acta phys. slov. 25 (1975), No. 2—3

PERSPECTIVES IN NUCLEAR-STRUCTURE INVESTIGATIONS WITH FAST NEUTRONS[1]

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Fields of nuclear-structure investigation with fast neutrons which hold some promise are reviewed. The reviewing is based on both the papers presented at the Smolenice meeting and a survey of recent literature. The following fields are discussed: the cluster structure of light nuclei, the reaction mechanisms of fast neutron reactions and the structure of resonances near the particle-emission threshold.

It was quite fortunate that the late count Pálffy built this castle, foreseeing that many years later scientific workers — vedecki pracovniki — will use it for their symposia. So, here we are, in this beautiful place, discussing fast-neutron physics, its present, past and future. And I have the pleasure to summarize this meeting and single out the main lines of the discussion.

Let me first tell that this Conference has been a pleasant surprise from the very beginning. As everybody knows, it is more difficult to do physics with fast neutrons than with charged particles. Moreover, neutron results are likely to be inferior. Thus the field of nuclear physics studies with fast neutrons is neither a promissing nor a growing field. It is, nevertheless, true that considerable activity has been going on in this field for many years (see, e. g., Ref. [1]). This fact calls for circumstantial and physical explanations. We shall skip the obvious first category — fast-neutron physics being the poor man's choice in a world of riches — and find a more noble explanation in the physical characteristics of neutron reactions. This is above all the fact that neutrons are the only nuclear particles (nucleons and nuclei) that can penetrate the atomic nucleus with an essentially zero kinetic energy. Thus, the exceedingly important field of the investigation of resonances, in particular of those just above the particle-emission threshold, is very much a *chasse gardée* of neutron physics.

This survey, however, will be dedicated more to nuclear-spectroscopy investigations *other than* slow neutron-capture resonance phenomena. The question then arises: What are these other fields of investigation, are they worth the effort and, if so, what information can they give us? The question of the uniqueness of the information obtained (that is, whether the same information could be obtained by other and, perhaps, easier means) should also be asked from time to time.

This Conference has provided us with answers to some of these questions. Summarizing it, I shall not, however, give a complete review of the present status of fast-neutron physics. I shall rather comment on the subjects which were discussed at this Conference as well as those where open problems make active investigation still possible and hold some promise. Extensive surveys of fast-neutron reaction studies are available in the literature (see., e. g., Ref. [2] and references therein) and the editors of CINDA have done an admirable job in listing the available literature in the field. The general scheme which we have thus adopted will bear on which the scheme of the survey; which may appear to be rather fragmentary. If so, nature is to blame.

A glance at recent publications in nuclear-structure studies with fast neutrons can give a rough idea of what topics were preferred by nuclear physicists working in the field. Table 1 shows a survey of 20 papers published in „Nuclear Physics“ in 1972 and 1973. The topics are subdivided in a rather arbitrary way. A striking feature is the virtual absence of spectroscopy via direct-reaction studies. On the other hand, states in the continuum of nuclei located up to several MeV above the particle-emission threshold are studied mostly by neutron scattering and absorption.

The variety of subjects studied with fast neutrons is quite understandable. Fast-neutron physics is not a field for itself. Fast neutrons are a way to excite

Table 1

Topics investigated by fast-neutron physicists in 1972 and 1973 sample of 20 papers. The number of contributions to this Conference on the same topic is given in parentheses.

Topics	Number of articles
— preequilibrium studies	2 (2)
— optical-model studies	2 (2)
— properties of unbound states	6 (2)
— systematics of cross sections and isometric ratios other than $(n, 2n)$	4 (1)
— the $(n, 2n)$ mechanism	2 (3)
— classical spectroscopy: (n, n') etc.	2 (1)
— others	2 (3)
total	20

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[1] Summary talk given at the International Symposium on Neutron Induced Reactions, September 2—6, 1974 at SMOLENICE, Czechoslovakia.

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the nucleus. The specificity of this entrance channel, however, restricts the possible areas of investigation, thus giving the field more coherence than, say, to physics with 10-MeV protons. Thus, I shall now tell the story of the International Symposium on Fast-Neutron Induced Reactions in Smolenice as seen and heard by an attentive listener.* The chapters of the story are what I believe to be the *grandes lignes* of the discussions at the Conference.

I. THE CLUSTER STRUCTURE OF LIGHT NUCLEI

This was a long time favourite topic of fast-neutron physicists. Nowadays, with energetic proton beams easily available, the interest has faded. Nevertheless, some work in this field is still going on. A long-standing problem tackled is the structure of nuclei in the p and lower $s-d$ shells. Suitable reactions, such as $^{16}O(n, \alpha)\ ^{13}C$ and $^{12}C(n, \alpha)\ ^{9}Be$, have been extensively studied. Less so the reactions on less convenient targets, such as ^{14}N or higher mass nuclei.

The idea of extracting structure information from such reactions is tied to the reaction mechanism, which, in turn, reflects the structure model used. Let us take as an example the $^{14}N(n, \alpha_0)\ ^{11}B$ reaction studied by Maxson et al. [3]. We start with postulating two possible reaction mechanisms, each implying a certain configuration for the ^{14}N nucleus (Fig. 1). In the ^{3}He pick-up interpretation of the $^{14}N(n, \alpha_0)\ ^{11}B$ reaction it is assumed that the ^{14}N target ($J^\pi = 1^+$) contains a configuration of a ^{3}He nucleus ($1/2^+$) coupled to a ^{11}B core in its $3/2^-$ ground state with an orbital angular momentum $l = 1$. The incident neutron ($1/2^+$) picks up the ^{3}He particle and couples on to it with $l = 0$ to form the emergent alpha particle (0^+). A second, alternative mechanism is the exchange or heavy-particle stripping reaction. Here the ^{14}N configuration should be supposed to consist of an alpha particle coupled to ^{10}B in its 3^+ ground state with $l = 2$. The ^{10}B core is stripped away from the pre-existing alpha and becomes attached to the incident neutron with the relative angular momentum $l = 1$, thereby forming the residual ^{11}B nucleus. In view of the lightness of the nuclei involved and, in particular, considering the fact that only the shape of the angular distribution is fitted, we can try to use a simple *PWBA* calculation. Such a calculation permits to include both mentioned mechanisms by varying the ratio Λ_1/Λ_2, where Λ_1 and Λ_2 are the products of the spectroscopic factors S for the various particles taking part in the reaction [4]. For the pick-up process:

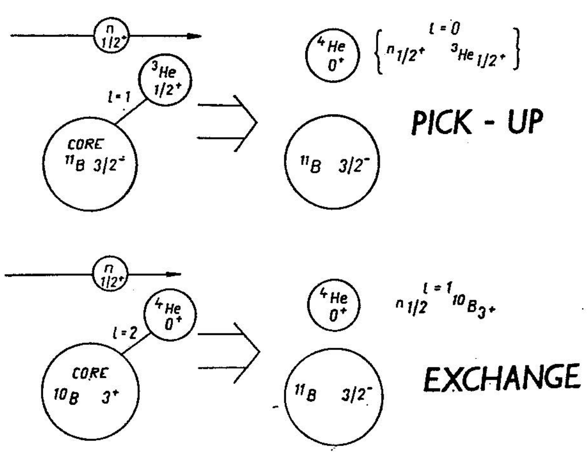

Fig. 1. The pick-up and exchange processes in the $^{14}N(n, \alpha_0)$ reaction (Ref. [3]).

$$\Lambda_1 = S(^{3}He)S(^{11}B)$$

and for the exchange process:

$$\Lambda_2 = S(^{10}B)S(\alpha).$$

The three curves of Fig. 2 fitting the angular distribution of $^{14}N(n, \alpha_0)\ ^{11}B$ give the results of various combinations of these processes. Curve A is a pure pick-up. Curves B and C are mixtures of pick-up and exchange processes (with a preponderance of the pick-up process), the difference being in the sign of the interference term between the two transition amplitudes (pick-up and exchange).

What is the value of the information obtained in such a way? In the above example it is rather qualitative. Almost any direct-reaction mechanism will fit the forward rise in angular distributions of, e. g., (n, α) reactions. In fact, even Hauser-Feshbach calculations, properly parametrized, could do so. Thus, the first conclusion that can be drawn is the presence of exchange processes, with its implication on the structure of ^{14}N.

Thus, it appears that data on backward angles are crucial for any conclusion on the reaction mechanism. The work presented by I. Turkiewicz [5] at this Symposium shows the angular distributions for the $^{9}Be + n \rightarrow {}^{4}He + {}^{6}He$ reaction from 0°—180°. (Fig. 3). The measured angular distributions do not appreciably vary with energy. Thus, the mechanism is likely to be direct. The dotted curves represent the results of pick-up + exchange (heavy particle stripping) calculations along the lines of Ref. [4], with the exchange contribution being preponderant. This implies a cluster structure of ^{9}Be in

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* The reader is also referred to an article by the author „*Selected Topics in Nuclear-Structure Investigations with Fast Neutrons*", Proc. 2nd Int. School of Neutron Physics, Alushta (The Crimea), 1974. JINR Dubna Report, D3-7991.

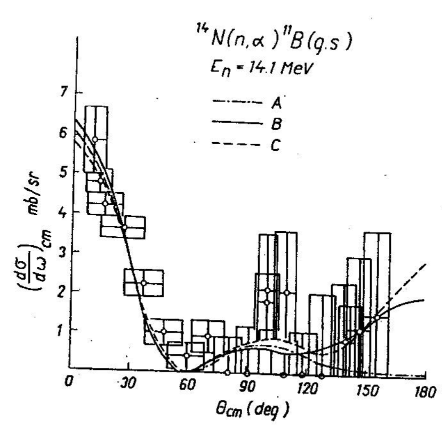


Fig. 2. Experimental and theoretical angular distributions for the $^{14}N(n, \alpha_0)\ ^{11}B$ ground state reaction. Curve *A*: pick-up only; curves *B* and *C*: *PWBA* for a mixture of pick-up and exchange reactions (Ref. [3]).

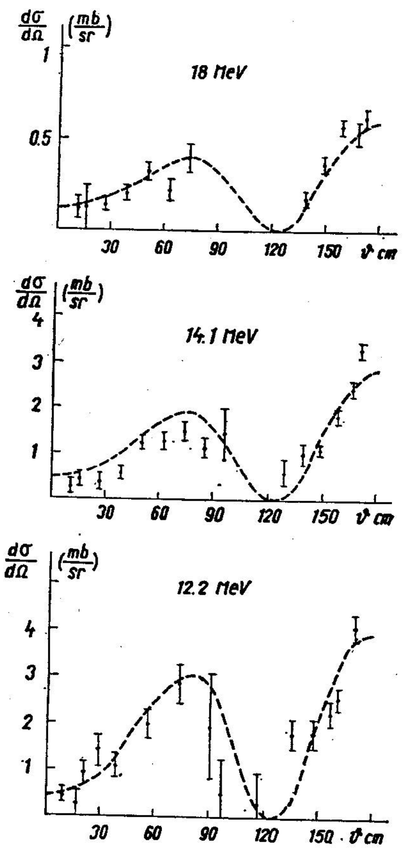


Fig. 3. Angular distributions of alpha particles from the $^9Be\ (n, \alpha)\ ^6Li$ reaction at 12.2, 14.1, and 18.0 MeV neutron energies. The dashed lines are the *PWBA* calculations based ob Ref. [4] (Ref. [5]).

terms of $^4He + ^5He$, where the ^4He part would be responsible for the strong backward peak. It would, however, be important to make sure that no other model calculation fits the angular distributions.

II. REACTION MECHANISMS

II. 1. The preequilibrium process

Many contributions to this Conference were dedicated to the preequilibrium theories of nuclear reactions. As this is a subject by itself, I shall not discuss the excellent review talks presented by Kalbach, Reif and others on this subject, but will only touch the problems that deal directly with fast-neutron reactions. Fast neutron induced reactions are, in fact, examples par excellence where one needs a mechanism different from both the direct and the compound nucleus formation.

In his contribution to this Conference Gadioli [6] showed that fitting 74 (n, p) total cross sections at 14 MeV, the Milan group had obtained a unique set of mass-independent $2p - 1h$ decay rates

$$w^3_{eq} \approx 0.4 \times 10^{-22}\ s^{-1}$$

at an excitation energy of $\sim$20 MeV. The values of w^3_{eq} did not vary from nucleus to nucleus and were in excellent agreement with the values obtained from analyzing the (p, n) reactions. It is always nice when cross-checking of a model gives satisfactory results.

The difficulties with the model start with the (n, α) reactions and with the emission of complex particles in general. As this was one of the main controversial topics at this Conference, we shall discuss it in more detail.

II. 2. The (n, α) reaction mechanism: excitation of single-neutron states and emission of complex particles

The controversy is here centred around the so-called preformation factor of complex particles in nuclei: Do complex structures exist in a prefabricated state in excited nuclei? If so, what kind of states are excited in nuclei by the emission of a complex particle? For (n, α) reactions this subject was introduced by the Warsaw group [7] several years ago and has since received much attention. A survey of the earlier results is given in Ref. [8]. The history of the method is the following. In 1968 Jaskoła et al. [7] noticed a similarity in structure between the $^{156}Tb(n, \alpha)\ ^{159}Eu$ spectrumand the single-neutron level density of ^{156}Eu. To explain this, they assumed that the knock-out mechanism, proceeding by the ejection of an alpha cluster from the surface necessarily implies the capture of a neutron by the remaining core which is usually unperturbed. The neutron fills up the single-neutron states of the core. Accordingly, the alpha energy spectrum should predominantely show the excitation of single-neutron states in the final nucleus. Of course, it is reasonable to expect the same mechanism for the (p, α) and the (n, α) reactions in the corresponding energy and mass regions.

Structure in the energy spectra of the emitted alpha particles was indeed observed in a number of (n, α) measurements on nuclei throughout the periodic table. An example is shown in Fig. 4, which shows a comparison of the $^{93}Nb(n, \alpha)\ ^{90}Y$ spectrum at 0° with levels in ^{90}Y excited by the (d, p) reaction on ^{89}Y.

The first obvious conclusion that can be drawn from this and similar comparisons is the alleged presence of alpha clusters on the nuclear surface. Of course, the example of the ^{93}Nb(n, α) ^{90}Y reaction is a very special one: the target nucleus $^{93}_{41}$Nb$_{52}$ is near a closed shell and single-particle aspects may be particularly visible. In fact, the comparison for (n, α) reactions on other nuclei is less striking.

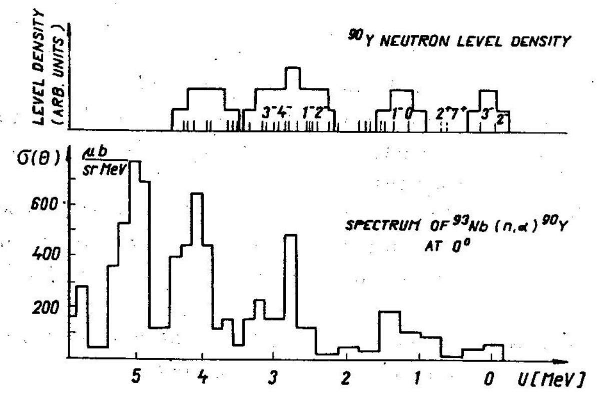


Fig. 4. The ^{93}Nb(n, α) ^{90}Y spectrum at 0° (lower figure) and the levels in ^{90}Y excited by the (d, p) reaction on ^{89}Y (upper curve) (Ref. [8]).

There are, however, two additional arguments that speak in favour of this picture and are related to the non-equilibrium aspects of the reaction mechanism. The first is the fact that the spectra of (n, α) reactions in this energy and mass range were successfully fitted by the Griffin version of the preequilibrium model with essentially only the first term ($n_0 = 3$) contributing [9]. This was interpreted in terms of the incident neutron exciting an alpha particle and creating an alpha hole; hence a three-exciton process. In addition, Colli and Marcazzan [10] fitted the absolute cross sections of (n, α) reactions by using a parameter Φ giving the probability for a neutron striking a prefabricated alpha cluster and ejecting it. The obtained values of Φ of the order of 10^{-1} (Fig. 5), were then used to calculate the alpha-decay probabilities of radioactive nuclei and reasonable fits were obtained. Thus a picture treating the behaviour of alpha particles as entities in the nucleus seemed feasible.

A second argument in favour of such an approach are the recent results of the Warsaw group [11], who have refined the qualitative arguments outlined before by the use of the Shapiro dispersion theory. They have calculated the contribution of the knock-out process (a triangular Feynman diagram in their calculation) and obtained very reasonable fits of the experimental data (Fig. 6).

What do these results mean in terms of structural information? A direct interaction excites by definition a small number of degrees of freedom. Thus, a removal of a group of nucleons becomes feasible. *In contrario*, the excitation of many degrees of freedom would mean sharing the energy among many nucleons and the probability of „group emission“ would be negligible.

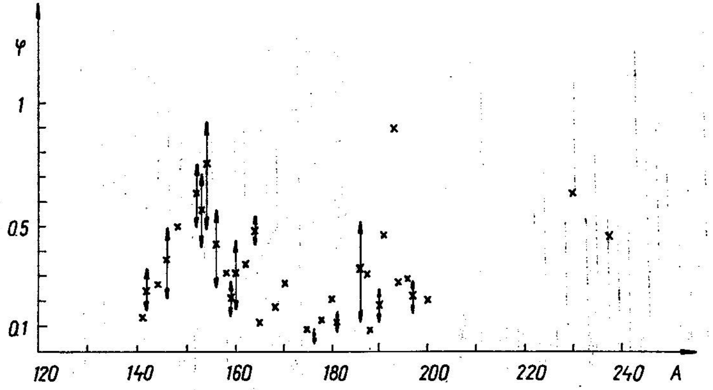


Fig. 5. The value of the „preformation“ parameter Φ shown as a function of the nuclear mass A (Ref. [10]).

The next question is: Are these groups or clusters already present in the nucleus (prefabricated) or are they created by some short-range interaction among nucleons at the moment of the reaction? The question is quite crucial and the results do not allow an unambigious answer.

A relatively new approach to this problem was undertaken by the Bratislava group [12]. The difference between this approach and the preformation approaches is that Ref. [12] does not consider the probability for the creation of an alpha cluster. Rather, as for one single nucleon, they consider the probability that four nucleons together have the right range of the alpha-emission energy. This does not make four nucleons an alpha cluster. This just gives all configurations of 2 protons and 2 neutrons with the right energy of emission of an alpha particle. In order to qualify for an alpha cluster, the four nucleons have to fulfil other conditions. These conditions are expressed by a normalizing factor the meaning of which is physically different from that of the classical preformation factor.

I have no specific suggestion to offer for the solution of this problem except the perennial „more experimental and theoretical investigations are necessary“.

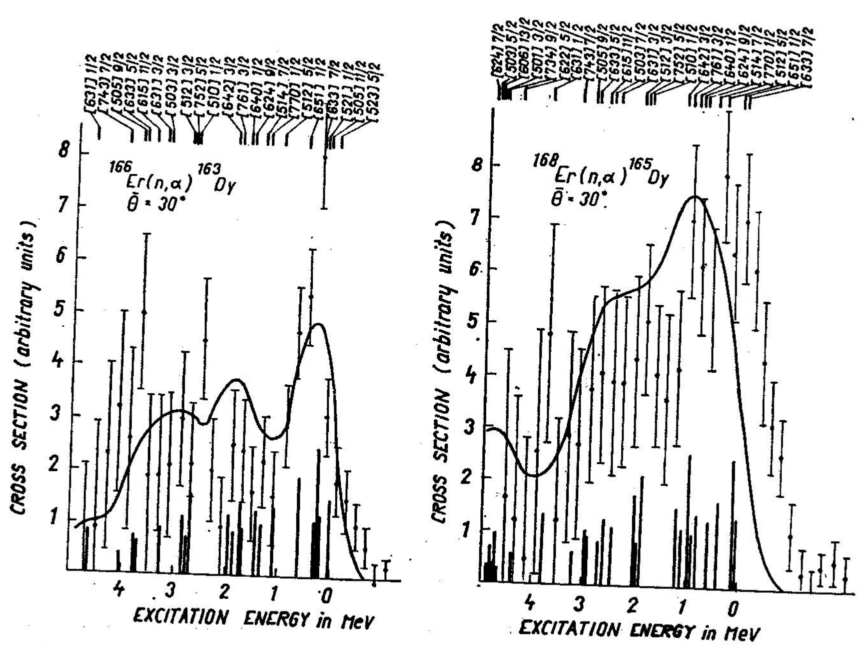


Fig. 6. Spectra of the ^{166}Er(n, α) ^{163}Dy and ^{168}Er(n, α) ^{165}Dy reactions and calculations using the Shapiro dispersion theory with a triangular diagram (knock-out). The vertical lines on the abscissa mean the position and strength of the singleneutron states in the final nucleus. The asymptotic quantum numbers of the Nilsson state are indicated above (Ref. [11])

III. STRUCTURE EFFECTS IN $(n, 2n)$ REACTIONS

The $(n, 2n)$ reaction appears to be the most innocuous of all neutron-induced reactions. In fact, even the ancient closed-form equations given in Blatt-Weisskopf's book fitted more than qualitatively the experimental data for a variety of nuclei and energies. Yet, there has been considerable controversy in the last years as to the existence of structural effects that could cause deviations from the crude compound-nucleus predictions. We shall list and briefly discuss some of them.

III. 1. The Csikai-Petö effect and shell-structure effects

In 1966 Csikai and Petö observed that the $(n, 2n)$ cross sections for a constant bombarding energy minus the $(n, 2n)$ threshold-energy difference $\{E_n - E_{th}(n, 2n)\}$ fall on straight lines when plotted against the neutron excess [13]. This relationship can be expressed by a simple linear dependence

$$\sigma(n, 2n) = k(N - Z) \quad (\text{for constant } E_n - E_{th}(n, 2n)), \tag{1}$$

where k is a constant irrespective of Z being odd or even (Fig. 7). The constancy of k was checked for data corresponding to an excitation of 3 MeV in the residual nucleus. At about the same time, there was a number of observations concerning shell effects in $(n, 2n)$ reactions [14]. Hille [15] also showed that the 14 MeV $(n, 2n)$ cross sections show the asymmetry parameter $(N - Z)/A$ dependence (first noticed by Barr et al. [16]), but found no shell structure dependence in the data.

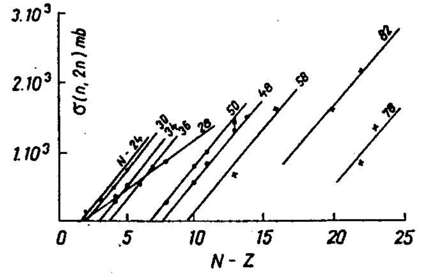


Fig. 7. $\sigma(n, 2n)$ plotted vs the neutron excess for a constant $\{E_n - E_{th}(n, 2n)\}$ energy difference (Ref. [13]).

Later, Chatterjee S. and Chatterjee A. [17] reviewed the whole subject of the $(n, 2n)$ systematics. They made a survey of data at excitation energies of 3, 6 and 7 MeV above the $(n, 2n)$ threshold and found that three general trends emerged: (i) a gross, structureless trend of the cross sections plotted against the neutron excess, (ii) a trend exhibiting shell effects, (iii) the Csikai-Petö trend.

The gross trend was fitted by an expression of the form

$$\sigma(n, 2n) \approx 45.2(A^{1/3} + 1)^2 \exp\left| -0.5\frac{N - Z}{A}\right| \text{mb} \tag{2}$$

at an excitation energy of 6 MeV above the $(n, 2n)$ threshold. The above equation is a phenomenological expression patterned on the Levkovski equation for the (n, p) reactions [18]. Clearly, the emission probability increases with increasing $(N - Z)/A$.

Chatterjee S. and Chatterjee A. assume that both the gross structure (Levkovski) trend (i) and the shell and Csikai-Petö trends ((ii) and (iii), respectively) are due to an excitation-energy shift from U to U' through a shift function F similar to that introduced by Rosenzweig [19]. Using this modified shift function F and introducing it into the level density $\varrho(U', j)$

Chatterjee S. and **Chatterjee** A. were able to account for both the shell effect and the asymmetry $(N-Z)$ correlations.

A point strongly stressed in Ref. [17] is the importance of eliminating the Q-value effects in the systematics of the $(n, 2n)$ cross sections. Contrary to the (n, p) and (n, α) reactions, the Q-value effects in the $(n, 2n)$ cross sections not far from the threshold play a foremost role. Hence the importance of normalizing the data to the same residual excitation energy (3, 6 and 7 MeV in Ref. [17]) rather than comparing the data at the same bombarding energy. In this way **Chatterjee** S. and **Chatterjee** A. explain why no shell effects were observed by **Hille** [15]; this author took the cross sections only at 14 MeV. Single-particle, viz. shell effects may, in fact, get lost in a cross-section comparison at unnormalized low residual excitations.

The interpretation of **Chatterjee** S. and **Chatterjee** A. is not without criticism. **Adam** and **Jeki** [20] used a formula similar to Eq. (2) in order to relate the $(n, 2n)$ cross section to $(N-Z)/A$:

$$\sigma_{emp}(n, 2n) = \{1 - c_1(A^{1/3} + 1) \exp[-c_2(N-Z)/A]\}c_3 \qquad (3)$$

A plot of Eq. (3) against $(N-Z)/A$ fits the mean of $\sigma_{measured}/\sigma_{emp}$ (Fig. 8). Both the measured and the calculated data are for a constant residual excitation $U = U_r = E_n - Q(n, 2n) = 3$ MeV. No deviation from the average trend is thus observed for $4 \leqslant N - Z \leqslant 21$. Since the agreement is good whether the number of neutrons is magic or not, or whether Z is odd or even, the conclusion of Ref. [20] is that no effects due to shell closure or by pairing energy are observed.

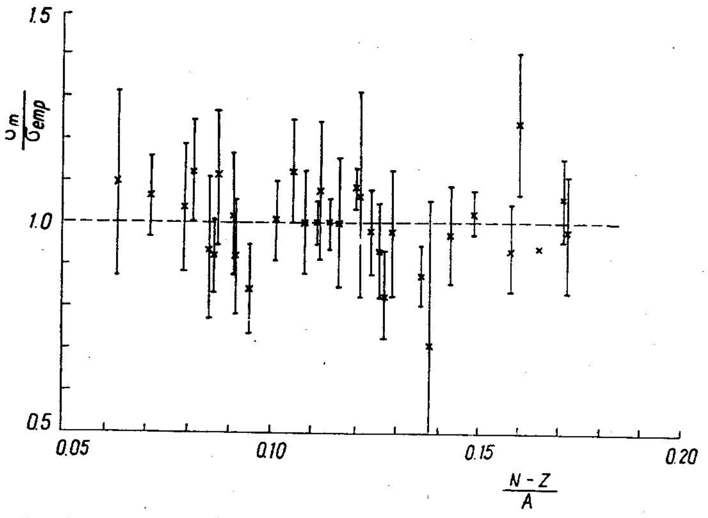


Fig. 8. Ratio of measured and predicted $(n, 2n)$ cross sections (Eq. (3)) for a constant residual excitation (Ref. [20]).

The $(n, 2n)$ cross sections for 18 elements at 14.7 MeV have been recently measured and analyzed by **Quaim** [21]. All data except those for ^{50}Cr, ^{54}Fe and ^{92}Mo agree within 10 % with Pearlstein's theoretical values based on simple compound nucleus assumptions [22] (Fig. 9). The deviations for the three mentioned nuclei can be explained in terms of their high threshold: A small experimental error in the energy determination might thus cause large deviations in the cross sections that rise steeply with the energy.

In a contribution to this Conference **Holub** [23] showed that the observation of shell-structure effects in the $(n, 2n)$ cross sections reported in Ref. [17] might be based on incorrect experimental values. In fact, the deviations from the average trend pointed out by Ref. [17] occur for the $(n, 2n)$ cross sections at 14 MeV on ^{88}Sr, ^{93}Nb, ^{109}Ag, ^{128}Te, ^{130}Te, ^{136}B and ^{151}Eu. The cross sections used in Ref. [17] referred only to one isomeric state and would thus be only partial cross sections. The new experimental data reported by **Holub** as well as those in Ref. [21] agree with the calculations by **Pearlstein** [22]. The minima observed in Ref. 17 would, therefore, be unreal. Thus, the recent results do not confirm the existence of shell-structure effects in the $(n, 2n)$ reactions.

Obviously, the whole subject of shell-structure effects in the $(n, 2n)$ cross sections is far from being closed.

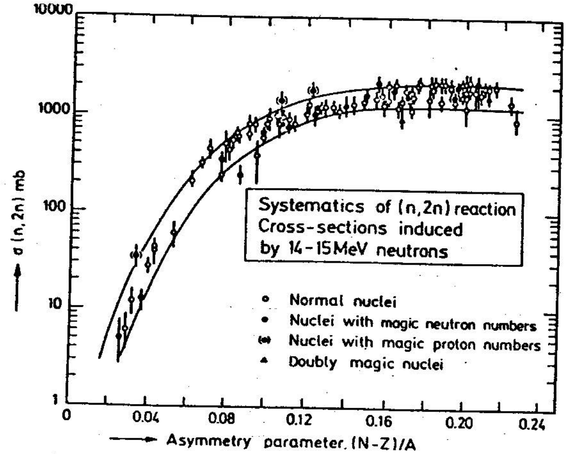


Fig. 9. Systematics of the $(n, 2n)$ reaction cross sections induced by 14–15 MeV neutrons (Ref. [21]).

III. 2. The decay of states near the neutron-emission threshold and the presence of nonstatistical processes in the (*n*, 2*n*) reactions

The early formulae for the (*n*, 2*n*) reactions proceeding via the compound-nucleus processes were derived under the assumption that the unbound states of nuclei decay by neutron emission whenever this is energetically possible. This assumption was open to criticism for several points of view, the most obvious being that the gamma decay can compete for energies slightly above the nucleon binding.

Discrepancies between theoretical and experimental cross sections for the (*n*, 2*n*) reactions have, in fact, been reported by several authors. The theoretical cross sections were usually larger than the experimental ones. If these discrepancies were connected with the neglect of gamma decay of the unbound states, then the same compound-nucleus theory, applied to inelastic neutron scattering, should give the opposite result. In fact, Abboud et al. [24] showed that experimental (*n*, *n*') cross sections were larger than the ones calculated by the compound-nucleus theory, when measured above the neutron-emission threshold. The unbound state populated by the emission of the first neutron might thus decay by emitting a gamma, not a second neutron.

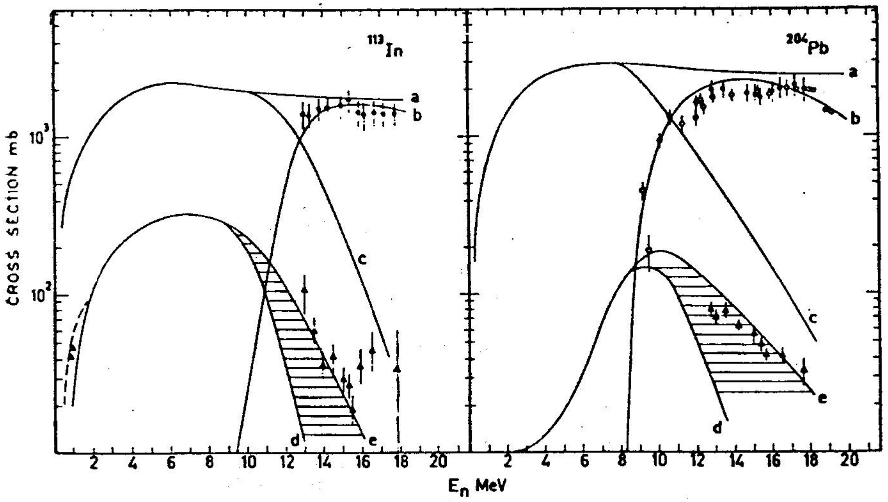


Fig. 10. Comparison of the experimental cross sections for the ^{113}In(*n*, *n*') and ^{204}Pb(*n*, *n*') cross sections (triangles) and the ^{113}In(*n*, 2*n*) and ^{204}Pb(*n*, 2*n*) cross sections (circles) with calculations. *a*: compound-nucleus formation cross sections; *b*: (*n*, 2*n*) reaction cross sections; *c*: neutron-scattering cross sections; *e*: cross sections for the formation of an isomeric state by non-elastic scattering. The shaded areas correspond to the integrated cross sections originating from the γ-decay of the unbound states (Ref. [25]).

This supposition was checked by Decowski et al. [25], who included the gamma decay of the unbound states in their calculations: This inclusion enhances the theoretical values of (*n*, *n*') and lowers the values for (*n*, 2*n*), in agreement with the experimental data (Fig. 10). This problem was discussed by Csikai [26] and Marcinkowski [27] at this Conference. Two possible reasons for such a behaviour were offered. The first is that the states where the gamma decay competes with the particle decay are states of a relatively high angular momentum. These states are excited by the incoming neutron,

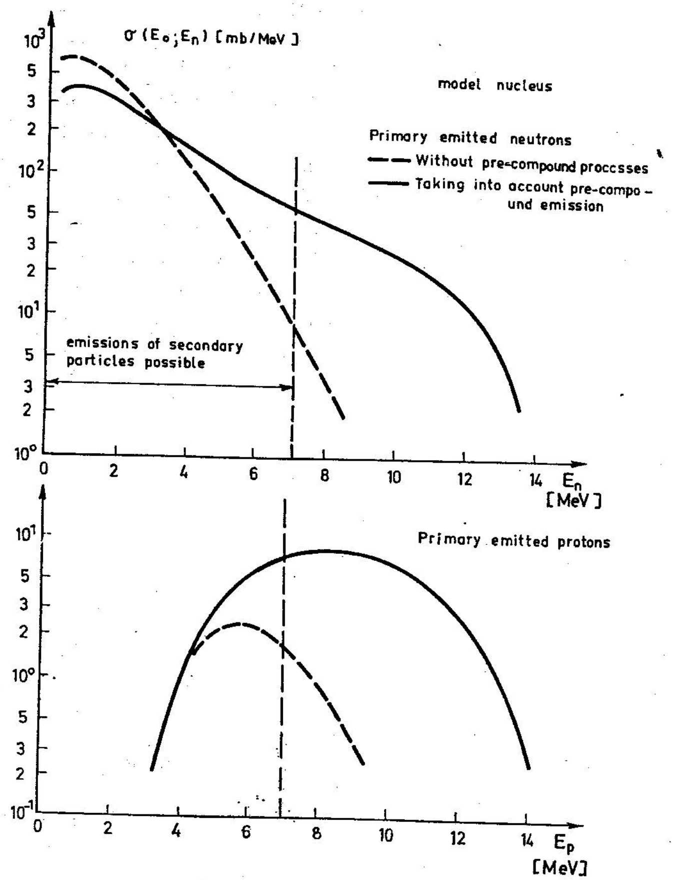


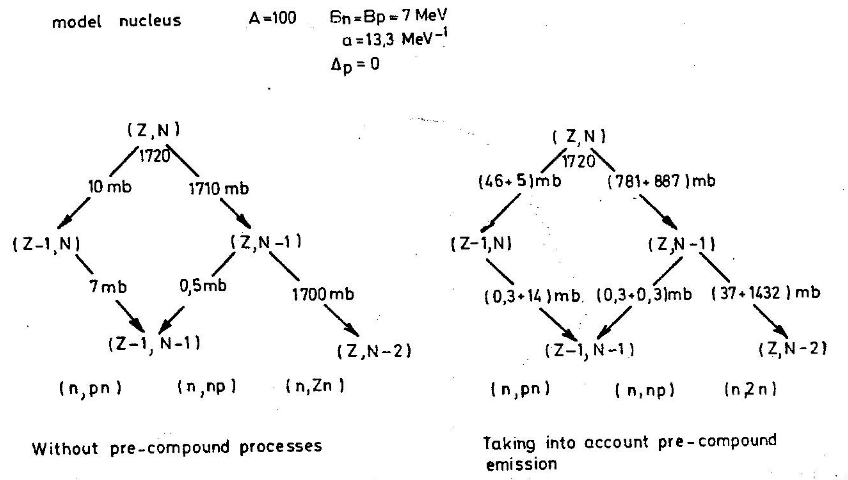
Fig. 11. The effect of the inclusion of preequilibrium processes in the emission of neutrons (upper figure) and protons (lower figure) following a 14 MeV neutron bombardment. The full lines represent the results when precompound processes were included. The net result is a hardening of the spectra, which reduces the fraction of the particle emission which can be followed by the emission of a secondary particle.

which brings in several units of angular momentum $\hbar$. As the first emitted neutron carries away little angular momentum (low energy), the residual state is a high-spin state. Its spin cannot be carried away by the (again low-energy) second neutron; hence the possibility of the gamma decay competition.

The second reason offered by Csikai [26] is that the decay to the collective levels of the intermediate nucleus in the first neutron-emission process is strongly enhanced. States of higher energy of excitation, capable of emitting the second neutron, are thus depleted; hence the reduction of the experimental $(n, 2n)$ cross section as compared with the statistical one.

Another possible explanation for the deviation of the $(n, 2n)$ cross sections from the statistical calculations was studied by Meister in a contribution to this Conference [28]. He calculated the effect of precompound processes in the emission of the first neutron of an energy E_n for a neutron bombarding energy of 14 MeV. The result is a hardening of the neutron spectrum, which causes the reduction of the fraction of the neutron emission which may be followed by the emission of a secondary particle (upper Figure 11).

The results of a typical calculation for a model nucleus $A = 100$ are shown diagrammatically in Fig. 12. The inclusion of preequilibrium processes (right-hand diagram) modifies the branching ratios already in the first step ($A \to A - 1$) in the above described sense (more high-energy neutrons emitted). The second step ($A - 1 \to A - 2$) is consequently modified, leading to smaller $(n, 2n)$ and larger (n, n') cross sections than those predicted by the statistical theory (left-hand diagram).



Without pre-compound processes

Taking into account pre-compound emission

Fig. 12. The results of a typical calculation for a model nucleus of $A = 100$. Left diagram: compound nucleus calculation. Right diagram: results of the inclusion of pre-equilibrium processes. Notice the change in the fraction of particles leading to the different points of the diagrams (different branching ratios).

Thus, the discrepancies between the statistical theory and the $(n, 2n)$ cross sections can be also understood in terms of the presence of preequilibrium processes.

IV. OPTICAL-MODEL STUDIES

Several interesting contributions in this field were presented at this Conference. For brevity's sake, I shall mention only the work of Lagrange [29] on a coupled-channel calculation of the interaction of neutrons with ^{238}U from 10 keV to 20 MeV. The same optical potential was used to fit (*i*) *s*- and *p*-wave strength functions, (*ii*) total cross sections and (*iii*) angular distri-

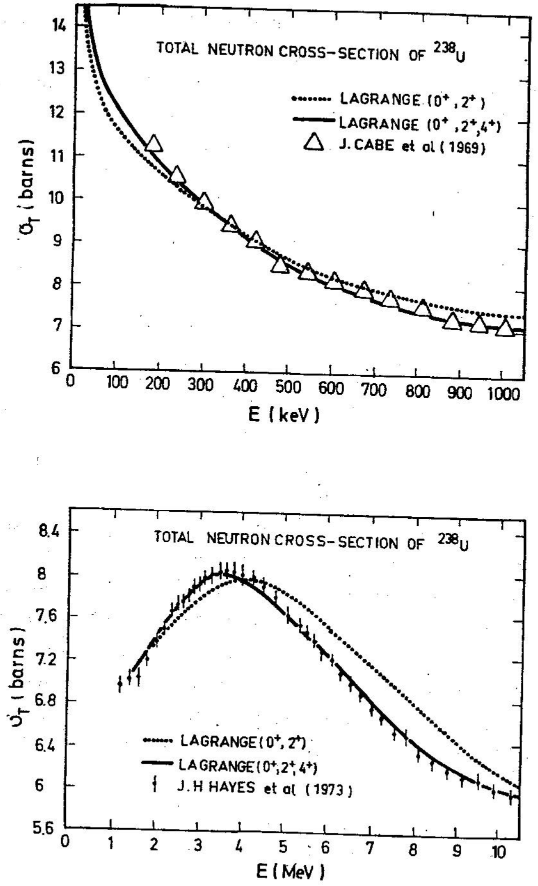


Fig. 13. Total neutron cross section of ^{238}U. The curves are coupled-channel calculations using two sets of basic states (Ref. [29]).

butions of elastic scattering. This calculation gives an excellent example of the importance of the choice of the basis set of states in a coupled-channel calculation. Fig. 13 shows the effect of including one additional basis state in the calculation: the fit is noticeably better (and fitting all data) when the coupling is performed for the 0^+, 2^+ and 4^+ states than when one of these states (the 4^+ state) is left out.

V. PROPERTIES OF STATES IN THE CONTINUUM NEAR THE PARTICLE-EMISSION THRESHOLD

This is a neutron field *par excellence*, since only low-energy neutrons can excite states in nuclei lying a few keV above the particle-emission threshold.* This technique was originally used for neutrons in the eV energy range; nowadays, modern time-of-flight techniques enable us to study resonances in the MeV range above the neutron-emission threshold.

This field by itself is a lecture topic and we can only treat it in a somewhat incomplete way. I feel that we have to include it in our review because of its enormous importance, but it is not within the range of this paper to review all recent experiments in the field. We will thus briefly illustrate it by one particular example, namely, the low-energy (n, α) reactions. This is a technique developed recently to study the nature of resonances in the neutron-energy range up to 1 keV [30]. Although this field of investigation is still developing, its potentialities are considerable. The main idea is the following: For nonfissionable nuclei the properties of resonant states that can be determined are E_0, Γ, Γ_n, Γ_γ and sometimes J^π. This information does not represent a typical structural information. New information on nuclear resonance states can be obtained by studying the (n, α) reaction. This is due to the fact that an alpha particle is a relatively simple particle and the theory of alpha decay is fairly well known. Of course, formidable experimental difficulties have to be surmounted: The cross sections for alpha emission are by several orders of magnitude (10^{-5}!) smaller than the corresponding (n, γ) cross sections. Nevertheless, in view of the small Coulomb penetrability of alpha particles, these cross sections could correspond to rather large partial widths.

The partial widths, $\gamma^2_{\alpha ijl}$, for the alpha decay of the resonant states are related to the total widths $\Gamma_{\alpha ij}$ by

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* In principle, we could excite these states by sharp monoenergetic gamma beams or other impractical methods.

$$\Gamma_{\alpha ij} = 2 \sum_l \gamma^2_{\alpha ijl} P_{jl} = 2\, \gamma^2_{\alpha ij} \sum_l P_{jl}$$

where $\gamma^2_{\alpha ij}$ is averaged over various values of l contributing to the transition $i \to j$, and P_{jl} is the nuclear Coulomb and centrifugal penetrability. The variations of the alpha decay as a function of the initial (compound) state i

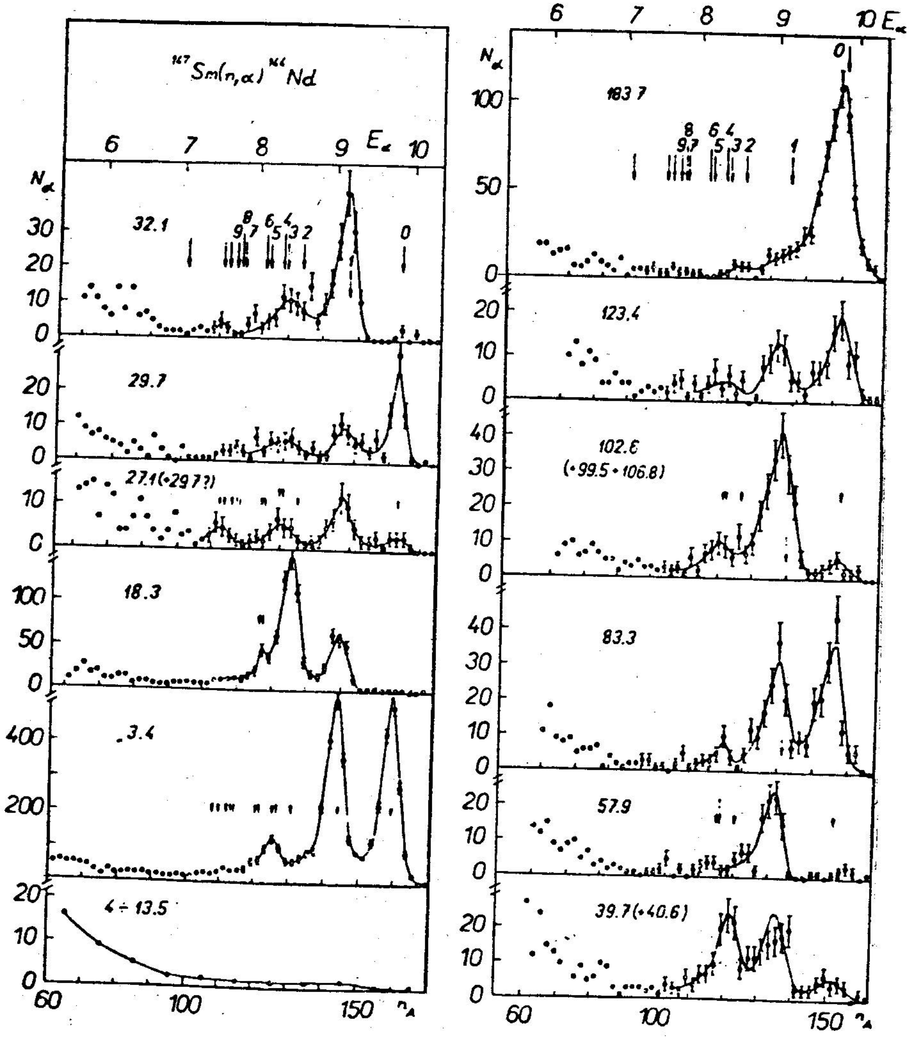

Fig. 14. Alpha-particle spectra from the ^{147}Sm(n, α) ^{144}Nd reaction at various neutron energies. Notice that various final states are populated from different resonances (Ref. [30])

and the final state j are given in Fig. 14. Some of the partial widths are very large. For instance, for the 184 eV resonance, the width of the partial alpha transition to the ground state is 30 times as large as the value averaged over other resonances with the same spin value.

It is of particular interest to compare reduced neutron and partial alpha widths for several nuclei. The data shown in Table 2 permit a preliminary conclusion that the ratio of the two reduced widths is close to unity for some nuclei. It is thus conceivable that there exists a structural parentage between the resonant states and the low-lying states in nuclei. Briefly, the above described method would permit the conclusion of a happy relationship between neutron spectroscopy on the one hand and classical nuclear spectroscopy on the other. Neutron spectroscopy has so far been dealing with resonant unbound states, while classical nuclear spectroscopy has so far been mostly investigating the low-lying states of nuclei.

Table 2

Comparison of reduced neutron and partial α widths*)

Target nucleus Widths	^{95}Mo		^{123}Te		^{143}Nd		^{145}Nd		^{147}Sm		^{149}Sm		^{155}Gd	
$\langle\gamma_n^2\rangle$ (eV)	4.3		1.9		5.0		1.9		1.9		1.2		0.23	
$\langle\gamma_\alpha^2\rangle$ (N) (eV)	0.21	(5)	0.5	(4)	0.8	(5)	1.15	(4)	0.08	(9)	0.007	(6)	0.005	(2)
$\langle\gamma_\alpha^2\rangle/\langle\gamma_n^2\rangle$	0.05		0.26		0.16		0.6		0.042		0.006		0.02	

*) The number of widths over which the averaging was made is given in the parentheses.

VI. CONCLUDING REMARKS

We have briefly scrutinized several fields where fast-neutron spectroscopy shows some promise. What, if any, is our conclusion?

There is little doubt that the investigation of resonant states near the neutron binding energy and its extension to higher incident neutron energies is one of most promising field the main field of interest in neutron spectroscopy. As regards the other fields, the investigation of the cluster structure in light nuclei and alpha clusterization in nuclei in general may give useful complementary information. Of course, this is the experimentalist's side. On the theoretical side there are many more questions to be answered. First, the nature of the „alpha" resonance above the neutron-emission threshold. Secondly, by the presumed presence of „prefabricated" alpha clusters in medium and heavy nuclei is far from being understood. Thus it seems that fast-neutron spectroscopy, which has already been proclaimed dead so many times, be buried,

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Received October 19th, 1974