accumulated on the course of this process for virtually all the elements existing in nature; even now, however, certain questions have not been completely clarified (for example, neutron capture by fission fragments and the mechanism of the capture process at energies above 5-6 MeV).

Investigation of the reverse reaction - (γ,n) - in the corresponding energy region have been far less extensive. Only in the mid-1960s, with the development of the necessary experimental technology, did it become possible to perform detailed measurements of cross-sections for (γ,n) reactions at energies several tens or hundreds of kilo-electron-volts higher than the neutron binding energy - i.e. precisely in that compound nucleus excitation energy region which had been studied most thoroughly in investigations of radiative neutron capture. The investigations of (γ,n) reactions near the threshold started by a group of physicists at the Lawrence Radiation Laboratory, USA, was taken up at other institutes; even now, however, the number of groups engaged in such investigations does not exceed about ten. Consequently, the total volume of information on (γ,n) reactions is considerably less than that of information on (n,γ) reactions.

At the same time, as will be explained below, the study of (γ,n) reactions yields certain information which cannot be obtained through the study of radiative capture. When, therefore, investigations of both types of reaction yield similar data, comparison of the results may be useful from the point of view of mutual verification, enabling one to draw a number of conclusions about the properties of the atomic nucleus and the course of various nuclear processes.

However, when one is comparing the characteristics of direct and reverse reactions in specific cases, one must bear in mind various circumstances which make a straight comparison of the data difficult. Moreover, one often encounters difficulties when one tries to clarify these circumstances and make accurate quantitative allowance for them. In making comparisons, therefore, one sometimes introduces simplifying assumptions, which naturally reduces the reliability of the conclusions. A number of questions arise in this connection. Which characteristics of (γ,n) and (n,γ) reactions can be compared and under what conditions? To what extent can results obtained in investigations of the one kind of reaction supplement information or ideas about the other kind? In what way can such a comparison contribute to the development or refinement of ideas about the course of nuclear interactions? What tasks arise in this connection for the theoreticians and experimentalists studying (γ,n) and (n,γ) reactions?

After a brief enumeration of the main results of investigations of (γ,n) reactions near the threshold, we discuss possible replies to some of these questions.

2. Main results of investigations of (γ,n) reactions near the threshold

The reviews which have appeared in recent years [1-3] reflect the main results of the experiments performed. Data from well-known experimental work are presented in Table 1, from which one can clearly see that the experiments fall into two groups - experiments in which the measurements were performed with a relatively low energy resolution (10-30 ns/m) and those in which the resolution was one or two orders higher (0.4-3 ns/m). Naturally, in the experiments belonging to the second group it proved possible to perform measurements over a much greater energy range (up to 1-2 MeV). However, the neutron detectors used in such measurements are unsuitable at low energies (below 15-20 keV) - i.e. precisely in the traditional region of resonance neutron geometry. The two groups of experiments therefore complement rather than exclude each other.

Table 1

Information on experimental investigations of (γ,n) reactions near the threshold

Inst.	Country	Year(s) of publication	Resolution (ns/m)	Neutron energy range (keV)	Bibliographic reference
LRL	USA	1966-1969	30-15	1 - 70	4,5
FEI	USSR	1971-1975	16-10	0,05-140	6 - 10
Int.At.,	USA	1973	(20-10)	0,04- 80	11
WRL,	UK	1970-1973	3	up to 1000	12,13
LRL,	USA	1971	0,6	15-2000	14
ANL,	USA	1971-1974	0,4	20-1400	15 - 17
OTC,	Canada	1972-1973	0,6	400-2500	18,19

As is well known, the direct results of time-of-flight measurements are graphs showing the detector count rate as a function of the analyser channel number - i.e. of time. After exclusion of the background, conversion of the time scale to an energy scale and the introduction of data on bremsstrahlung flux intensity and detector efficiency, the curves can be transformed into curves showing (γ,n) reaction cross-sections as a function of neutron (or photon) energy. It is relatively easy to make the one important correction - for the energy resolution of the spectrometer. However, each of the above-mentioned operations is inevitably a source of errors which reduce the accuracy of the final result.

For each well resolved resonance it is possible to find the main resonance parameters E_γ, σ_o and Γ direct from the $\sigma_{\gamma n}(E_n)$ curve. Moreover, using the Breit-Wigner formula to describe the resonance shape, it is possible to determine one more resonance parameter:

$$g_\gamma \Gamma_{\gamma o} = \frac{\sigma_o \Gamma^2}{4\pi \lambda_\gamma^2 \Gamma_n} \tag{1}$$

or, for $\Gamma_n \approx \Gamma$,

$$g_\gamma \Gamma_{\gamma o} = \frac{\sigma_o \Gamma}{4\pi \lambda_\gamma^2} \tag{2}$$

The resonance area A is sometimes used in determining $g_\gamma \Gamma_{\gamma o}$:

$$g_\gamma \Gamma_{\gamma o} = \frac{A}{2\pi^2 \lambda_\gamma^2} \tag{3}$$

Here g_γ is the spin factor and $\Gamma_{\gamma o}$ the partial width of direct radiative transition to the ground state.

Much more substantial and valuable information about nuclear levels can be obtained if one measures the angular as well as the energy distribution of photoneutrons; in the most favourable cases one can determine uniquely the momentum and parity of an excited level of a target nucleus. For example, if the ground states of the initial (A) and final (A-1) nucleus have the parameters shown in Fig. 1 and measurements indicate an isotropic photoneutron distribution for some resonance, then one can assume that $\ell = 0$ for these neutrons, from which it follows that $I^\pi = I^-$. This enables one to determine not only the spin factor g_γ (and consequently $\Gamma_{\gamma o}$), but also the type of gamma transition (E1 in the present case). Thus, it becomes possible to study separately the contributions of E1, M1 and E2 transitions in the absorption of photons by a nucleus.

Lastly, if values of $\Gamma_{\gamma o}$ are determined for several resonances of the same type, then by averaging them one can find the radiative strength function for transitions of different multipolarity - for example,

$$S_{\gamma o}(E1) = \langle \Gamma_{\gamma o}(E1) \rangle / D \tag{4}$$

(and similarly for M1, E2, etc.), whereby the mean distance between levels can be determined in the course of the experiment itself or taken from other sources.

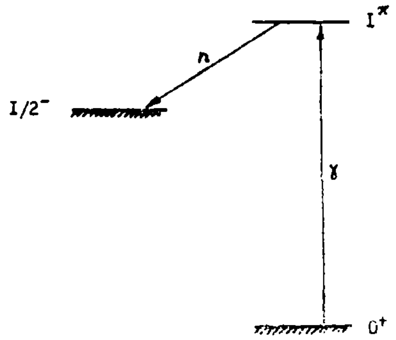

Fig. 1. Scheme of (γ,n) reaction

In conclusion, we would mention the accuracy achieved in the measurement of different resonance parameters. The determination of E_o and Γ depends in principle only on the absolute calibration of the energy scale of the spectrometer, which can be carried out with an accuracy no worse than 1%. For well resolved resonances extending over a fairly large number of analyser channels, the error in the determination of Γ is 5–10% if the background exclusion errors are taken into account. In the case of resonances lying close together, when determining E_o and Γ one must allow for the possibility of inter-resonance interference; however, with modern methods of analysing experimental data this can be done fairly correctly and accurately. At the same time, in the determination of absolute values of the cross-sections σ_o and of the associated quantities $\Gamma_{\gamma o}$ and $S_{\gamma o}$ errors of the order of 30–50% are quite possible owing to background exclusion uncertainties and to errors in calculating bremsstrahlung yields and spectra. If $S_{\gamma o}$ is determined on the basis of a small number of resonances, an additional error – due to fluctuations of the partial widths – may arise. The study of angular distributions entails only relative measurements, in which many of the factors causing uncertainties in absolute cross-section values play no role. It is usually enough to measure the ratio of the neutron intensities corresponding to one resonance for only two angles – for example, 90° and 135°: $Y_{90°}/Y_{135°}$. As a consequence, the accuracy in measuring this ratio is significantly higher than that in determining cross-section values; however, here also the need to "match" the data obtained from different detectors places certain limitations on the measurement accuracy which can be achieved. In Table 2 we present a summary of the characteristic values of errors in the measurement of different photoneutron resonance parameters.

Table 2

Characteristic accuracy in measuring photoneutron resonance parameters

Parameter	Characteristic errors (%)
E_0	≤ 1
Γ	5 - 10
Y_{90^0}/Y_{135^0}	5 - 10
σ_0, $\Gamma_{\gamma 0}$, S_γ	30 - 50

3. Comparison of data on (γ,n) and (n,γ) reactions near the neutron binding energy

The cross-sections for direct and reverse reactions are linked by the principle of detailed balance, which can be written in the following form in the case under consideration:

$$\sigma_{n\gamma} = \sigma_{\gamma n} \frac{(\hbar k)^2}{p^2} \frac{2I_a + 1}{2I_{a-1} + 1}, \qquad (5)$$

where p is a neutron pulse and k is a photon wave number. Leaving aside for a time the circumstances which make it difficult to use this relationship in practical calculations, let us state briefly the reasons why a comparison of the results of investigations of (γ,n) and (n,γ) reactions could prove useful.

1. Information about cross-sections for reactions involving the nuclei of unstable isotopes

If, in the reaction $A(\gamma,n)B$, nucleus A is stable and nucleus B is radioactive, measurement of the cross-section for the reverse reaction $B(n,\gamma)A$ may prove to be either very difficult or altogether impossible, whereas it is relatively simple to measure the cross-section for the direct reaction. Such a situation arises in particular with the reaction $^{56}Fe(\gamma,n)^{55}Fe$, which has been the subject of considerable study. By exploiting such a possibility one could increase considerably the number of nuclei whose radiative capture cross-sections are known, which would be useful both for the development of ideas above this type of nuclear reaction and for purely practical tasks.

2. The capture of neutrons by an excited nucleus

This process is virtually impossible to observe because of the extremely short lifetime of the nucleus in the excited state. The corresponding process in reverse reactions is the formation of the final nucleus with excitation of the appropriate level. Such processes are easily detected in experiments through changes in the photoneutron spectrum as the maximum bremsstrahlung energy is varied. By way of example one can cite the strong resonance peak at neutron energies of about 2 keV in the energy spectrum of photoneutrons from the reaction $^{56}Fe(\gamma,n)^{55}Fe$; as demonstrated in Refs 11 and 7, this peak corresponds to transitions to the first excited level of the ^{55}Fe nucleus. Since the structure and other characteristics of a nucleus in an excited state can differ considerably from those of the nucleus in the ground state, it may be of interest to investigate the interaction of a neutron with such an excited nucleus.

3. Measurement of the momenta and parities of excited nuclear states

As already noted (Fig. 1), values of I^{π} for excited nuclear states in the reaction $A(\gamma,n)B$ can be determined by measuring the angular distributions of the photoneutrons. In such cases, when both nucleus A and nucleus B are stable, the same characteristics can also be obtained through the study of radiative capture; in the case of a (γ,n) reaction, however, experimentation is somewhat simpler. Jackson et al. [15-17] have presented in tables the results of measurements of $Y_{90°}/Y_{135°}$ for individual resonances of ^{53}Cr, ^{57}Fe, ^{61}Ni, ^{207}Pb and ^{208}Pb nuclei. These measurements revealed, in particular, groups of resonances in ^{207}Pb and ^{208}Pb nuclei due to M1 transitions with a total radiative strength of 125 eV and 51 eV respectively. Thus, the investigation of a (γ,n) reaction near the threshold is one possible way of seeking and studying the structural peculiarities of photoneutron cross-sections associated with the absorption of gamma photons of varying nature and polarity.

4. Radiative force functions

Besides (γ,n) reactions, the values of radiative strength functions can also be determined using the results of investigations of reactions occurring under the effect of neutrons. In Ref.[2], experimental data on values of $S_\gamma = \langle\Gamma_{\gamma ij}\rangle/D$ for E1 and M1 transitions from work on both (γ,n) and (n,γ) reactions are compared among themselves and with the results of calculations based on different models of the mechanism of the interaction of photons with nuclei. By way of example we present in Fig. 2 the results of such a comparison for $S_\gamma(E1)$ with the result of Weisskopf's single-particle estimate:

$$\langle\Gamma_{\gamma ij}(E1)\rangle/D = 8{,}8\cdot 10^{-9}\cdot E^3\cdot A^{2/3} \qquad (6)$$

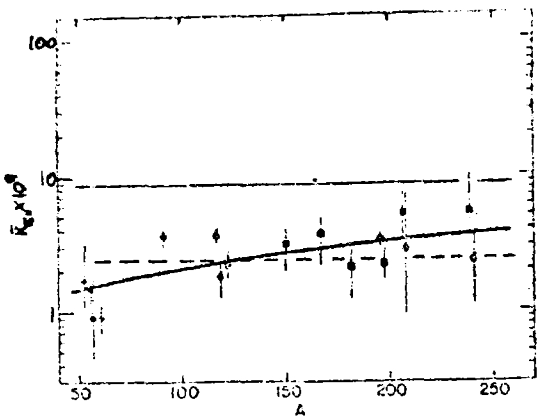

Fig. 2. Comparison of reduced values of radiative strength functions $\overline{K}_{E1} = S_\gamma E^{-3}A^{-2/3}$ measured by the photoneutron resonance method (•) and other methods (∘,■) with the single-particle estimate prediction (continuous horizontal line). The broken line is the same estimate reduced arbitrarily by a factor of 3.5 [2]. The sloping line corresponds to the relationship $S_\gamma \sim E_\gamma^3 A^{1.24}$.

As can be seen, the experimental data obtained by different methods agree on the whole among themselves and can therefore be regarded as complementing one another. However, neither the single-particle estimate nor the estimate based on the Axel-Brink model.

$$\langle\Gamma_{\gamma ij}(E1)\rangle/D = 6{,}1\cdot 10^{-15}\cdot E^5\cdot A^{8/3} \qquad (7)$$

permits sufficiently accurate prediction either of the absolute values of the strength functions or of their dependence on mass number and gamma energy.

The strength functions for M1 resonances correspond only very approximately to the quantity proposed by Bollinger:

$$\langle \Gamma_{\gamma ij}(M1) \rangle / D = 18 \cdot 10^{-3} \cdot \varepsilon^{3} \qquad (8)$$

which, however, also diverges strongly from the single-particle estimate. Moreover, none of the models mentioned is capable of describing strength function deviations from monotonic dependence on mass number – and the fact that such deviations occur is fairly clear from the currently available experimental data. In particular, one finds anomalously low values of $S_{\gamma}(E1)$ for light nuclei (see Fig. 2), a decline in the strength of M1 transitions in the gold-tantalum region and a sharp increase for lead. However, we would point out that: 1. Because of the limited amount of data, it is not yet possible to compare values of S_{γ} for one nucleus obtained by different methods since comparison is possible only on the basis of average values for large assemblies of nuclei; 2. The experimental data are scarce, the errors are large and it is still not possible to speak of a clearly defined structure in the dependence $S_{\gamma}(A)$.

Both of the above-mentioned models give the dependence of $S_{\gamma}(E1)$ on A in the form A^{n}, where $n = 2/3$ in the first case and $n = 8/3$ in the second. However, careful study of Fig. 2 and of the corresponding figure for the Axel-Brink model shows that the true dependence on A is stronger than that indicated by the single-particle estimate, but weaker than that indicated by the Axel-Brink model. Keeping the dependence of S_{γ} on E_{γ} given by these models, one can try to select the exponent n in such a way as to obtain the best agreement with the experimental data. In the first case $n = 1.24$ (the inclined continuous curve in Fig. 2) and in the second $n = 1.56$. It is therefore reasonable to expect that the true mean dependence of S_{γ} on A will be close to A^{n}, where $n = 1.40 \pm 0.16$, and that more precise determination of the energy dependence of S_{γ} will enable one to select n with a much higher degree of reliability. If this conclusion is confirmed by data still to be obtained, the need for its theoretical justification will arise.

5. Non-resonant processes

As is well known, the non-resonant ("direct" and "semi-direct") capture of neutrons is especially pronounced at relatively high neutron energies (10–15 MeV), where σ_{NR} may be several orders of magnitude greater than the cross-section for capture through the compound nucleus. However, owing to the weak dependence of σ_{NR} on neutron energy, this process also occurs at lower energies - in the resonance and thermal regions. Although direct measurement of σ_{NR} in these regions is possible (for example, in the intervals between widely separated resonances), it is greatly hampered by various side effects. The same can be said about measurements of cross-sections for non-resonant processes in reverse, (γ,n), reactions. At the same time, interference when one is adding the amplitudes of resonant and non-resonant processes must lead to the observed deformations of individual resonance peaks; this is found in the analysis of experimental data.

A number of authors [20, 21] have investigated in detail the shape of the resonance observed in the reaction $^{208}Pb(\gamma,n)^{207}Pb$ near E_n = 41 keV. The values of σ_{NR} obtained by them differ considerably (12.5 ± 2.5 mbarn and $1.3^{+2.7}_{-0.7}$ mbarn respectively). It is noted in Ref. [21] that the lower of these values is in good agreement with the results of measurements with neutrons; however, it is several times greater than the value which follows from the theoretical estimate of Lane and Lynn. The calculations performed in Ref. [21] show that there is no need to assume the existence of anomalous direct capture in order to explain this difference; one need only make correct allowance for the contribution of resonances lying close together. A second example is the resonance at 91 keV in the (γ,n) reaction in ^{53}Cr, for which σ_{NR} = 0.2 mbarn. Non-resonant processes in other nuclei have also been sought, but the resulting information is less reliable.

6. Correlation of partial widths

It is worth comparing values of $\Gamma_{\gamma o}$ obtained in investigations of (γ,n) reactions with those found in measurements with neutrons of reduced neutron widths Γ_n^o. The discovery of a correlation between these quantities for groups of levels of the same type and of the same nucleus may be regarded as an indication of the existence of common initial states for the neutron and radiative channels. The intermediate structure of cross-sections has been found for ^{29}Si, ^{57}Fe and other nuclei. It should be noted, however, that the reliability with which one can establish the existence or absence of correlations depends entirely on the comprehensiveness and accuracy of the partial width measurements. The appearance of new experimental data may therefore lead to qualitatively opposite conclusions; in other words, the results of correlation analysis possess relatively low stability with respect to experimental errors. By way of example one may cite the story of the analysis of the group of $1/2^+$ resonances in the case of ^{207}Pb in the energy range 400–500 keV. This group was first discovered in measurements with neutrons, and even then an assumption that it was linked with the initial state was expressed. In one of the first photonuclear investigations [14], values of $\Gamma_{\gamma o}$ were determined for ten resonances in this group and, as a result of the analysis performed, a value of 0.44 was obtained for the correlation coefficient ϱ. For some time this was regarded as a classical case of the discovery of an initial state through observation of the correlation between neutron and radiative widths. In a later investigation [17], however, new values were obtained for $\Gamma_{\gamma o}$ and a further $1/2^+$ resonance was found; as a result of this, the value attributed to ϱ was reduced to 0.1, which – if one allows for possible error – does not exclude the complete absence of a correlation. However, if a correlation between $\Gamma_{\gamma o}$ and Γ_n^o can be established with sufficient reliability in such cases, this way of comparing the results of neutron and photonuclear investigations can yield very useful information about the properties of atomic nuclei.

Having enumerated the varied possibilities for comparing data on (γ,n) and (n,γ) reactions, we must return to expression (5) and explain why it cannot be widely used.

It is obvious that (γ,n) and (n,γ) reactions are not completely equivalent, owing to the possibility of radiative transitions from an initially excited state to lower-lying levels of nucleus A (Fig. 3). Naturally, such transitions also occur when this nucleus is excited by a photon; however, the emission of a gamma photon means in this case that no (γ,n) reaction has taken place, so that the cross-section for the (γ,n) process with emission of a neutron of a certain energy is proportional to $\Gamma_{\gamma o}$. With the reverse reaction, any radiative transition to a lower level means that the neutron capture process has been completed, so that $\sigma_{n\gamma} \sim \Gamma_\gamma$.

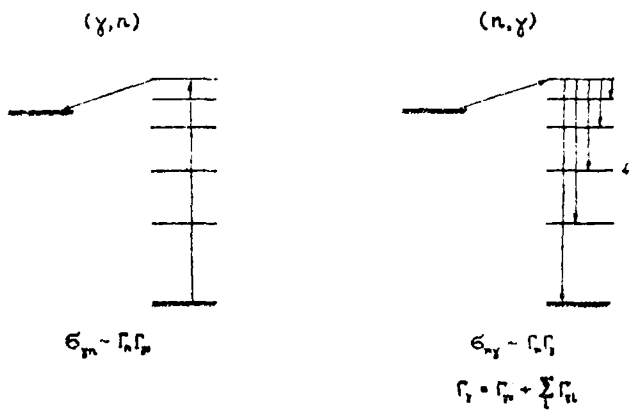

Fig. 3. Scheme of (γ,n) and (n,γ) reactions

Thus, a straight comparison of cross-sections for (γ,n) and (n,γ) reactions using expression (5) is impossible. However, there are two ways out of this situation.

Radiative neutron capture with a single-photon transition to the ground state is directly analogous to a (γ,n) reaction. Such capture events can be detected experimentally by measuring the energy spectra of the prompt capture gamma radiation, and their partial cross-sections can therefore also be determined. With this method one can overcome certain serious experimental difficulties, but it cannot be used for all nuclei; hence, even isolated verification of its admissibility would be of some interest.

The second possibility of comparing data on (γ,n) and (n,γ) reaction cross-sections involves using the "Brink hypothesis", according to which the same giant resonance can be constructed at each excited level of a nucleus as in the ground state. If the "Brink hypothesis" is valid, the measured value of $\Gamma_{\gamma o}$ will enable one to construct the total width Γ_{γ}, which opens up the possibility of comparing values of $\sigma_{\gamma n}$ and $\sigma_{n\gamma}$ using expression (5). The "Brink hypothesis" was used in comparing radiative strength functions obtained by different methods both among themselves and with theoretical estimates (see above). However, since the validity of the "Brink hypothesis" is not obvious, there may be doubts about the admissibility of this approach. At the same time, the accumulation of factual data on (γ,n) and (n,γ) reactions and increases in measurement accuracy may prove useful as regards verification of the "Brink hypothesis" and understanding the mechanism of these reactions as a whole.

4. Conclusion

Although about ten years have passed since the start of investigations of (γ,n) reactions near the threshold, the data are still very scarce. Measurements have been performed for a relatively small number of elements, and even then by no means all isotopes and energy ranges have been investigated (Fig. 4). Nevertheless, these limited investigations have yielded very interesting results which confirm the promise of this approach to the study of the properties of the atomic nucleus.

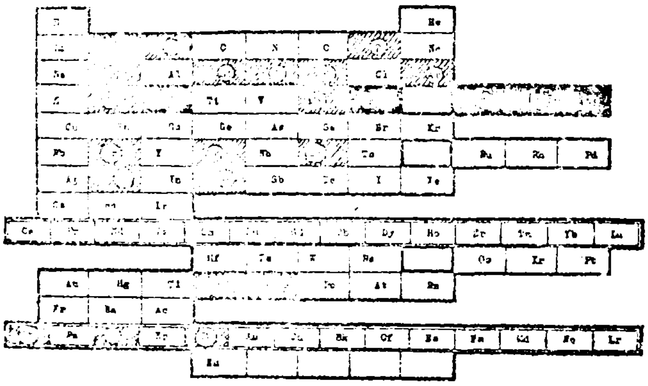

Fig. 4. Experimental information on (γ,n) reactions near the threshold. The light hatching indicates elements for which the data relate only to neutron energies above 15-20 keV. The dark rectangles indicate elements for which there are data relating to lower energies; the completely black rectangles indicate elements for which measurements have been performed at the Institute of Physics and Power Engineering and the cross-hatching indicates elements for which measurements have been performed at other laboratories.

The main tasks at present are clearly to accumulate more information - extending investigations to other nuclei, energy ranges and parameter sets - and to increase the accuracy of measurements. It is particularly worth studying chains of neighbouring stable isotopes such as ^{56}Fe-^{57}Fe-^{58}Fe or ^{60}Ni-^{61}Ni-^{62}Ni, for which direct measurements of cross-sections for both direct and reverse reactions are possible. It is extremely important to arrive at a reliable division of resonances according to their spin characteristics since this is connected with the search for and study of giant resonances caused by the absorption of photons of differing nature and multipolarity (E1, M1, E2, etc.).

Investigations of radiative neutron capture and of (γ,n) reactions near the threshold are natural ways of obtaining information about nuclear levels lying in the neutron binding energy region. It is to be expected that further investigations of such reactions and combined analysis of the results will yield new data on the structure of the atomic nucleus and the properties of nuclear interactions.

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