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NUCLEAR DATA FOR THERMONUCLEAR REACTORS

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ABSTRACT

The nuclear data required for designing thermonuclear reactors are discussed on the basis of a theoretical reactor concept.

An analysis is presented of the nuclear data published up to the end of 1969 on the three principal materials expected to be used in thermonuclear reactors: ^{6}Li, ^{7}Li and Nb.

The nuclear data requirements for such reactors are considered in the final section of the paper.

I. INTRODUCTION

The controlled thermonuclear fusion research programmes of all countries [1, 2] are aimed primarily at obtaining a stable plasma and ultimately at producing useful thermonuclear energy.

In the modern world, with its rapid population growth and rapid industrialization, controlled fusion has from the outset been regarded not simply as a possible method of producing energy, but as one of the main routes to further progress in power engineering as a whole. The present conference is not the place for a discussion of energy requirements and ways of meeting them. It should perhaps be mentioned, however, that there are many serious arguments in favour of the possible application of thermonuclear energy: apart from the economic advantages and virtually unlimited supplies of fuel there is the relatively low level of radioactive waste (less by a factor of 10^6 than in the case of nuclear power stations), which at the present time is one of the main criteria in choosing between methods of energy production.

Although no decisive breakthrough has so far been made in plasma physics research, i.e. it has not been possible to obtain a plasma with the parameters (density, confinement time, temperature) necessary for "igniting" a controlled thermonuclear reaction, the progress made in recent years has considerably stimulated interest in the technological and economic aspects of thermonuclear power generation and hence in the engineering characteristics of possible thermonuclear reactor models.

At the first international conference devoted to the engineering aspects of thermonuclear power engineering (Culham, United Kingdom, September 1969) the main problems of thermonuclear power engineering were analysed on the basis of the current status of research in plasma physics and associated fields. From the proceedings of this conference it may be concluded (as was stressed at the conference itself by participants) that in addition to problems directly connected with achieving the principal aim - the creation of a stable plasma with the required parameters - there are a number of extremely important problems which, although not directly connected with the principal aim, will have to be solved before thermonuclear power generation becomes a real possibility. Of these "ancillary" problems, that of nuclear data is a particularly general and serious one. A knowledge of the nuclear microconstants is as essential in designing thermonuclear reactors as it has been in the calculation and subsequent construction of fissile reactors. One aim of the present paper is to encourage a wide circle of experimental research workers to perform the nuclear data measurements necessary for the design of a thermonuclear reactor.

In order to provide a concrete and clear description of the nature of the neutron-nuclear interactions occurring in a thermonuclear reactor we shall examine them on the basis of a possible reactor design.

It is assumed that a solution can be found for the principal physical problem, the creation of a stable plasma, which is not discussed in the present work.

II. THERMONUCLEAR REACTOR DESIGN

Table 1 shows four types of fusion reaction which can in principle be used for thermonuclear power generation [3].

Table 1

No.	Type of reaction	Energy (MeV)		
		Charged particles	Neutrons	Radiation
1	$D + T \rightarrow {}^4He + n$	3.37 (19%)	14.1 (80%)	0.13 (1%)
2	$D + D$ (50%) $\rightarrow {}^3He + n$; (50%) $\rightarrow T + p$	1.2 (33%)	1.2 (33%)	1.2 (33%)
3	$D + {}^3He \rightarrow {}^4He + p$	14.4 (79%)	0	3.9 (21%)
4	$D + {}^6Li$ (~50%) $\rightarrow {}^7Be + n$; (~30%) $\rightarrow Li + p$; (~20%) $\rightarrow {}^4He + {}^4He$	-9.2 (-147%)	3 (47%)	13.4 (200%)

Comments: (1) The energy distributions of the fusion reactions are approximations.

(2) The figures in brackets are percentages of the total reaction energies.

It is still difficult to say which of the reactions shown in the above table will be the principal one in the thermonuclear power station of the future. Given the plasma energy level required and the nuclear cross-sections of the charged particles, the reaction most easily produced is $D + T \rightarrow {}^4He + n$. About 80% of the total energy of this reaction is released in the form of neutron kinetic energy, which is converted by moderation and absorption of the neutrons.

The total energy released in a single fusion event is substantially increased when the neutron is absorbed, because of its binding energy. If it is assumed that the slow neutrons are largely absorbed by lithium-6, the total effective heat becomes:

$$Q'_{DT} = Q_{DT} + 4.8 \text{ MeV} = 22.4 \text{ MeV}.$$

There are quite a large number of possible thermonuclear reactor designs based on the DT reaction [4-6]. As the fundamental nature of neutron-nuclear interactions does not depend on the design features of the reactor, design differences do not play a major role in the present study. Consequently, without discussing the relative advantages of various reactor designs we shall consider just one possibility. Figure 1 shows a reactor design based on a toroidal closed trap system of the Tokamak type [7, 8]. The dimensions and arrangement of the components of the reactor blanket have been taken from [7] and are only tentative. It is assumed that the reactor burns a mixture of equal quantities of deuterium and tritium and that almost all the energy released, in the form of "thermonuclear" neutrons, is converted to thermal energy in the blanket surrounding the vacuum chamber containing the plasma. The main interactions between the neutrons and matter are concentrated in this "breeding blanket", which we assume to extend from the wall of the vacuum chamber to the vicinity of the superconducting magnetic coils confining the plasma. As practically all the neutron-nuclear interactions occur inside the blanket, our discussions will be limited to this region.

The breeding blanket of a thermonuclear reactor is designed to fulfil a number of functions:

(a) The conversion of the kinetic energy of thermonuclear neutrons to thermal energy and the transfer of this energy by means of coolants to the power plant;

(b) The regeneration of tritium in order to maintain the thermonuclear reaction at least at the rate at which the tritium "burns". This can be accomplished by means of the reactions

$$^{7}Li(n,n', {}^{4}He)T, \text{ and}$$
$$^{6}Li(n, {}^{4}He)T;$$

(c) As only one neutron is emitted for each tritium atom that is "burned", neutron multiplication by reactions of the type (n,2n) is necessary;

(d) The blanket must shield the superconducting coils from neutron and gamma radiation.

The most important technical characteristics of a thermonuclear reactor are its total thermal power P_T and its dimensions. On the basis of the conditions for a self-sustaining fusion reaction (Lawson's criterion [9]) and for stability of a plasma in closed systems [10], and from the permissible durability characteristics of the materials and the critical value of the magnetic fields produced by the superconducting coils [11] the minimum thermal power of a Tokamak thermonuclear reactor is estimated at several gigawatts [7].

At such power levels the thermonuclear neutron flux at the wall of the vacuum chamber will be approximately 10^{15} n-cm^{2}-sec [12].

III. MATERIALS FOR THERMONUCLEAR REACTOR COMPONENTS

As in the case of fission reactors, the choice of materials for the blanket of a thermonuclear reactor is determined not only by technological factors such as mechanical strength, thermal conductivity and corrosion and radiation resistance, but also by nuclear-physics characteristics - especially the various neutron cross-sections. Since the development of a thermonuclear reactor is only in the initial stage, it should be borne in mind that as our knowledge increases in depth and scope the demands made on materials will change - that is to say, materials which on the basis of current ideas appear to be the most suitable may subsequently be relegated to second place.

We shall review briefly the conditions to which materials will be exposed in a thermonuclear reactor and the requirements which they will have to meet.

1. Vacuum chamber wall

Approximately one quarter of the kinetic energy of the "thermonuclear" neutrons and all the bremsstrahlung and cyclotron radiation energy emitted by the plasma is absorbed in the wall. Calculations [13] have shown the temperature of the vacuum chamber wall to be about 1000°C. As the wall is in a region where there are very high fluxes of neutrons with energies varying over a fairly wide range, the material used must have a small capture cross-section. In addition, it is desirable that the material of the wall should allow neutron multiplication by the (n,2n) reaction. These requirements can probably be met by niobium [14] or molybdenum [15], but at present it is difficult to choose between them.

2. Tritium regeneration

It has been mentioned above that one of the fuel components of a thermonuclear reactor, namely tritium, can be regenerated by means of reactions with lithium.

The reaction ^{7}Li(n,n', ^{4}He)T can be produced only by fast neutrons (reaction threshold 2.8 MeV [16]). In addition, the formation of a tritium nucleus does not entail the disappearance of the neutron, which may take part in further interactions. The efficient use of this reaction is therefore of great importance. As molten lithium (melting point approximately 179°C) can also be employed as a coolant, it could be used with advantage for cooling the vacuum chamber wall, where the neutron spectrum is hardest.

The cross-section for the reaction $^{6}Li(n, ^{4}He)T$ is largest (σ = 946 barns) in the thermal range, so that the region of tritium regeneration by this reaction must be located beyond the neutron moderation zone.

3. Coolant

Efficient cooling of the vacuum chamber wall and removal of heat from the moderator are of very great importance. As already mentioned, molten lithium - or its salts (for example, $2LiF-BeF_2$ [17]) - should be a very efficient coolant and ought perhaps to be considered first. The main difficulty in using a liquid metal coolant is that high losses occur when it is pumped across magnetic field lines. In reference [15] consideration is also given to molten lead, organic liquids, water and a number of other possibilities. However, they are much less efficient than molten lithium or its salts, and sometimes impracticable.

4. Neutron multiplication

As calculations have shown [18], the required level of tritium regeneration can also be attained without additional neutron multipliers, solely on the basis of (n,2n) reactions in structural materials (e.g. Nb) and (n,n'T) reactions in ^{7}Li. However, these calculations entail a number of assumptions and do not reflect an actual thermonuclear reactor design. Consequently, it may be found that additional neutron multipliers are required in the final version of the reactor. The most efficient neutron multiplier apart from fissionable materials is Be, but its high cost and inadequate radiation stability limit its usefulness in a thermonuclear reactor. Neutron multiplication can also be achieved by (n,2n) reactions in heavy elements such as Pb and Bi. Final conclusions on this question still have to be reached.

5. Neutron moderation

As half of the total neutron energy is absorbed in the moderator [15], a rational and careful choice of materials is very important. For physical, design and economic reasons it is important that the thickness of the breeding blanket and consequently of the moderator zone, should be minimized. Thus, there is a great attraction in the use of materials with a high moderating capacity (i.e. with a high hydrogen or deuterium content) such as lithium deuteride (LiD) or zirconium hydride. However, the rather high temperature of the moderator and a number of technological factors limit the application of such materials. The most likely material for the moderator is graphite.

6. Shielding of the coils

The choice of materials for shielding the superconducting magnetic coils of the thermonuclear reactor is determined largely by the neutron and gamma-ray spectra in the blanket and by the limited thickness of the shielding layer. This imposes considerable restrictions on the range of materials which can be used for the purpose. It is considered [15] that such materials as lead, water and boron will be used for shielding the coils.

IV. NUCLEAR DATA FOR THERMONUCLEAR REACTORS

1. The purpose of nuclear data

From the above brief account it can be seen that the range of materials which may well be used in constructing a thermonuclear reactor is already quite extensive: ^{6}Li, ^{7}Li, Be, B, C, O, F, Nb, Mo, Pb, Bi and others. It is clear that the choice cannot be made without adequate knowledge of the neutron-interaction characteristics of these materials. However, this knowledge is necessary not only in selecting materials for the thermonuclear reactor, but also as the starting point for a whole series of other tasks, the most important of which are as follows:

(1) All the neutron-physics calculations and the nuclear heating calculations for the breeding blanket - these calculations also cover tritium regeneration, energy production and all related problems;

(2) If one takes into account the high plasma neutron fluxes (10^{15} n/cm^2-sec), there is also the problem of the radiation stability of the materials. At an initial neutron energy E_i = 14.1 MeV the extent and nature of the radiation damage will be affected considerably not only by elastic scattering, as in the case of fission reactors, but also by inelastic interactions. Consequently, a knowledge of such cross-sections as (n,p), (n,α) and(n,2n) [19] is very important for calculating radiation stability;

(3) Calculation of the radiation shield for the superconducting coils of the thermonuclear reactor, for which knowledge of the neutron interaction cross-sections is necessary. In the case of

thermonuclear reactor shielding the calculations are complicated by the fact that a large part of the gamma radiation generated in the blanket results from inelastic collisions of fast neutrons, concerning which there is very little experimental data.

At present the designing of thermonuclear reactors is in an early stage - the stage where designers make preliminary physical, heat, engineering and other calculations on the basis of which the feasibility of designs and their economic competitiveness can be assessed. For calculations of this kind the problem of the accuracy of the nuclear data is still not very acute. However, each stage of development requires greater accuracy in respect of constants measured in the past or of information on constants not yet measured.

2. Review of nuclear data

To facilitate discussion we shall divide the "thermonuclear" neutron energy region into two ranges: from thermal values to energies of the order of 5 MeV and from ~ 5 MeV to 14 MeV.

The first energy range is the traditional one for fission reactors and the amount of accumulated nuclear data may be considered sufficient for the thermonuclear reactor calculations required in this neutron energy range.

For the higher energy range (5-14 MeV) there is much less experimental information, particularly between 8 MeV and 13 MeV. This is easily explained. Neutron interactions in this energy region are not very important as far as fission reactors are concerned and in most cases have been ignored. Consequently, the nuclear data requirements for this region have been very limited. The problems arising in connection with the development of thermonuclear reactors have made it necessary to think once again about collecting nuclear data for this energy range.

As already mentioned, the list of materials which might be used in a thermonuclear reactor is already quite extensive and it is virtually impossible in a single article to carry out a detailed analysis of all the available nuclear data for all those materials. We shall therefore limit ourselves, by way of example, to a detailed examination of the interaction cross-sections of three of the most important elements: lithium-6, lithium-7 and niobium.

(a) Lithium total cross-sections

Transmission measurements are the simplest form of total cross-section measurement. However, if the total cross-section values are to be obtained to within 1% and with an energy resolution of 0.5% or better, a number of conditions have to be satisfied. The use of strong neutron sources in conjunction with the time-of-flight method [20] seems to give the most accurate total cross-section values obtainable at the present time.

Figures 2 and 3 show total cross-sections for ^{6}Li and ^{7}Li, based on data taken from [27-31 and 42]. The authors of [28] carried out a long series of total cross-section measurements at 240 different neutron energies valued between 3 MeV and 15 MeV, with a statistical accuracy of 0.6-2%, and an energy resolution of 2.5-11.5%. Some of these values, indicated by black triangles, are given in Figures 2 and 3. The continuous curves are based on evaluated data [49].

(b) Lithium-6 partial cross-sections

Elastic scattering accounts for a large part of the total cross-section in the case of lithium isotopes. Figure 4 shows the cross-section for elastic neutron scattering in ^{6}Li. The data shown have been taken from [21-26]. The continuous line represents evaluated data [49]. The total scattering cross-sections were obtained by integrating the measured differential scattering cross-sections. The accuracy of the individual cross-section values varies from 3% to 10%. Although in the energy region under discussion there is little experimental data, according to [22] the scattering cross-section of this isotope can be adequately represented by a straight line.

The inelastic scattering of neutrons in lithium isotopes is characterized both by discrete groups of neutrons, corresponding to narrow excited states of the target nucleus, and by a continuous spectrum occurring for a variety of reasons - e.g. three-particle decay. Even when the final reaction products are the same, the shape of this spectrum depends on the way in which the reaction proceeds. If lithium is regarded as one of the main elements in a thermonuclear reactor, it is important to know what reactions are responsible - and to what extent they are responsible - for the scattered neutron spectrum observed and how the contributions of the various reactions change as a function of the energy of the incident neutrons. This question has not yet been clarified completely.

Figure 5 shows the cross-section for the reaction $^{6}Li(n,n'd)^{4}He$; the data are taken from [21-23 and 32]. The continuous curve is based on evaluated data [49]. Although the accuracy of the individual values is approximately 10%, the scatter of the points is noticeably greater. A systematic discrepancy is observed between the experimental data obtained from neutron spectrum measurements [21, 22 and 23] and the data obtained by recording charged particles in a photo-emulsion containing ^{6}Li [32]. In order to understand and eliminate the errors in the cross-section values for the reaction $^{6}Li(n,n',d)^{4}He$, which is the second neutron-^{6}Li interaction in magnitude, additional measurements are required throughout the energy range under consideration.

The (n,2n) reaction in ^{6}Li, with its energy threshold at 6.2 MeV, has been studied only at two neutron energies: $\sigma = 33 \pm 15$ mbarns at 10.2 MeV [38]; $\sigma = 70 \pm 6$ mbarns [38], 50 ± 10 mbarns [37] and 78.1 ± 4.1 mbarns [39] at 14 MeV.

From the point of view of regenerating one of the thermonuclear reactor fuel components (i.e. tritium) reactions of the type (n,T) are very important. Figure 6 shows data on the reaction $^{6}Li(n,T)^{4}He$ taken from [27, 33-37 and 48]. The continuous curve corresponds to the data given in [49]. As can be seen, the results of the various authors are in good agreement. In the energy range 8-12 MeV, however, experimental data are completely lacking.

The reaction $^{6}Li(n,p)^{6}He$, with its threshold at 3.1 MeV, has been quite thoroughly investigated in the energy range from the threshold value to 9 MeV, and also at 14 MeV [36, 40, 41 and 50]; the cross-section is relatively small.

As ^{6}Li decays preferentially by particle emission, inelastic neutron scattering in ^{6}Li entails virtually no gamma emission. Gamma rays are emitted only from levels from which particle emission is forbidden - e.g. because of the nature of the isotopic spin. The gamma radiation from such a level (3.56 MeV) has been studied [50] only in the energy range 4.1-7 MeV.

(c) Lithium-7 partial cross-sections

The sum of the cross-sections for elastic scattering and inelastic scattering cross-sections at the 0.478-MeV level of ^{7}Li is given in Figure 7; the data were taken from [21-26]. The continuous line represents data from [49]. The total scattering cross-sections were obtained by integrating the measured differential cross-sections. As can be seen from the data in Figure 7, there are only nine neutron energies at which measurements have been carried out in the range 3-14 MeV and only one experimental point in the range 8-13 MeV. It is difficult on the basis of so few experimental values to plot a detailed curve of the scattering cross-section as a function of neutron energy, particularly in view of the wide clear maximum in the 4.3-MeV region.

The main inelastic neutron scattering process in ^{7}Li is the reaction in which tritium is formed; it is the principal source of tritium regeneration by fast neutrons. Figure 8 shows the relationship between the cross-section for the reaction $^{7}Li(n,n',T)^{4}He$ and neutron energy in the range 3.5-15 MeV [21, 22, 23, 32, 44, 45 and 47]. The continuous line corresponds to data from [49]. In view of the importance of this reaction for thermonuclear reactors the scatter of the individual cross-section values is too large, while - as in the case of most interactions - experimental points are lacking altogether between ~ 10.7 MeV and ~ 13.5 MeV. Moreover, it is not completely clear what the various reaction paths contribute to the neutron spectrum [51] or what is attributable to direct processes as compared with the formation of a compound nucleus. All this makes it difficult to interpret the experimental data and to determine reliably the energy and angular characteristics of the reaction.

The first excited state of ^{7}Li(0.478 MeV) decays with gamma emission. Apparently, this is virtually the only gamma radiation emitted during the interaction of neutrons with the ^{7}Li nucleus, but it occurs in a relatively high proportion of such interactions. Figure 9 shows the cross-section for the inelastic neutron scattering reaction $^{7}Li(n,n',\gamma)^{7}Li$ at the 0.478-MeV level, obtained essentially by measuring the gamma radiation. The data were taken from [21, 22, 24, 43, 46 and 52]. The continuous curve is based on evaluated data from [49]. An interesting point is the divergence of the experimental data in reference [22] and [46], especially at a neutron energy of 7.5 MeV.

The cross-section for the (n,2n) process in ^{7}Li was measured at two neutron energy values: at 10.2 MeV, $\sigma = 27 \pm 15$ mbarns [38]; at 14 MeV, $\sigma = 56 \pm 5$ mbarns [38] and 49.7 ± 3.2 mbarns [39]. At the same time, according to the data given in [49], the cross-section for this reaction at the energies mentioned is 10 mbarns and 22 mbarns respectively

Other reactions in ^{7}Li, such as (n,3n) and (n,d), have negligible cross-sections [39, 40 and 41] and are not discussed here.

(d) Niobium total cross-section

Figure 10 shows the niobium total cross-section; the data are taken from [29, 53 and 54]. The continuous curve is based on data from [55]. The experimental data, obtained both some time ago and recently [54 and 56], show good agreement. In addition, a detailed analysis of the experimental data and the comparison with theoretical values made in [28] have also indicated good agreement. In particular, the experimental and theoretical values for Nb given in [57] agree to within 3%.

(e) Niobium partial cross-sections

Experimental data on partial cross-sections are much scarcer in the case of niobium than in that of lithium isotopes. Figure 11 shows cross-section values for elastic neutron scattering in niobium taken from [58-61]. The continuous curve is based on data from [55]. The values of the cross-sections at neutron energies 5 MeV and 14 MeV were obtained by us by integrating the differential scattering cross-sections given in [59 and 61].

Figure 12 shows effective cross-section values for inelastic interactions taken from [58, 60, 61 and 62]. The continuous and broken lines are based on data from [55]. The broken line represents recommended inelastic scattering cross-section values. In the energy range 4-6 MeV the inelastic scattering cross-section practically coincides with the inelastic interaction cross-section as the radiative neutron capture cross-section decreases with increasing energy and is already small at this point (1.5-3 mbarns), while the cross-section for the (n,p) process, although increasing, is not yet very large. The continuous spectrum of the inelastically scattered neutrons is essentially an evaporation spectrum [60, 62 and 63], although even at the initial neutron energy of 5-7 MeV the direct interaction plays a notable part [62] and accounts for 5-7% of the inelastic scattering cross-section. In [64] recommended inelastically scattered neutron spectra are presented for niobium over the initial energy range 0.5-15 MeV. The spectra were obtained by processing and interpolating all the experimental data on inelastic scattering published up to 1967. A method for the interpolation, evaluation and compact presentation of data on inelastic neutron scattering is given in [65].

As so few experimental results are available (none in the range 8-13 MeV) it is not possible to compare the data of different laboratories on the cross-sections for elastic and inelastic scattering in niobium.

At neutron energies in the range 10-15 MeV the difference between the cross-section for inelastic interactions and that for inelastic scattering is determined mainly by the effective cross-section for the (n,2n) process. The energy dependence of the (n,2n) reaction cross-section is shown in Figure 13; the data are taken from [66-70]. The continuous curve is based on recommended data from [55]. It should be mentioned that the discrepancy between individual values for the (n,2n) reaction cross-section at 14-15 MeV is much greater than the errors indicated by the authors.

An accumulation of helium in niobium through the action of neutrons is brought about by several processes [68, 70-74]. The cross-section for this process at 14.5 MeV is approximately 17-18 mbarns. Figure 14 shows values of the cross-section for one of the processes; the others are characterized by smaller cross-sections.

The cross-section for the (n,p) reaction at 14 MeV is 22 $\pm$ 8 mbarns [75]. The probability of radiative capture in niobium at 14 MeV is negligible [68].

From the above review of nuclear data on three elements we can draw the following conclusions:

(1) For neutron energies in the range 5-15 MeV there are considerably less nuclear data than for lower energies. For most processes the experimental data are concentrated in the 5-8 MeV energy range and around 14 MeV, whereas in the 8-13 MeV energy range there are for a number of processes at best one or two experimental points;

(2) Where there are several experimental points and comparison is possible, there is in a number of cases a discrepancy in the data which is greater than the measurement errors indicated by the authors;

(3) For some processes the evaluated recommended cross-section values differ substantially from the measured values.

Of the elements of interest from the point of view of thermonuclear reactors, lithium isotopes have been studied most thoroughly; for the other elements (e.g. niobium) the amount of experimental data is considerably smaller.

3. Nuclear data requirements

With increasing neutron energy the number of ways in which neutrons can interact with nuclei increases substantially. In particular, many of the induced reactions result in the emission of charged particles.

As the energy of thermonuclear neutrons is considerably higher than the average energy of fission spectrum neutrons, the number of possible reactions will also be substantially higher. It is quite clear, therefore, that in order to meet the requirements of thermonuclear reactor calculations, it will be necessary to study far more nuclear interactions than in the case of fission reactors.

Apart from this general comment regarding the nuclear data requirements for thermonuclear reactors, it is worth discussing in more detail two types of nuclear data which are considerably more important for thermonuclear reactors than for fission reactors.

1. As has been mentioned (cf. Table 1), when the D + T reaction is used, 80% of the total energy produced by the thermonuclear reactor is attributable to the energy of thermonuclear neutrons, and this has to be converted to thermal energy in the blanket surrounding the vacuum chamber. Accordingly, energy release in the blanket due to the

slowing-down and capture of neutrons becomes much more important than in the case of fission reactors.

The total energy released in the blanket of a thermonuclear reactor is attributable to the following processes:

(a) Slowing-down of charged particles occurring as a result of various reactions involving interactions with neutrons;

(b) Slowing-down of recoil nuclei formed during elastic and inelastic neutron scattering;

(c) Ionization moderation of beta particles during the decay of unstable reaction products;

(d) Absorption of secondary gamma rays.

At the present stage in the development of thermonuclear reactors all the above-mentioned processes, with the exception of the absorption of gamma rays, can be quite satisfactorily calculated on the basis of the available information. The situation is somewhat different with respect to the calculation of the energy release which depends on the absorption of secondary gamma radiation and accounts for approximately half of the total energy release in the reactor blanket.

The gamma radiation spectra obtained in thermal neutron capture have been studied in detail [76], but most of the gamma radiation emitted in the reactor blanket is due to the inelastic interactions of fast neutrons and the gamma-ray spectra due to these processes have received little study.

2. Another important field in which a lack of experimental nuclear data is felt is that of the angular distributions of secondary neutrons.

For fission reactors, questions associated with neutron anisotropy do not in general play a critical role, except in certain specific cases - e.g. small fast-neutron reactors with a thick reflector-blanket, reactor shielding calculations, etc.

In the case of thermonuclear reactors the position is somewhat different. As the blanket of a thermonuclear reactor must be extremely thin and the initial energy of the fast neutrons rather high, the scattering anisotropy of secondary neutrons is of great importance.

Measured data on the angular distributions of secondary neutrons are therefore extremely important for the neutron physics calculations of the thermonuclear reactor blanket.

V. CONCLUSIONS

In the present paper an attempt has been made to show that nuclear interactions in the energy region of thermonuclear neutrons has so far received little study and at the same time to encourage experimentalists to measure those nuclear cross-sections which are essential in thermonuclear power engineering.

While the main task in the case of fission reactors is to improve the accuracy of already available nuclear data [77-79], it is still necessary in the case of thermonuclear reactors to fill in the gaps.

It is our hope that the experimental difficulties which will have to be overcome in obtaining nuclear data for thermonuclear reactors will be outweighed by success in finding a solution to the most important problem of the century.

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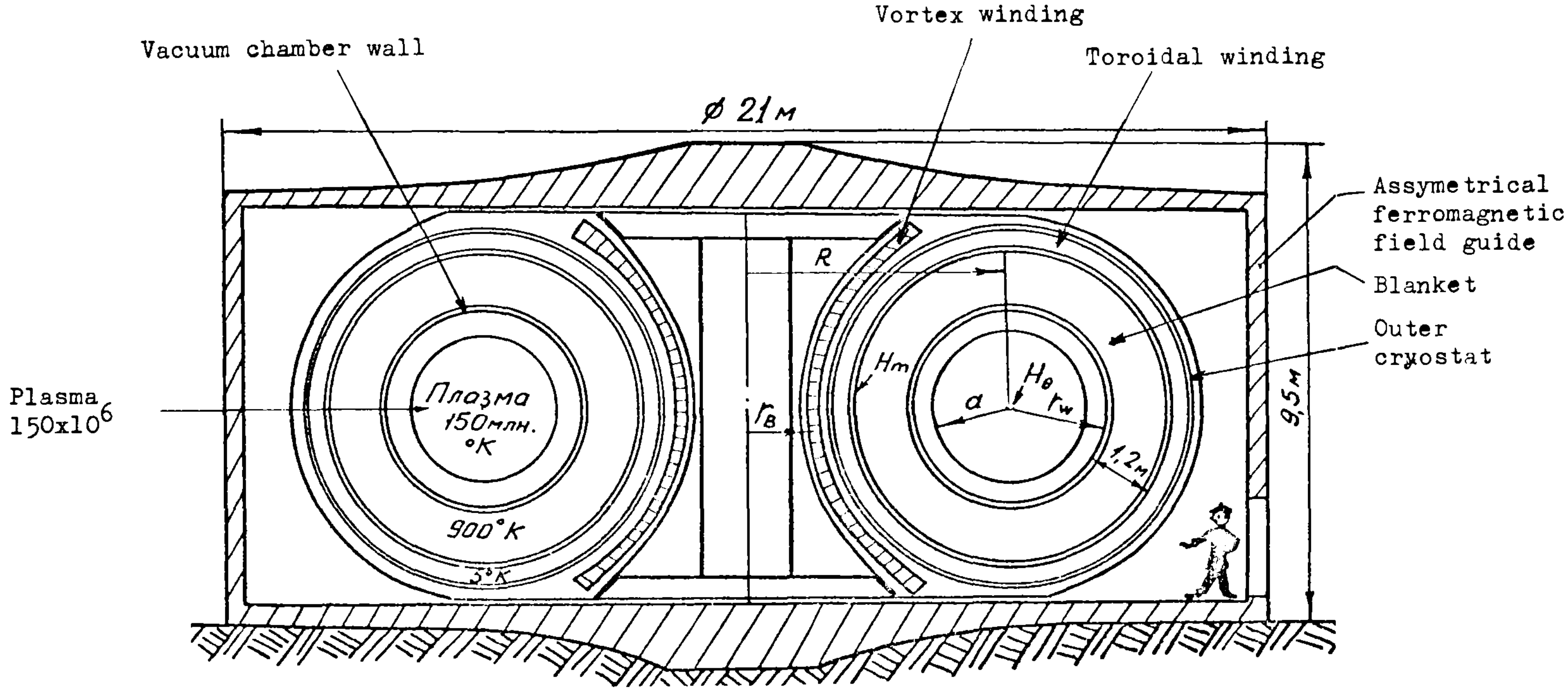


Fig. 1. Sectional view of the 2 million kW(e) Tokamak reactor

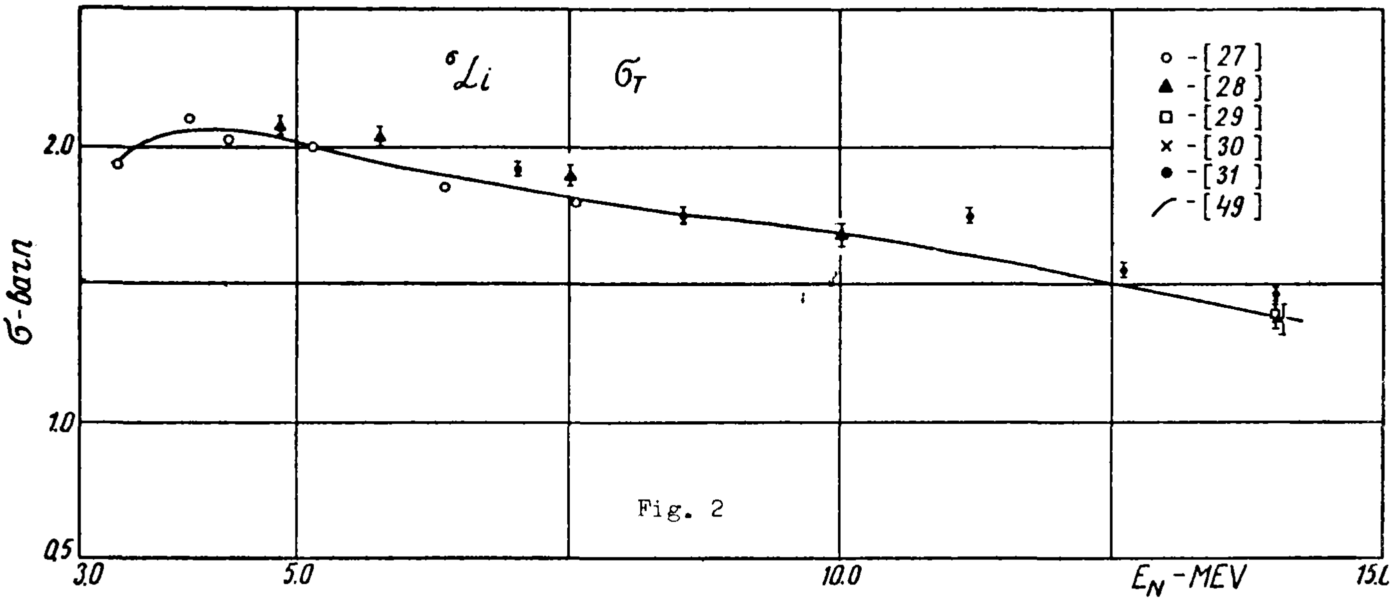
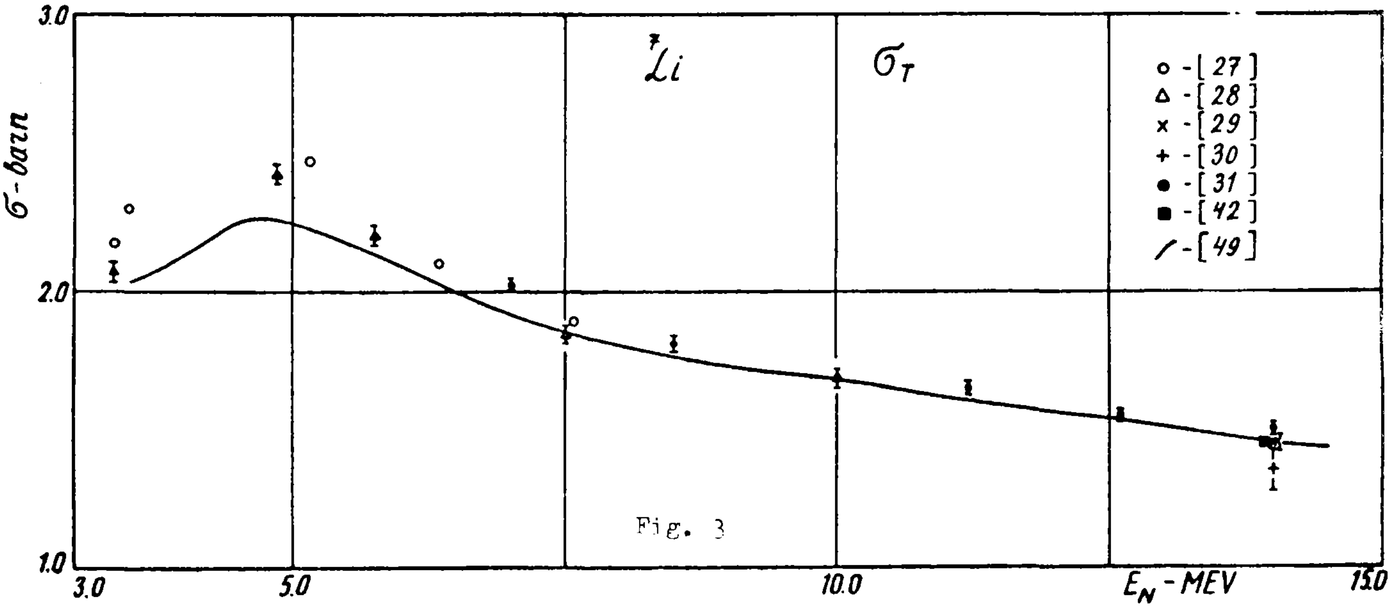


Fig. 2



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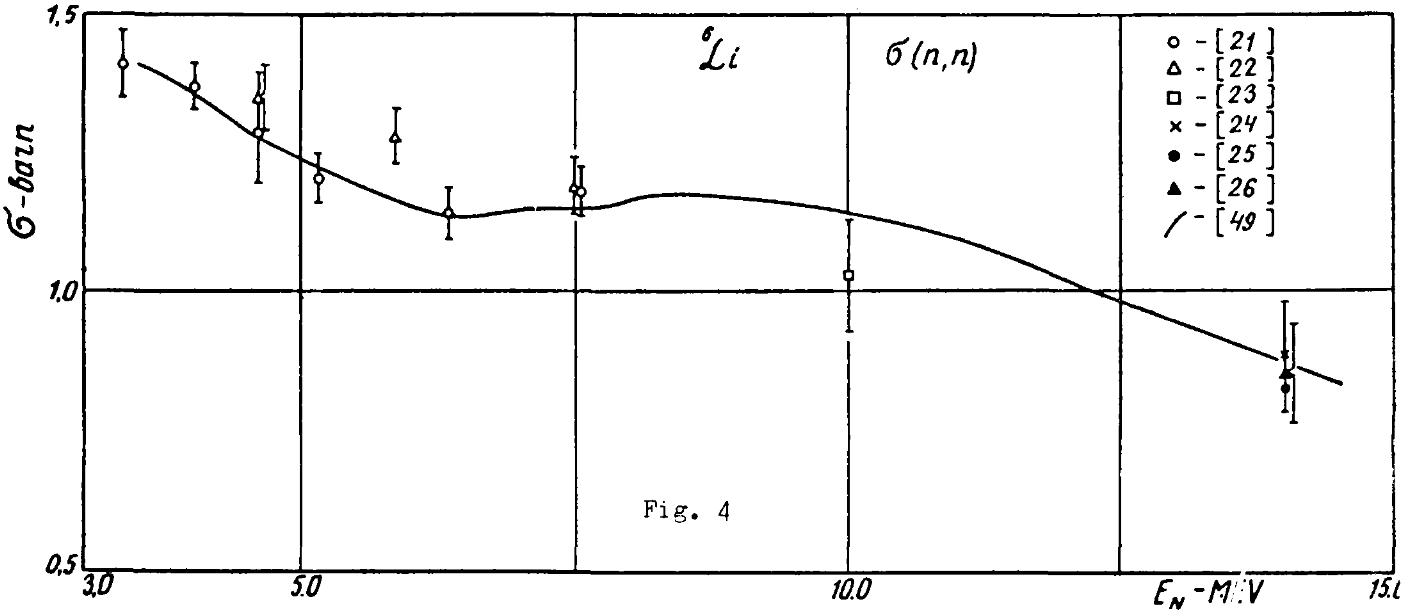

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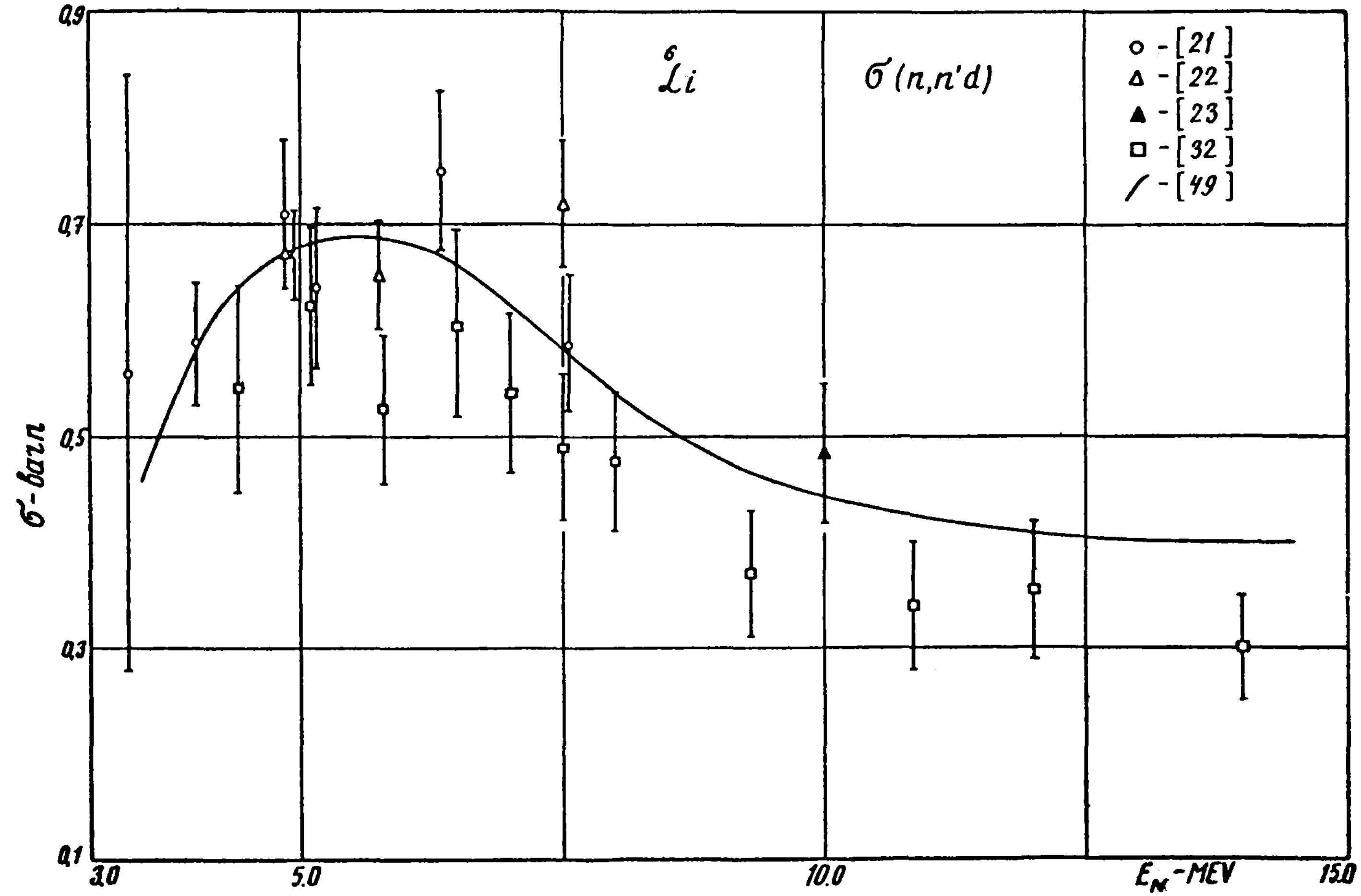


Fig.5

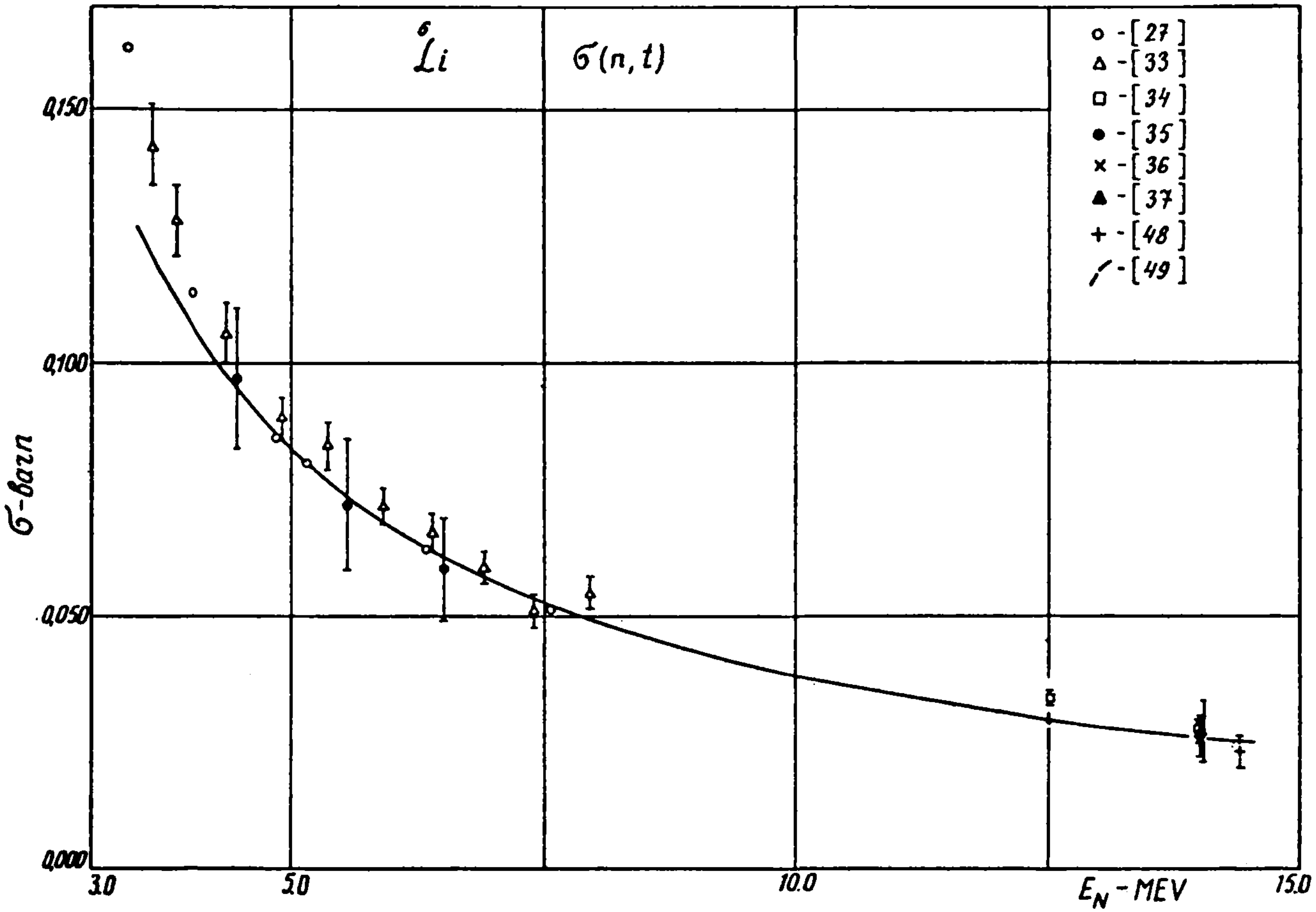
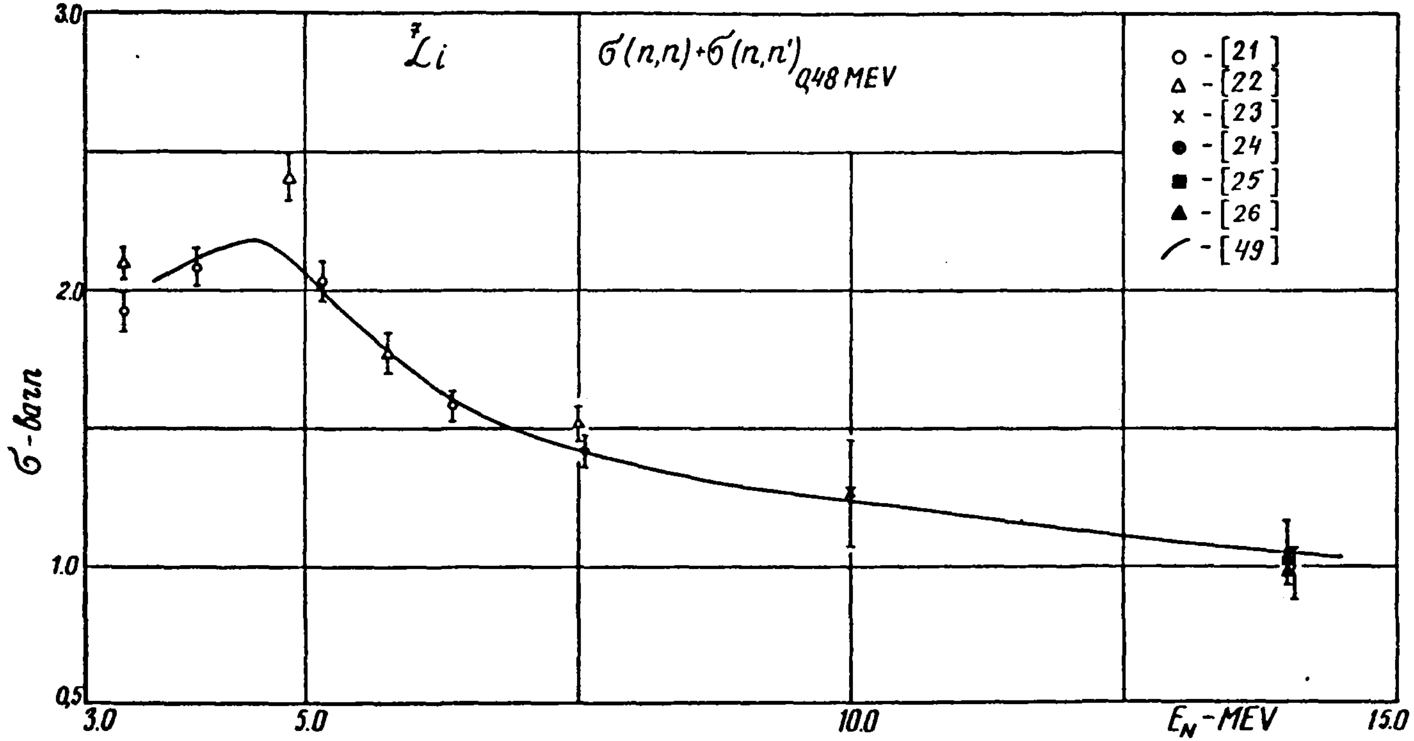
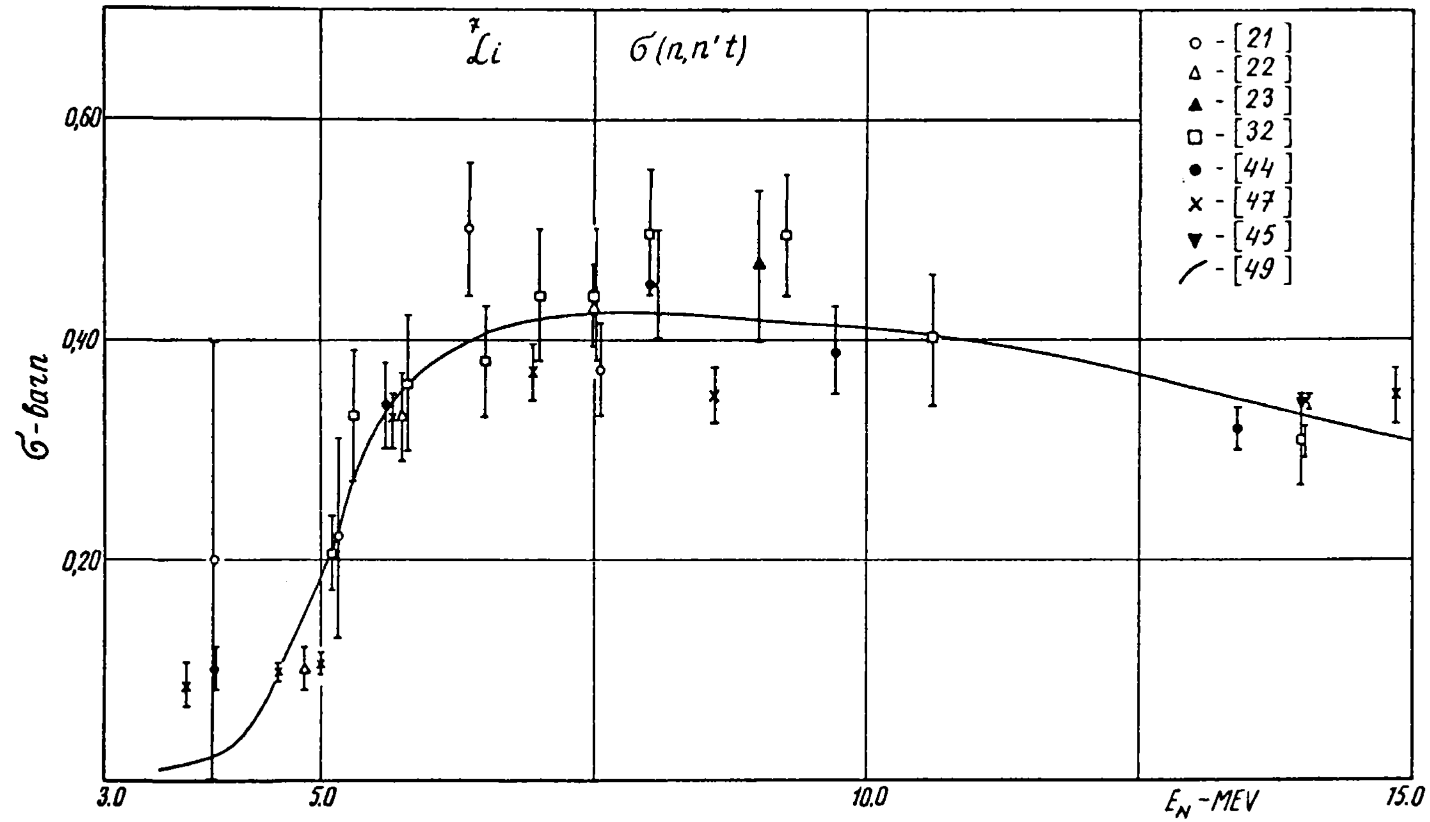

^6Li
σ(n,t)
o - [27]
Δ - [33]
□ - [34]
● - [35]
× - [36]
▲ - [37]
+ - [48]
/ - [49]
σ-barn
0,150
0,100
0,050
0,000
3.0
5.0
10.0
15.0
E_N - MEV

Fig. 6



^{7}Li
σ(n,n)+σ(n,n')0.48 MEV
○ - [21]
△ - [22]
× - [23]
● - [24]
■ - [25]
▲ - [26]
- [49]
σ-barn
3.0
2.0
1.0
0.5
3.0
5.0
10.0
E_N-MEV
15.0

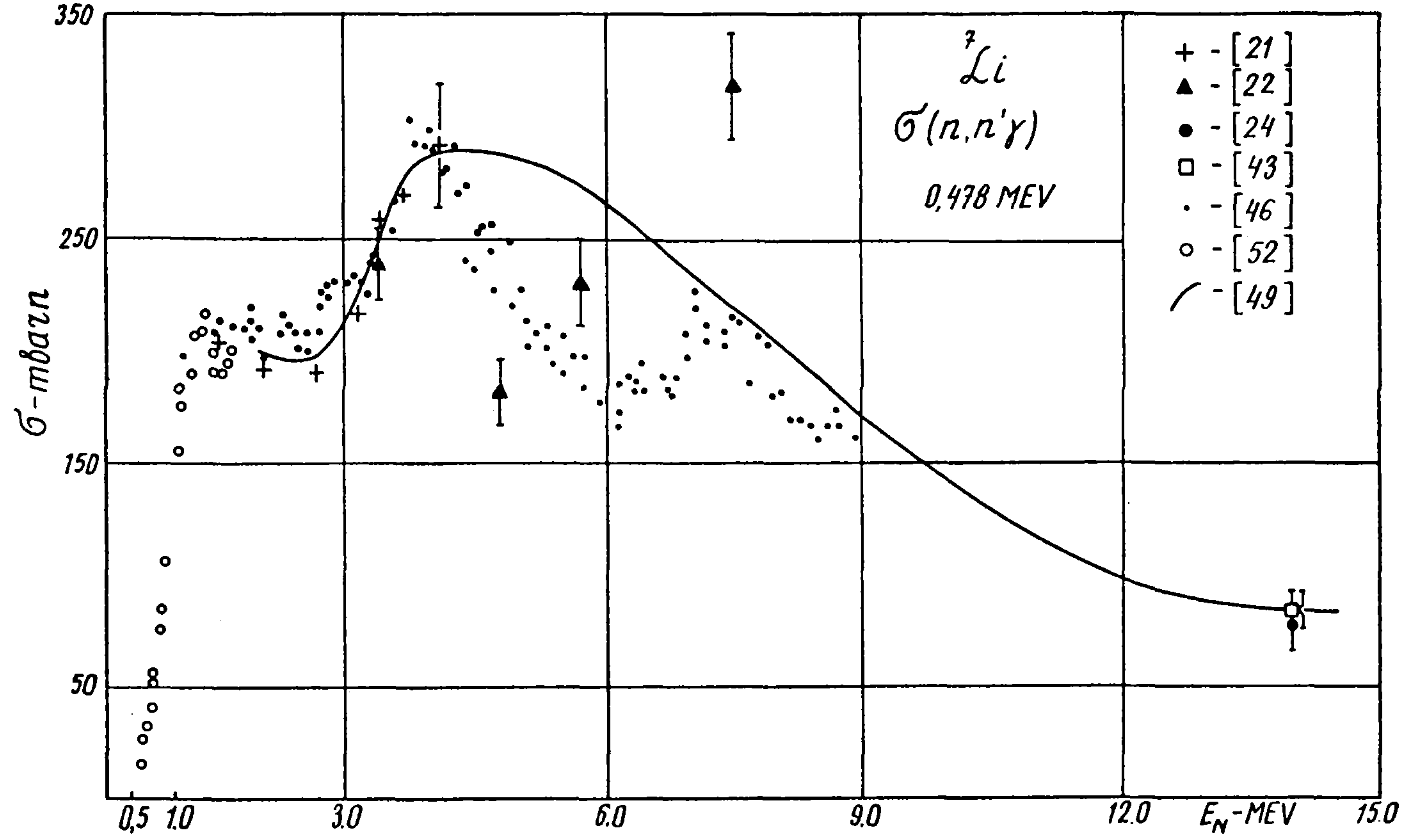
Fig.7



⁷Li
σ(n,n't)
○ - [21]
△ - [22]
▲ - [23]
□ - [32]
● - [44]
× - [47]
▼ - [45]
- [49]
0,60
0,40
0,20
σ-barn
3.0
5.0
10.0
E_N -MEV
15.0

Fig. 8

Рис. 6



350
250
150
50
σ-mbarn
0,5
1.0
3.0
6.0
9.0
12.0
E_N-MEV
15.0
⁷Li
σ(n,n'γ)
0,478 MEV
+ - [21]
▲ - [22]
● - [24]
□ - [43]
· - [46]
○ - [52]
- [49]

Fig. 9

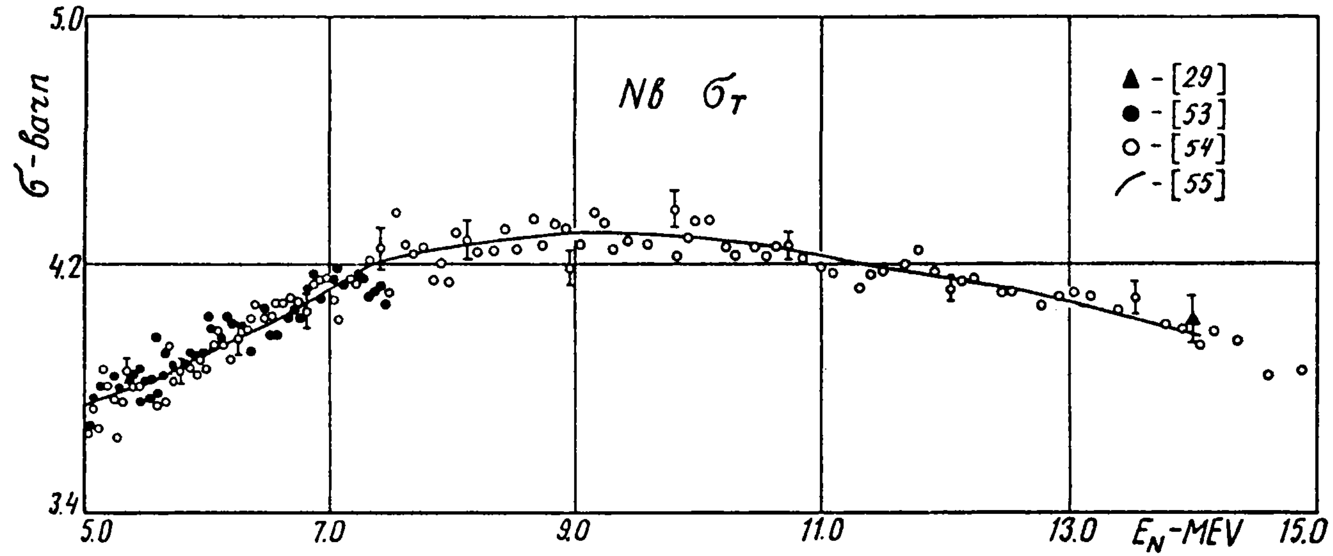


Fig. 10

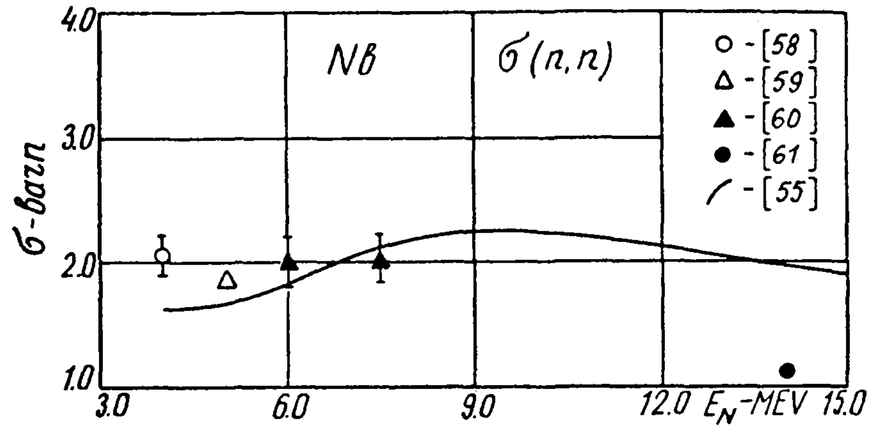


Fig. 11

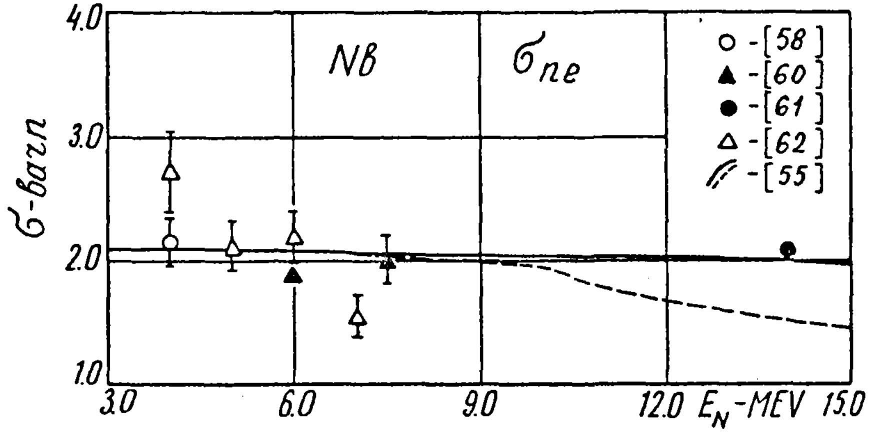


Fig. 12

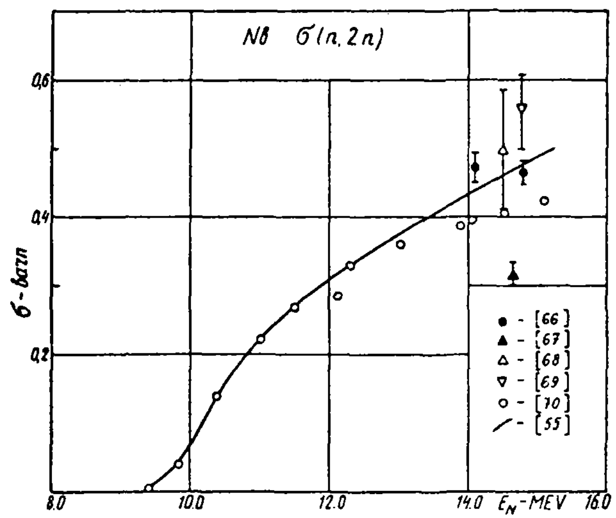


Fig. 13

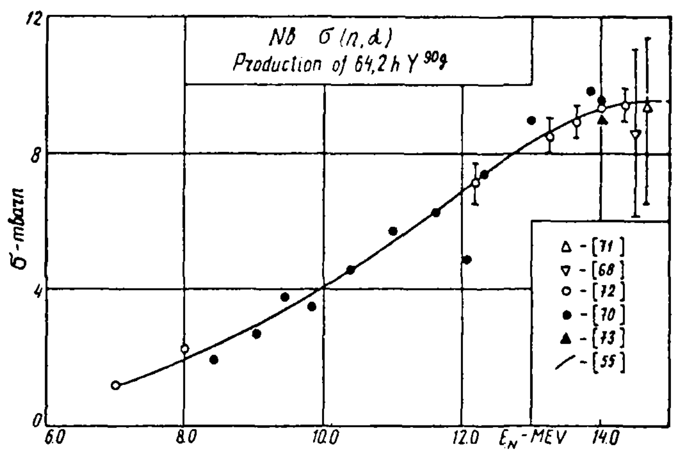


Fig. 14