International Atomic Energy Agency

INDC(CCP)-223/L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

INELASTIC SCATTERING OF NEUTRONS

O.A. Sal'nikov
Institute of Physics and Power Engineering, Obninsk, USSR

Translated by the IAEA

June 1984

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Reproduced by the IAEA in Austria
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84-02808

INELASTIC SCATTERING OF NEUTRONS

O.A. Sal'nikov
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The study of the inelastic scattering of neutrons dates back a long time - almost, in fact, to the discovery of the neutron - and the subject is not expected to be exhausted in the near future. As experimental techniques gradually improve, so new and more detailed information on this process, which plays a fundamental role in science and technology, is constantly coming to light. There are two reasons for the interest shown in the inelastic scattering of neutrons:

1. It is an extremely valuable tool for the investigation of the atomic nucleus; the spectra and angular distributions of inelastically scattered neutrons and γ-quanta accompanying inelastic scattering yield information on the structure of the nucleus, the quantum characteristics of excited states (often inaccessible by other means of investigation) and the mechanism of nuclear reactions;

2. In fast reactors fission neutrons lose energy largely through inelastic scattering; it is this process which forms the reactor's neutron spectrum and determines all its most important characteristics, which in turn determine the efficiency of the reactor. These include, for example, the coefficient of nuclear fuel conversion (KV). The same applies to the planned hybrid thermonuclear reactors.

As a result of the development of experimental techniques it has been possible over the past five to ten years to determine with far greater precision the nuclear physical constants which characterize neutron inelastic scattering and to discover a number of new features governing its mechanism.

The present review focuses mainly on the mechanism of inelastic scattering, since this is a fundamental problem; only when the reaction mechanism is correctly understood will it be possible to predict changes in the characteristics of inelastic scattering as a function of the energy and the specific type of nucleus. The most detailed characteristic and, hence, the one most sensitive to the reaction mechanism is the double-differential cross-section:

$$\sigma(E_o, E', \theta),$$

which indicates the probability that a neutron with an initial energy of E_o and moving through an angle of 0^o will, after interacting with the nucleus, receive the energy E' and fly off at an angle θ^o. In inelastic scattering the target nucleus remains in an excited state, but since the nucleus is a quantum system the excitation energy can only assume specific values determined by the quantum characteristics of the particular nucleus, i.e. the energy of the excitation level, its spin and its parity (our investigation being conducted within a centre-of-mass system).

In the excitation energy region of the residual nucleus, where the width of the excitation levels is $\Gamma < D$ (D being the distance between the levels), the spectrum of the inelastically scattered neutrons is discrete. However, in the region where $\Gamma > D$ this spectrum becomes continuous (the region of overlapping levels). In practice, in the spectrometry of inelastically scattered neutrons the transition from the discrete to the continuous spectrum occurs at an earlier stage - when the experimental energy resolution ΔE_{exp} exceeds D. For the sake of convenience the region under investigation $\sigma(E_o, E'\theta)$ can be divided into two parts: the region of discrete spectra and the region of overlapping levels.

The region of overlapping levels

In the excitation energy region where $\Gamma > D$ the spectrum of inelastic-scattered neutrons is solid (continuous). Normally, this kind of spectrum is observed under experimental conditions if the initial neutron energy exceeds 5-6 MeV. However, in actual fact the spectrum in this energy region is more complex; it consists of a genuinely continuous section and a number of discrete lines corresponding to the excitation of the first lower levels, which have merged into a solid spectrum, not because in their case $\Gamma > D$ but because $\Delta E_{exp} > D$ (ΔE_{exp} being the energy resolution in the experiment). Figure 1 shows the effect of resolution on the observed spectra of inelastic-scattered neutrons of niobium-93 for an initial energy of 14 MeV [1]. In this energy region the angular distributions of inelastic-scattered neutrons are asymmetrical with respect to the angle $\theta = 90^o$ and the greater this asymmetry the greater the energy of these neutrons (see Fig. 2). In the spectra of the inelastic-scattered neutrons in this energy region a contribution of "hard" neutrons may be observed; the better the resolution of the spectrometer, the more marked this contribution.

The "hardness" of the spectrum and the asymmetry of the angular distributions with respect to the angle $\theta = 90^{\circ}$ point to the presence in the spectra of inelastic-scattered neutrons, the mechanism by which they appear being different from the statistical mechanism and even probably unrelated to the formation of the compound nucleus. The determination of this mechanism and its contribution to the general spectrum is very important because, although, as Fig. 2 [2] shows, it is not considerable (only 5 to 15%, depending on the nucleus and the initial neutron energy), if it is disregarded the statistical characteristics of the nucleus can be seriously distorted and false conclusions reached (regarding, in particular, the energy dependence of these characteristics).

In order to explain the observed neutron emission spectra Griffin proposed in 1965 [3] a "statistical model of intermediate structure" (exciton model), which accounted for the great hardness of the spectrum by the fact that some of the neutrons are emitted by the compound nucleus in the process of establishing statistical equilibrium, at which stage the excitation energy is still distributed between the small number of excitons. According to this model, the inelastic scattering cross-section can be presented in the form of two components - equilibrium and pre-equilibrium - as follows:

$$\sigma_{in}(E_o, E') = \sigma_{in}^{equ}(E_o, E') + \sigma_{in}^{pre-equ}(E_o, E') \qquad (1)$$

In later studies [4], which take account of all the possible transitions, the cross-section of this pre-equilibrium component is expressed as follows:

$$\sigma_{in}^{pre-equ}(E_o, E') = \frac{\sigma_{cn}(2S+1)\, m\, \sigma_{inv} \cdot E'}{4\pi^2 \hbar^3 \, \overline{|M|^2} \, g_o^2 \cdot E^{*3}} \sum_{\substack{n=n_o \\ \Delta n=2}}^{\bar{n}} (n^3 - n) \left(\frac{U}{E^*}\right)^{n-2} \qquad (2)$$

where: σ_{cn} is the cross-section for the formation of the compound nucleus,

S is the spin of the incident particle,

m is the mass of the incident particle,

$|M|^2$ is the mean square of the matrix element for the transition from the state with n excitons to a state with (n+2) excitons,

$E^* = E_o+Q$ is the excitation energy of the compound nucleus,

$U = E_o-E'$ is the excitation energy of the residual nucleus,

n_o is the initial number of excited states (excitons),

$\bar{n}$ is the number of excitons in the most probable configuration of the nucleus in a state of statistical equilibrium,

σ_{inv} is the cross-section of the inverse process.

If we designate the combination:

$$\frac{\sigma_{cn}\,(2s+1)\,m\,\sigma_{inv}}{4\pi^2\hbar^3\,\overline{|M|^2}\,g_o^2\,E^{*3}} = A_{\text{pre-equ}} \tag{3}$$

which is possible, since all the values in it are constant for a given initial energy E_o, then

$$\sigma_{in}^{\text{pre-equ}}(E_o,E') = A_{\text{pre-equ}}\cdot E' \sum_{\substack{n_o \\ \Delta n=2}}^{\bar{n}} (n^3-n)\left(\frac{U}{E^*}\right)^{n-2} \tag{4}$$

and Eq. (1) is transformed into (I')

$$\sigma_{in}(E_o,E') = \sigma_{in}^{\text{equ}}(E_o,E') + A_{\text{pre-equ}}\cdot E' \sum_{\substack{n_o \\ \Delta n=2}}^{\bar{n}} (n^3-n)\left(\frac{U}{E^*}\right)^{n-2} \tag{I'}$$

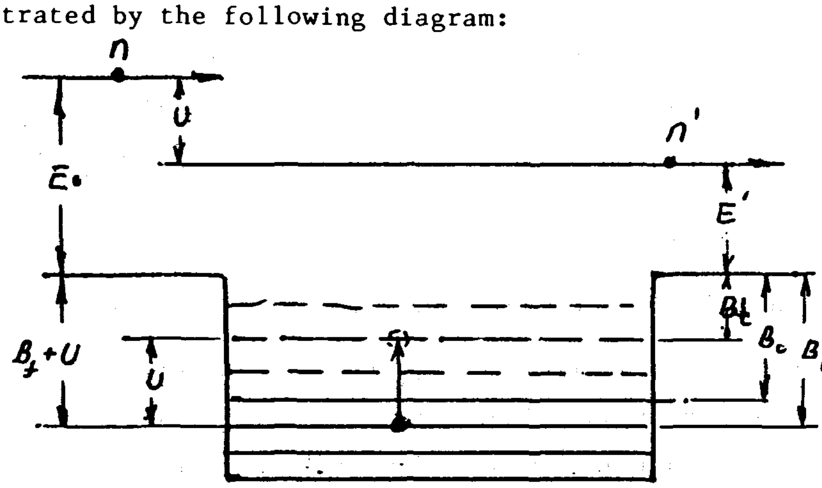
$A_{\text{pre-equ}}$ can be regarded as a normalization coefficient in the process of matching the theoretical cross-section (spectrum) with the experimental one, and its value depends on which expression is used in describing the equilibrium part of the cross-section: a Maxwell distribution ($\sigma_{in}^{\text{equ}} = A^M E' e^{-E/T}$), the Fermi-gas model ($\sigma_{in}^{\text{equ}} = A_{\text{equ}}^{\varphi-r} \frac{E'}{U^{5/4}} e^{2\sqrt{aU}}$ or the Hauser-Feshbach calculation.

Studies were also conducted in which $\sigma_{in}^{\text{pre-equ}}(E_o,E')$ was calculated theoretically without normalization to the experimental data [5]. In actual fact, normalization is implicit in the choice of the optical model for the calculation of σ_{cn} and σ_{inv}.

The exciton model has been widely used in describing the spectra of inelastically scattered neutrons (differential cross-sections) and has given satisfactory results [6]. This model does not, however, describe the angular distributions of inelastic-scattered neutrons. Furthermore, the observed asymmetry in the angular distributions conflicts with the assumptions on which the model is based, namely that the compound nucleus passes through a phase, for which the angular distributions must be symmetrical in relation to the scattering angle $\theta = 90^{\circ}$. This suggests that the exciton model is incomplete and therefore speaks in favour of the application - in conformity with the established laws - of models in which the great hardness of the spectrum and asymmetry of the angular distributions is attributed to a different reaction mechanism, i.e. to a direct mechanism or, in other words, a reaction in which no compound nucleus is formed. One such model was proposed by Luk'yanov, et al. [7,8]. It is postulated in this model that the double-differential cross-section for the inelastic scattering of neutrons can also be expressed as the sum of two components,

$$\sigma_{in}(E_0, E', \theta) = \sigma_{in}^{equ}(E_0, E', \theta) + \sigma_{in}^{direct}(E_0, E', \theta) \qquad (5)$$

the first equilibrium and the second direct. Part of the inelastic scattering of neutrons due to the direct mechanism arises as the result of the interaction of the incident particle with one of the nucleons of the nucleus. This can be illustrated by the following diagram:



where: — — — denotes the vacant levels,

——— the filled levels,

B_o the minimum nucleon binding energy in the unexcited nucleus,

B_i the binding energy of the i nucleon in the nucleus,

B_f the binding energy of the nucleon excited as a result of direct interaction with the particle incident upon it,

E_o the initial energy of the neutron,

E' the energy of the inelastically scattered neutron,

$U = E_o - E'$ the excitation energy of the nucleus,

li,ji the orbital and total momenta of the i-th nucleon (initial state), and lf,jf the orbital and total momenta of the f-th nucleon after interaction.

The contribution of the direct mechanism to the double-differential cross-section for inelastic scattering can be expressed as follows:

$$\sigma_{in}^{direct}(E_0, E', \theta) = \sqrt{\frac{E'}{E_0}}(E_0 - E')\sum_{if} \beta_{if} \frac{n_i(2j_f+1-n_f)}{(2j_i+1)(2j_f+1)}\left[\frac{\sqrt{\beta_i}+\sqrt{\beta_f}}{q_0\sqrt{E_0}} \operatorname{arctg}\frac{q_0\sqrt{E_0}}{\sqrt{\beta_i}+\sqrt{\beta_f}}\right]^2 \times \tag{6}$$
$$\times \sum_L Z^2(l_i j_i\, l_f j_f | \tfrac{1}{2} L)\, j_L^2(q_0 k R_{if})$$

where:

n_i denotes the number of nucleons in the i-th shell;

n_f denotes the number of nucleons in the f-th shell, i.e. the expression $\frac{n_i(2j_f+1-n_f)}{(2j_i+1)(2j_f+1)}$ is the coefficient which takes account of the population of the levels: it is equal to 1 for transitions from a completely filled shell to a completely empty one;

$q_o = \frac{q}{k}$, $q(\theta) = |\vec{k} - \vec{k}'|$ is the value of the pulse transmitted to the nucleus, ($\vec{k}$ being the pulse of the incident neutron and $\vec{k}'$ that of the inelastic-scattered neutron) $q_0 = \sqrt{1 + \frac{E'}{E_0} - 2\sqrt{\frac{E'}{E_0}}\cos\theta}$;

Z_L is the coefficient of the Blatt-Bidenharn vector structure;

j_L is the spherical Bessel function of the order L;

R_{if} and β_{if} are parameters: R_{if} denotes the effective radius of the nucleus for the transition $i \to f$ (the lower limit of integration by the r transition matrix element); β_{if} is the "weight" of the transition $i \to f$ ($o \leq \beta_{if} \leq 1$).

Integrating expression (6) with respect to the angle θ yields the differential cross-section for inelastic scattering produced by the direct mechanism:

$$\sigma_{in}^{direct}(E_0, E') = \gamma \sqrt{\frac{E'}{E_0}}(E_0 - E') \tag{7}$$

Using this method, the authors of Refs [7,8] analysed the double-differential cross-sections for the inelastic scattering of neutrons of chromium, iron, cobalt, nickel and niobium nuclei for initial energies of 14.1 and 9.1 MeV. Figure 3 shows the results obtained. The theoretical value of the direct inelastic scattering cross-section was normalized to the experimental results. Use was made of the fact that

$$\sigma_{in}^{equ}(E_0, E', \theta) = \sigma_{in}^{equ}(E_0, E', \pi-\theta)$$

and therefore

$$\sigma_{in}^{exp}(E_0, E', \theta) - \sigma_{in}^{exp}(E_0, E', \pi-\theta) = \sigma_{in}^{direct}(E_0, E', \theta) - \sigma_{in}^{direct}(E_0, E', \pi-\theta) \qquad (8)$$

whence the normalization coefficient:

$$C = \frac{\sigma_{in}^{exp}(E_0, E', \theta) - \sigma_{in}^{exp}(E_0, E', \pi-\theta)}{\sigma_{in}^{direct(theor)}(E_0, E', \theta) - \sigma_{in}^{direct(theor)}(E_0, E', \pi-\theta)} \qquad (9)$$

The equilibrium part was taken as:

$$\sigma_{in}^{equ}(E_0, E', \theta) = \alpha(E_0, E', \theta) E' e^{-\frac{E}{T}} \qquad (10)$$

It was shown that, once the transition $i \rightarrow f$ is selected, for a specific initial neutron energy, from the excitation energy and angular distribution, this neutron distribution can be predicted for the same excitation energy, but, as Fig. 3 shows, for other initial energies the angular distribution can differ considerably in form from the initial distribution.

In examining the differential cross-sections (spectra) expressions (7) and (10) were applied; in expression (10)

$$\alpha(E_0, E', \theta) \equiv (E_0).$$

In applying expression (7) it was assumed that the first discrete levels had merged into a continuous spectrum, since $\Delta E_{exp} > D$. A similar method of analysis was employed in Ref. [9] for uranium-238 nuclei. The authors showed that physically correct results could be obtained only by calculating the direct part of the cross-section in the form of (7); the level density parameter is close to the resonance parameter and is virtually constant, while the use of other expressions, namely (4) and (11),

$$\sigma_{in}^{direct}(E_0, E') \sim \left(\frac{E'}{E_0}\right)^{1/2}, \quad [\rho(E_0 - E') \simeq Const] \qquad (11)$$

derived in Ref. [10], results in a strong dependence of parameter "a" on E_o (see Fig. 4). The interval over which parameter "a" varies by a factor of approximately 1.5 is 3 MeV, a value comparable with the range of the excitation energies observed in neutron spectra at a given initial neutron energy. If these changes in the parameter "a" are genuine, they should result in a theoretically different scattered neutron spectrum shape (see Fig. 5); this conflicts with the experiment.

Thus, the expressions for double-differential cross-sections and differential cross-sections (spectra) proposed in Ref. [7] give a physically correct picture of the inelastic scattering of neutrons; but the method proposed needs to be normalized to the experimental results, though only for one initial neutron energy. It can be regarded as a method of parametrizing the inelastic neutron scattering cross-sections.

A theoretically based model has been devised for calculating direct processes, which are regarded in the model as collective excitations of a vibrational type in spherical nuclei and of a rotational type in deformed nuclei. For calculation purposes use is often made of the strong channel-binding model or the Born approximation of distorted waves. The results of calculations based on this model more or less agree with the experimental data. In Ref. [11], for instance, the experimental value obtained for the direct inelastic scattering cross-section for ^{113}In nuclei at an initial neutron energy of 5.34 MeV is 194 $\pm$ 12 mb, whereas the theoretical calculation based on the above-mentioned model gave 280 mb. Account should also be taken of the fact that the authors of similar calculations maintain that their data are "absolute", i.e. unrelated to experimental results. However, the process of normalization is implicit through the selection of the parameters of the optical model in such a way that the results are close to the experimental ones. The same applies to the calculated results for the double-differential inelastic scattering cross-sections. In Fig. 6 [12] the calculated and experimental data are compared for the case of inelastic scattering of neutrons with an initial energy of 14.3 MeV in iron-56 nuclei. For the sake of comparison the excitation region of a single-phonon state 3^-(Q = 4.51 MeV, β = 0.28) is taken. Good agreement is observed for angles from 0^o to 90^o only; for angles of 120^o and 150^o the calculated and experimental results differ by one order of magnitude. Consequently, this model also fails, at present, to give a sufficiently precise and complete description of the inelastic scattering of neutrons.

A question arises as to whether it might not be incorrect to assume that the spectrum of inelastic-scattered neutrons is conditioned by extreme circumstances only, i.e. by the emission of neutrons as a result of direct processes and by the nucleus reaching a state of statistical equilibrium. Might closer agreement with the experimental results be perhaps achieved by adding a further extreme factor, namely that of neutrons emitted by the nucleus in the process of attaining statistical equilibrium? Figure 6 shows, however, that nothing can be added since the theoretical curve rises higher than the experimental points. The fact that nothing can be added is also clear from the data for niobium-93 (see Fig. 2). This is not, of course, direct evidence of the absence of a contribution (or a negligibly small one) by pre-equilibrium processes; such evidence would be provided by measuring the emission time for inelastic-scattered neutrons, which unfortunately is at present beyond our capabilities. (It would be necessary to measure times between 10^{-16} and 10^{-22} s.) In the meantime, we are obliged to investigate the reaction mechanism (n,n') on the basis of spectra and angular distributions. In order to elucidate the role played by pre-equilibrium forces in the inelastic scattering of neutrons, a study [11,19] was conducted on both (n,n') and (p,n) reactions in target nuclei yielding the same compound and residual nuclei. Earlier studies along similar lines focused on α-particles and deuterons, but the results obtained were ambiguous both because of the great divergence of the moments introduced into the compound nucleus and because of the divergence in type of the actual particles forming the compound nucleus. In the case of the nucleons (protons and neutrons) these differences are insignificant. Altogether there are four pairs of these stable nuclei. The pair consisting of indium-113 and cadmium-113 was taken:

$$\left.\begin{array}{l} {}^{113}\mathrm{In} + n \\ {}^{113}\mathrm{Cd} + p \end{array}\right\} \rightarrow {}^{114}\mathrm{In}^{*} \rightarrow {}^{113}\mathrm{In}^{*} + n'$$

Initial neutron and proton energies were selected such that the excitation energy of the ^{114}In compound nucleus was the same in both reactions. Figure 7 shows the spectra of neutrons from these reactions for two initial neutron and proton energies. It may be observed that these spectra differ markedly in the hard part and coincide in the low energy region: the hard part of the neutron spectra from the reaction (n,n') is approximately 20 times greater than that from the reaction (p,n). The same marked difference is observed in the angular distributions of the emitted neutrons; it is symmetrical in relation to the angle $\theta = 90^{o}$ for (p,n) reactions and asymmetrical for (n,n') reactions.

Comparison of the two reactions suggests that the reaction (p,n) relates almost entirely (within the experimental limits of accuracy) to the compound nucleus, whereas in the reaction (n,n') a substantial contribution is made by direct processes. The excitation model offers no explanation for such a marked difference in the spectra, whereas the notion of a direct reaction mechanism readily accounts for it: in direct inelastic neutron scattering a change occurs in the energy of the incident neutrons and in the direction in which they are travelling as a result of their interaction with individual nucleons of the nucleus. These nucleons are not knocked out, however, since it would require a far greater transmitted pulse to do so and it is therefore less probable. In this case the small contribution of direct processes to the reaction (p,n) is understandable. The equilibrium components of the spectra, however, are identical for both reactions. They have the same characteristics: for example, the level density obtained in the analysis of neutron spectra from the reaction (p,n) describes perfectly the equilibrium (statistical) component of the inelastic neutron scattering spectrum. Thus, this experiment has once again demonstrated the lack of physical support for the exciton model.

Yet despite the arguments set out above in support of the existence of only two inelastic neutron scattering mechanisms - direct and equilibrium - the possible existence of a pre-equilibrium component (admittedly considerably smaller and "softer" than predicted by the exciton model) cannot be ruled out altogether. In the first place, we have no means of distinguishing between the equilibrium and pre-equilibrium components (especially if the latter is small) since they have the same kind of angular distribution, i.e. they are both symmetrical with respect to the scattering angle $\theta = 90^{o}$). If the contribution of the pre-equilibrium component is small, great spectrum hardness may go unnoticed against the background of a suppressing equilibrium component. Second, it remains unclear why the values of the moments of inertia derived from the analysis of the angular distributions of inelastic-scattered neutrons which have passed through the compound nucleus stage are significantly lower for a number of nuclei than the theoretical values.

Let us consider how the moment of inertia is derived from the experimental data on inelastic neutron scattering. According to the Hauser-Feshbach formalism the double-differential inelastic scattering cross-section can be expressed as follows:

$$\sigma_{in}^{equ}(E_0, E', \theta) = \frac{1}{4 k_0^2} \sum_{KJ} \sum_{\ell j \ell' j'} g(J) \frac{T_{\ell j}(E_0) \sum_{\ell' j' \pi'} T_{\ell' j'}(E') \rho(U', I', \pi')}{\sum_{\ell'' j'' \pi''} \int_0^{U_{max}} T_{\ell'' j''}(E'') \rho(U'', I'', \pi'')} \times \tag{12}$$

$$\times B_K(\ell, s, j, I_0, J) B_K(\ell', s', j', I', J) \times P_K(\cos\theta)$$

where:

I_o is the target nucleus spin;

J is the compound nucleus spin;

$g(J)$ is the level density of the compound nucleus with spin;

B_k is the combination of the Cline-Gordon coefficient and the Wigner symbol;

$p(u, I, \pi)$ is the level density with spin I and parity Π; and

$P_k(\text{Cos}\ \theta)$ is a Legendre polynomial of the order K.

The level density is obtained by applying notions related to the model. More often than not the degenerate Fermi-gas model is applied, but the effects characteristic of an actual nucleus (shell structure in single-particle state spectra, the presence of nucleonic pair interaction) are accounted for by variations of the model parameters. In this case the density of the excited levels of the nuclei is expressed as follows:

$$\rho(U, I) = \frac{\sqrt{\pi}}{24} \frac{\exp[2\sqrt{a(U-\Delta)}]}{\sigma a^{1/4} (U-\Delta)^{5/4}} \cdot \frac{(2I+1)}{2\sqrt{2\pi}\,\sigma^2} \exp\left[-\frac{(I+\frac{1}{2})}{2\sigma^2}\right] \tag{13}$$

where:

a is the parameter of level density energy dependence;

Δ is the effective excitation energy displacement; and

σ is the parameter of level density spin dependence.

In the Fermi-gas model the spin dependence parameter is related to the moment of inertia of the nucleus by the following dependence:

$$\sigma^2(U) = \mathcal{F} \cdot t = 0{,}00957 \cdot \eta \sqrt{\frac{U-\Delta}{a}}\, r_0\, A^{1/3} \tag{14}$$

where:

$\mathcal{F}$ is the moment of inertia of the nucleus;

t is the thermodynamic temperature; and

$\eta = \frac{\mathcal{F}}{\mathcal{F}_0}$ is the ratio of the moment of inertia of the nucleus to the solid-body moment (the moment of inertia of a solid sphere with $R = r_0 A^{1/3}$).

If the experimental angular distribution is then expanded with respect to the Legendre polynomial as follows, for example:

$$\int_{\Delta E' = 1\,\mathrm{MeV}} \sigma(E_0, E', \theta)\, dE' = \frac{1}{4\pi} \sum_{k=0}^{3} b_k^{exp} \cdot P_k(\cos\theta) \tag{15}$$

and if the ratio $(b_2/b_0)^{exp}$ indicating the degree of anisotropy is then established and compared with the ratio $(b_2/b_0)^{theor}$, calculated by means of Eq. (12) by varying the value η in (14) to the point where $(b_2/b_0)^{exp} = (b_2/b_0)^{theor}$, then the agreement of the results will mean that we find η, i.e. $\mathcal{F}$. Figure 8 [14] shows the results of this determination of $\mathcal{F}$, or $\mathcal{F}/\mathcal{F}_0$.

Analysis of the Hauser-Feshbach formula shows that the anisotropy of angular distributions is determined by the relationship $\frac{\langle J^2\rangle\langle j^2\rangle}{\sigma^4}$ [15], i.e. the stronger the anisotropy, the smaller the moment of inertia. The anomalously small moments of inertia obtained from analysing inelastic scattering data may either mean that our ideas about the moments of inertia of excited nuclei are inaccurate (we will not be discussing this question here) or else point to the contribution of non-equilibrium processes to those inelastically scattered neutrons regarded in the analysis as emitted nuclei in a state of statistical equilibrium. According to Ref. [16], this contribution must have increased anisotropy of angular distribution and its presence can bring about an apparent decrease in the moment of inertia. If this point of view is adopted it provides a means of evaluating the contribution of this pre-equilibrium component:

the discrepancy between the experimental anisotropy and the theoretically calculated value (with the moment of inertia derived from the theory) must give the contribution of this pre-equilibrium component. Preliminary calculations showed that if the entire anisotropy observed in Ref. [14] is attributed to the pre-equilibrium component, the equilibrium component being considered isotropic, then its contribution is approximately 5%. This approach does not account, however, for the large moments of inertia observed for a number of nuclei where no assumptions whatsoever are made regarding the pre-equilibrium component.

The discrete level region

This region covers an excitation energy interval from several dozen keV for heavy (mainly fissionable) nuclei to 2-4 MeV for light nuclei. The energy interval of this region is often determined from the initial neutron energy, which also determines the range of possible excitation energies, rather than in relation to the excitation energy. In this region all the information concerning the inelastic scattering of neutrons is contained in the excitation functions of individual levels, such functions also being the subject of experimental and theoretical study.

Thanks to the substantial improvement in energy resolution in both neutron measurements and, more particularly, the recording of inelastic scattering γ-beams (hundreds of eV), the fine structure of the excitation function has now emerged (see Fig. 9). This fine structure is a manifestation of the fluctuation of the compound nucleus level density (in some cases, however, it is simply a manifestation of individual levels). Unfortunately, it cannot as yet be predicted or analysed because of the problems inherent in the identification of such states. Analysis of excitation functions has so far remained on the level of the Hauser-Feshbach formalism, although much has been done to elucidate the nature of excited levels. The elucidation of fine structure is of great importance for practical matters such as shielding; the application of averaged cross-sections can give rise to serious errors in such calculations.

The authors of various recent studies [17] claim that even in this region of excitation energy direct processes have a part to play in the inelastic scattering of neutrons. However, the only evidence they adduce to support their claim is circumstantial; neither angular distributions nor spectral shape can be applied in this case in order to identify the reaction mechanism (n,n'). The claim is based on the fact that the experimentally measured cross-section exceeds the calculated cross-section by 20-30% when all the possible parameters of the optical model are used. Thus, there have been published recently studies which question the mechanism of inelastic scattering in this seemingly well-researched energy region.

In conclusion, despite the fact that certain problems have been resolved, one particular instance being the determination of the significant role played by direct processes in the inelastic scattering of neutrons, there are enough unresolved questions remaining to keep the experimental physicists and theoreticians occupied.

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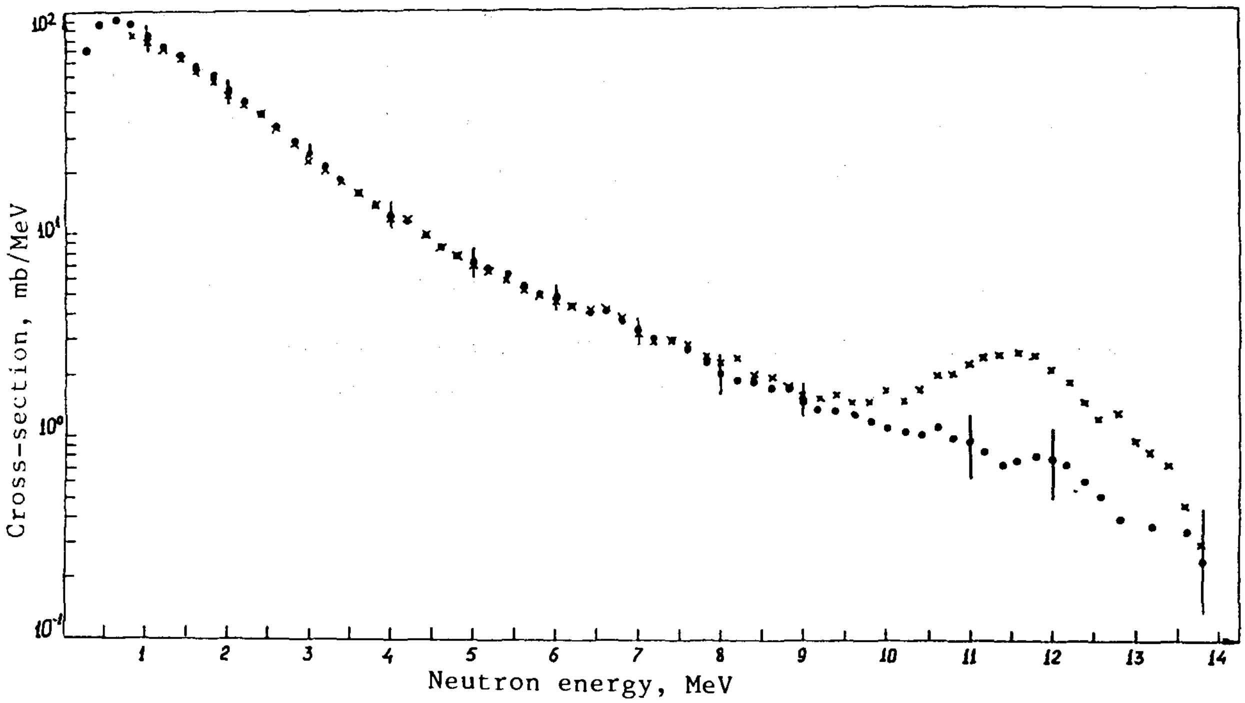

Fig. 1. Spectrum of neutrons emitted from niobium-93 nuclei. Initial neutron energy 14 MeV [1].

● - Path length 2 metres

x - Path length 7 metres

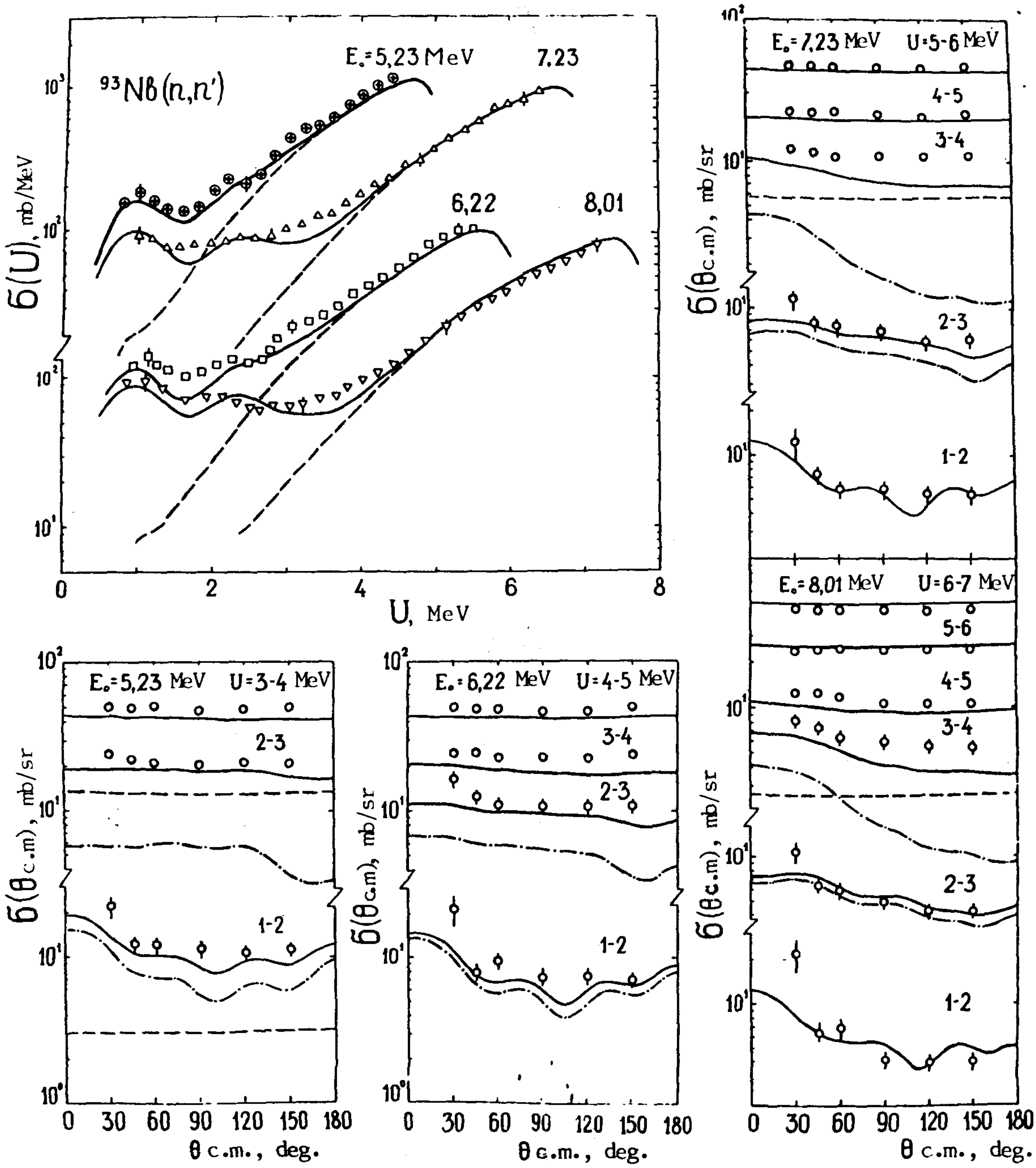

Fig. 2. Angular distributions of inelastic-scattered neutrons in niobium-93 [2]. Initial energies: 5.34 MeV; 6.22 MeV; 7.23 MeV; 8.01 MeV.

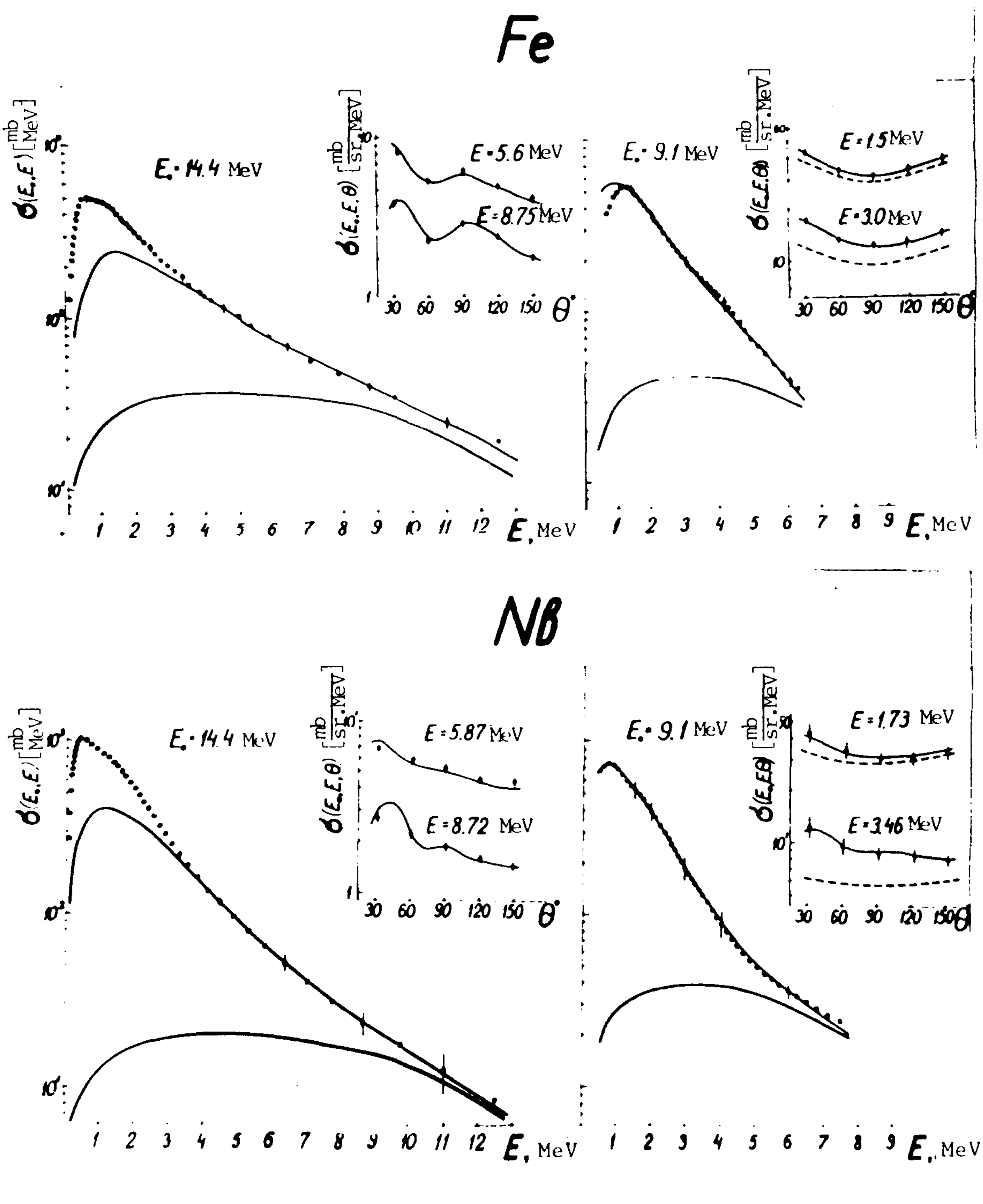

Fig. 3. Analysis of the neutron emission spectra and angular distributions of inelastic-scattered neutrons from iron and niobium nuclei for initial energies of 9.1 MeV and 14.4 MeV [8].

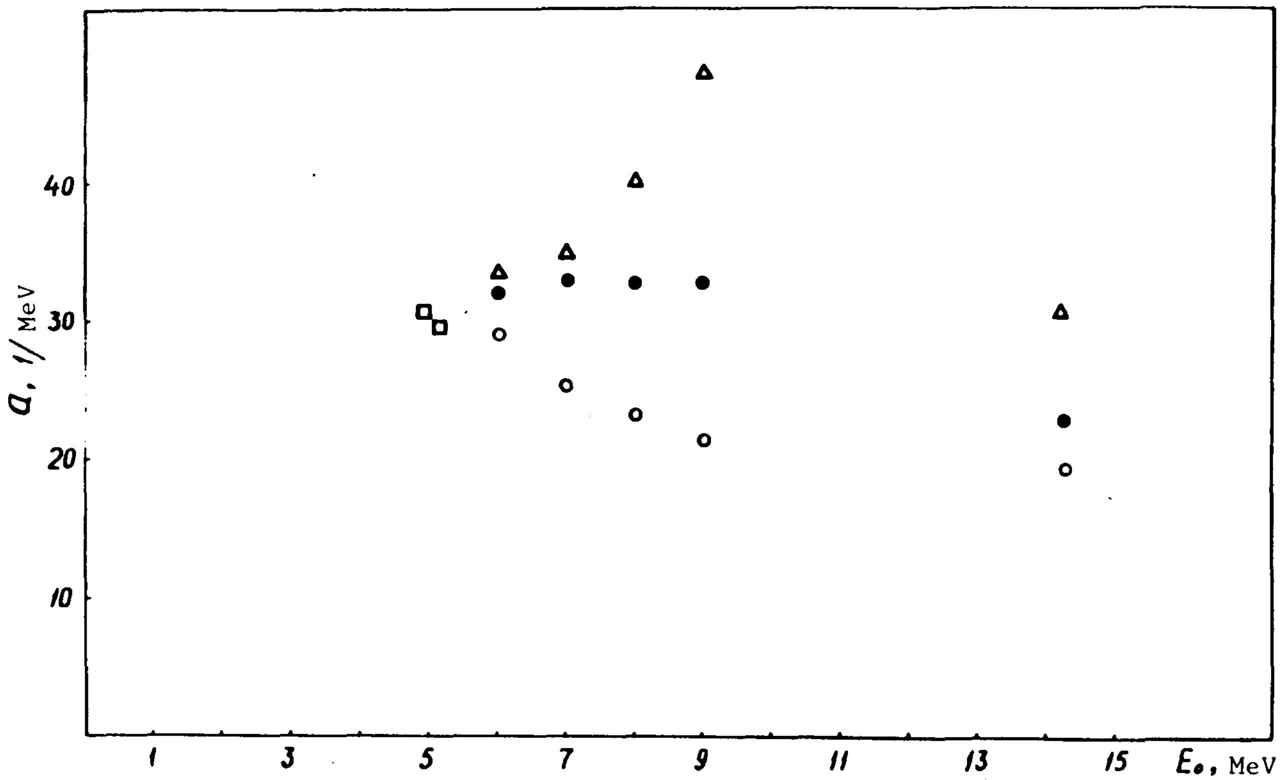

Fig. 4. Dependence of the nuclear level density parameter "a" on initial neutron energy [9].

Δ - exciton model [3,4]

● - according to Refs [7,8]

o - according to the notions set forth in Ref. [10]

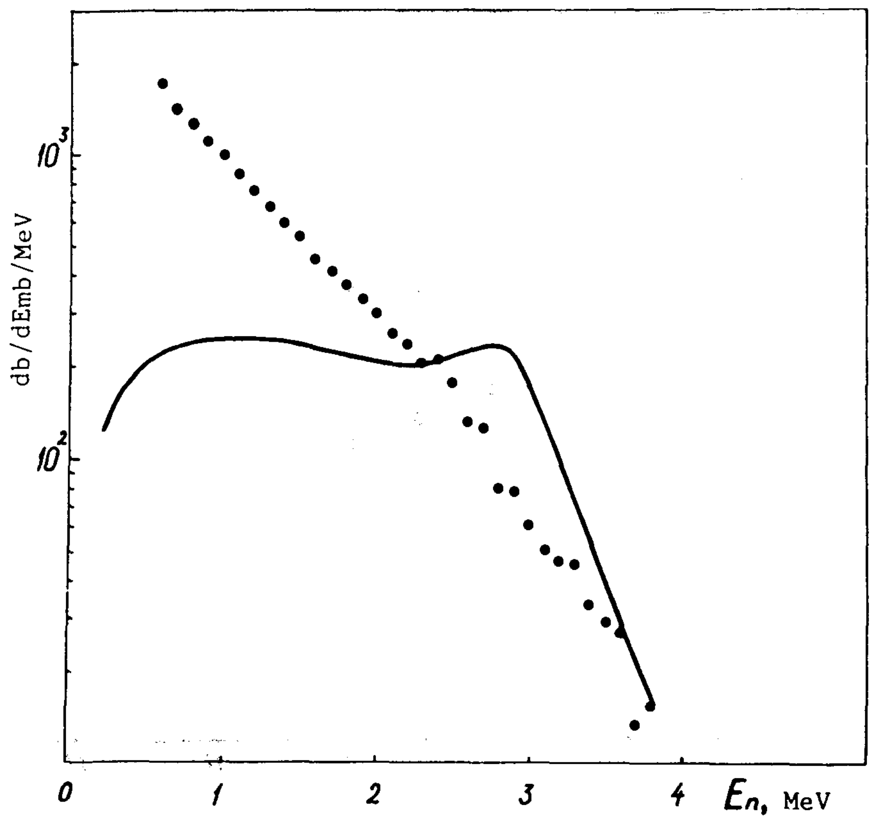

Fig. 5. —— The neutron spectrum taking account of the contribution of direct processes in accordance with Ref. [10].

● The observed spectrum.

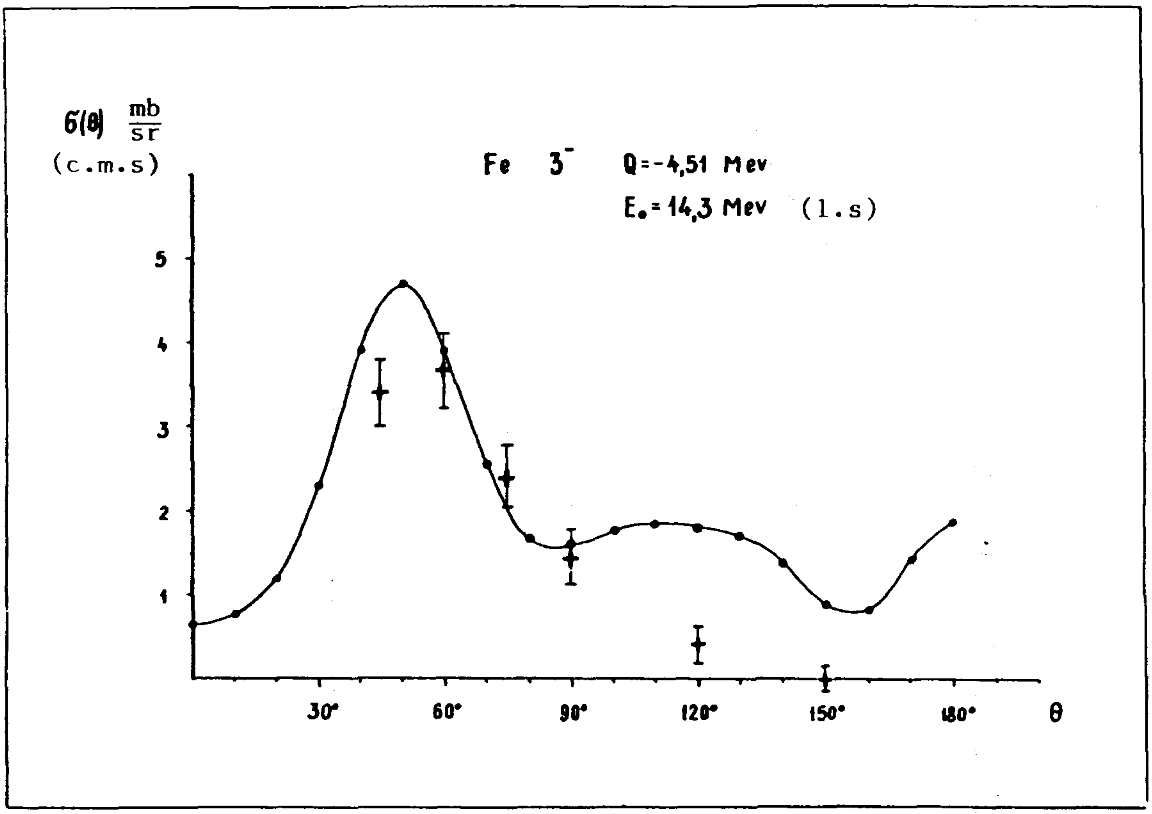

Fig. 6. Angular distributions of inelastically scattered neutrons with excitation of the level 3^- in iron-56 for an initial neutron energy of 14.3 MeV [12].

—●— Theoretical calculation

\+ Experiment

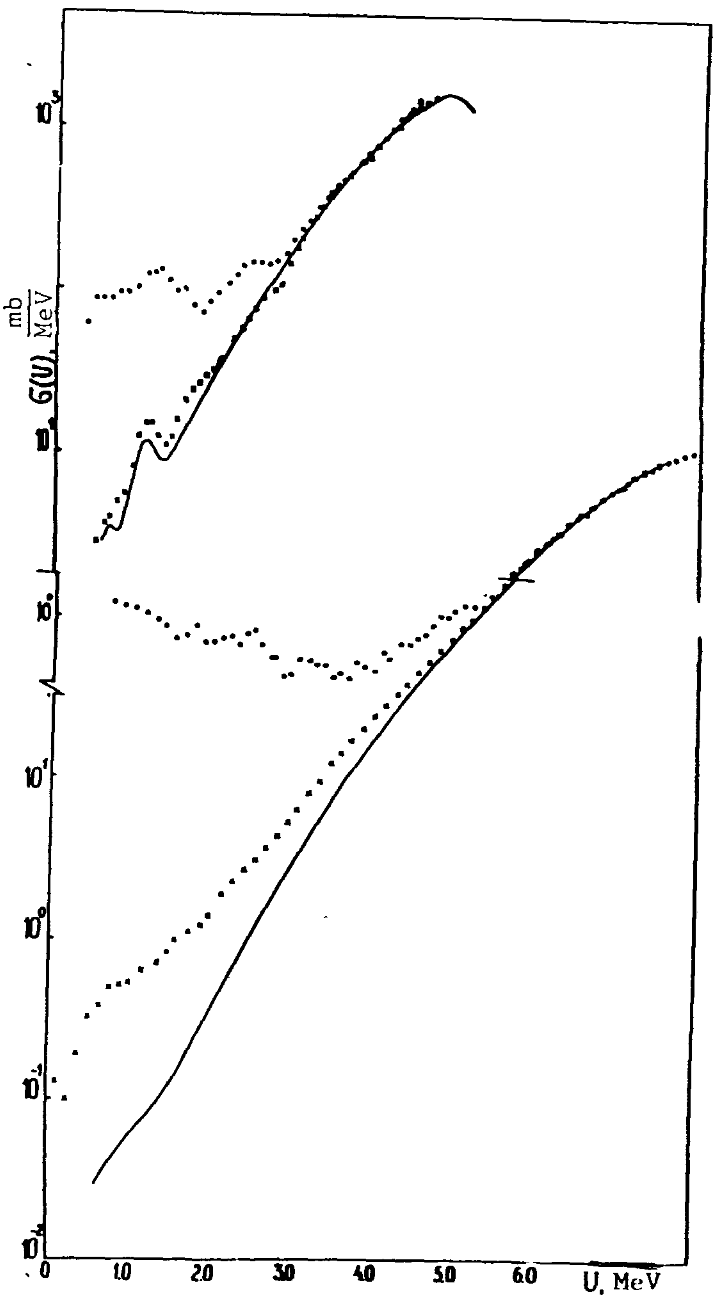

Fig. 7. Neutron spectra from the reactions $^{113}In(n,n')^{113}In$ and $^{113}Cd(p,n)^{113}In$ for two initial neutron and proton energies [11,19].

o - From the reaction $^{113}In(n,n')^{113}In$

x - From the reaction $^{113}Cd(p,n)^{113}In$

— - Theoretical calculation according to Hauser-Feshbach

Upper curves - E_{n_o} = 5.34 MeV, E_{p_o} = 6 MeV

Lower curves - E_{n_o} = 8.53 MeV, E_{p_o} = 9 MeV

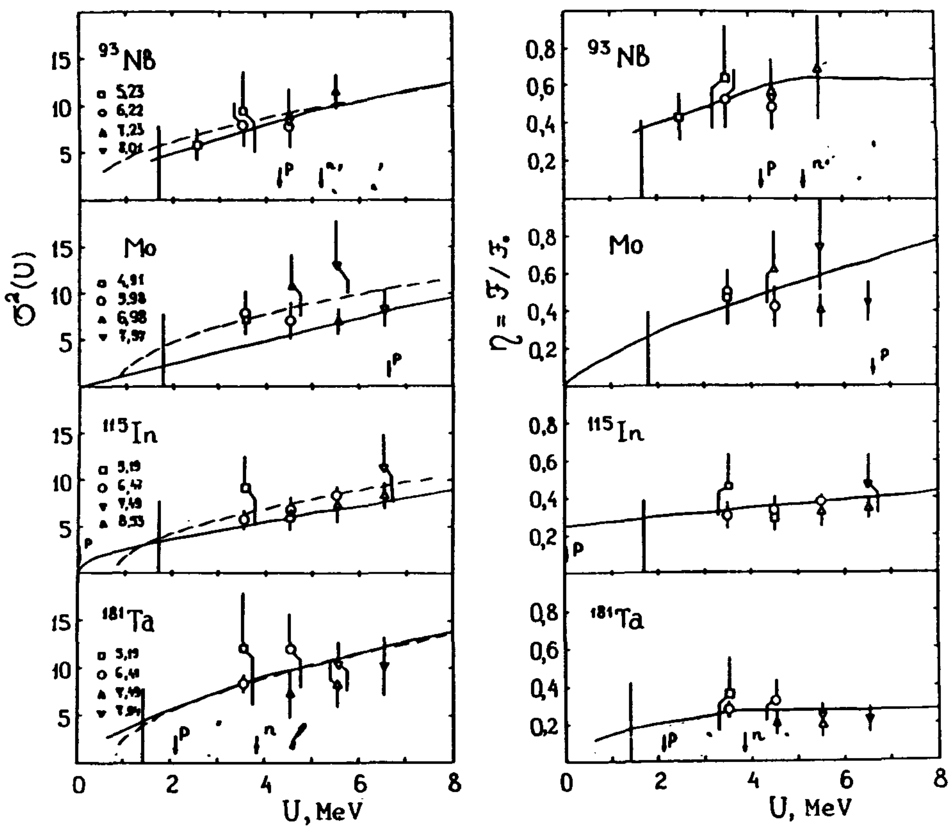

Fig. 8. The value of the level density spin dependence parameter σ^2 and the ratio of the real nucleus moment of inertia to the solid-body moment of inertia [14].

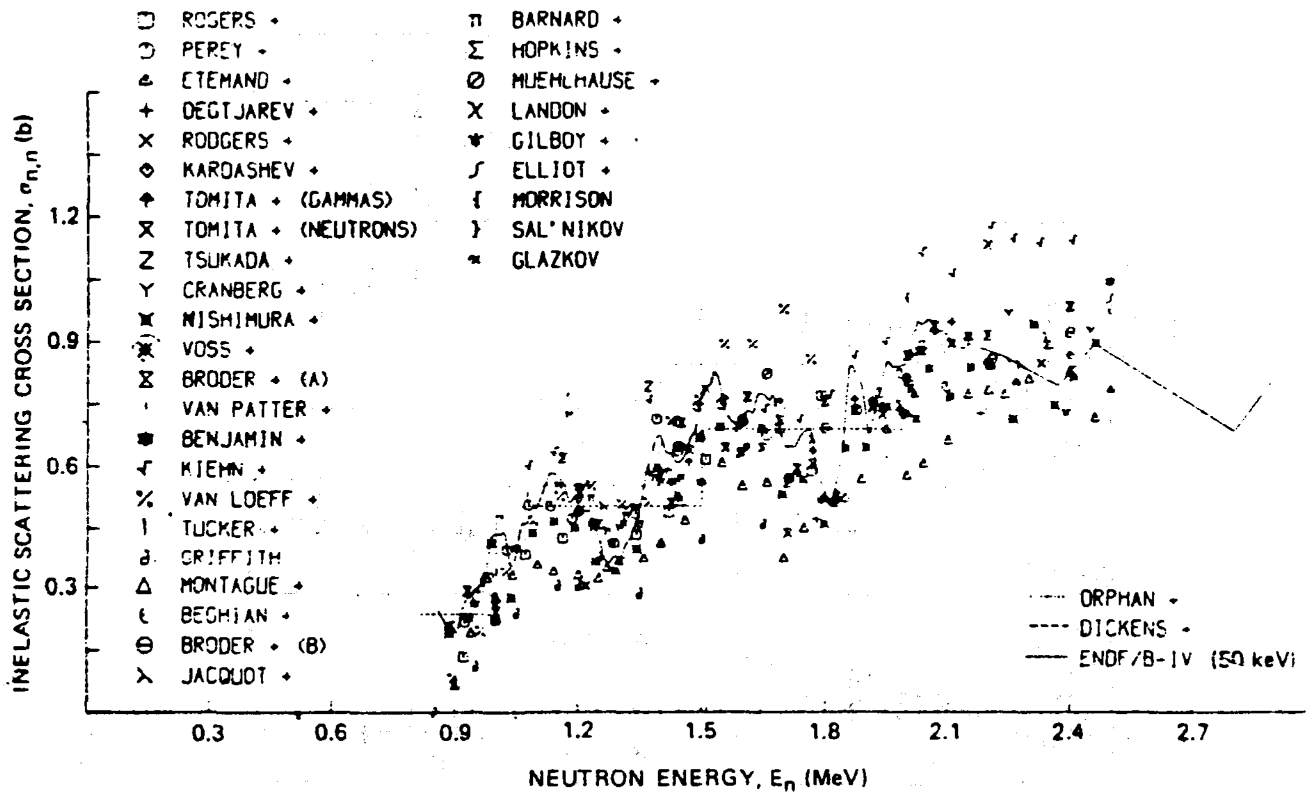

Fig. 9. Excitation level function Q = -846 MeV for iron-56 [18].