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FAST NEUTRON INDUCED REACTIONS[1]

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This review outlines a few investigations concerning the fast neutron induced reactions. The following subjects are discussed; total, elastic and non-elastic cross sections; reaction cross sections for (n, n'), $(n, 2n)$, (n, t) and (n, γ) processes.

I. INTRODUCTION

It is a great pleasure for me to fulfil the honouring request of the Organizing Committee to give the introductory lecture to this Symposium. First of all, allow me, please, to express our appreciation for the kind invitation to Smolenice to discuss the problems of fast neutron induced reactions. I think we all are most grateful to Professor Blažek, Dr. Bederka, Dr. Ribanski and everybody, who have been engaged in the organization of this Symposium.

In my lecture I should like to review a few subjects from those investigations where the neutrons produced in a D + T reaction, using small neutron generators, play the main role.

Owing the technical reasons most of the data for fast neutron induced reactions were measured at 14 MeV and the free parameters in nuclear reaction models were determined at this energy. The discrepancies between experiment and theory are very often due to the unmeasured or unreliable experimental data; therefore it is important to survey the present status of the investigations for fast neutron interactions.

II. TOTAL, ELASTIC AND NON-ELASTIC CROSS SECTIONS

The total neutron cross sections σ_T are known for the elements with a few exceptions and also for a few stable isotopes at 14 MeV. As can be seen in Fig. 1. the data for other energies are scarce [1, 2].

The measurements of σ_T with a high accuracy and resolution for separated isotopes could give further useful information on the fine and intermediate structure in the mass number dependence of $\sigma_T(A, E)$.

Marshak and Richardson [3] have shown the effect of nuclear deformation on the 14 MeV total cross sections. From such a type of measurements data for the deformation parameter can be found. Recently Frank et al. [4] observed a resonance at $E_n = 16.8$ MeV in the ^{207}Pb + n process by the measurement of $\sigma_T(E)$. This experiment was repeated at ANL by Harvey et al. and at LLL by Barschall and no detailed structure was observed in the entire energy range [5].

It is well known that σ_T is equal to the sum of $\sigma_{EL} + \sigma_{NE}$. The integrated elastic scattering cross sections are known from direct measurements only for 26 elements at 14 MeV. A number of them can be derived by subtracting the non-elastic from the total cross section: $\sigma_{EL'} = \sigma_T - \sigma_{NE}$. As for the differential scattering cross section there are no measurements for about 30 % of the elements, while for others large discrepancies can be found in the shapes and absolute values of the σ_{EL} function; this makes any conclusions for the potential form and the parameters rather uncertain. In the case of heavy nuclei the inelastic scattering contributions to the σ_{EL} lead to incorrect conclusions, see e. g. the small angle anomaly for U and Pu.

The non-elastic cross sections were measured for 42 elements. More data are needed especially for very light and very heavy elements. It should be noted, however, that the corrections for multiple scattering are difficult to perform especially for light elements. The non-elastic cross sections divided by their black nucleus values depend on the mass number, which can be explained by the assumption that the nuclear radius parameter r_0 is not constant. According to our investigations the $r_0(A)$ function from σ_{NE} is in good agreement with that determined by electromagnetic methods [6].

From the analysis of the total cross sections we found an approximate correlation for light nuclei between the nuclear radius parameter and the reciprocal of the binding energy per nucleon (ε), $r_0\varepsilon \approx 11$ MeV fm. In Fig. 2 results of the Hartree-Fock calculations are plotted against the mass number. It can be seen that the different forces used by the two calculations lead to a well detectable shift in the respective $r_0\varepsilon$ values, hence this correlation can be used to check the applied forces, and to estimate the unknown nuclear radius if the binding energies are available.

According to our investigations the total, integrated elastic, non-elastic and differential elastic scattering cross sections can be well described in a wide range of mass numbers and neutron energies not only by the quantum mechanical optical model but also by a simple semi-classical model, using analytical expressions [1, 2, 6]. In this latter model the same parameter set

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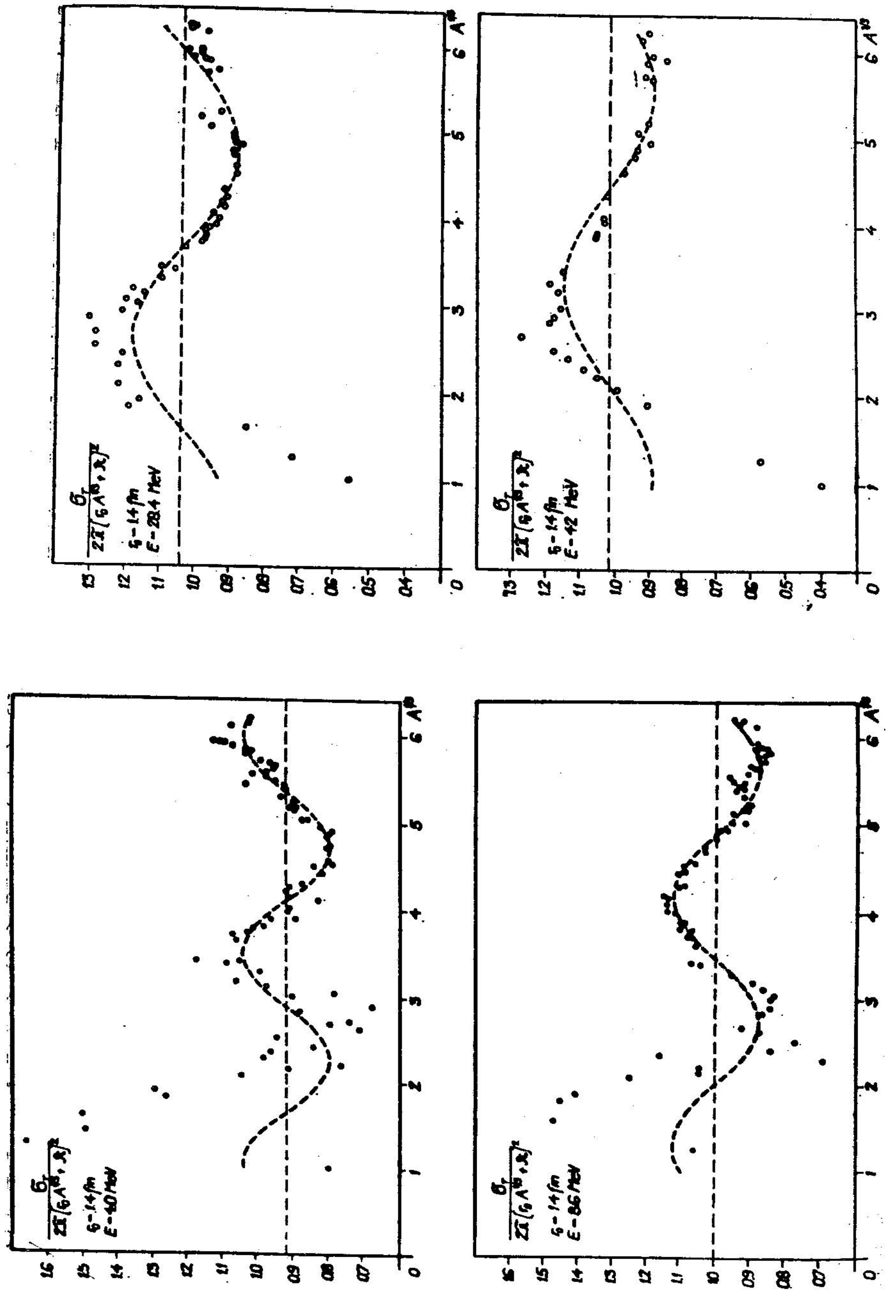

Fig. 1. Experimental total neutron cross sections divided by the black-nucleus value as a function of $A^{1/3}$.

can be used for the calculation of σ_T, σ_{EL}, σ_{NE} and $\sigma_{EL}(\vartheta)$ values (dashed curves in the figures). Measured and calculated $\sigma_{EL}(\vartheta)$ values are shown in Fig. 3 for different mass numbers. The form and the magnitude of the forward peaks are fairly well reproduced without normalizing constants.

III. REACTION CROSS SECTIONS

The components of σ_{NE} are inelastic scattering, capture, reactions and fission. At 14 MeV the main processes are the $(n, n'\gamma)$, $(n, 2n)$, (n, p), (n, α) and for fissionable nuclei the (n, f), but the (n, t), $(n, {}^3\mathrm{He})$ and (n, γ) reactions have also theoretical and practical importance. Though there are different models, e.g. statistical, pre-equilibrium, direct, semi-direct for the interpretation of cross sections, these attempts, so far, have not been successful.

The ratios of $\sigma_{n,2n}$ and σ_{NE} values plotted against the target neutron number at 14 MeV show that the $(n, 2n)$ cross sections give about 80% of σ_{NE} above $N = 60$, therefore by the study of the $(n, 2n)$ reaction one can get

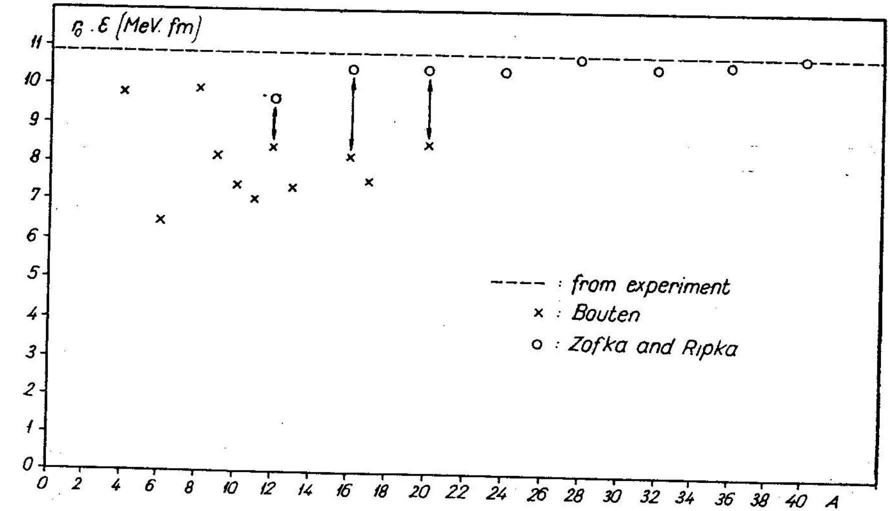

Fig. 2. $r_0\varepsilon$ values for light nuclei, calculated by the Hartree-Fock method using different forces; circles: density dependent effective interactions, crosses: $B1$ force of Brink-Boeker.

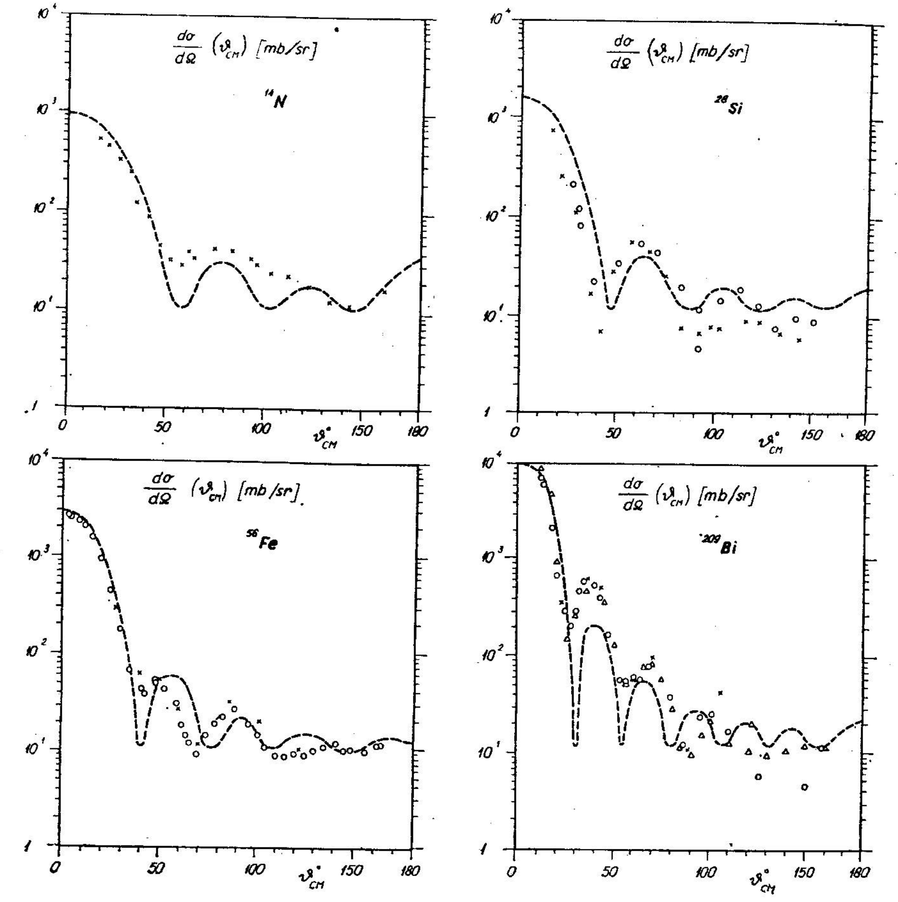

Fig. 3. Comparison of experimental and calculated differential elastic scattering cross sections for N, Si, Fe and Bi.

information on those properties of nuclei which are dominant in nuclear reactions. According to the Weisskopf-Ewing rule at 14 MeV and $N > 60$, the saturation value of the $(n, 2n)$ excitation function should be equal to σ_{NE}. The experiments [15] show considerable deviations depending on the symmetry parameter $N-Z$ (Fig. 4). The emission of a second neutron is probably restricted by the angular momentum conservation. In the $(n, 2n)$ reaction the angular momentum of the excited state of the target nucleus can not be transferred to the second neutron; therefore the electromagnetic de-excitation should

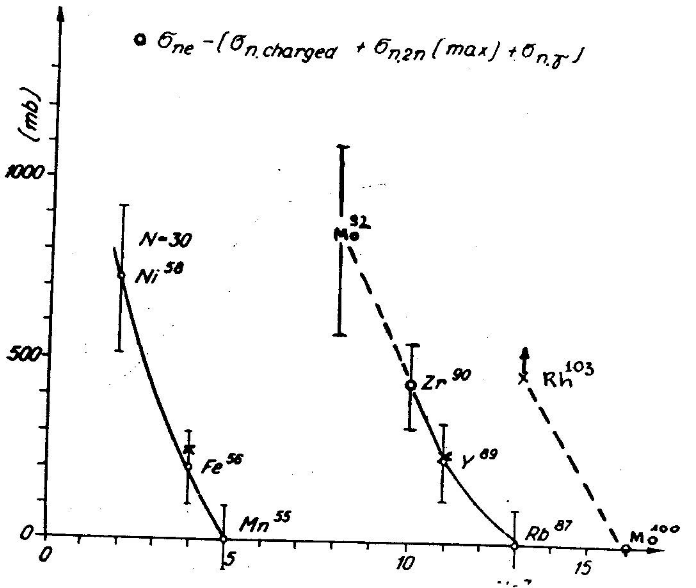

Fig. 4. $N-Z$ dependence of the (n, n') cross sections.

be considerable. There is an other explanation of this phenomenon, namely the cross sections for the (n, n') processes leading to low lying collective levels, depend on $N-Z$ and are considerably higher than expected on the basis of the statistical model.

By the measurement of neutron spectra from the inelastic scattering in coincidence with the gamma quanta — apart from elucidating this problem — important results could be obtained of the reaction mechanism and of the characteristics of these states. A systematic determination of the Γ_γ/Γ_n ratio from the (n, n') and the $(n, 2n)$ neutron spectrum measured at a given excess energy above the $(n, 2n)$ threshold would be important, too. Measurements with 14 MeV neutrons have verified the possibility of neutron scattering on collective states. The data for the angular distributions of neutrons scattered in an inelastic way are scanty and those measured by different authors show significant disagreements. A further problem is that $\sigma_{n'}(\vartheta)$ values have not been measured for small $\vartheta < 20°$) and large ($\vartheta > 130°$) angles. It should be noted, however, that the inelastic scattering cross sections, even for the isomeric states, are very scarce at 14 MeV. There are no data in a wide range of nuclei and in many cases only a lower limit can be given.

The ^{103}Rh$(n, n')\,^{103m}$Rh reaction is a marked example of significant discrepancies in the excitation functions of the (n, n') processes. Because of the low

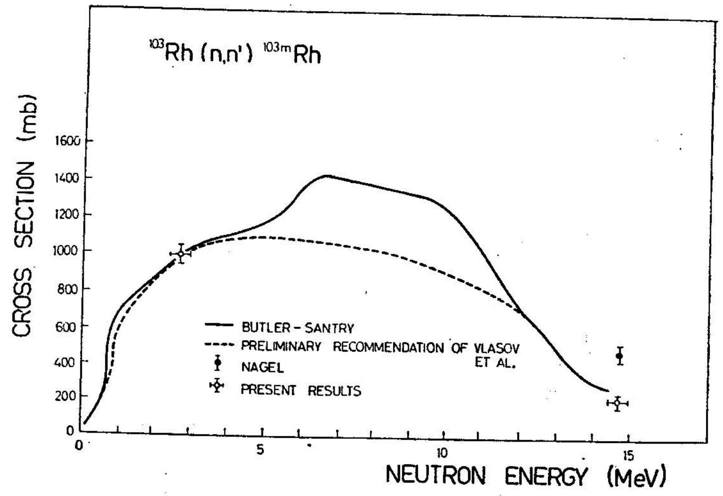

Fig. 5. Recommended excitation functions for the ^{103}Rh (n, n') ^{103}Rh reaction.

threshold and large cross section of the ^{103}Rh(n, n') reaction, rhodium is widely used for the measurements of the neutron flux and spectrum. Our investigations [7] at 3 MeV, 14 MeV and for the ^{252}Cf neutron spectra suggest the necessity of reinvestigation of the excitation curve (Fig. 5). The earlier excitation functions show significant discrepancies above 5 MeV.

Starting from this observation it is necessary to emphasize the importance of small neutron generators and sources in the determination of standard points on the excitation curves and to find reliable data for normalizing angular distributions and energy spectra.

During the last years special attention was paid among fast neutron induced reactions to the (n, t) and (n, γ) processes.

The knowledge of the (n, t) and $(n, ^3\mathrm{He})$ cross sections for D + T neutrons is important in assessing the ^{3}He and ^{3}H concentrations build-up in fission reactors and in future fusion reactors. In addition to this practical utility, the study of these reactions may add to our understanding of the emission of the ^{3}H and ^{3}He three-nucleon structures, and may contribute to our information on the nuclear cluster formation on the diffuse nuclear surface. The $(n, ^3\mathrm{He})$ reaction is especially important for exciting two proton hole configurations in nuclei.

There are only few data for (n, t) reactions and the cross section values measured by different authors are inconsistent; that is why only the roughest tendencies can be established. According to our earlier investigations the cross section values for the (n, t) and $(n, ^3\mathrm{He})$ reactions are much higher than

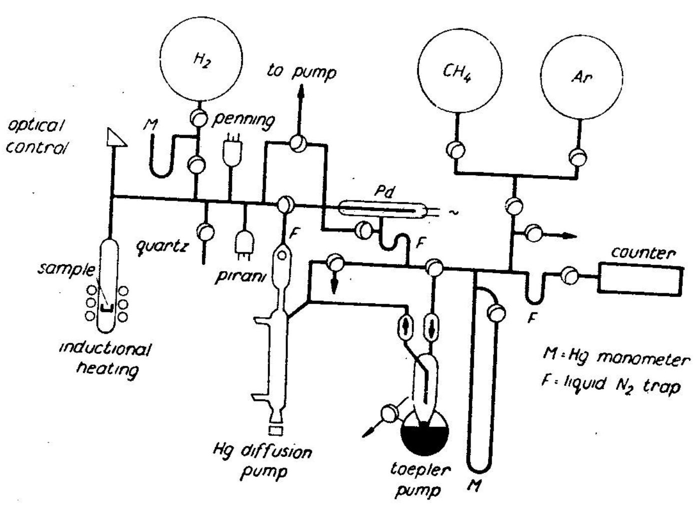

Fig. 6. Vacuum system for tritium extraction.

those expected on the basis of the statistical model [8]. It can be supposed that the high cross section values of these reactions are caused by direct effects.

For light nuclei a direct particle detection is possible together with the measurement of energy and the angular distributions. In the case of medium and heavy nuclei only integrated cross sections were determined by the activation method, combined with radiochemical separations to remove the disturbing activity from the high yield reaction products. This procedure was adopted in our earlier experiments [9] by which we gave a convincing evidence for the occurrence of the $(n, ^3\mathrm{He})$ reactions on ^{103}Rh and ^{133}Cs. The existence of this reaction was confirmed later by Husain [10] and Qaim [11] and newer results for a few nuclei were given, too. According to the measurements of Qaim, the $(n, ^3\mathrm{He})$ cross section at 14 MeV for medium and heavy nuclei lie between 2 and 10 μbarn, while the values given by Diksic et al. [12] for the same region are a few hundred μb in many cases. Further measurements are necessary to clear up the origin of the large spread in the experimental data from different laboratories.

The measurement of the tritium beta activity by our method renders possible the investigation of the (n, t) cross sections in the whole mass number range. The extraction of tritium produced in the samples makes the measurement of cross sections in the order of μb possible. An advantage of the method is that it can be applied, on principle, to any target nucleus, irrespective of the fact whether the residual nucleus is radioactive or not; however, for elements consisting of several isotopes only the average cross section is obtained, or separated isotopes should be used.

Systematic investigations were carried out in our laboratory for the determination of (n, t) cross sections at 14 MeV using the tritium beta counting technique [13].

The scheme of the vacuum system for degassing the sample and filling the counter can be seen in Fig. 6. The samples were heated by the induction method or in a resistance furnace in suitable crucibles. The developing gas together with the carrier H_2 gas was filled into a proportional counter through a heated Pd tube by a Hg diffusion and a Teopler pump.

Obviously, the most critical point of this method is the yield of degassing; therefore, the same apparatus was used for the measurement of the cross section for $^{39}K(n, t)\,^{37}A$. The gas mixture from the irradiated K sample together with the Ar + H_2 carrier gas was filled to the Pd valve, which separated Ar from H_2. First tritium was measured, then the counter was filled with argon, and Auger electrons following the electron capture in ^{37}Ar were detected. The energy resolution of the proportional counter is shown in Fig. 7. As ^{39}K has an abundance of 93 % in natural potassium, this was a check of the tritium-activity method. The results of the two different methods agree within the error limits proving the reliability of our degassing procedure.

The measured (n, t) cross section values, together with the literature data, are presented in Fig. 8 as a function of the target atomic number.

For medium and heavy nuclei the cross sections lie in the microbarn region. It would be difficult to draw general conclusions from a few data, but a strongly decreasing tendency with an increasing atomic number can be seen on which deviations, arising from the individual properties of the nuclei, are superimposed. Further data are needed to prove the existence of a peak near $Z = 26$ proposed by Qaim et al. [14] (dashed curve in Fig. 8).

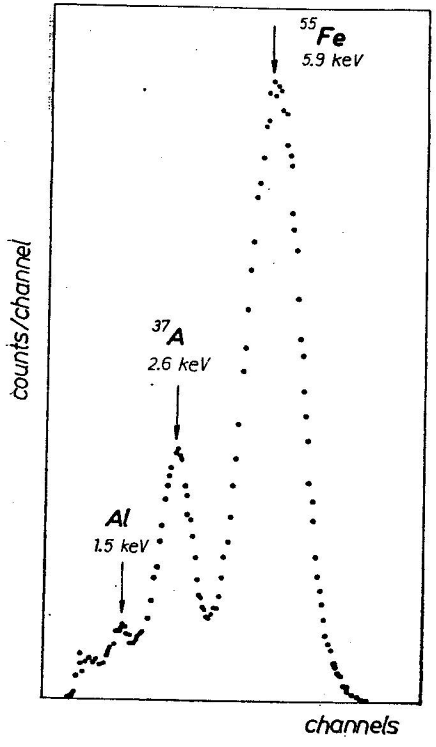

Fig. 7. Pulse height distribution measured by the proportional counter.

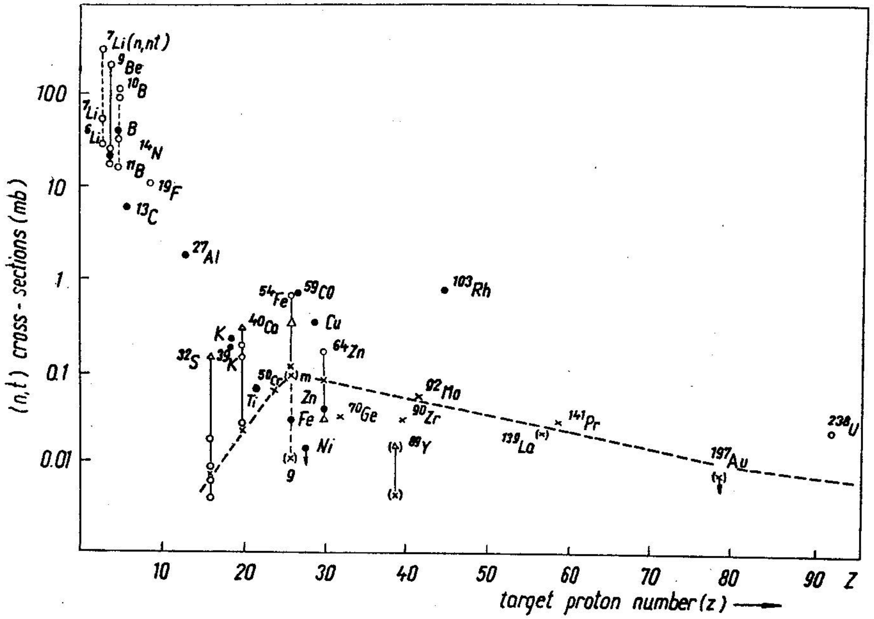

Fig. 8. (n, t) cross sections as a function of the target proton number at 14 MeV.

As it can be seen in Fig. 9, if an $(N - Z)/A$ dependence exists at all, similarly as in other neutron reactions, it is significantly weaker than in the case of the (n, p) and the (n, α) processes.

Measured (n, t) cross sections and their calculated values, using the statistical model, are of the same order of magnitude. The ratio of the (n, t) and the $(n, {}^3He)$ cross sections, for ^{59}Co and ^{103}Rh does not agree with that calculated on the basis of the statistical model. The great differences, about 5 order of magnitude, arise mostly from the $(n, {}^3He)$ reaction. This means that the direct effects (knock-out and pick-up) play a much higher importance in the $(n, {}^3He)$ reaction than in the (n, t) process.

For determination of (n, γ) cross sections at 14 MeV two methods are used: the activation technique (σ_{act}) and measurements of prompt gamma-ray spectra (σ_{int}). Earlier measurements using the activation method resulted in (n, γ) values by an order of magnitude higher than determinations based on the integration of the partial cross sections for gamma-rays to bound states in the final nuclei. Recently, the cross section measurements have been repeated with improved activation methods and some of the authors have found a good

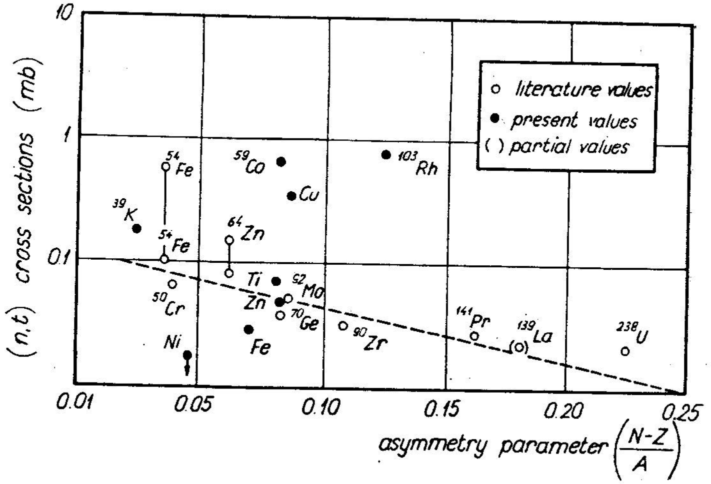

Fig. 9. (n, t) cross sections as a function of the $(N-Z)/A$ parameter.

agreement between σ_{int} and σ_{act}, while according to other investigations the σ_{act} are generally higher than σ_{int}. The difference is small near the closed neutron shells, but for other nuclei it amounts to a factor of two or three. Thus e.g., in the case of ^{208}Pb the cross sections in the giant resonance regions measured by the activation method agree well with those determined by the prompt gamma spectra. To explain the discrepancy between σ_{act} and σ_{int} and to establish the magnitude of the γ-ray cascades from the capture state to the bound states through the unbound states, further precise activation measurements are needed in the whole mass number region. Starting from the assumption that the secondary neutrons resulting from the (n, n'), $(n, 2n)$, (n, pn) processes in the sample and in the target can seriously disturb the activation results, measurements with improved target sample arrangements are in progress. The present results indicate the significant contribution of the secondary neutrons to the (n, γ) cross sections.

I think that the few subjects reviewed in my lecture will serve as good examples of emphasizing the importance of fast neutrons, produced by small accelerators, in the basic nuclear research for the near and far future.

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