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STATUS OF HIGH ENERGY NEUTRON CROSS SECTIONS *

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ABSTRACT

This paper is a review of the current status of neutron-induced reactions of interest to the fusion community in the 10- to 50-MeV neutron energy range. Although there has been significant activity in this area since the 1977 BNL Symposium on Neutron Cross Sections from 10 to 40 MeV, this review concludes that there are many areas which require more experimentation to obtain the requested accuracy. Examples of various neutron data obtained since 1977 are presented and compared to determine the extent of agreement. An attempt is made to determine what the prospects are for satisfying the fusion data needs defined by the USDOE based upon progress to date.

INTRODUCTION

The nuclear data needs of the fusion-energy program have become more defined as a result of the technical progress in the various fusion concepts (i.e., Tokomaks, magnetic mirrors, ICF, etc.). In particular, system studies of reactor designs have provided direction for material selection and hence cross sections of importance. In addition, the construction of the RTNS-II and the advent of the FMIT facility have provided great stimulus for providing nuclear data needs for radiation-damage studies.

The purpose of this paper is to review the field of high energy neutron differential cross sections in the 10- to 50-MeV energy range since the 1977 BNL symposium on this topic. The review will not be comprehensive but will concentrate on progress to date on the specific requests of the U. S. Department of Energy Fusion Program. The reader is referred to a recent article

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by Haight [1] which not only discusses many of the neutron cross sections covered in this paper but also lists previous reviews on neutron data for fusion.

NEUTRON DATA REQUESTS

The neutron data will be discussed according to the requests of the U. S. fusion energy program as delineated by C. R. Head at the IAEA Conference on Nuclear Data for Fusion Reactor Technology [2] held in Vienna in 1978 along with subsequent revisions [3] to that request list. The data will be separated into the needs of the following areas:

1. Data for the Fusion Materials Development Program;
2. Data for the Next Generation of D-T Reactor Designs;
3. Data for D-T Fusion Engineering Prototype and Demonstration Power Plant Designs.

It is difficult to cover every reaction for each element that is of interest. We will concentrate, instead, on providing an overview which should allow the reader to determine the state of the field at this time.

1. DATA FOR THE FUSION MATERIALS DEVELOPMENT PROGRAM

a. Data for FMIT

The main needs pertain to the shielding design for this materials test facility. In particular, total cross section, angular-dependent elastic scattering, and total nonelastic cross section data for Fe, O, Si, Ca, and C are presently required to an accuracy of 10-15% with a longer term (1983) requirement of 5%.

There are several laboratories which have addressed these needs. Both the University of California at Davis [4] and ORELA [5] have recently obtained total cross section (σ_T) data in the 10- to 50-MeV range of the required accuracy for all these elements. In addition, σ_T measurements have been made recently [6] at the WNR facility for carbon and oxygen. Although the quoted accuracy for all these measurements is better than 5%, the agreement is not always so good. Figure 1 shows the case for Fe where a significant discrepancy exists between the Davis and ORELA data. As Fig 2 shows, including all the σ_T data for Fe clouds the picture even more. The only reasonable assessment at this time is that the short term requirement for 10-15% accuracy has been met, but additional work is necessary to satisfy the longer term need for 5%.

For elastic scattering ($\sigma_{e\ell}$) in the 20- to 50-MeV range, only Ohio University has published any results [7]. Their data are in the 20- to 26-MeV range for Fe, O, Si, and Ca. The quality of the data meets the 10-15% short term need. Recently, U. C. Davis has done some preliminary $\sigma_{e\ell}$ measurements [4] for carbon at 40 MeV to develop a technique that can be used for satisfying some of these data requirements.

For the total non-elastic cross section, σ_{non}, U. C. Davis developed a technique [4] for obtaining these data which is schematically represented in Fig. 3. Basically, the technique works if σ_T is well known, and if a significant fraction of the elastic cross section is contained within the forward solid angle of the detector. Then σ_{non} is determined from

$$\sigma_{non} = \sigma_T - n\sigma_{e\ell}^{OM}$$

using an optical-model (OM) calculation. The result for σ_{non} is not extremely sensitive to the choice of OM parameters. Data have been obtained at 40 and 50 MeV for C, O, Fe, and Ca which meet the 10-15% accuracy requirement in some cases; the most notable exception being C at 40 MeV. This technique is capable of being extended to energies below 40 MeV, particularly if reasonable optical-model parameters exist.

b. Dosimetry Data

Dosimetry cross sections are needed in the 1- to 50-MeV range for a variety of materials to improve the accuracy of flux-spectral measurements and for material-damage-rate calculations. It is unreasonable to discuss the current situation for all thirteen isotopes listed by the USDOE for dosimetry use. Instead, we shall concentrate on cobalt since it appears to be a most promising material.

Cobalt has four reactions of interest to dosimetry, i.e., (n,p), (n,2n), (n,3n), and (n,4n). For the ^{59}Co(n,p) reaction, D. L. Smith of ANL has obtained [8,9] data that cover the 2.6- to 10-MeV energy range and whose accuracy (3-6%) is sufficient for present needs. Near 14 MeV, there is a plethora of data, all of which is not consistent. Table I lists a variety of measurements from 1960 to 1978 which vary over an order of magnitude. If one ignores the result of Jeronymo et al. [14], then the picture is not quite so bad although still unacceptable. The most recent measurement of Fukuda et al. [10] agrees well with Vonach and Munro, [12] Allan, [16] Alvar et al., [11] and Hassler et al. [15] Above the 14- to 15-MeV region, only the suspect data of Jeronymo et al. [14] exist. Clearly there is a need for more accurate data.

For the (n,2n) cross section, Frehaut et al. [18] have data from threshold to 15 MeV, which meet the accuracy requirements of 10-20%. From 16 to 24 MeV, Veeser et al. [19] also have reported data that meet this accuracy. For the (n,3n) reaction, only

Veeser et al. [19] report any data. Their measurements extend from the threshold to 24 MeV with an accuracy of 40% near the threshold and 25% near 25 MeV, neither of which meet the requested accuracy of 10-20%. There are no data reported for the (n,4n) reaction.

It is clear that there is not sufficient data for cobalt to meet these dosimetry needs. Techniques exist for obtaining the (n,xn) data particularly near threshold where the breakup neutrons from the various source reactions do not cause a problem. Such (n,xn) data near threshold are a great aid to model calculations in extending the region of interest above which data cannot be obtained easily. The ^{59}Co(n,p) reaction requires a monoenergetic source, hence its extension to higher energies will require source characterization and unfolding.

The situation for the entire list of requested dosimetry cross sections is not satisfactory. A very comprehensive review of dosimetry data was reported in 1978 by A. B. Smith et al. [20] The conclusions of that review were that only 15% of the primary dosimetry reactions were adequately known with another 35% known with marginal certainty. This has not changed in the intervening two years. There are virtually no data above 28 MeV, and it will be difficult to provide experimental data for all reactions in this energy region. Nuclear-model calculations will have to supply some of the needs. If accurate data are provided at a few energies, calculations should be able to extrapolate with sufficient accuracy. This will be considered more in the Discussion section.

Total helium-production cross sections are also required to complement the radiometric measurements in obtaining flux spectral information. Requirements are for Al, Fe, Cu, Ti, Ni, W, and Au in the 0- to 40-MeV range. Since there is an overlap of this request with that for material damage calculations, this discussion will be covered in Section 1(c).

In addition, fission-fragment track recorders are being developed for dosimetry at FMIT. Fission cross sections, σ_f, in the 14- to 40-MeV range are requested. There are very few data points for σ_f above 20 MeV, and the accuracy and energy resolution are not very good. This is an area where data could be obtained easily for several elements, such as ^{238}U, ^{232}Th, and ^{237}Np, relative to ^{235}U at a variety of white sources (e.g., ORELA, LLL, WNR) or at a quasi-monoenergetic source such as U. C. Davis. Unfortunately, the ^{235}U fission cross section itself is not known so that a measurement relative to the (n,p) cross section probably would be necessary to provide absolute cross section values.

c. Material-Damage Calculations

Differential-angular cross sections for elastic scattering and all nonelastic reactions for Fe, Ni, Cr, Al, Cu, W, Sn, Ti, and V are needed at a few neutron energies between 15 and 35 MeV for material-damage experiments and calculations.

Elastic-scattering data exist for several of the requested elements in the energy range from 15 to 26 MeV. However, no data exist above 26 MeV. Ohio University has performed measurements on Al [7], Fe [7], Ni [21], and Si [22] between 20 and 26 MeV. Winkler et al. [23] (IRK, Vienna) have measured elastic scattering for Cr at 15 MeV. Galloway et al. [24] (Edinburgh) have made differential-elastic measurements for Cu and W. The requested accuracy is 10% for neutron energies below 25 MeV decreasing to 40% at 35 MeV. The Ohio University measurements are accurate to 5-10%; the results of Winkler have a 15% uncertainty; the Galloway results appear to be within the 10% request.

The request for angular and energy distributions for all emitted particles in nonelastic reactions is, of course, quite comprehensive. Since it is not possible to discuss all pertinent reactions, we shall concentrate on discussing neutron-inelastic scattering and charged particle spectra from neutron reactions.

For differential inelastic scattering, Corcalciuc et al. (Studsvik) have reported results [24a] for ^{56}Fe(n,n') from 16 to 22 MeV. Ohio University has obtained inelastic-scattering data for ^{58,60}Ni [21] at 24 MeV, for Si [22] at 20 and 26 MeV, and for ^{116}Sn [25] at 24 MeV. Winkler et al. [23] (IRK, Vienna) report new inelastic-scattering measurements for [illegible] at 15 MeV.

For (n, charged particle) measurements involving a determination of the energy spectra and angular distributions of emitted particles, there have been several active groups, most notably that of Haight and Grimes at LLL. Their data cover energy and angular distributions for Al [26], Fe [27], Ni [27], Cr [27], V [28], Ti [26], Cu [27], and Nb [28] for an incident-neutron energy near 15 MeV using a quadrupole spectrometer. A spectrum of emitted protons from Ni for an angle of 90 degrees is shown in Fig. 4. The data were taken at seven angles between [illegible] and 135°. Examples of angle-integrated α-particle emission spectra for Cr, Fe, Ni, and Cu isotopes are shown in Fig. 5.

Measurements of the ^{50}Cr(n,α) and ^{93}Nb(n,α) energy and angular distributions have been performed by Vonach et al. [29] at 14 MeV using a multitelescope proportional-counter-scintillator system. A multi-angle reaction chamber has been developed at Geel [30] to measure (n,α) energy and angular distributions at 5 angles. Initial measurements [31] on Cr, Fe, and Ni have been in the 5- to 10-MeV range but are capable of being extended to higher energies. Cookson and Wise [32] have developed a proportional-counter-scintillator at Harwell. Initial measurements are planned for Fe, Ni, and Cr near 15 Mev.

All of the above facilities have been developed for use at neutron energies near 15 MeV. Several laboratories have been active above 15 MeV. A facility has been developed at U. C. Davis [4] for neutron-induced charged particle measurements in the 20- to 60-MeV region. The initial measurements have been for the $^{12}C(n,x\alpha)$ reaction at E_n = 40 MeV. Plans are to extend such measurements to other materials of interest.

Ohio University has constructed a quadrupole spectrometer for differential charged particle spectral measurements. Experiments on $^{58}Ni(n,p)$ at 20 MeV and $^{12}C(n,3\alpha)$ to 25 MeV are planned. [33]

Total differential helium and hydrogen production cross sections are needed at a few points in the 15- to 35-MeV range to allow unfolding of integral helium and hydrogen production data. Virtually all the data on these cross sections exist near 15 MeV although there are plans to measure helium production cross sections at IRK (Vienna) for ^{63}Cu in the 12- to 20-MeV range [34]. Paulsen *et al.* [35] (Geel) also report data for $^{54}Fe(n,p)$, $^{54}Fe(n,\alpha)$ and $^{56}Fe(n,\alpha)$ in the 12- to 17-MeV region using activation methods. The measurements at 15 MeV have been performed by several laboratories using a variety of techniques. Table II compares the results obtained by LLL [26-28] at 15 MeV for a series of elements using a quadrupole spectrometer, by Rockwell International [36] using the helium-accumulation technique and by Qaim [37] (Julich) using activation methods. The agreement in all cases is quite good. Table III compares results for isotopes of Cu and Ti in which both the activation technique and the quadrupole spectrometer were employed. The results of Qaim *et al.* [38] for ^{65}Cu agree well with the results of Grimes *et al.* [26,27] (LLL) while the results of Winkler [39] for ^{63}Cu do not agree well with the LLL results. The Winkler data have a small (2.5%) uncertainty compared to the LLL results (17%). However, a comparison made by Winkler in Ref. 39 of all the data to date indicates that the activation results tend to yield smaller $^{63}Cu(n,\alpha)$ cross sections than the direct alpha-particle measurements. The source of this discrepancy is not known. Preliminary results [10] from Kyushu University for $^{63}Cu(n,\alpha)$ using activation techniques, however, agree well with the LLL results.

The data needs for material-damage calculations are being addressed in a fairly comprehensive manner. There is a need for data at a few energies above 15 MeV to check calculations, however. Adequate techniques exist for providing the required data.

2. DATA FOR THE NEXT GENERATION OF D-T REACTOR DESIGNS

a. Neutron Emission Spectra

The spectra of neutrons as a function of secondary angle and energy are required for selected neutron energies in the 9- to 15-MeV range for the elements listed in Table IV. The required accuracy is 10%.

This area has been addressed with significant experimental activity. Table IV indicates the incident neutron energies for which data have been obtained, and the laboratories at which the experiments have been performed. Fig. 6 shows the LASL results for ^{6}Li and ^{7}Li at an incident energy near 10 MeV. Fig. 7 shows the preliminary TUNL results for emission spectra from a variety of elements including angular spectra for Fe at an incident neutron energy of 10 MeV. Iwasaki *et al.* [40] (Tohoku University) have obtained neutron emission spectra for Al at 12 scattering angles for an incident neutron energy near 15 MeV. Morgan and Perey [41] have measured neutron-emission spectra at ORELA for Al and Cu at incident energies between 1 and 20 MeV. Their technique yields data at one secondary angle near 130° (lab). Chalupka *et al.* [45] (IRK, Vienna) have completed measurements of angle-integrated secondary neutron spectra for elements listed in Table IV. Some of these results will be presented at this conference.

The accuracies obtained in the measurements discussed above all meet the 10% accuracy requirement except for those of Iwasaki *et al.* who quote a 7-17% uncertainty in their data.

b. Helium and Hydrogen Production

Helium and hydrogen production cross sections are requested in the 9- to 15-MeV range for the same elements listed in Table IV. As mentioned in Section 1(c), most of data exist near 15 MeV where a considerable variety of techniques have been used. Measurements at 15 MeV on Al, Ni, Cu, Fe, and Cr were discussed in Section 1(c). Data for the remaining elements in Table IV will be discussed below.

For carbon, Farrar and Kneff [46] (Rockwell International) report data at 15 MeV using the helium accumulation method. They plan similar measurements on ^{6,7}Li, ^{10,11}B, Pb, and Si. Ohio University has obtained preliminary data [47] for ^{12}C(n,α_0) at 9 MeV. LLL plans both helium and hydrogen production cross section measurements at 15 MeV on ^{7}Li, ^{11}B, and Si using their quadrupole spectrometer [48].

The measurements made or planned at 15 MeV appear to address the needs adequately. However there is clearly a need for more data at a few energies below 15 MeV.

c. Breeding Reactions in ^{7}Li

Data on the ^{7}Li(n,n't) reaction are required for incident-neutron energies between 11 and 14 MeV. The requested accuracy is 5% although 10% would be valuable. Data have been obtained by measurement of tritium accumulation by Brown *et al.* [49], Osborn and Wilson [50], and Wyman and Thorpe [51]. A direct measurement was performed by Rosen and Stewart [52] in which the triton tracks were observed in photographic emulsions. In addition, this cross section was extracted from neutron emission spectral measurements. All of these data are compared in Fig. 8. It was stated in Haight's review article [1] on fusion data that the ^{7}Li(n,n't) cross section is uncertain to 25% which is consistent with Fig. 8. A measurement of this cross section by β counting the tritium produced is being conducted at Harwell by Uttley and Swinhoe [53]. A collaborative measurement is also being planned by Julich and Geel in this energy region[54].

3. DATA FOR D-T ENGINEERING PROTOTYPES AND DEMONSTRATION POWER PLANT DESIGNS

a. Neutron Emission Spectra

Similar to the request of 2(a) above, neutron spectra as a function of secondary angle and energy are required for selected energies between 9 and 15 MeV. The elements requested are listed in Table V. along with the laboratories which have made recent measurements. The data from Morgan *et al.* [55] at ORELA for Nb and Ti span the entire incident neutron energy range of interest but are for a single secondary angle. The data from IRK [45] (Vienna) are angle-integrated spectra at 14 MeV incident neutron energy. The most complete data are those from LASL for ^{9}Be and ^{11}B for incident-neutron energies of 10 and 14 MeV. The data of Tohoku University for Nb at 15.4 MeV incident-neutron energy cover 12 angles from 25° to 155°. The accuracy of all these measurements is better than the requested 10% except for the Tohoku measurements which vary from 7% to 17%.

b. Secondary Gamma Production Cross Sections

This request is for (n,xγ) data from the inelastic threshold to 15 MeV for ^{10}B, ^{11}B, and Ti with a 10% accuracy. The most complete results are the data of Morgan *et al.* [55] for Ti (Fig. 9) which cover the entire range of interest with an accuracy of a few percent or better. For ^{10}B, Nellis *et al.* [57] have obtained (n,xγ) data for incident-neutron energies between 0.5 and 5 MeV and at 14 MeV. Haouat *et al.* [58] measured (n,xγ) cross sections from 7 to 10 MeV for ^{11}B. Bezotosnyi *et al.* [59] have measured secondary gamma production at 14 MeV for both ^{10}B and ^{11}B.

DISCUSSION

It is clear from the preceding sections and from the number of contributed papers to this session that there has been considerable activity in certain areas of data needs for the 10- to 50-MeV region. It is interesting to compare what has actually been measured in the interim since the 1977 BNL Symposium on this topic with the recommendations of the Working Group on Differential Data at that meeting. Their report was divided into two parts: (i) transmutation and specific damage cross sections; (ii) dosimetry cross sections.

For charged particle production, one of the main recommendations was for measurements at selected energies between 15 and 50 MeV for selected isotopes to check nuclear model calculations. Above 15 MeV, the only differential data published are those of Paulsen et al. [35] for the ^{54}Fe(n,α) reaction using activation technique. However, there are measurements planned [33] at Ohio University for ^{58}Ni(n,p) near 20 MeV and ^{12}C(n,3α) up to 25 MeV. Also, a collaborative measurement is planned [54] for the ^{63}Cu(n,α)^{60}Co reaction in the 12- to 20-MeV region by Geel and IRK (Vienna) using the activation technique.

Although there are not many new data above 15 MeV at this point, there have been significant developments in experimental techniques. These include an (n, charged particle) facility at U. C. Davis [4], a new multitelescope proportional counter - CsI scintillator system at IRK (Vienna) [29], a multi-angle reaction chamber (charged-particle telescopes) at CBNM Geel [30], a proportional counter - CsI scintillator system at Harwell [32], and new quadrupole spectrometers at Ohio University [33] and LLL [48]. Such developments will stimulate new measurements above 15 MeV. Indeed, U. C. Davis has already reported some preliminary ^{12}C(n,xα) data for E_n = 39 MeV. Such developments will stimulate new measurements above 15 MeV. The report also recommended feasibility studies into the use of white sources for (n, charged particle) measurements since there is a possibility of obtaining data over the entire energy range. There has been some development at ORELA in this direction with no data to date. Feasibility studies are planned for WNR by N. King of LASL [60].

For total cross sections, the Working Group recommended that measurements be performed over the entire 15- to 50-MeV range. As has been seen, this is one area that has received considerable attention. The total cross section measurements at U. C. Davis, ORELA, WNR, and NBS all provide valuable data with which calculations can be compared for all elements of interest to the fusion program. However, the ability to provide 1% statistical data does not guarantee equal systematic errors as can be seen in the comparison of σ_T data for Fe in Fig. 2. It is important to have several laboratories provide data that agree to within statistical errors so that the model calculations are useful. These discrepancies should disappear as the experimentalists learn more about how to do such measurements in this energy range.

Most of the data for elastic scattering come from the Ohio University group for the energy range between 20 and 26 MeV. U. C. Davis is considering elastic-scattering measurements in the 30- to 50-MeV range but have only preliminary data for carbon at 40 MeV. It may be difficult to obtain a significant set of data above 30 MeV since the number of facilities capable of doing the measurements are small. The use of calculations will have to be extensive and charged-particle scattering data should be very useful in this regard.

For the elements of interest, data for (n,xn) reactions above 20 MeV are limited. Direct measurements are possible but require care in understanding of the breakup neutron spectrum above 30 MeV. There are no new measurements planned at the present time. Data from (p, xn) reactions could be valuable for comparison with model calculations.

Data in the 9- to 15-MeV range is becoming more plentiful as various laboratories have begun to publish neutron-emission spectra, (n, charged particle) data, tritium-breeding data, elastic and inelastic-scattering cross sections. There should not be any difficulty in meeting the needs of the fusion program as was pointed out by the Working Group in 1977. In 1980, the picture looks even better.

In the area of dosimetry cross sections, the Working Group on Differential Cross Sections defined an appropriate program necessary to provide these needs in a short time scale. The recommendations included formation of a study group of measurers - users - evaluators/theorists to define 10 to 15 critical reaction types. The request list now includes 30 reaction types for 13 elements. The review of Smith et al. [20] stated that such a list is too long and probably redundant in certain areas. We would agree with this assessment. It will be difficult to obtain adequate experimental data for all the reactions over the 1- to 50-MeV range. Initially it would be better to specify fewer cases which have the possibility of achieving satisfactory accuracies by both experimentation and calculation. Another recommendation of the Working Group regarding dosimetry cross sections was that secondary reference standards were to be determined to 3% accuracy relative to H(n,n) for use in these dosimetry measurements. It is not clear that this point has received adequate attention. Measurements above 30 MeV are difficult because the characterization of the source is vital in understanding the activation results. The region above 30 MeV has received very little effort in the past 3 years, and no measurements are planned. Below 30 MeV, there is activity because the measurements are easier to perform and the neutron sources easier to use. Although more data are required, this lower energy region should be addressed adequately in the future. In particular, measurements at Geel in collaboration with IRK (Vienna) should be valuable. Measurements by Qaim et al. in Julich should also provide important data.

CONCLUSIONS

Haight concluded his review of this subject in 1977 with the observation that the picture for the future was bright even though there were very few data because of the arsenal of new experimental techniques. Three years later, it is easy to remark that the picture is even brighter. There are even more techniques, and there are more laboratories contributing to the field. The data in the 9- to 15-MeV range appear to be of very high quality. Although the data above 15 MeV are still limited, there are new programs planned or in progress to address many of the areas.

The main recommendation of the 1977 Working Group on differential data was that the bulk of the data required for applications should come from model calculations verified by some experimental data. Good theoretical tools for such calculations are certainly available to provide evaluated data sets for many of the fusion data needs. This is evidenced by the eleven contributed talks on this subject later in the conference. It would be very appropriate for the theorist/evaluator community to provide more guidance to the experimentalist now that more experimental programs are underway. Rather than obtaining data for every request, it would be better to first make the best calculations possible to determine which cross sections are sensitive and require the most emphasis in a particular problem.

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REFERENCES

1. R. C. HAIGHT, "Neutron Cross Sections for Fusion," Proc. Conf. Nuclear Data for Technology, Knoxville, 1979 - to be published; also R. C. HAIGHT, "Review of Neutron Data: 10 to 40 MeV," Proc. Symposium on Neutron Cross Sections 10 to 40 MeV, Brookhaven National Laboratory, 1977, p. 201.

2. C. R. HEAD, "Nuclear Data Requirements of the Magnetic Fusion Power Program of the United States of America," Proc. Conf. On Nuclear Data for Fusion Reactor Technology, IAEA, Vienna, 1978, p. 1.

3. R. N. NG, "Magnetic Fusion Energy Program Nuclear Data Needs - Revision," letter to S. L. Whetstone, April, 1980.

4. U. C. DAVIS Progress Report to NSF, July 1, 1977 to June 30, 1979, Report No. UCD-CNL 192.

5. D. C. LARSON, J. A. HARVEY, and N. W. HILL, "Neutron Total Cross Sections of Hydrogen, Carbon, Oxygen, and Iron from 500 keV to 60 MeV," Proc. Conf. on Nuclear Data for Technology, Knoxville, TN, 1979 - to be published.

6. P. W. LISOWSKI *et al.*, "Neutron Total Cross section Measurements at WNR," these proceedings.

7. J. A. RAPAPORT *et al.*, "Neutron Scattering Measurements at Ohio University in the Energy Range 7-26 MeV," Proc. Symposium on Neutron Cross Sections 10-40 MeV, Brookhaven National Laboratory, 1977, p. 247.

8. D. L. SMITH and J. W. MEADOWS, "Cross Section Measurements of (n,p) Reactions for al, Ti, Fe, Co, and Zn from Near Threshold to 10 MeV," Nucl. Sci. Eng., **58**, 314 (1975).

9. D. L. SMITH and J. W. MEADOWS, "Measurement of Cross Sections for the ^{59}Co(n,p) Reaction Near Threshold," Nucl. Sci. Eng., **60**, 187 (1976).

10. K. FUKUDA *et al.*, "Activation Cross Sections for Co for 14.6-MeV Neutrons," Report No. NEANDC (J)-56U, 1978, p.44; also see NEANDC(J)-61U, 1979, p. 94.

11. K. ALVAR, "Proton Energy and Angular Distributions from (n,p) and (n,np) Reactions," Nucl. Phys. **A195**, 289 (1972).

12. L. LEVKOVSKI *et al.*, Sov. Nucl. Phys., **8**, 4 (1969).

13. H. VONACH and J. MUNRO, "^{59}Co(n,p) Cross Section at 14.8 MeV," Nucl. Phys., **68**, 445 (1965).

14. J. JERONYMO *et al.*, "Absolute Cross Sections for Some (n,p), (n,α), and (n,2n) Reactions," Nucl. Phys., **47**, 157 (1963).

15. F. HASSLER and R. PECK, "Neutron-Induced Reactions in Third and Fourth Shell Nuclei," Phys. Rev., **125**, 1011.

16. D. L. ALLAN, "An Experimental Test of the Statistical Theory of Nuclear Reactions," Nucl. Phys., **24**, 274 (1961).

17. I. PREISS and R. FINK, "New Isotopes of Cobalt; Activation Cross Sections of Nickel, Cobalt, and Zinc for 14.8 MeV Neutron," Nucl. Phys., **15**, 326 (1960).

18. J. FREHAUT, Proc. 3rd All-Union Conf. Neutron Physics, Kiev, 1975, Vol. 4, p. 303.

19. L. VEESER, E. ARTHUR, and P. YOUNG, "Cross Sections for (n,2n) and (n,3n) Reactions above 14 MeV," Phys. Rev., *C16*, 1792 (1977).

20. A. B. SMITH *et al.*, "Nuclear Data for High-Energy Neutron-Damage Studies," NEANDC Meeting, Oak Ridge, Tn, 3-7 April, 1978.

21. Y. YAMANOUTI *et al.*, "Elastic and Inelastic Scattering of 24 MeV Neutrons From Even Isotopes of Ni," Proc. Conf. Nuclear Data for Technology, Knoxville, 1979 - to be published.

22. J. RAPAPORT *et al.*, "Neutron Elastic Scattering on T = 0 Nuclei," Nucl. Phys., *A286*, 232 (19 7).

23. G. WINKLER, K. HANSJAKOB, and G. STAFFEL, "Measurement of Differential Elastic and Inelastic Scattering Cross Sections with 14-MeV Neutrons on Barium and Chromium," Proc. Conf. Nuclear Data for Technology, Knoxville, 1974 - to be published.

24. R. GALLOWAY and F. WATSON, "Polarization and Differential Cross Sections for Elastic Scattering of 16-MeV Neutrons," Report No. NEANDC(E) - 192U, Vol 8, 1978, p. 121.

24a. V. CORCALCIUC *et al.*, "A Study of the Neutron Induced Reactions for ^{19}F, ^{56}Fe, and ^{59}Co in the Energy Interval 16 to 22 MeV," Nucl. Phys., *A307*, 445 (1978).

25. R. W. FINLAY *et al.*, "Isospin Effects in Nucleon Inelastic Scattering from Closed Shell Nuclei," Nucl. Phys. - to be published, 1980.

26. S. GRIMES, R. HAIGHT, and J. ANDERSON, "Measurement of Sub-Coulomb-Barrier Charged Particles Emitted from Aluminum and Titanium Bombarded by 15-MeV Neutrons," Nucl. Sci. Eng., *62*, 187 (1977).

27. S. GRIMES *et al.*, "Charged-Particle Emission in Reactions of 15-Mev Neutrons with Isotopes of Chromium, Nickel, and Copper," Phys. Rev., *C19*, 2127 (1979).

28. S. GRIMES, R. HAIGHT, and J. ANDERSON, "Charged-Particle-Producing Reactions on ^{51}V and ^{93}Nb," Phys. Rev. *C17*, 508 (1978).

29. H. VONACH *et al.*, "Investigation of the Energy and Angular Distributions of Protons and Alpha Particles from (n,p) and (n,α) Reactions," Proc. Int. Symp. on the Interaction of Fast Neutrons with Nuclei, Gaussig, 1978., p. 161.

30. H. LISKIEN *et al.*, "Recent Development of Special Detection Systems at the Van de Graaff of CBNM," Proc. Int. Conf. on the Interaction of Fast Neutrons with Nuclei, Gaussig, 1979.

31. A PAULSEN *et al.*, "Measurement of (n,α) Cross Sections on Cr, Fe, and Ni in the 5- to 10-MeV Range," Proc. Conf. Nuclear Data for Technology, Knoxville, 1979 - to be published.

32. J. COOKSON and C. WISE, "(n, α) Cross Sections," Report No. NEANDC(E) - 192U, Vol. 8, 1978, p. 61.

33. G. RANDERS-PHERSON, Ohio University - private communication (1980).

34. H. VONACH, Institut fur Radiumforschung und Kernphysik, Vienna - private communication (1980).

35. A. PAULSEN *et al.*, "Cross Sections for the Reactions ^{54}Fe(n,α), ^{54}Fe(n,p)," Nucl. Sci. Eng., 72, 113 (1979).

36. H. FARRAR and D. KNEFF, "Helium Generation in Twelve Pure Elements by 14.8-MeV Neutrons," Trans. Am. Nucl Soc., 28, 197 (1978).

37. S. QAIM *et al.*, 9th Symp. on Fusion Technology, Garmisch, 1976, p. 589.

38. S. QAIM and G. STOCKLIN, "Measurement and Systematics of Fast Neutron Induced Hydrogen and Helium Producing Reaction Cross Sections for FRT - Related Structural Materials," Proc. Specialist Meeting, CBNM, 1977, p. 327.

39. G. WINKLER, "Precise Measurement of the ^{63}Cu(n,α) Cross Section with 14-MeV Neutrons," Nucl. Sci. Eng., 67, 260 (1978).

40. S. IWASAKI *et al.*, "Neutron Energy Spectra and Angular Distributions for Al and Nb(n,xn) Reactions at 15.4 MeV," Proc. Conf. Nuclear Data for Technology, Knoxville, 1974 - to be published.

41. G. L. MORGAN, "Cross Sections for Cu(n,xn) and Cu(n,xγ) Reactions Between 1 and 20 MeV," Report No. ORNL-5499 (1979); G. L. MORGAN and F. G. PEREY, "Cross Sections for Al(n,xn) and Al(n,xγ) Reactions Between 1 and 20 MeV," Report No. ORNL/TM-5241 (1976).

42. P. LISOWSKI *et al.*, "Cross Sections for Neutron-Induced, Neutron-Producing Reactions in ^{6}Li and ^{7}Li at 5.96 and 9.83 MeV," Report No. LA-83-42 (1980).

43. P. LISOWSKI, Los Alamos Scientific Laboratory - private communication (1980).

44. A. BEYERLE *et al.*, "Double-Differential Neutron Scattering Cross Sections for Fe, Cu, Ni, and Pb between 8 and 12 MeV," Proc. Conf. Nuclear Data for Technology, Knoxville, 1979 - to be published.

45. A. CHALUPKA et al., "Measurement of Angle-Integrated Secondary Neutron Spectra from Interaction of 14-MeV Neutrons with Medium and Heavy Nuclei," Proc. Int. Symp. on the Interaction of Fast Neutrons with Nuclei, Gaussig, 1979.

46. D. KNEFF and H. FARRAR, "Helium Generation in Fusion Materials," Damage Analysis and Fundamental Studies Quarterly Status Report, Jan.-Mar., 1979; also see Ref. 36.

47. R. FINLAY, Ohio University - private communication (1980).

48. R. HAIGHT, Lawrence Livermore Laboratory - private communication (1980).

49. F. BROWN *et al.*, J. Nucl. Energy, *A/B17*, 137 (1963).

50. A. OSBORN and H. WILSON, AWRE (1961) - private communication in Ref. 1.

51. M. WYMAN and M. THORPE, Los Alamos Scientific Laboratory Report No. LA-2235 (1958).

52. L. ROSEN and L. STEWART, "Neutron-Induced Disintegration of ^{6}Li and ^{7}Li," Phys. Rev., *126*, 1150 (1962).

53. C. UTTLEY and M. SWINHOE, "The ^{7}Li(n,n'αt) Reaction," Report No. NEANDC(E)-192U, Vol. 8, 1978, p. 60.

54. S. QAIM, Der Kernforschungsanlage Julich - private communication (1980).

55. G. L. MORGAN, "Cross Sections for the Ti(n,xn) and Ti(n,xγ) Reactions between 1 and 26 MeV," Report No. ORNL-5563, 1979; G. L. MORGAN and F. G. PEREY, "Cross Sections for the Nb(n,xn) and Nb(n,xγ) Reactions between 1 and 20 MeV," Report No. ORNL/TM-5829, 1977.

56. D. L. DRAKE *et al.*, "Double-Differential Beryllium Neutron Cross Sections at Incident Neutron Energies of 5.9, 10.1, and 14.2 MeV," Nucl. Sci. Eng., *63*, 401 (1977).

57. D. NELLIS, W. TUCKER, and I. MORGAN, "Gamma-Ray Yield from Neutron Interactions with ^{10}B," Phys. Rev. *C1*, 847 (1970).

58. G. HAOUAT et al., Jour. de Phys. Suppl., *S31*, 148 (1970).

59. S. BEZOTOSNYJ *et al.*, Proc. All-Union Conf. on Neutron Physics, Kiev, 1975, Vol. 4, p. 133.

60. N. S. P. KING, Los Alamos Scientific Laboratory - private communication (1980).

61. Y. YU and D. G. GARDNER, "Cross Sections of Some Reactions of Ar, Ti, Ni, Cd, and Pb with 14.1-MeV Neutrons, Nucl. Phys., *A98*, 451 (1967).

62. P. YOUNG, Los Alamos Scientific Laboratory - private communication (1980).

TABLE I

$^{59}Co(n,p)$ Cross Sections Near 14 MeV

Measurement	Reference	E_n(MeV)	Cross Section(mb)
Fukuda *et al.*	10	15	53.1 ± 4.5
Alvar *et al.*	11	14	73 ± 22
Levkovski *et al.*	12	15	37 ± 6
Vonach and Munro	13	14.8	53 ± 12
Jeronymo *et al.*	14	14.9	425 ± 70
Hassler *et al.*	15	14	48 ± 5
Allan	16	14	51 ± 10
Preiss and Fink	17	14.8	83 ± 8

TABLE II

Helium Production Cross Sections Near 15 MeV for Material-Damage Calculations

Laboratory	Technique	Al	Fe	Ni	V	Nb	Ti
LLL[a]	Spectrometer	121 ± 25	43 ± 7	97 ± 16	17 ± 3	14 ± 3	(d)
Rockwell Int.[b]	Helium Accumulation	142 ± 7	48 ± 3	98 ± 6	18 ± 2	17 ± 5	38 ± 3
Julich[c]	Activation				16 ± 1		

[a] Ref. 26, 27, 28

[b] Ref. 36

[c] Ref. 37

[d] Isotopic Data for ^{46,48}Ti in Ref. 26

TABLE III

Helium Production Cross Sections Near 14 MeV for Cu and Ti Isotopes

Laboratory	Technique	^{63}Cu	^{65}Cu	^{46}Ti	^{48}Ti
LLL[a]	Spectrometer	56 ± 10	13.5 ± 2.0	94 ± 18	26 ± 6
Julich[b]	Activation		17.7 ± 4.[illegible]		
IRK, Vienna[c]	Activation	40.7 ± 1			
Ill. Inst. Tech.[d]	Activation				39 ± 6
Kyushu Univ.[e]	Activation	50.4 ± 5.7			

[a] Ref. 26, 27

[b] Ref. 38

[c] Ref. 39

[d] Ref. 61

[e] Ref. 10

TABLE IV

List of Elements for which Neutron Emission Spectra are requested in the 9- to 15-MeV region for the next generation of D-T reactor designs along with laboratories performing recent measurements.

Element	Laboratory	Incident Neutron Energy(MeV)
Al	Tohoku Univ.[a] ORELA[b]	15.6 1 - 20
^{7}Li	LASL[c]	10, 14
C	LASL[d]	14
Ni	TUNL[e] IRK, Vienna[f]	10, 12 14
Cu	TUNL[e] IRK, Vienna[f]	10, 12 14
^{10}B	LASL[c]	10, 14
Fe	TUNL[e] IRK, Vienna[f]	10, 12 14
Cr	IRK, Vienna[f]	14
Pb	TUNL[e]	10, 12
Si		
W	IRK, Vienna[f]	14
O		
N		

[a] Ref. 40
[b] Ref. 41
[c] Ref. 42
[d] Ref. 43
[e] Ref. 44
[f] Ref. 45

TABLE V

List of Elements for which Neutron Emission Spectra are requested in the 9- to 15MeV range for D-T fusion engineering prototype and demonstration power plant designs. Included are the laboratories performing recent measurements.

Element	Laboratory	Incident Neutron Energy(MeV)
Fe	LASL[a]	10, 14
Ti	IRK, Vienna[b]	14
	ORELA[c]	1 - 20
Nb	Tohoku Univ.[d]	15.6
	ORELA[c]	1 - 20
	IRK, Vienna[b]	14
Sn	IRK, Vienna[b]	14
Mo	IRK, Vienna[b]	14
V		
^{11}B	LASL[e]	10, 14
F		

[a] Ref. 56
[b] Ref. 45
[c] Ref. 55
[d] Ref. 40
[e] Ref. 42

FIGURE CAPTIONS

1. A comparison of total cross-section results for Fe obtained at U. C. Davis (Brady - Ref. 4) and at ORELA in 1979 (Larson - Ref. 5). The ORELA results are plotted in 5-point averages.

2. A comparison of total cross section results for Fe obtained at U. C. Davis (Ref. 4), at ORELA in 1979 (Ref. 5), at Karlsruhe (Cierjacks - Ref. 62), and at ORELA in 1972 (Perey - Ref. 62). All ORELA results are plotted as 5-point averages; the Karlsruhe data are plotted as 15-point averages.

3. A schematic representation of the experimental arrangement us[illegible] C. Davis (Ref. 4) to obtain non-elastic c[illegible]ion data.

4. Proton-emission cross section at 90° for Ni obtained by Grimes *et al.* (Ref. 27) at LLL using a quadrupole spectrometer.

5. Angle-integrated alpha-particle-emission cross sections (n,xα) for Cr, Fe, Ni, and Cu isotopes obtained by Grimes *et al.* (Ref. 27). The data are averaged into 500 keV bins; the solid line is a Hauser - Feshbach calculation; the dashed line represents alphas emitted from the first compound nucleus.

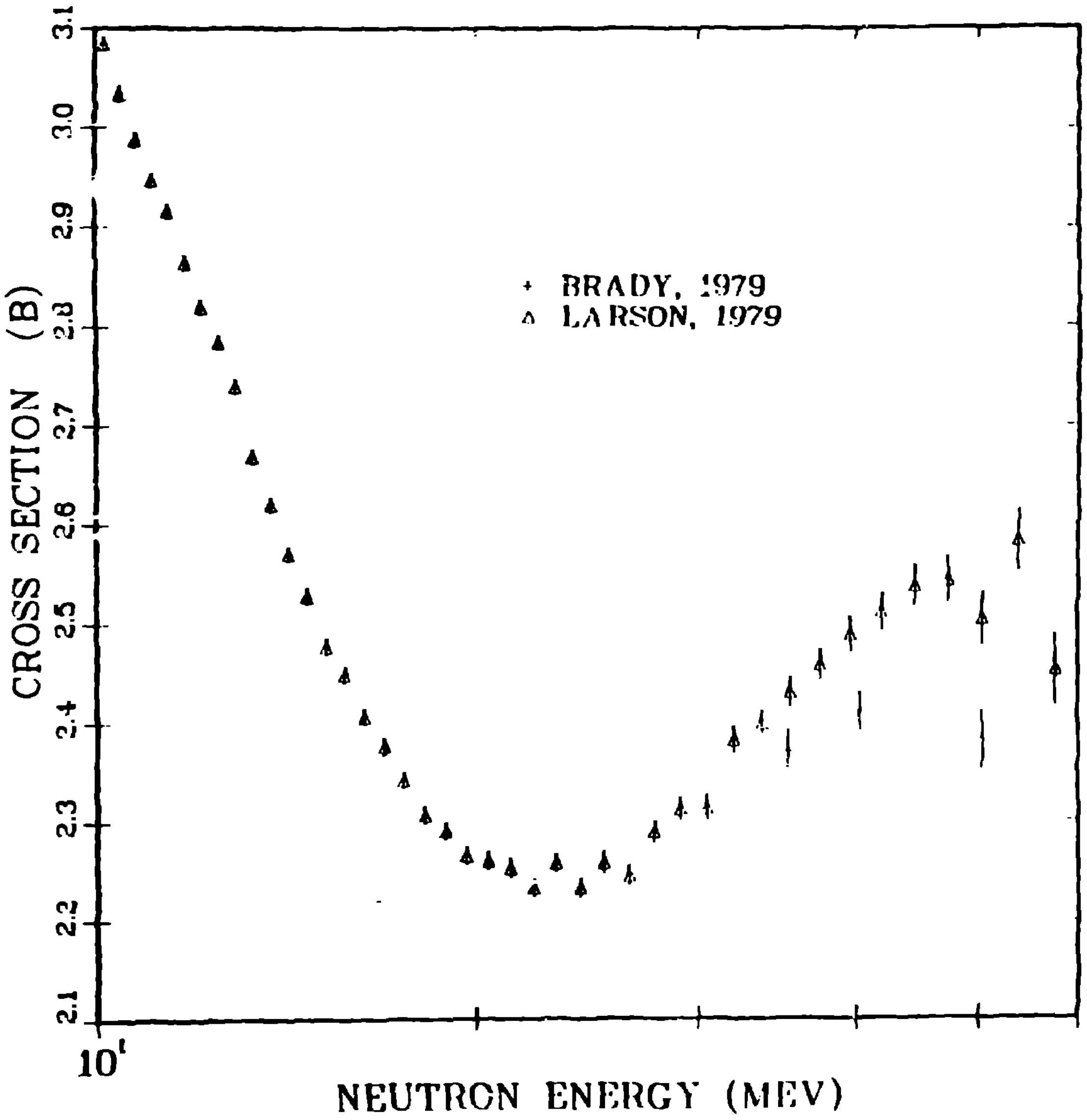
6. Neutron emission spectra for ^{6}Li and ^{7}Li at 2 angles for 10-MeV incident neutrons obtained as LASL (Ref. 42).

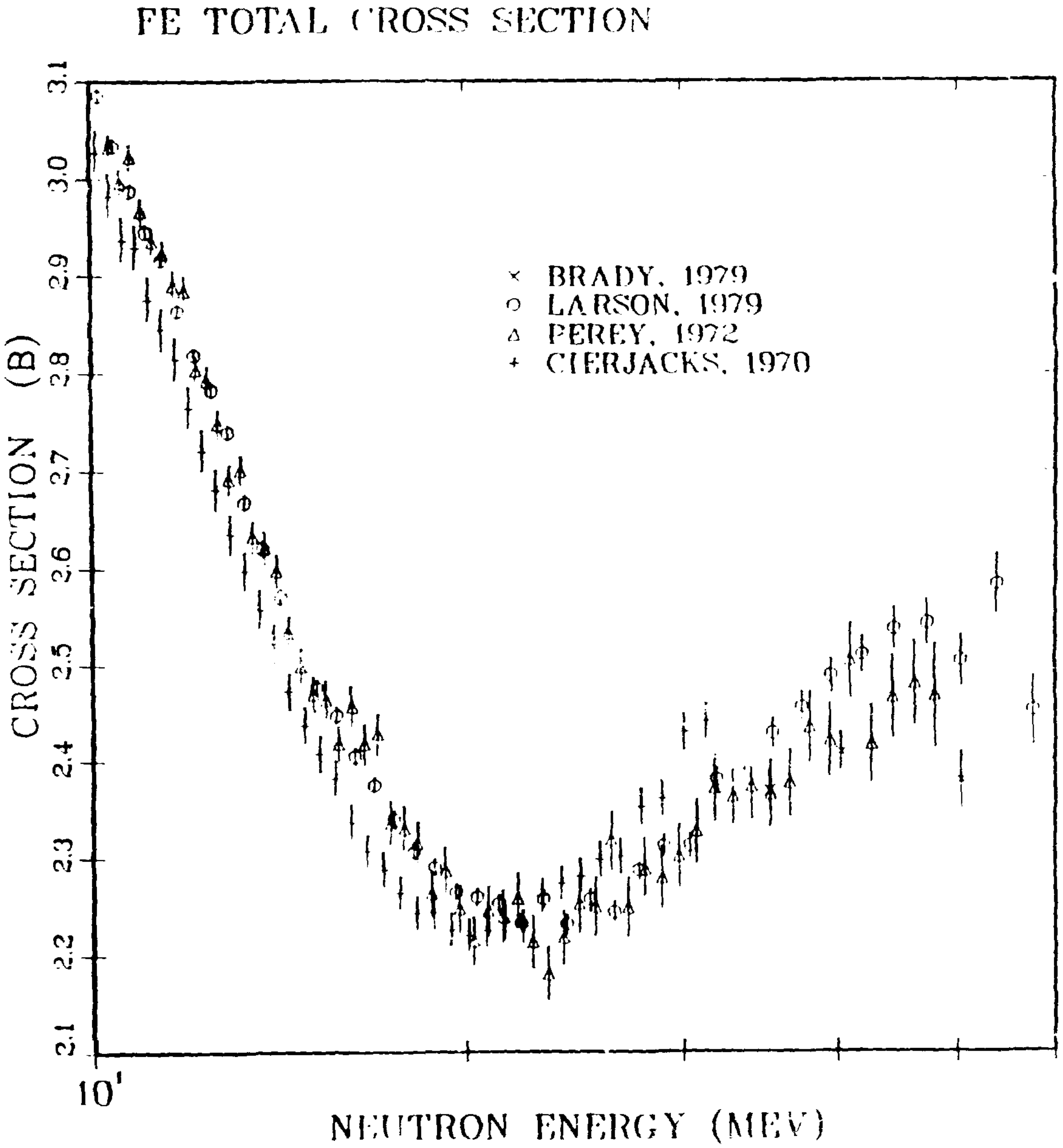
7. Preliminary neutron-emission spectra obtained at TUNL (Ref. 44) for Fe, Ni, Cu, and Pb at 12-MeV incident-neutron energy and lab angle of 125° (left plot); neutron emission spectra for Fe at 5 angles for an incident-neutron energy of 10 MeV (right plot.)

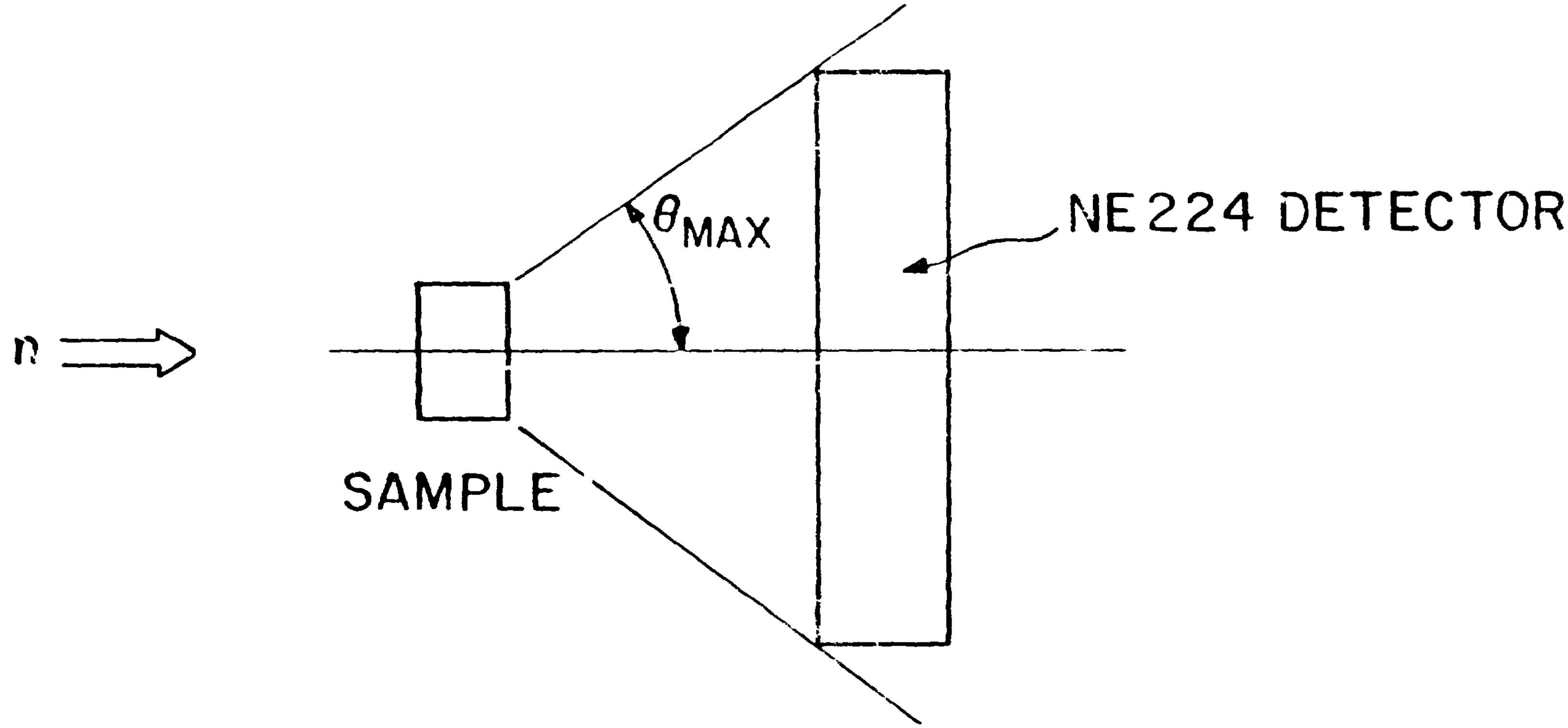
8. Cross-section data for the ^{7}Li(n,n'αt) reaction. Tritium accumulation results are Ref. 49 solid circles, Ref. 50 solid square, Ref. 51 solid inverted triangles. The open circles are from photographic emulsions (Ref. 52). The remaining data are deduced from neutron-emission spectra. This figure is from Haight (Ref. 1).

9. Integrated yield of secondary gamma rays with $E_\gamma > 0.3$ MeV as a function of incident-neutron energy for Ti. The solid line is the ENDF/B-IV evaluation.

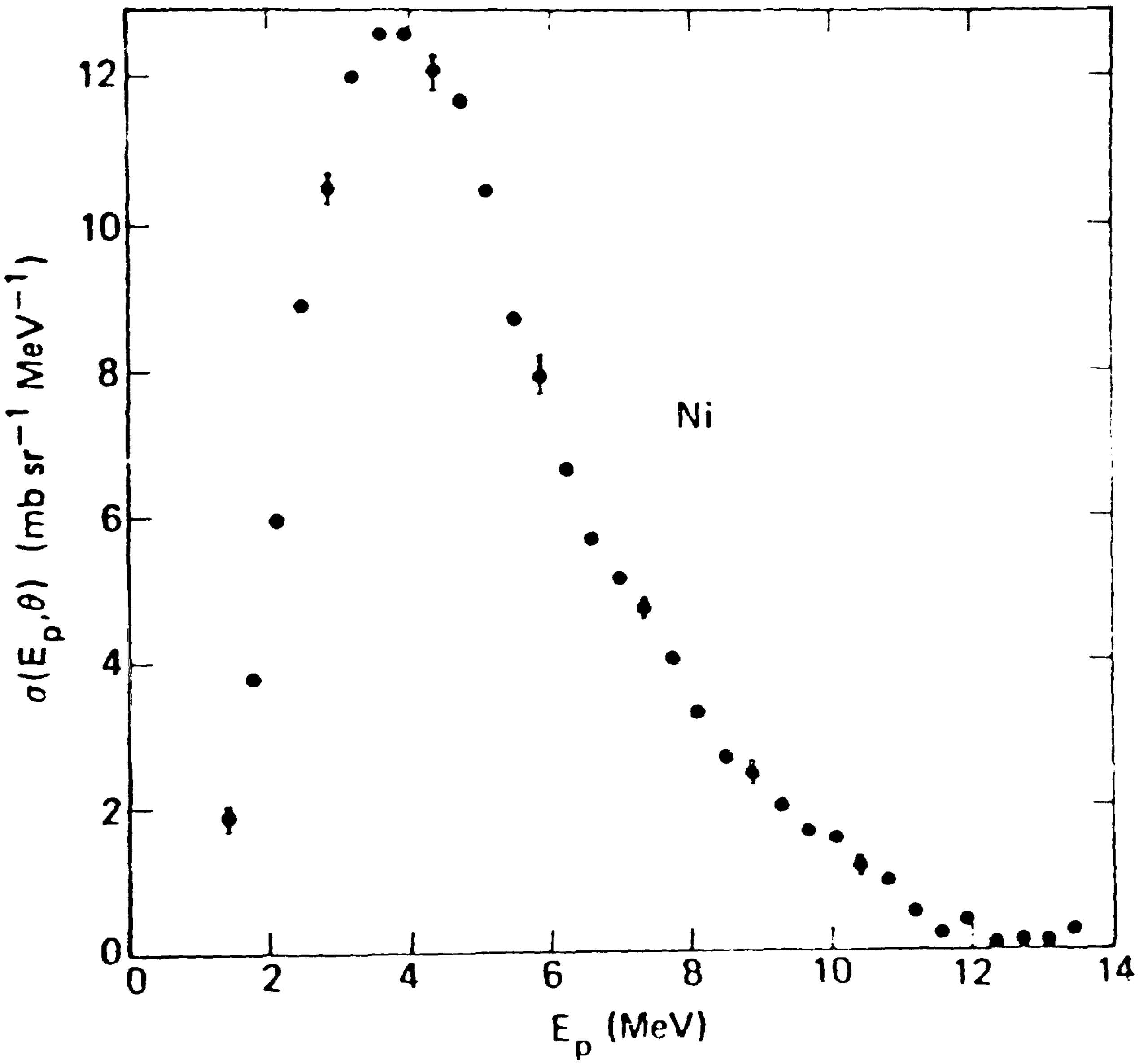
FE TOTAL CROSS SECTION

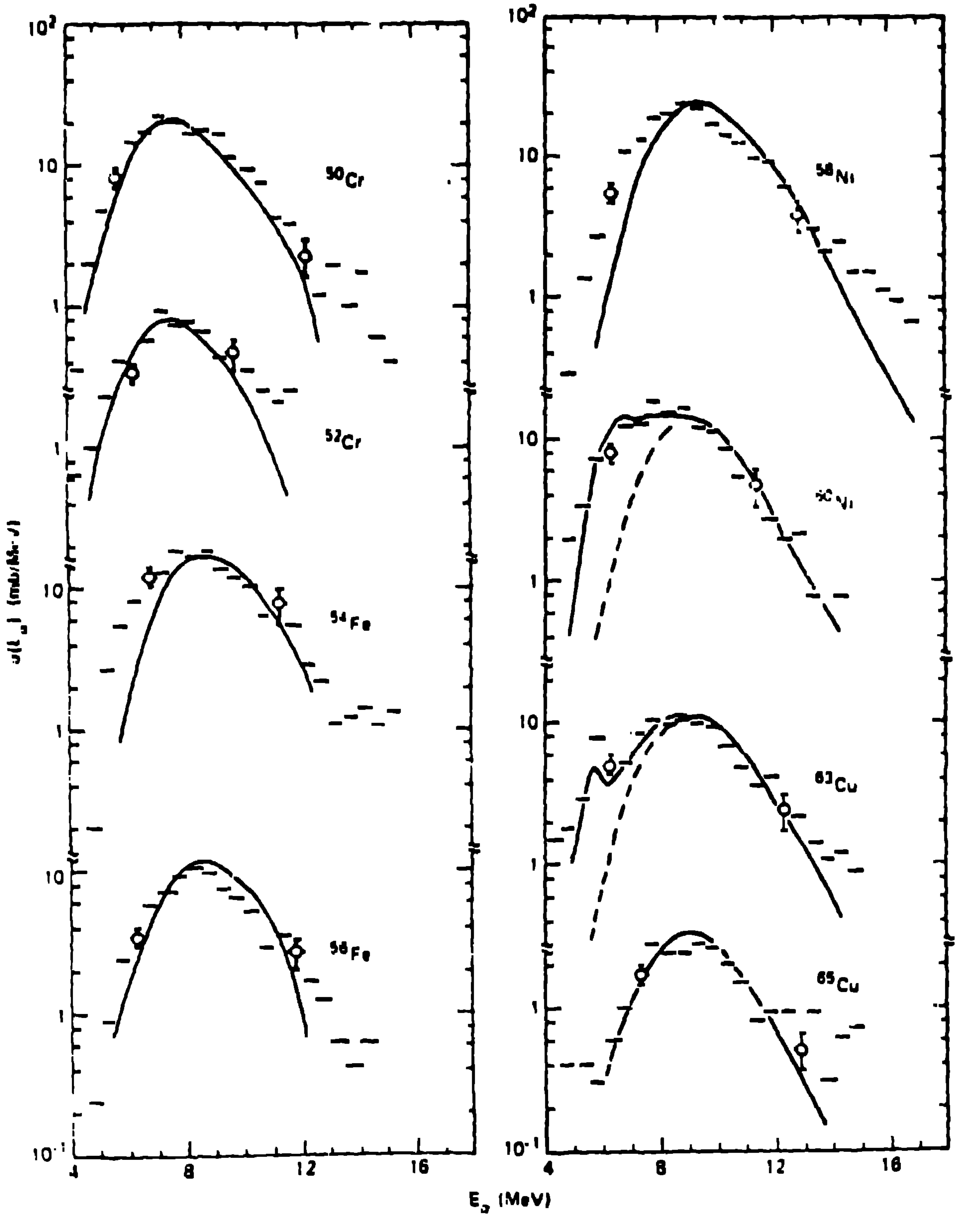



FE TOTAL CROSS SECTION
CROSS SECTION (B)
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
10¹
NEUTRON ENERGY (MEV)
× BRADY, 1979
○ LARSON, 1979
△ PEREY, 1972
+ CIERJACKS, 1970

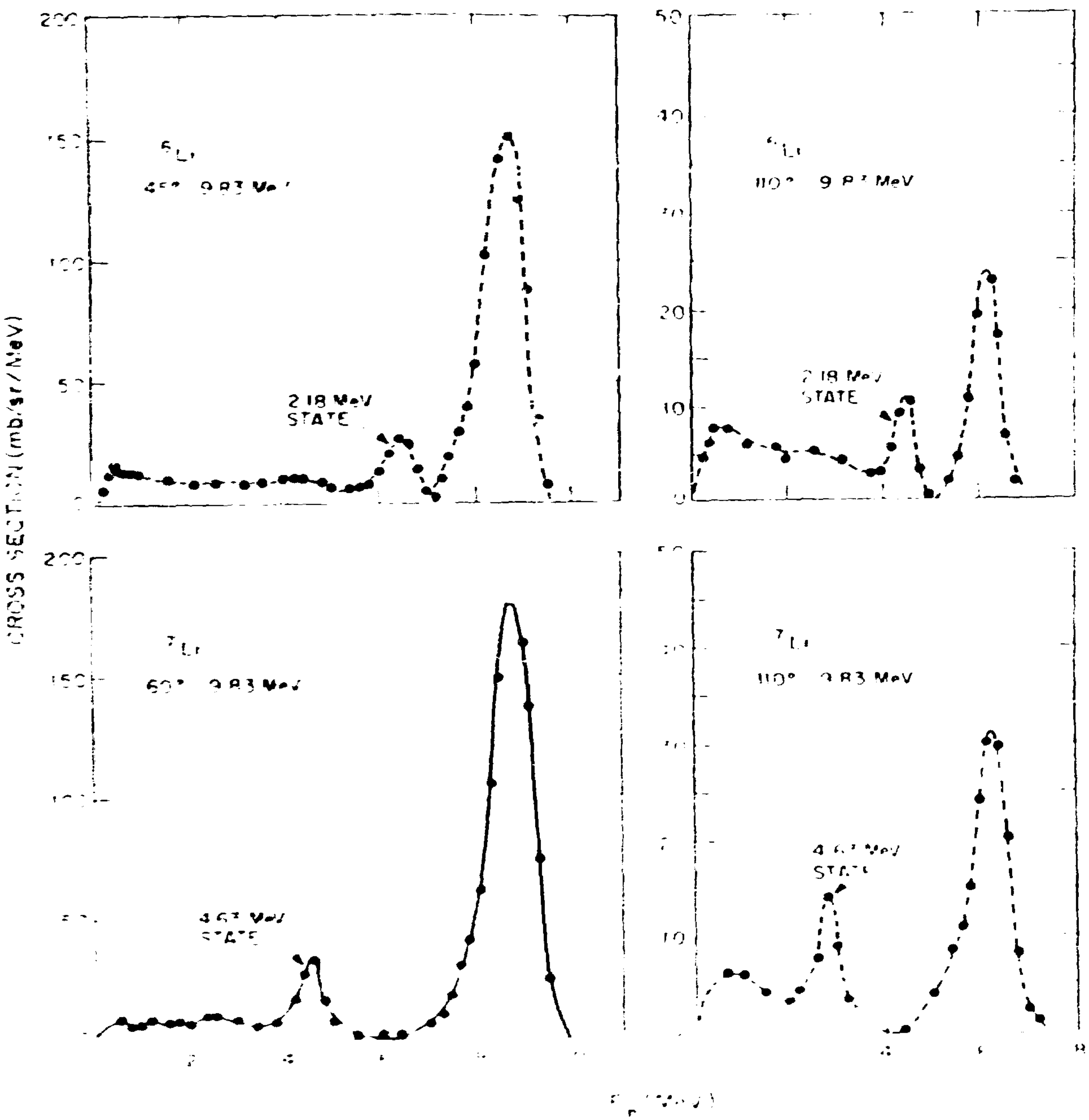


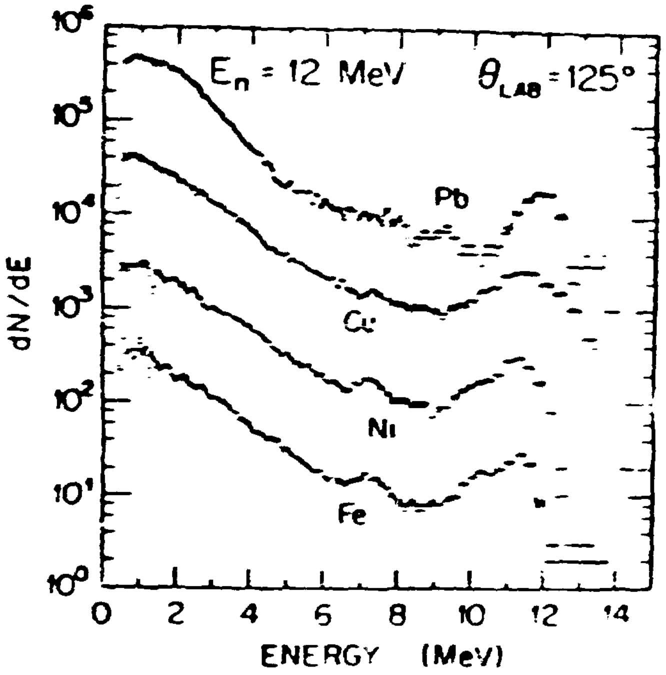
$$\sigma_{NON} = \sigma_{TOT} - \eta \sigma_{EL}^{OM}$$


σ(E_p,θ) (mb sr^-1 MeV^-1)
E_p (MeV)
Ni
0
2
4
6
8
10
12
14

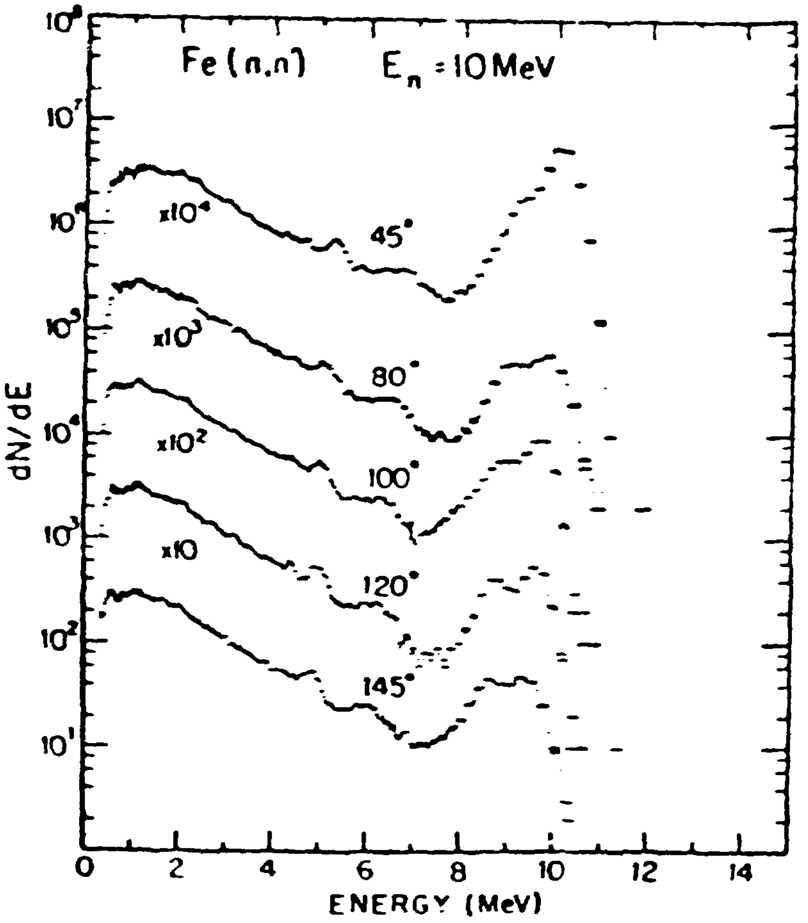


^{50}Cr
^{52}Cr
^{54}Fe
^{56}Fe
^{58}Ni
^{60}Ni
^{63}Cu
^{65}Cu
10^2
10
1
10^{-1}
4
8
12
16
E_α (MeV)

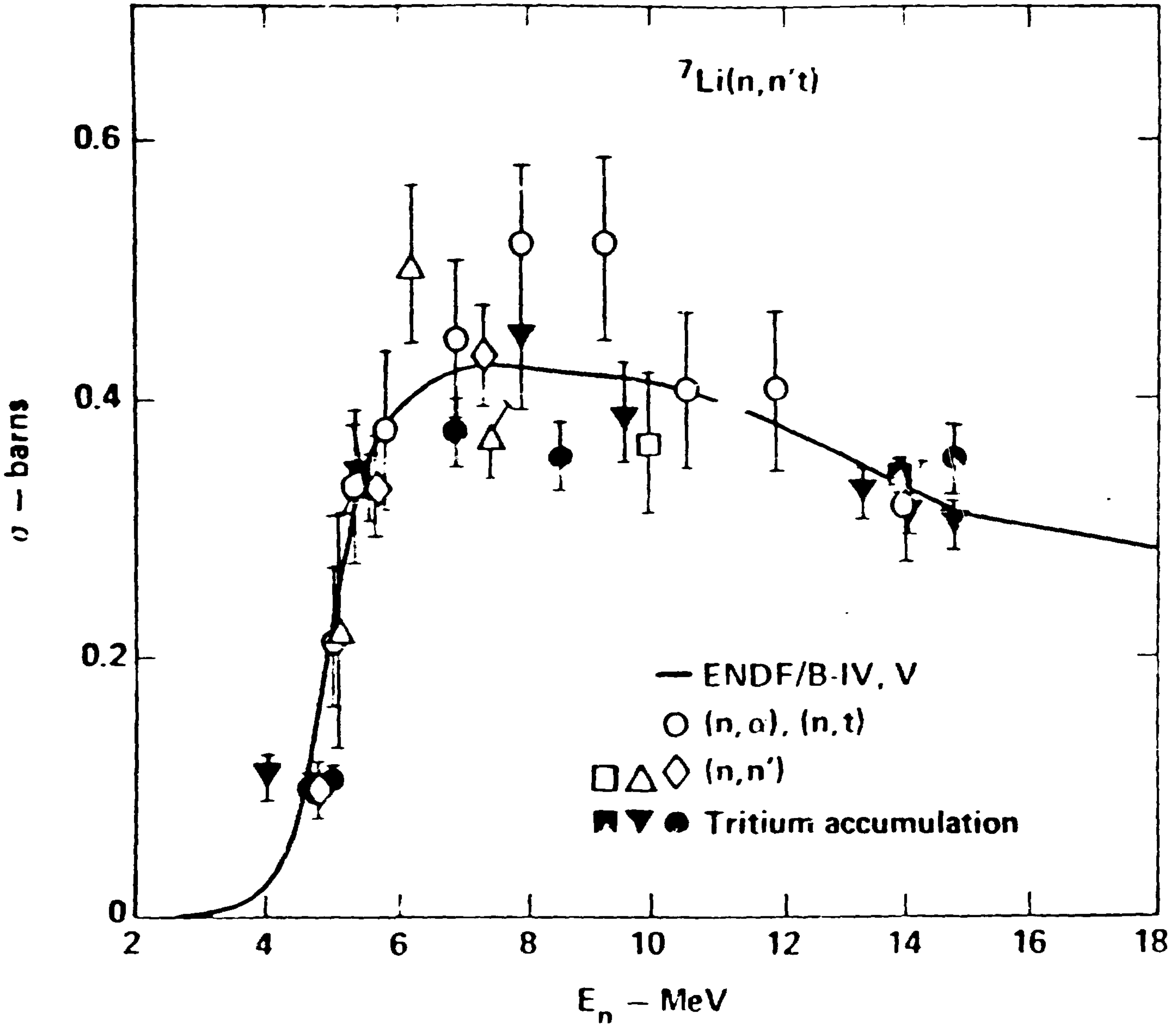

CROSS SECTION (mb/sr/MeV)
^{6}Li
45° 9.83 MeV
2.18 MeV
STATE
^{6}Li
110° 9.83 MeV
2.18 MeV
STATE
^{7}Li
60° 9.83 MeV
4.63 MeV
STATE
^{7}Li
110° 9.83 MeV
4.63 MeV
STATE
200
150
100
50
0
50
40
20
10
0
2
4
6
8
E_p (MeV)



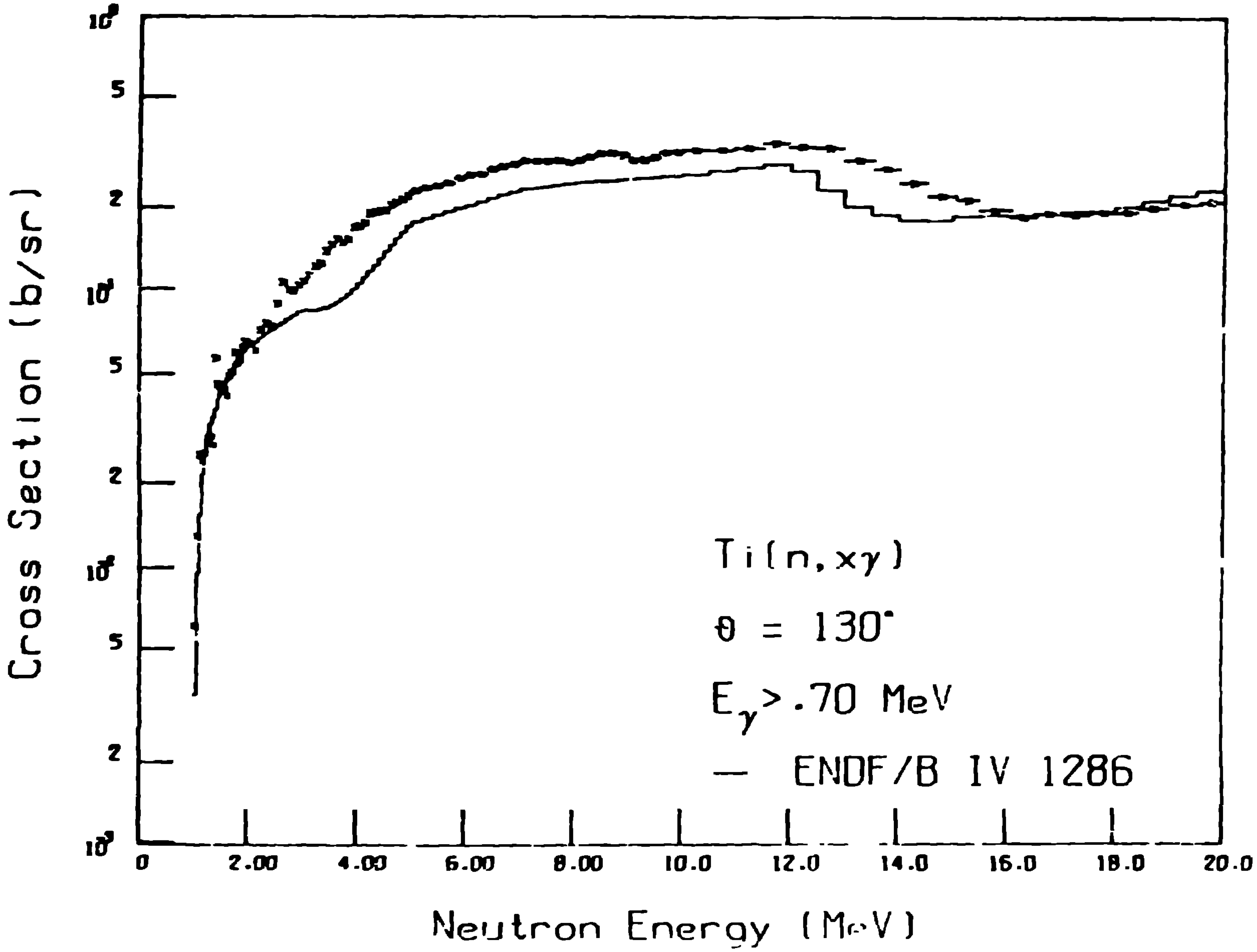
E_n = 12 MeV
θ_{LAB} = 125°
Pb
Cu
Ni
Fe
dN/dE
10^0
10^1
10^2
10^3
10^4
10^5
10^6
0
2
4
6
8
10
12
14
ENERGY (MeV)



Fe (n,n')
E_n = 10 MeV
x10^4
45°
x10^3
80°
x10^2
100°
x10
120°
145°
dN/dE
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
0
2
4
6
8
10
12
14
ENERGY (MeV)



^{7}Li(n,n't)
σ — barns
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
E_n — MeV
— ENDF/B-IV, V
○ (n,α), (n,t)
□△◇ (n,n')
■▼● Tritium accumulation


Ti(n,xγ)
θ = 130°
Eγ>.70 MeV
— ENDF/B IV 1286
Cross Section (b/sr)
Neutron Energy (MeV)
10^0
5
2
10^-1
5
2
10^-2
5
2
10^-3
0
2.00
4.00
6.00
8.00
10.0
12.0
14.0
16.0
18.0
20.0