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PROGRESS IN THE STUDY OF NUCLEAR STRUCTURE WITH NEUTRONS

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Introductory Talk at the Conference on Nuclear Structure Study with Neutrons, Budapest, July 31 - August 5, 1972.

Франк И.М. **E3 - 6757**

Развитие исследований структуры ядра с помощью нейтронов

Препринт содержит текст вводного доклада, прочитанного 31 июля 1972 г. в Будапеште на Конференции по изучению стуктуры ядра с помощью нейтронов.

В первой части доклада после небольшого исторического введения говорится о связи фундаментальных и прикладных проблем, характерной для нейтронной физики. Во второй части отмечается значение исследований с быстрыми нейтронами и подчеркивается необходимость дальнейшего прогресса в экспериментальной технике. В третьей части доклада рассмотрено развитие исследований ядер с помощью резонансных нейтронов в период времени после Антверпенской конференции 1965 г. В заключительной части доклада обращается внимание на поразительное многообразии свойств нейтронных резонансов ядер и на возможности их изучения.

Препринт Объединенного института ядерных исследований.
Дубна, 1972

Frank I.M. **E3 - 6757**

Progress in the Study of Nuclear Structure with Neutrons

The paper contains the Introductory Talk given at the Conference on Nuclear Structure Studies with Neutrons which was held in Budapest on July 31 - August 5, 1972.

After a brief historical introduction, the first part of the paper is devoted to the relationship between fundamental problems of neutron physics and its applications characteristic of neutron physics. In the second part, the importance of studies using fast neutrons and the necessity of developing the experimental technique are noted. In the third part, the development of nuclear studies by means of resonant neutrons during the period following the 1965 Antwerp Conference is reviewed. In the concluding part, attention is drawn to the impressing variety of the properties of neutron resonances and the possibilities of their studying.

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I. Introduction

1972 is an anniversary year for neutron physics. On February 17 was the fortieth anniversary of the day when Professor Chadwick submitted for publication his famous paper ''Possible Existence of a Neutron'' which appeared in ''Nature'' on February 27, 1932 /1/. In fact, during the two previous years physicists had begun their investigations of neutron radiation without knowing what they dealt with and had called it Bothe-Becker beryllium rays /2/. As long as ten years before that Professor E.Rutherford had pronounced the prophetical words about the possible existence of a neutral particle /3/. As to the experimental observation of the neutron, one should recall the fact that Frederic and Irene Joliot-Curie came close to this discovery when they detected recoil protons produced in hydrogen by Bothe and Becker rays. It was just the experiments on the generation of recoil nuclei and their analysis that led Professor Chadwick to this discovery.

Only ten years separate the experimental discovery of the neutron from the realization of the nuclear chain reaction with the aid of neutrons. That decade was rich in outstanding achievements, many of which are of direct importance to the problems considered at this Conference. Now I would only like to emphasize that the so rapidly developing relationship between neutron physics and the nuclear energy problem involved a limited understanding of neutron physics for a number of years. This relationship leads us to consider it as not only a problem of nuclear physics, which has a number of important applications, but rather as one of the branches of technical physics. However, gradually the fundamental trends of nuclear investigations with neutrons were developing and became a subject of wide international discussions. First of all I refer here to the 1965 Conference at Antwerp, which was entitled "Nuclear Structure Study with Neutrons". This title entirely fitted the topics covered at that Conference [4] and emphasized the fact that nuclear investigations with neutrons were not only important, but also original, which made it possible to separate them as an independent subject for discussions. The Antwerp Conference was preceded by the 1957 International Conference which had taken place at the Columbia University [5] as well as by a number of relatively small meetings, mainly of national character.

It is not by chance that the present Conference in Budapest has the same title as the one at Antwerp. In this connection I should in a sense, build a bridge across the seven years which separate the two Conferences. It goes without saying that I cannot give a full review of all problems and, therefore, I shall mention only a few selected examples.

II. Applications of Neutron Physics

First of all it is worth emphasizing that the links between neutron physics and applications have been destroyed neither in 1965, nor at present. In his introductory lecture to the Antwerp Conference Professor Bretscher paid special attention to the necessity of determining the constants which characterize the interaction of neutrons with nuclei. This practical application of the results obtained in neutron physics has in no case lost its significance. It is pleasant to note that nowadays a wide international collaboration in this field of science takes place through IAEA.

Practical requirements do not always consist simply in a compilation of data. The development of nuclear energy constantly brings forward new difficult tasks for neutron physics. As an illustration, one can mention the recent determination of the value of α, i.e., the ratio of neutrino capture to fission, for plutonium for a wide energy range. Since there have been no reliable methods for such measurements, the first results obtained in different countries appeared to contradict each other to a considerable extent. It is clear in this situation that the international cooperation in this and similar fields would be of invaluable importance. The applications of neutron physics are not restricted to nuclear energy. We know that neutron capture cross sections and their energy dependence are important, for example, for astrophysics, and some neutron physics methods are extensively used in other branches of science. For instance, slow neutron optics begins to turn into an independent science which has a wide range of applications in the physics of condensed matter. In particular, we may expect significant achievements in the study of the structure of the molecules of animate matter, which quite recently have been the monopoly of x-ray diffraction analysis. It is also possible that inelastic scattering of slow neutrons will be employed to study the dynamics of biophysical processes.

Not only the problems arising in reactor construction, but also other applications of neutron physics stimulate now the development of neutron sources and experimental methods. For instance, the completion of reactors with high flux density in Brookhaven and Grenoble, the importance of which one cannot help mentioning, also opens up wide future possibilities for the physics of condensed matter.

There is no doubt that the close relationship between the solution of fundamental problems and applications, which was mentioned in Antwerp, continues. In fact, this relationship is deeper than it may look at first sight. If we recall the development of nuclear energy, we cannot help noting that, at one time, the theoretical ideas of Bohr-Frenkel were of exceptional importance. According to these ideas the fission process is considered in analogy to the fission of a charged liquid drop. However, it became clear shortly afterwards that this phenomenon is extremely complicated, and the further development of its technical applications was mainly based upon empirical data. It is evident that any new fundamental results in fission physics and any subsequent progress in theoretical understanding must have practical applications. This most important progress is actually taking place in fission physics at present. We only need to recall the discovery of spontaneously fissioning isomers at Dubna[7] and the subsequent discoveries of the fluctuations of subthreshold fission cross sections[8] at Saclay (France) and in Belgium. Shortly afterwards these discoveries led to the assumption of the double-humped fission barrier that was discussed at the International Symposium at Dubna in 1968[9,10]. As a result, for the first time the Bohr model of the fission barrier has undergone essential changes.

I think that during the years following the Antwerp Conference in the development of links between theory and applications, the fundamental problems to which this Conference is devoted became of greater importance. I have illustrated this by an example from fission physics.

III. Studies with Fast Neutrons

From the point of view of methods and purposes, neutron physics consists of several fields, which are connected to some extent. I shall mention only a few of them. As we remember, the investigation of the interaction of fast neutrons with nuclei (H.Barshall, 1953) resulted in the optical model of the nucleus. Then a considerable advance in its development resulted from charged particle studies. From the physical point of view, of course, experiments both with protons and neutrons are required. In the second case the interpretation of the results is simplified because of the absence of the Coulomb interaction which is especially important for scattering at small angles. However, some experimental difficulties arise here. At the Antwerp Conference the progress in experimental techniques for studies with fast neutrons, especially the time-of-flight method, was discussed. In many cases it was rather helpful to use the possibility of separating neutrons from gamma-rays using pulse shape discrimination in scintillation counters. The most significant results have been obtained from experiments with neutrons of energies up to a few MeV. At the same time rapid progress has also taken place in experiments with charged particles. If we speak about the energy region usually studied by means of modern electrostatic tandem generators, protons have some advantages compared to neutrons. These advantages are connected with the possibility of producing monoenergetic beams and separating elastic and inelastic scattering. If the first excited state is less than 100 keV above the ground state, it is not always possible to separate completely elastic and inelastic components for incident neutron energies above 10 MeV. In addition, some difficulties arise because of the small amounts of separated isotopes that are available as target materials. Nevertheless, investigations of this energy region have been carried out /11,12/.

As an illustration, I give in Fig. 1 the energy dependence of the total cross section of the ^{207}Pb nucleus for neutrons in the region 13-17 MeV /12/. One can observe here a deviation from the smooth behaviour, i.e., a peak at 16.7 MeV. The peak height is about 0.2 barn, i.e., approximately 4% of the total cross section which is 5.5 barn. It is worth noting that the anomaly is observed in the energy region where ^{208}Pb has to have its isobaric analog states (the peak is about 1 MeV higher than the expected position of the analog of the ^{208}Tl ground state).

Owing to the forbiddenness, the excitation of isobaric analog states by neutrons should occur with small probability. However, it is quite natural to expect that the possibility of observing them requires only sufficiently good energy resolution and experimental accuracy.

IV. Progress in the Studies with Resonant Neutrons

Resonant and thermal neutrons form a specific field of nuclear structure study with neutrons. During the last few years great progress has been made in the resolving power of neutron spectrometers, experimental methods and data handling. In this connection one should mention the appearance of a number of spectrometers with high resolution, such as ORELA. These spectrometers have made possible the observation of regularities in the distribution of neutron resonances. These regularities had not previously been observable /40/. At the same time the necessity of a detailed analysis of neutron resonances leads increasingly to the specialization of spectrometers to certain operating conditions, and an increase in resolution is not always the main aim.

The classical method from which neutron spectroscopy originated is the measurement of transmission curves from which neutron and total widths of resonances are deduced. The storage of experimental data was ahead of its analysis. A particular difficulty was that the data for separated isotopes were poor. As was remarked by Dr. Julien in his report at the Antwerp Conference, considerable progress in data analysis was characteristic of that period, however at that time there was still insufficient information available even about the spins of s-resonances /13/.

The progress of the classification, acquisition and analysis of experimental results has been very rapid after the Antwerp Conference. For elements with many isotopes a number of s-and p-wave resonances has been identified and their spins determined. Nevertheless, I think that during the last five years our understanding of the s -wave strength function has changed considerably. However, these new data contained important results. The theoretical predictions that the strength function is an average characteristic of the nucleus, as was expected according to the nuclear optical model, were confirmed. Only some properties of the A-dependence of the strength function, namely a small hump in the region of $A = 165$[14,15,16] and especially the region of the minimum near to $A = 120$[17,18] are exceptions. In order to explain them, some further assumptions were required [19,20]. The strength function should vary slowly in a short interval of Z and A. In fact, this has been experimentally observed and very vividly illustrated by a comparison of the strength function values of even and odd isotopes with neighbouring masses. Indeed, the difference between the level densities in odd and even isotopes may differ by two orders of magnitude; the neutron widths also vary in such a way that the strength function remains practically unchanged. For instance (see Fig. 2), for a ^{155}Gd target $D = 1.8 \pm 0.3$ eV, while for ^{160}Gd $D = 170$ eV. At the same time the strength functions for these nuclei are $S = (2.1 \pm 0.3) \times 1.0^{4}$ and $S = (2.6 \pm 1) \times 10^{-4}$ respectively, i.e., identical within the limits of errors [14].

Our attention has been drawn to the fact that the values of the strength function for most nuclei have considerable errors. This is quite natural if we take into account that both the level spacings and widths fluctuate over a wide range. Apparently the probability of increasing the accuracy is not very large, because the neutron energy interval for which an analysis is possible is limited and the number of resonances it contains is not very large.

Because of large fluctuations in the experimental values of the strength function, the latter cannot be regarded as a sensitive measure of deviations from the statistical model. This fact has manifested itself vividly in the search for the spin dependence of the nuclear strength function for s-neutrons, which was stimulated by the hypothesis of doorway states. A thorough analysis of the results obtained indicates that even if in any of the nuclei a difference of nuclear strength functions is observed for resonances with spins $l + 1/2$ and $l - 1/2$, even if it exceeded the statistical error, the result would, nevertheless, be unconvincing. If such a deviation were observed in a single case among many nuclei studied, it might well be a random fluctuation [21]. The same applies to the energy dependence of the strength function. Fig. 3 shows the energy dependence of the sum of the reduced neutron widths of resonances in the interval of 0 to 250 eV for ^{149}Sm. It is difficult to approximate the distribution of the points by a straight line which it should be. Rather it can be represented by three linear segments. In this case we obtain for the values of the strength function $(2.8 \pm 1) \times 10^{-4}$ and $(11.1 \pm 3.6) \times 10^{-4}$ for the intervals 0-40 eV and 40-100 eV, respectively. According to the authors' estimate /22/ the probability of such a fluctuation is 0.2%. Nevertheless, one cannot draw with certainty an unambigous conclusion that this fluctuation is not a random one. One would have to be convinced that this kind of anomaly is not an exception.

Strictly speaking, even if these deviations manifested themselves more often than expected, we would nevertheless be unable to state in all cases that this is a violation of statistical theory. These deviations may also be a manifestation of some statistical properties albeit unforeseen by the existing nuclear model, which would require a further development of this model.

If we speak of the interaction of resonant S-wave neutrons with nuclei as a whole, both the strength function and the distributions of resonance neutron widths and spacings obey rather well the conclusions drawn on the basis of the existing model of the nucleus. The cases of violations are so far rare and can possibly be regarded as unimportant exceptions. We have a less clear understanding of the regularities for p-wave neutrons. To clear them up, further development of experimental methods is required. One should consider for this purpose the method of polarized neutrons and targets and the development of the moving sample method /18/ which was discussed in Antwerp /23/. The current development of some other methods is also of great importance.

The results available indicate that the strength function has a number of interesting peculiarities if one considers it in a wider energy range than has previously been done in nuclear spectroscopy. The problem of the strength function as it is related to intermediate structure was discussed at the Conference in Albany in 1971 /24,25/. That Conference was devoted not only to studies with neutrons although a considerable fraction of the programme covered this subject. I would like to recall that the subject of that Conference was the study of the statistical properties of nuclei. However, in some reports attention was paid to the problem which arise when the statistical representations turn out to be insufficient. I would say this very problem was at the centre of attention at the Conference. This was stressed in the concluding discussions under the chairmanship of Professor E.P.Wigner /26/.

V. Resonance Properties

It is typical for neutron spectroscopy that on the basis of the properties of some individual resonances one can determine only one or another characteristic of their behaviour. This is caused by the fact that until recently it seemed hopeless to find out anything about the structure of neutron resonances. Indeed, the total gamma width of resonances Γ_γ remains unchanged from resonance to resonance within the limits of errors, i.e., they practically do not depend on the individual nature of the resonances. As to the specific values of neutron widths of resonances there is no reason to interpret them in any way other than according to the Porter-Thomas distribution.

The situation began to change after the study of gamma-ray spectra in the capture of neutrons in individual resonances, i.e., in the investigation of the partial gamma widths $\Gamma_{\gamma\nu}$. Already at the Antwerp Conference Urbanec et al. reported /27/ some data which showed for the example of barium how diverse the spectra of capture gamma-rays are from the decay of individual resonances. These data were obtained using lithium-germanium detectors, which became at that time of increasingly wider use.

Dr. Vervier /28/ discussed in his report to that Conference the possibility of using *Li–Ge* detectors for the study of neutron capture gamma-rays. He suggested that the study of the spectra of individual resonances will be carried out in the future. As we know, the hopes for these detectors and their application have been completely justified. The study of neutron capture gamma-rays has long ago became an original branch of nuclear spectroscopy and has been discussed at an international symposium /29/. It is well known now that gamma-ray spectra are different not only for resonances with different spins. Instead, the cases when the spectra from different resonances with the same spin have considerable similarity are rare exceptions. The experimental data obtained at Brookhaven indicate that *p*-wave resonances in molybdenum represent this exceptional case /30/.

The gamma-ray spectra which are so different for various resonances have revealed an extremely large variety of properties of individual resonances. The neutron spectrometry using photo-nuclear reactions (γ,n) which has been developed considerably during the last few years has also led to the display of some individual features of resonances determined by the probability of transitions between the resonant and the ground state (see, e.g., /31/).

During recent years it has become clear that for a not very small number of nuclei one can observe the decay of resonances accompanied by alpha-particle emission, Γ_a -the alpha-widths of the resonances; these widths fluctuate very strongly. Fig. 4 gives the experimental curve for the yield of gamma-rays (the upper plot) and of alpha-particles from the capture of neutrons in the resonances of ^{149}Sm /32/.

One can see that the curves are quite different due to the fluctuations of the widths Γ_a . In this case the spectrum of alpha-particles is observed which corresponds to the decay in which the product nucleus is left in the ground or in any of the excited states. Such spectra of alpha-particles are also an individual feature of resonances. The problem of the alpha decay of resonances will be considered in Yu.P.Popov's contribution to this Conference. Here I would only like to note that the peculiarities of alpha decay form a new group of the characteristics of individual resonances.

The determination of magnetic moments of resonances should also be regarded as part of these individual characteristics for the investigation in which only the first steps have been taken. Up to now, the moments of only two resonances of an erbium nucleus have been measured /33/.

It is quite natural that the abundance of information characterizing an individual resonance stimulated the theoretical consideration of the problem of resonance structure /34/ , to which the report by V.G.Soloviev at this Conference is devoted.

I believe that the situation may be described in the following way. There are resonances with identical quantum characteristics, i.e., the same spin and parity. The corresponding excitation energies of the nucleus are also almost identical. Indeed, even if the distance between resonances is a few keV, this value is still by three orders of magnitude less than the neutron binding energy. Nevertheless, as we have already seen such resonances have rather different properties, and we are still helpless in our attempts to explain these differences.

There is no doubt that the structure of such excited states as neutron resonances is very complicated, and therefore one can hardly find any additional quantum characteristic to describe their differences. It would be more natural to continue thinking that we cannot learn anything about the structure of an individual resonance, i.e., the theory can give us no information except the average partial width $\Gamma_{\mu\nu}$ for a given decay mode and the distribution law for this value. In practice, however, searches are being performed for doorway states and for intermediate structure to clear up their nature, i.e., attempts are being made to overcome this negative viewpoint. We know that at least some of these attempts have been successful.

We can base all these attempts only on the features of resonance decay or inverse processes associated with the probability for the production of the resonance. Therefore, it may be helpful to introduce a special term for the relative value of the probability for each individual decay mode of a resonance. I have used the convention of calling this ''the affinity'' with a given decay mode. This can be quantitatively defined as a ratio of the reduced partial width $\Gamma^0_{\mu\nu}$ to its average value of $<\Gamma^0_{\mu\nu}>$ for many resonances. In some cases the character of resonance affinity has rather characteristic peculiarities It has turned out, for example, that the 183.7 eV resonance of ^{147}Sm (the state $J = 3^-$)has an abnormally great probability for alpha-particle emission associated with the decay to the ground state /35/. A sixfold increase of this transition probability is observed compared to the average value measured for nine resonances with $J=3^-$, i.e., the affinity of the 183.7 eV resonance for alpha-decay to the ground state $R_{a0} = 6$. The neutron widths of ^{147}Sm resonances have been studied /20/, and Dr. Becvar has investigated the resonance gamma-spectra. It has appeared that the reduced neutron width of this resonance is 6 times larger than the average, i.e., R_n 6. Thus, this resonance appeares to be singled out in at least two decay channels. However, if we have no possibility of assigning this fact to the peculiarities of resonance structure, we shall be forced to consider it accidential. The problem of this resonance will also be discussed in a contribution by Yu.P.Popov.

A search for correlations in different decay modes is a reasonable way to study the nature of resonances. However, it is a very hard problem from the experimental point of view. The correlation of neutron widths with the partial widths $\Gamma_{\gamma\nu}$ is observed in those cases where the state of the valence neutron makes a noticeable contribution to the resonance structure, as has been clarified by experiments with molybdenum carried out at Brookhaven. Apparently one cannot expect a simple picture in other cases.

Now we shall turn to the problem of doorway states which was discussed in Professor Feshbach's report to the Antwerp Conference /36/. At that time only one particular and simple case of doorway states was known, namely, isobaric analog states. During the years following that Conference this problem has been studied to a considerable extent, but it does not seem to become simpler. In addition to the valence neutron, one can single out some other cases. One of the interesting peculiarities is the presence of a maximum in the region of 5.5 MeV (sometimes called ''pigmy resonance'') in the spectrum of capture gamma-rays for nuclei close to thallium. This maximum was first observed by L.V.Groshev and co-workers in the capture of thermal neutrons and was considered in the work by Bartholomew who assumed that it was associated with a doorway state [37]. The latter shows up at the capture of neutrons over a wide energy interval.

Apparently a simple configuration prevails in the structure of many resonances only in selected cases. As a rule, we can expect a complicated superposition of such simple configurations. When considering the characteristics of the decay of individual resonances on the basis of the nature of their affinity, we shall perhaps succeed in classifying them either by similarities or differences. There is still hope that we shall be able in this way to obtain some information about their structure and their complexity. It may possibly happen that when we know the regularities of the resonance distribution to which some contributions to this Conference are also devoted (see, e.g.[38,39]), we shall be in a position to recognize a group of levels that would present the components of superfine structure. Further progress can be also expected in the study of the general properties of states (separated or overlapping) that produce one or another giant resonance.

Nuclear structure studies have apparently entered a period when one can expect a much deeper understanding of the nature of nuclear states at high excitations than has previously been possible. Besides, we should not forget the importance of studying the properties of the neutron itself as an elementary particle. This fact should be taken into account when we note that the energy region in which investigations are carried out is continuously expanding, and not only in the direction of higher energies. During the last few years experiments have been performed with neutrons of lowest energies, namely, ultracold neutrons. The problem of the use of these neutrons is a task for the future.

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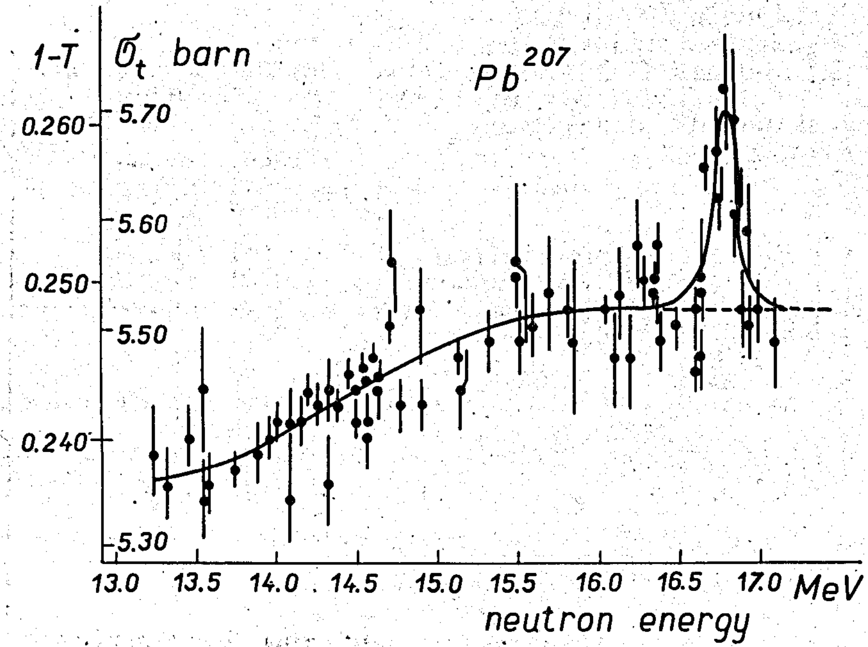

Fig. 1. Total cross section for the interaction of neutrons with a ^{207}Pb nucleus in the energy region 13.5 - 17 MeV.

Target	D_{ev}	$S \cdot 10^4$
Gd^{155}	1,8	2,1 ± 0,3
Gd^{160}	170	2,6 ± 1

Fig. 2. Comparison of the strength functions and level spacings for ^{155}Gd and ^{160}Gd targets.

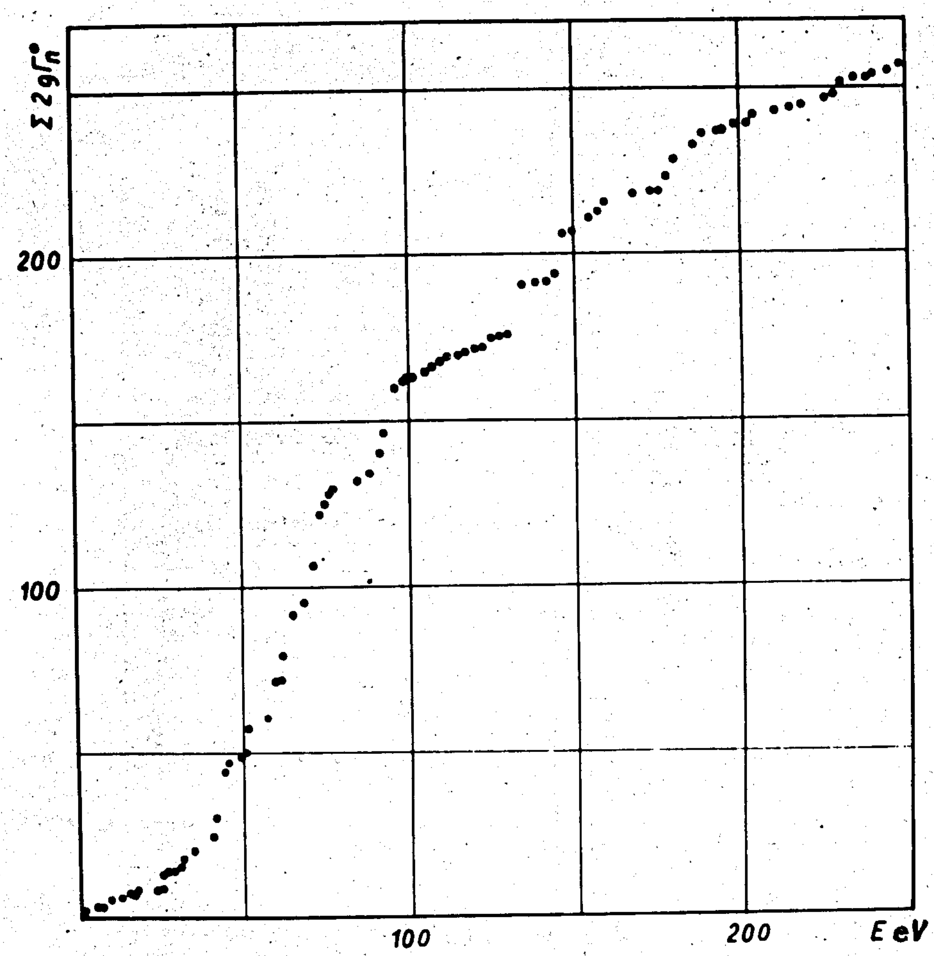

Fig. 3. The energy dependence of the sum of reduced widths for ^{149}Sm.

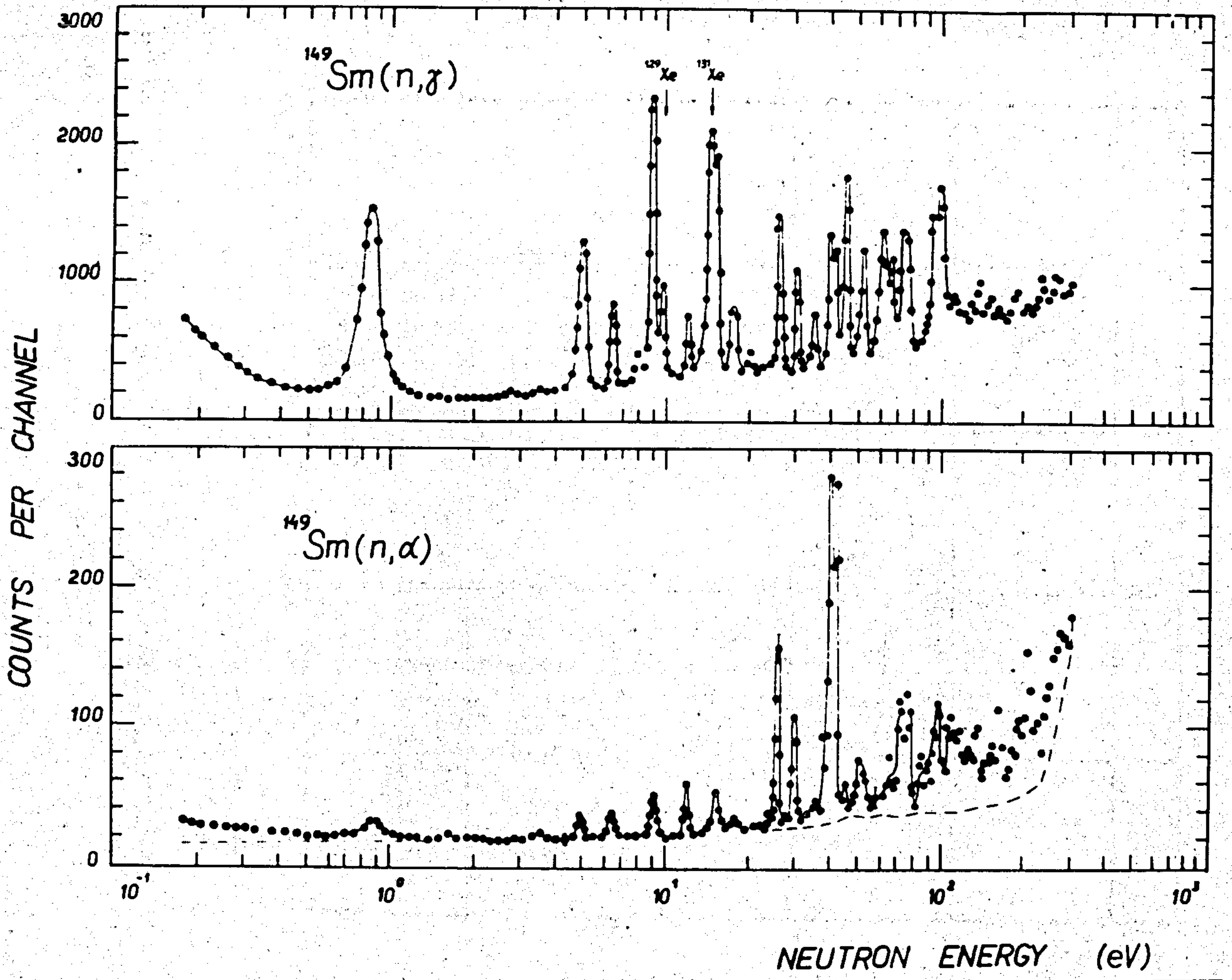

Fig. 4. The experimental curves measured using the time-of-flight method for the yield of gamma-rays (upper plot) and alpha-particles (lower plot) produced in the capture of neutrons in ^{149}Sm .