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AN EVALUATION OF THE NEUTRON-INDUCED SCATTERING, REACTION AND PHOTON-PRODUCTION CROSS SECTIONS OF CARBON

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P. LE FLOCH, Y. PATIN, J. SIGAUD

Service Physique Nucléaire, Centre d'Etudes de Bruyères-le-Châtel
B.P. n° 61-92120-Montrouge (France)

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ABSTRACT -

An evaluation of the neutron-induced cross sections of carbon has been completed for the energy region 10^{-5} eV to 20 MeV. The recommended data are based on experiments, some of which have been performed at Bruyères-le-Châtel. Energy and angular distributions of secondary neutrons and photons are included. The adopted values are discussed. The evaluated data are avaibable on magnetic tape in ENDF/B.IV format.

EVALUATION DES DONNEES RELATIVES A L'INTERACTION DES NEUTRONS D'ENERGIE INFERIEURE A 20 MeV AVEC LE CARBONE

RESUME -

Nous avons rassemblé et analysé les principaux travaux relatifs à la réaction n + C dans la gamme d'énergie comprise entre 10^{-5} eV et 20 MeV. Nous en avons déduit un ensemble complet de données cohérentes. Les valeurs adoptées dans cette évaluation sont commentées,discutées et comparées à celles des évaluations antérieures. Ces données ont été enregistrées sur bande magnétique dans le format ENDF/B.IV.

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I - INTRODUCTION

Carbon cross-section data are of interest in a number of applied areas. Detailed knowledje of differential cross sections for neutrons scattered by carbon is required for calculations of neutron transport in shielding materials for fusion and fission reactors. Accurate nuclear data for the components of human tissue are necessary for medical use of fast neutrons in radiotherapy and radiography [1] ; the cross-section needs are particularly important for neutrons above 15 MeV energy. In addition, neutron data on carbon have been proposed as standards for neutron flux measurements and energy calibration [2] .

Several previous evaluations of carbon data have been made up to 15 MeV neutron energy (see part II.1). In the present work, a first attempt of a neutron cross-section evaluation in the range from 0 to 20 MeV has been made.

A complete literature survey was not performed for this study, although the most recent available cross-section measurements are included; but we have concentrated principally above 8 MeV where no discussion of the data seems to have been reported yet.

The recent neutron differential cross-section measurements of Haouat et al. from this laboratory [3] have provided accurate and detailed data for elastic and inelastic scattering, mainly in the range from 9 to 14 MeV, which had been characterized by a lack of data. Also the recent $(n,n'\gamma)$ measurements for carbon reported by Morgan et al. from ORNL [4] have been used in the present work, along with previous data, to deduce the photon production cross sections and the γ-ray angular distribution coefficients.

From reported data for the $^{13}C(\gamma,n)^{12}C$, $^{9}Be(\alpha,n)^{12}C$ and $^{11}B(d,n)^{12}C$ reactions, (see parts II.2, II.5, and II.8) we have deduced the values of the cross sections for the (n,γ), (n,α) and (n,d) reactions respectively using the reciprocity theorem.

The decay of the ^{12}C nucleus into three α-particles above 7.653 MeV excitation energy gives rise to the $(n,n'3\alpha)$ reaction. Its contribution to the total cross section, above 12 MeV, is of major importance. In the previous evaluations many inconsistencies remained for the $(n,n'3\alpha)$ cross sections; moreover very crude hypotheses were made to describe the secondary neutron energy and angular distributions.

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On the basis of experimental studies related to the mechanism of the $^{12}C(n,n'3\alpha)$ reaction, we have estimated the contribution of the partial cross sections to the total $(n,n'3\alpha)$ yield. The neutron spectrum is described by a sum of Gaussian and Maxwellian distributions. The secondary neutron angular distributions have been estimated on the basis of the available data.

Our recommended values are compared with E N D F/B.III and IV data.

Natural carbon consists of 98.892% ^{12}C and only 1.108% ^{13}C. Then for most practical applications it can be treated as ^{12}C.

The Q-values and thresholds of the neutron-induced reactions corresponding to the n+^{12}C system are summerized in table 1 and shown in fig.1. The reactions having a threshold higher than 20.3 MeV have been omitted.

II - NEUTRON INDUCED SCATTERING, REACTION AND PHOTON-PRODUCTION CROSS SECTIONS.

1° - Total cross section

The total cross-section data for carbon are of particular importance since they have been proposed as a standard from 0 to 20 MeV [2] . The total cross section for this element has been measured or evaluated by many groups; a complete literature survey was not performed for this study, but most of the recent measurements were included: they are listed in table 2. The data of Cierjacks et al. [5] , from 0.5 to 20 MeV, are characterized by a good energy resolution and a precise energy calibration; however they have been found to be systematically higher than the values of other groups listed in table 2. The data of Schwartz et al. [6] , between 0.5 and 15 MeV, have been measured with an energy resolution not so good as that of Cierjacks et al. [5] , but they are estimated to be, all over the energy range, very accurate. Except at the location of sharp resonances, these measurements have been considered with a high degree of confidence in the present work. On the other hand total cross-section measurements have been carried out at A N L in the energy range 1.5 - 5.0 MeV, and recently reported by Holt et al. [7] . A monoenergetic neutron source was used, with an energy spread between 2 and 5 keV. The results are in good agreement with those obtained from linear accelerators using white source techniques and particularly with those of Schwartz et al. [6] and Foster and Glasgow [8] .

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A more detailed discussion of the total cross sections is presented below. For convenience, the resonance parameters for neutron energies between 0 and 20 MeV are listed in table 3.

From thermal value up to 2.0-MeV neutron energy, the total cross section for carbon exhibits no resonance structure. It has been evaluated by two independant groups [9,10] ; from 0.2 to 2.0 MeV their recommended values have been compared to those measured at O R N L by Perey et al. [11] , and found to be consistent with the measurements, the maximum deviation between the measurements and the recommended data being 2%. A set of total cross sections, in the range from 0.1 eV to 2.0 MeV, has been obtained with the aid of an averaging procedure of the above-discussed data. The thermal value of the total cross section has been deduced from the evaluations of Leonard et al. [12] and Story et al. [13] which are considered as a standard. These two evaluations have gathered all the available carbon thermal cross-section measurements from the year 1946 to 1970. These data are listed in table 4. Our recommended value, for thermal neutrons, is 4.728 ± 0,008 b. Below this energy, the 1/v contribution of the radiative capture cross section to the total cross section, has been taken into account as described in section II.2.

Between 10 eV and 2.0 MeV, the variation of the total cross section with neutron energy has been expressed by a polynomial in energy which was fitted to the averaged data by minimizing χ^2. The proposed values are given by the expression:

$$\sigma(E) = 4.725 - 3.251E + 1.316E^2 - 0.227E^3 \text{ (barn)}$$

where E is the neutron energy in MeV. The evaluated data from 10^{-5} eV to 2 MeV are shown in Fig.2: the accuracy is believed to be better than 1%.

At the neutron energy of 2.077 ± 0.002 MeV, the ^{12}C+n reaction reaches the resonance at 6.863 MeV in ^{13}C (table 3); the total width of this resonance is 6 keV and the value of the total cross section at the peak is 6.020 b, taken from ref. [11] . Between 2.1 and 2.7 MeV the total cross section shows no resonance (fig.3). The comparison between the available experimental values denotes that the data of Cierjacks et al. [5] are 4 to 6% higher than Schwartz et al. [6] , Foster et al. [8] and Perey et al. [11] results; the adopted values in this energy range have been

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mainly based on the data of Schwartz et al. [6] ; the accuracy is estimated to be 2%.

At E_n = 2.816 ± 0.004 MeV, the transmission measurements of Perey et al. [11] exhibit a minimum associated with the resonance at 7.545 MeV in ^{13}C. This resonance was ignored in the evaluation file ENDF/B.III. However it has been observed by Cierjacks et al. [5] and Schwartz et al. [6] and more recently by Holt et al. [7] : it is now included in the ENDF/B.IV file. The total width of less than 5 keV, reported by Ajzenberg-Selove [14] for this resonance is consistent with the data of ref. [5,7,11] (table 3).

Between 2.84 and 4.81 MeV the data of Schwartz et al. [6], Cierjacks et al. [5] and Perey et al. [11] are in good agreement, whereas, at the 3.05 MeV interference dip, the results of Foster and Glasgow [8] exhibit a significant shift to lower energies and the values of Fossan et al. [15] are substantially shifted to higher energies. The work of Galati et al. [16] gives more precision about the ^{13}C resonance parameters at $E_{exc.}$ = 8.879 MeV (E_n = 4.261 ± 0.002 MeV): these parameters are given in table 3. The proposed values, obtained by smoothing the composite results of ref. [5,6,11] in the energy range 2.84 - 4.81 MeV, are given with 2% accuracy (fig.3).

By fitting the total cross-section data, between 0 and 5 MeV, simultaneously with elastic angular distributions and polarization data, experimental phase shifts have been obtained [16,18] . They have been compared to those deduced either by a multichannel R-matrix analysis [19,22] or by a coupled-channel calculation [23,24] . The various predictions are in good agreement with the measurements, and they served as a guide in this work, especially for the differential cross-section data.

From 4.81 to 8.00 MeV, the data of Cierjacks et al. [5] , Schwartz et al. [6] , Perey et al. [11] and Fossan et al. [15] which are in good agreements with regards to the energies of the resonances have been considered. Between the sharp resonances the recommended total cross-section values are those of Schwartz et al. [6] . The data of Cierjacks et al. [5] are significantly higher in this region, the deviation being as large as 7% between 5.0 and 6.0 MeV (fig.4). The values at the resonances are taken from Perey et al. [11] . In the energy range 4.81 - 7.50 MeV the accuracy is believed to be 4%.

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Between 8.0 and 15.0 MeV, where many broad overlaping resonances are present (table 3), the time-of-flight measurements of Cierjacks et al. [5] , Schwartz et al. [6] , Perey et al. [11] , Foster and Glasgow [8] and Fossan et al. [15] are in satisfactory agreement (fig.5). Nearly all the data lie in a band of total width approximately 8% of the average cross section. We have used a composite of those measurements to represent the total cross section in the range 7.5 - 15 MeV. The accuracy of these evaluated data in this energy range is thus about 4%.

In the region extending from 15 to 20 MeV, the total cross section is characterized by a smooth shape with two broad resonances at E_n = 16.20 MeV and E_n = 19.56 MeV (table 3). In this energy range the only available data seem to be those of Cierjacks et al. [5] and Perey et al. [11] . These two measurements agree remarkably well, so that the evaluated curve has been obtained by averaging both data sets (fig.5). The cross sections are given with 6% incertainty.

The evaluated total cross section from 1 to 20 MeV is displayed in fig.6.

2° - Radiative capture cross section.

The recommended values for the (n,γ) cross section for thermal neutrons are for the two isotopes of natural carbon [25] :

$$^{12}C \qquad \sigma(n,\gamma)_{th} = 3.36 \pm 0.3 \text{ mb}$$

$$^{13}C \qquad \sigma(n,\gamma)_{th} = 0.9 \pm 0.2 \text{ mb}$$

These recommended values have been strongly influenced by the data of Jurney and Motz [26] . At low energy, i-e $E_n \leqslant 100$ keV, the (n,γ) cross section has been assumed to vary with neutron energy according to the 1/v law.

The radiative capture is the inverse of the nuclear photo-effect; by applying the reciprocity theorem, the (n,γ) cross sections can be deduced from the (γ-n) data. The excitation function for the $^{13}C(\gamma,n)$ reaction has been measured by Cook [27] ; using these data we have obtained the (n,γ) cross sections from 0.2 to 20 MeV: they are displayed in fig.7.

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They exhibit two broad resonances located at $E_{exc.} = 13.3 \pm 1$ MeV ($\Gamma = 5 \pm 1$ MeV) and at $E_{exc.} \simeq 22$ MeV ($\Gamma \simeq 7$ MeV) in ^{13}C. The radiative capture cross section, from thermal energy up to 20 MeV, is very low and does not exceed 0.07% of the total cross section.

The capture γ-ray spectrum for thermal neutrons has been measured by Thomas et al. [28] and Spilling et al. [29] . The decay scheme obtained from the analysis of the results is given in fig.8. The total multiplicity for thermal neutrons is 1.32 photons per capture.

3° - Elastic scattering cross sections.

The recommended data for elastic scattering cross sections have been obtained from various measurements over the incident neutron energy range 0.1 - 19.9 MeV.

a) - $E_n < 4.81$ MeV - For incident neutron energies above 0.1 eV and below the threshold of the inelastic scattering to the first excited level in ^{12}C, the integrated elastic scattering cross section has been taken equal to the total cross section. This assumption results in a (n,γ) cross section that is too small above 0.1 eV (0.07% of the total cross section). Angular distributions for the elastic scattering have been measured from 0.1 MeV to 4.81 MeV by several groups (see table 5). The deviation between the total cross sections determined from polynomial fits to the observed angular distributions and the recommended values were found to be consistent within the uncertainties which are not larger than 4%.

b) - $4.81 \leq E_n \leq 8.00$ MeV - Above 4.81 MeV the inelastic scattering channel is open; it competes with the elastic scattering and the radiative capture channels, the latter having still a negligible contribution. In the energy range from 4.81 to 8.00 MeV many resonances give rise to strong variations in the total cross section and therefore in the elastic cross section. In order to analyse these resonances, many measurements have been carried out by Galati et al. [16] , by Velkley et al. [30] , and by Perey et al. [31] from O R N L; some of the data of O R N L are not yet published. These data precise and complete earlier ones (table 6).

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All the data of the O R N L group have been included in the E N D F/B.IV evaluation, and most of the recommended values, in the energy range from 4.81 to 8.0 MeV, have been accepted for the present evaluation (fig.9).

c) - $8.0 \leq E_n \leq 15$ MeV - Between 8.0 and 15 MeV our evaluation has been mainly based upon the time-of-flight measurements performed on the Bruyeres-le-Châtel facility by Haouat et al. [3,32] . Two sets of data on neutron elastic scattering differential cross sections were determined by normalization to the n-p scattering cross section near 0°. The data at 12 MeV incident neutron energy of ref. [3] have been reanalyzed: at the forward angle $\theta_{CM} = 10.8°$, the differential cross section has been increased by 34%, hence, the differential cross section at 0° is greater than wick's limit. The new value of the integrated cross section at 12 MeV is, then, 865 ± 50 mb. The uncertainties of all the data of ref. [3] do not exceed 8%. The data expressed in the center-of-mass system, were fitted to a Legendre polynomial expansion using the least-squares method. The zero-order coefficients were used to deduce the integrated cross sections. The variation of the elastic cross section as a function of neutron energy is displayed in fig.10 along with the E N D F/B data (version III and IV). Also are included in this figure the previous measurements of Perey et al. [31] and Velkley et al. [30] below 9 MeV and those of Bouchez et al. [33], Clarke et al. [34] and Spaargaren et al. [35] above 14 MeV. (see table 7); these data compare favourably with most of the values of Haouat et al. [3,32] . Recently Purser et al. from T U N L [36] have measured the elastic neutron scattering by carbon between 9 and 15 MeV. Their preliminary results seem to be in overall good agreement with Haouat et al. data [3] . Although they are not quantitatively considered in the present work, the T U N L measurements increase the degree of confidence in this evaluation from 8.0 to 15.0 MeV.

The comparison of our evaluated data with the previous E N D F/B curves shows significant discrepancies of about 7 to 15%: the previously recommended values seem too high around 11 and 12 MeV and systematically low between 12.5 and 14.5 MeV (fig.10).

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d) - $15 \leqslant E_n \leqslant 20$ MeV - The integrated elastic cross section has been measured, over the energy range 14-20 MeV, by Boreli et al. [38]. They used a spherical shell of pure graphite surrounding a neutron detector shielded from the neutron source by a shadow cone. The elastic scattering data had to be corrected for many effects so that the accuracy is 15%. The data show two broad structures centered at 15.8 and 19.5 MeV associated with the two resonances in ^{13}C at 19.5 and 23 MeV. On the other hand angular distributions for neutron elastically scattered by carbon have been obtained at 15, 17.27, 18.25 and 19.9 MeV [35,39]. We have used a composite of all these results, listed in table 8, to deduce the set of proposed values with uncertainties of 12%. The adopted values in the present evaluation are plotted in fig.10.

4° - Inelastic scattering cross sections - $^{12}C(n,n')$ and $^{12}C(n,n'\gamma)$ cross sections.

The available data of neutron inelastic scattering to the first excited level in ^{12}C are listed in tables 6,7,8. A complete analysis has been performed from the threshold (4.812 MeV) up to 20 MeV. Moreover the integrated cross sections for neutron inelastic scattering have been compared with the γ-ray production cross section for the $^{12}C(n,n'\gamma)$ reaction. As mentionned in the introduction the low value of the separation energy for secondary particle emission in $^{12}C(Q = -7.275$ MeV) is the main reason why only the 4.439 MeV γ-ray is produced by inelastic scattering.
The 4.439 MeV (2^+) photon angular distribution may be represented by an expression of the form:

$$\frac{d\sigma}{d\Omega}(\mu) = \frac{\sigma_{int.}}{4\pi}\left[1 + 5A_2P_2(\mu) + 9A_4P_4(\mu) \right]$$

where μ is the cosine of the reaction angle and $P_\ell(\mu)$ is the ℓ^{th}-order Legendre polynomial. If we assume that the fourth order coefficient in the Legendre polynomial expansion is small, then the integrated cross section is equal to 4π times the differential cross section at the zero-value of the second-order Legendre polynomial (55° or 125°). In the present evaluation this hypothesis has been found to be valid from 4.8 to 8.0 MeV and is also verified between 8.0 and 14.5 MeV. It has been assumed that this hypothesis is still valid above 15 MeV.

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a) - <u>$4.81 \leqslant E_n \leqslant 8.0$ MeV</u> - The recommended values, between 4.8 and 8.0 MeV, are those of E N D F/B.IV mainly based on the partly published data of the O R N L group [31] . Other measurements, also listed in table 6, are in good overall agreement with the recommended values. Several evaluations [40,41] of the integrated cross sections for neutron inelastic scattering by the first excited level in ^{12}C were based on the $(n,n'\gamma)$ measurements of Day et al. [42] and Hall and Bonner [43] in the energy range 4.8 - 8.8 MeV. These data have been found to be too high by about 85% [44] . The most recent data of integrated cross sections for neutron inelastic scattering are compared in fig.11 with the γ-ray production cross sections. From 6.35 to 7.50 MeV the inelastic scattering is governed by resonances in ^{13}C having spins < 3/2. In this energy range the 4.439 MeV γ-ray angular distribution is strictly limited to a $P_2(\mu)$ term, and the integrated cross section is equal to the 125° (or 55°) differential cross section multiplied by 4Π. The neutron and γ-ray data shown in fig.11 are consistent not only from 6.35 to 7.50 MeV but over all the range 4.8 - 8.0 MeV. We may then deduce that the fourth-order coefficient is zero or low in this energy range.

b) - <u>$8.0 \leqslant E_n \leqslant 15$ MeV</u> - From 8.0 to 15.0 MeV the proposed values have been mainly deduced from the data of Haouat et al. [3,32] . These data were found to be in good agreement with those previously reported below 9 MeV [30,31] and above 14 MeV [34] , except those of Bouchez et al. [33] at 14.5 MeV which seem too high by about 60%. As for the elastic scattering the same qualitative agreement with the preliminary results of Purser et al. [36] has been found for the inelastic scattering. The inelastic scattering data of Haouat et al. [3,32] have been found, within the uncertainties, very similar to those deduced from the $(n,n'\gamma)$ measurements at 125°, by Morgan et al. [4] (fig.12). We may conclude that the fourth-order coefficient is, also, very low in this energy range. Finally the present evaluation has been compared to the previous ones: E N D F/B.III and B.IV. Strong discrepancies appear and relatives differences by more than 50% can be seen, mainly between 9.5 and 14.0 MeV (fig.12).

A large amount of data on (n,n') and $(n,n'\gamma)$ measurements, between 14 and 15 MeV, is available; most of these data are listed in table 9. In spite of the errors on the quoted values, a structure appears at about 14.8 MeV, at the location of a resonance observed in the total cross section.

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c) - 15 $\leqslant E_n \leqslant$ 20 MeV - In the energy range 15 - 20 MeV, a few data which have large uncertainties have been reported on neutron inelastic scattering. Some of them cannot be adopted: the inelastic scattering data of Spaargaren et al. [35] at 15.0 MeV are consistent with those of Bouchez et al. [33] at 14.5 MeV, which seem too high, and the inelastic cross sections deduced from the measurements of Deconninck and Meulders at Louvain University [39] which are, between 17.25 and 19.88 MeV, nearly constant and equal to about 170 mb. This last value is in complete disagreement with the data of Morgan et al. [4] , obtained from (n,n'γ) measurements at 125°. Only those last data have been considered in the present evaluation. The recommended values are given with an uncertainty estimated to 15%.

We have plotted in fig.13 the evaluated data related to the inelastic scattering to the first excited level from threshold up to 20 MeV.

5° - The $^{12}C(n,\alpha_0)^{9}Be$ cross section.

The threshold for the $^{12}C(n,\alpha_0)^{9}Be$ reaction occurs at 6.181 MeV (Q = - 5.702 MeV). Only the (n,α_0) reaction leaving ^{9}Be in its ground state is considered as an absorption reaction. The (n,α) reactions leading to the ^{9}Be excited states contributes to the $(n,n'3\alpha)$ reaction and their yields will be estimated in section III.4.

The experimental data for the (n,α_0) reaction are gathered in table 10. Other informations can be obtained from measurements of the inverse $^{9}Be(\alpha,n_0)^{12}C$ reaction by using the reciprocity theorem for nuclear reaction. The (α,n_0) measurements, used in this work, are listed in table 11. The available data extend from the threshold up to a neutron energy of 19 MeV.

From 7.3 MeV, where the (n,α_0) cross section becomes significant, to 8.75 MeV neutron energy the proposed values of (n,α_0) cross sections have been mainly based on the (α,n) data of Retz-Schmidt et al. [45] reported by Obst et al. [46] . In this energy range, two values have been reported by Van der Zwan et al. [47] : the first one at 8.09 MeV is close to Retz-Schmidt et al. [45] data to better than 10%, the second one at 8.41 MeV is significantly lower by 30%.

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The earlier measurements by Risser et al. [48] in (α,n) reaction and by Davis et al. [49] in (n,α) reaction are consistent in shape but smaller in magnitude by approximately a factor of 2 compared to the values of Retz-Schmidt et al. [45] .

Between 8.75 and 14 MeV the (α,n) measurements of Retz-Schmidt et al. [45] , Van der Zwan et al. [47] , Verbinski et al. [50] and Obst et al. [46] have been considered; they are very consistent, in the overlaping energy intervals, within less than 10% (fig.14). Moreover the value of Verbinski et al. [50] at 13.7 MeV is in good agreement with the absolute measurements of the (n,α_0) reaction cross section near 14 MeV [51-54] . The adopted value at 14.0 MeV is 80 ± 10 mb. The proposed data, between 8.75 and 14.0 MeV, are a composite of the above mentioned values; the accuracy is estimated to be 12%.

Above 14 MeV our evaluation has taken into account the (n,α) measurements of Chatterjee et al. [56] at 14.5 MeV. Brendle et al. [51] at 15.6 MeV, Huck et al. [57] at 16.0 and 17.0 MeV, normalized to $\sigma_{n,\alpha}$(15 MeV) = 80 ± 10 mb, and the (α,n) value of Nilsson et al. [55] at 16.3 MeV. Between 15 and 19 MeV two sets of cross sections have been reported by Salathe et al. [58] in (n,α) experiment and by Deconninck et al. [59] in (α,n) reaction; they have not been accepted for the present evaluation: these data are smaller by a factor of about 2 than the above mentioned values in the overlaping range 15 - 17 MeV. However, the shape of the cross section curve has been used to extend our evaluation from 17 to 20 MeV. The accuracy of the proposed data between 14 and 20 MeV is believed to be 20%.

6° - The ^{12}C(n,n'3α) cross section.

At neutron energies higher than 7.887 MeV occurs the ^{12}C(n,n'3α) reaction (Q =-7.275 MeV) but the cross section becomes significant above 10 MeV. The secondary neutrons cover a wide energy range, and thus, the (n,n'3α) integrated cross section has been mainly determined from the observation of the three α-particles. The cross sections have been measured by several groups listed in table 12. The most complete data are those of Frye et al. [60] which extend from 12.85 to 18.80 MeV neutron energy and those of Vasil'ev et al. [61] which span from the threshold to 19 MeV; however the experimental uncertainties vary between 30% and 50%.

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The values of the $^{12}C(n,n'3\alpha)$ cross sections, proposed in this work, have been principally obtained by subtracting from the total cross section the sum of the cross sections for the other reactions. The evaluated curve (fig.15) shows two broad structures around 12 and 16 MeV. The first hump at 12 MeV is confirmed by the recent integral measurements of Cramer and Oblow [62] who used annular scatterer techniques, and the second one by the measurements of Vasil'ev et al. [61] who used nuclear emulsion techniques. The accuracy of the proposed data is given to be 20% from 7.9 to 15.0 MeV and 25% between 15.0 and 20.0 MeV.

7°- The $^{12}C(n,p)^{12}B$ and $^{12}C(n,p\gamma)^{12}B$ cross sections.

The threshold for the $^{12}C(n,p)^{12}B$ reaction occurs at 13.646 MeV (Q = - 12.588 MeV). The residual ^{12}B nucleus decays by emission of beta-particle having a maximum energy of 13.370 MeV and a half life whose adopted value is 20.3 ± 0.1 ms [63] . The beta transitions go by 97.1% directly to the ground state of ^{12}C [14] . The evaluated data for the (n,p) cross section have been based on the work of Rimmer et al. [63] who measured the excitation function by detecting β-decay of the ground state of the ^{12}B produced over a range of incident neutron energy from 14.5 to 22 MeV. Kreger and Kern [64] , using also activation techniques, have measured the $^{12}C(n,p)$ cross section between 14.9 and 17.5 MeV; their results are in good agreement within the uncertainties with the data of Rimmer et al. [63] below 16 MeV; above this energy they are higher by a factor of approximately 2. This discrepancy may be explained by the fact that Kreger and Kern [64] used different methods of neutron monitoring below and above 16 MeV, without performing any normalization measurement. The evaluated curve is displayed in fig.16 along with the data of Rimmer et al. [63] and Kreger and Kern [64] . The proposed values include all the individual (n,p) level excitation cross sections; they are given with 15% accuracy.

No experimental (n,pγ) data seem to be available; nevertheless it is believed that the feeding of the excited states in ^{12}B is not strong [63] , and the photon production from this reaction has been ignored in this evaluation.

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8° - The $^{12}C(n,d)^{11}B$, $^{12}C(n,d\gamma)^{11}B$ and $^{12}C(n,np)^{11}B$ cross sections.

The Q-value for the $^{12}C(n,d_0)^{11}B$ reaction is Q = - 13.733 MeV and the threshold is 14.888 MeV. The evaluated curve for the (n,d_0) cross section from the threshold up to 20 MeV is given in fig.17. The experimental cross sections of Ames et al. [65] and Class et al. [66] for the $^{11}B(d,n_0)^{12}C$ reaction have been converted to $^{12}C(n,d_0)^{11}B$ cross sections by means of the reciprocity theorem. The proposed data are given with 15% accuracy.

The cross sections for the (n,d) reaction to the excited state in ^{11}B and for the (n,np) reaction are very small; they have been ignored in the present work, as well as the photon production from these reactions. A crude estimation has been made using Hauser-Feshbach calculations: the (n,d) cross section for the excited states in ^{11}B is believed to be less than 10% of the (n,d_0) cross section at E_n = 20 MeV.

9° - Consistency of the data.

The proposed curves for total and partial cross sections,between 2 and 20 MeV are gathered in fig.18. The evaluated data for all the partial cross sections except for elastic scattering have been summed at various energies. We have thus deduced a set of non elastic cross sections from 10^{-5} eV up to 20 MeV. On the other hand several measurements of this cross section have been reported [38,52,67-75] . They are generally consistent with the proposed values except for the data at 14 MeV of Flerov et al. [72] and Graves et al. [52] .

The estimation of the effects of uncertainty in nuclear data is useful in many practical applications. For this purpose we have summerized in table 18 the uncertainties in the various cross sections for several neutron energies ranges. The estimates are rough but significant. The uncertainties are mainly based upon quoted errors in the experimental measurements, although in many cases we have modified the original estimates, particularly near threshold for the reactions where the errors are much larger than those given in table 13. The uncertainties in the non elastic cross section are also listed: they have been obtained from errors in the total and elastic cross sections.

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III - NEUTRON AND γ-RAY DIFFERENTIAL CROSS SECTIONS.

1° - Elastic neutron angular distributions.

a) - $E_n \leqslant 4.81$ MeV - Various and detailed results on elastic differential cross sections are available below 4.81 MeV, where only the elastic and the very weak (n,γ) channels are open. The measurements are listed in table 8; they exhibit a good overall consistency. The observed angular distributions together with polarization data have been well described either in the multichannel R-matrix formalism [7,19-22] or by a coupled channel calculation [23,24] . All the above mentioned differential cross sections have been considered in E N D F/B.IV; the evaluated data from this file were adopted, for neutron energies below 4.81 MeV, in the present work.

b) - $E_n \geqslant 4.81$ MeV - Above 4.81 MeV up to 9 MeV, the elastic cross section exhibits many structures, and angular distributions have been extensively measured by Galati et al. [16] up to 7 MeV, by Perey et al. [31] from 4.5 to 8.5 MeV, and from 5.22 to 8.69 MeV [34] , and by Velkley et al. [30] from 7.2 to 9.0 MeV (see table 6). In the energy range from 9 to 14 MeV, which was characterized by a lack of data in previous evaluations, the recent neutron differential cross section measurements of Haouat et al. [3,32] provide accurate and detailed data. The data at 12 MeV of ref. [3] have been, however, reconsidered at the center-of-mass angle of 10.8°, the new value of the differential cross section being 581.1 ± 47.0 mb/sr. These measurements are confirmed by the preliminary results of Purser et al. [36] . Moreover they are anchored by the forward angle elastic scattering measurements of Bucher et al. [76] at the center-of-mass angles between 2.9° and 15.2°, in the energy range 7.4 - 9.5 MeV (fig.19), and by the backward angle measurements of Perey et al. [77] at 129° center-of-mass angle, in the energy range 8 - 14.5 MeV. On the last figure the agreement with the data of Haouat et al. [3,32] is very satisfactory.

The evaluated Legendre coefficients for $\ell = 1$ through $\ell = 6$ have been deduced from the fitted values for neutron energies between 5 and 15 MeV. (fig.20).

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The coefficients are defined by:

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{\sigma_{int.}}{4\pi} \sum_{0}^{\ell_{max}} (2\ell+1)\, f_\ell P_\ell(\cos\theta)$$

with $f_0 = 1$ and $|f_\ell| \leq 1$

Between 15 and 20 MeV, since there is no sharp structure in the integrated elastic cross section, smooth curves were drawn through the coefficients obtained from Legendre fits to the data of Deconninck and Meulders [39] , at 17.27, 18.25 and 19.88 MeV. The evaluated curves are displayed in fig.20 for $\ell = 1$ through $\ell = 6$. The consistency of the proposed values, has been checked by comparing the elastic differential cross sections to the measurements by Boreli et al. [38] at 30.5°, 39.2°, 54.75° and 90.0°, by Perey et al. [77] at 129° and by Harlow et al. [78] at 38.8°, 54.7°, 90.8° and 127.5° center-of-mass angles (fig.21).

2° - Inelastic neutron angular distribution for the 4.439 MeV level.

a) - $4.81 \leq E_n < 15$ MeV - Due to the presence of many structures in the excitation function, differential cross sections for inelastic neutron scattering to the first excited level of ^{12}C(4.439 MeV) have been measured in detail from threshold up to 9 MeV by several groups [16,30,31] (table 9). The agreement between the various data which were considered is rather satisfactory. The Legendre coefficients deduced from these data are displayed in fig.23 for $\ell = 1$ through $\ell = 4$. From 9 to 14.5 MeV the proposed values have been obtained from the data of Haouat et al. [3,32] . Around 14 MeV many data are available: they are listed in table 12. The evaluated Legendre coefficients from 9 to 15 MeV are shown in fig.22 for $\ell = 1$ through $\ell = 5$.

b) - $E_n \geq 15$ MeV - The differential cross-section measurements of Deconninck and Meulders [39] have been considered for the estimation of the energy dependance of the Legendre coefficients between 15 and 20 MeV although the integrated cross section deduced from these measurements were not taken into account in our evaluation. These angular distributions seem to be the only available data.

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The inelastic Legendre coefficient from $\ell = 1$ through $\ell = 5$ are also displayed in fig.22.

3° - Photon angular distributions.

We have considered in the present study only the photon angular distributions for the $(n,n'\gamma)$ reaction to the first excited level of ^{12}C, since the photon production from other reactions is negligible compared to the 4.439 MeV γ-ray cross section.

a) - $4.81 \leqslant E_n \leqslant 9$ MeV - In the energy range from threshold to 9 MeV, two groups have measured the photon angular distributions: Drake et al. [79] , between 4.0 and 7.67 MeV, at angles ranging from 25° and 110°, and Lachkar et al. [80] from this laboratory, between 5.8 and 8.8 MeV, at angles from 25° to 125°. As mentionned in section II.4, the Legendre coefficients obtained from a fit to these data suggest that the fourth-order coefficient is very low if not zero. The $(n,n'\gamma)$ measurements made by Morgan et al. [4] which include data at 90° and 125° provide further information on the anisotropies of the 4.439 MeV γ-ray angular distributions. The values of the A_2 coefficient deduced from the data of Morgan et al. [4] have been found in satisfactory overall agreement with the data of Drake et al. [79] and Lachkar et al. [80] . The evaluated curve for the A_2 coefficient, shown in fig.23, is based upon these sets of data.

b) - $E_n \geqslant 9$ MeV - The measurements of Morgan et al. [4] at 90° and 125° span the energy range 9 - 20 MeV. As mentionned above and in section II.4 the A_4 coefficient is assumed to be zero. The evaluated curve for A_2 is then given only the basis of the data of Morgan et al. [4] (fig.23). However the 4.439 MeV photon angular distributions of Drake et al. [81] at 14.2 MeV and Morgan et al. [82] at 14.7 MeV confirm the value of the A_2 coefficient obtained from Morgan et al. [4] results.

4° - Neutron energy and angular distributions for the $^{12}C(n,n'3\alpha)$ reaction.

Above 7.887 MeV neutron energy, the $^{12}C(n,n'3\alpha)$ reaction is energetically allowed. As discussed in section II.5, the yield for this reaction is significant above 10 MeV. Moreover, its contribution to the total

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cross section is an increasing function of the neutron energy up to 16 MeV and, above 16 MeV, slowly decreasing up to 20 MeV.

The mechanism of the $^{12}C(n,n'3\alpha)$ reaction has been investigated mainly above 14 MeV, particularly in kinematically complete experiments using nuclear photoplates or cloud chamber techniques (tables 14). All the studies have concluded that the reaction proceeds primarily through some sequential processes involving intermediate nuclei in particle unstable states. The level schemes of the intermediate nuclear systems reached through the reaction are given in fig.24. No evidence for the simultaneous break-up has been reported up to 20 MeV neutron energy. Similar studies of the $^{12}C(p,p'3\alpha)$ reaction have been carried out and the same conclusions were drawn [83-85] . Furthermore, it can be deduced from the analysis of the data that the largest contribution, about 80%, to the (n,n'3α) cross section comes from the inelastic neutron scattering, leaving the ^{12}C nucleus in the excited states above 7.653 MeV excitation energy. The remaining part, about 20% of the yield, seems to be attributed to the $^{12}C(n,\alpha)^{9}Be$ reaction with the intermediate ^{9}Be nucleus in the 2.43 MeV excited state decaying by 2α + n emission.

As an illustration, a neutron energy spectrum from ref. [86] is given in fig.25. The peaks for Q = - 7.653 and Q = - 9.638 MeV states and the humps for Q = - 10.84 and Q = - 11.83 MeV states are superposed on a continuum mainly due to the scattering from the broad (∿ 3 MeV) level at 10.3 MeV in ^{12}C, and also partly due to the $^{12}C(n,\alpha)^{9}Be^{*} \rightarrow 2\alpha + n$ reaction. Such a spectrum is, in shape, definitely different from an evaporation spectrum as supposed in previous E N D F/B evaluations. In the present work, a more convenient shape is proposed. The neutron spectrum is assumed to be a sum of Gaussian distributions associated with the ^{12}C excitation states, and of an evaporation spectrum due to the $^{12}C(n,\alpha)^{9}Be^{*}$ reaction. The width of each Gaussian is taken equal to the total width of the corresponding ^{12}C level as given in column 2 of table 15. The contribution of the partial cross sections to the total (n,n'3α) yield has been estimated and given in table 15.

The angular distributions for neutrons scattered by high excited states in ^{12}C have been measured at 14.1 MeV by Grin et al. [87] and compared to the previously reported data of Bouchez et al. [33] and Clarke et al. [34] .

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Although some uncertainties remain, approximate shapes of the angular distributions for 14.1 MeV neutrons scattered by the 7.653 and 9.638 MeV states can be deduced. A rough estimation of these angular distributions for incident neutron energies from 10 to 20 MeV has been attempted by refering to the elastic angular distributions in the same energy range. A reason of such a procedure is based on the theoretical analysis made by Grin et al. [88] tending to prove from coupled-channel calculations, the coupling of the 0^+ (7.653 MeV) and 3^- (9.638 MeV) states to the ground and first excited states. Neutrons scattered by higher excited states in ^{12}C are supposed isotropically distributed. The same assumption is made for neutrons from the sequential process involving, through the (n,α) reaction, an intermediate ^9Be nucleus in excited states.

IV - CONCLUSION

There are several areas where the present evaluation is deficient and improvements could be made. Specifically, between 15 and 20 MeV neutron energy, some remaining uncertainties should be removed by new cross section measurements of inelastic scattering, (n,n'3α) and (n,α) reactions.

A detailed resonance-theory analysis, above 5 MeV, would improve this evaluation and lead to good resonance parameters. A great improvement would come, also, from using reaction-theory calculations for all the partial cross sections and, principally, for the (n,p) and (n,d) cross sections.

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- TABLE CAPTIONS -

Table 1 : Q-values and thresholds for the n + ^{12}C reactions. All the Q-values used in this evaluation are taken from the mass excesses tables of Wapstra and Gove [37].

Table 2 : Total cross section data used in this evaluation.

Table 3 : ^{13}C level parameters most of the data have been taken from ref. [14].

Table 4 : Thermal neutron total cross section of carbon.

Table 5 : Summary of neutron elastic scattering measurements used in this evaluation for $E_n \leqslant 4.8$ MeV.

Table 6 : Summary of neutron elastic and inelastic scattering measurements used in this evaluation for E_n in the range from 4.8 to 8.0 MeV.

Table 7 : Summary of neutron elastic and inelastic scattering measurements used in this evaluation for E_n in the range from 8.0 to 15 MeV.

Table 8 : Summary of neutron elastic and inelastic scattering measurements used in this evaluation for E_n in the range from 15 to 20 MeV.

Table 9 : Summary of (n,n') and (n,n'γ) measurements considered in this evaluation for E_n in the range from 14.0 to 15.0 MeV.

Table 10 : Summary of $^{12}C(n,\alpha_o)$ cross-section measurements used in this evaluation.

Table 11 : Summary of $^{9}Be(\alpha,n)$ cross-section measurements used in this evaluation. The energy range plotted in this table is that of the neutron produced by the inverse reaction.

.../...

- FIGURES CAPTIONS -

Figure 1 : Energy level diagram for the A = 13 mass system.

Figure 2 : Evaluated total cross section from 10^{-5} eV to 2 MeV.

Figure 3 : Evaluated total cross section from 2 to 4.8 MeV with the data on which it is based.
a : ref.[5] , b : ref.[15] , c : ref.[6] , d : ref.[89] ,
e : ref.[11].

Figure 4 : Measured and evaluated total cross section from 4.8 to 8 MeV. The same conventions as in Fig. 3 are adopted.

Figure 5 : Measured and evaluated total cross section from 8 to 20 MeV. The same conventions as in Fig. 3 are adopted.

Figure 6 : Evaluated total cross section from 1 to 20 MeV.

Figure 7 : Evaluated (n,γ) cross section from 0 to 20 MeV.

Figure 8 : Decay scheme and branching ratios for thermal radiative capture.

Figure 9 : Evaluated elastic scattering cross section from 0.1 to 8.0 MeV.

Figure 10 : Measured and evaluated elastic scattering cross sections from 8 to 20 MeV.
a : ref.[3] , b : ref.[32] , c : ref.[31] , d : ref.[30] ,
e : ref.[33] , f : ref.[38] , g : ref.[35] , h : ref.[39].

Figure 11 : Measured and evaluated (n;n') and (n,n'γ) cross sections for the 4.439 MeV level from 4.8 to 8.0 MeV.
a : ref.[3] , b : ref.[80] , c : ref.[16] , d : ref.[77] ,
e : ref.[79] , f : ref.[89] , g : ref.[4] , h : ref.[31].

Figure 12 : Measured and evaluated (n,n') and (n,n'γ) cross sections for the 4.439 MeV level.from 8 to 20 MeV.
a : ref.[3] , b : ref.[32] , c : ref.[4] , d : ref.[30] ,
e : ref.[31] , f : ref.[33] , g : ref.[34].

Figure 13 : Evaluated inelastic scattering cross section to the first excited level in ^{12}C in the energy range from threshold to 20 MeV.

.../...

Figure 14 : Measured and evaluated (n,α) cross sections from threshold to 20 MeV.
a : ref.[45] , b : ref.[46] , c : ref.[50] , d : ref.[54] , e : ref.[49] , f : ref.[52].

Figure 15 : Measured and evaluated (n,n'3α) cross sections from threshold to 20 MeV.
a : ref.[60] , b : ref.[61] , c : ref.[122].

Figure 16 : Measured and evaluated (n,p) cross sections from threshold to 20 MeV.
a : ref.[63] , b : ref.[64].

Figure 17 : Evaluated (n,d) cross section from threshold to 20 MeV.

Figure 18 : Evaluated total and partial cross sections from 2.0 to 20 MeV.

Figure 19 : Measured small-angle elastic scattering data from 8 to 9.5 MeV.
a : ref.[3] , b : ref.[76].

Figure 20 : Evaluated Legendre coefficients for elastic scattering.

Figure 21 : Measured and evaluated elastic scattering cross sections at selected angles.
a : ref.[3] , b : ref.[35] , c : ref.[38] , d : ref.[39] , e : ref.[77] , f : ref.[78].

Figure 22 : Evaluated Legendre coefficients for inelastic scattering to the 4.439 MeV level in ^{12}C.

Figure 23 : Evaluated second-order Legendre coefficient for (n,n'γ) angular distribution.

Figure 24 : Composit energy-level diagram for the intermediate nuclei reached through the (n,n'3α) reaction.

Figure 25 : Measured secondary-neutron spectrum in the laboratory system for 14.1 MeV laboratory incident neutrons. No correction for experimental resolution was made. Arrows indicate the mean energy of the neutrons scattered by the excited levels of ^{12}C listed in table 15.

- TABLE 1 -

REACTION	Q-VALUE	THRESHOLD ENERGY
$^{12}C(n,\gamma)^{13}C$	$Q = +\ 4.947$ MeV	$E_{thr.} = 0$
$^{12}C(n,n)^{12}C$	$Q = 0$	$E_{thr.} = 0$
$^{12}C(n,n')^{12}C^{*}$	$Q = -\ 4.439$ MeV	$E_{thr.} = 4.812$ MeV
$^{12}C(n,\alpha_0)^{9}Be$	$Q = -\ 5.702$ MeV	$E_{thr.} = 6.181$ MeV
$^{12}C(n,n'3\alpha)$	$Q = -\ 7.275$ MeV	$E_{thr.} = 7.887$ MeV
$^{12}C(n,p)^{12}B$	$Q = -\ 12.588$ MeV	$E_{thr.} = 13.646$ MeV
$^{12}C(n,d)^{11}B$	$Q = -\ 13.733$ MeV	$E_{thr.} = 14.888$ MeV
$^{12}C(n,np)^{11}B$	$Q = -\ 15.957$ MeV	$E_{thr.} = 17.299$ MeV
$^{12}C(n,2n)^{11}C$	$Q = -\ 18.722$ MeV	$E_{thr.} = 20.296$ MeV

- TABLE 2 -

AUTHORS	REFERENCE IN THE TEXT	LABORATORY	ENERGY RANGE (MeV)	REMARKS
FOSSAN et al.	[15]	Univ. Wisconsin	3.4 - 16 MeV	Experimental data
SCHWARTZ et al.	[6]	N B S	0.5 - 15 MeV	"
CIERJACKS et al.	[5]	K F K	0.3 - 30 MeV	"
FOSTER et al.	[8]	B N W	2.5 - 15 MeV	"
PEREY et al.	[11]	O R N L	0.2 - 20 MeV	"
HOLT et al.	[7]	A N L	1.5 - 5.0 MeV	"
FRANCIS et al.	[9]	K A P L	10^{-10} - 15 MeV	Evaluated data
NISHIMURA et al.	[10]	J A E R I	up to 2 MeV	"
PEREY et al.	[89]	O R N L	10^{-10} - 20 MeV	"

- TABLE 3 -

RESONANCE ENERGY E_n (MeV)	^{13}C EXCITATION ENERGY (MeV)	Γ_{total} (keV)	J^{π} ; T	DECAY MODE
2.0778 ± 0.0015	6.863	8 ± 2	$5/2^+$	n
2.816 ± 0.004	7.545	3 ± 2	$5/2^-$	
2.946 ± 0.002	7.665	80	$3/2^+$	n
3.580 ± 0.080	8.249	1200 ± 200	$3/2^+$	n
4.261 ± 0.020	8.879	210 ± 20	$1/2^-$	n
4.936 ± 0.006	9.500	11 ± 4	$(3/2^-)$	n
5.371 ± 0.006	9.901	30 ± 4	$3/2^-$	n,n' $\Gamma_{el}/\Gamma_{total} = 0.70 \pm 0.10$
6.295 ± 0.005	10.754	57 ± 4	$7/2^-$	n,n' $\Gamma_{el}\ \Gamma_{total} = 0.70 \pm 0.10$
6.350 ± 0.010	10.805	24 ± 3		n,n'
6.554 ± 0.010	10.993	32 ± 5	$(1/2^+)$	n,α,n' $\Gamma_{el}\ \Gamma_{total} = 0.40 \pm 0.10$
6.645 ± 0.010	11.078	8 ± 4		n,n'
6.660 ± 0.010	11.090	62	$(1/2^-)$	n,n'
7.368 ± 0.010	11.744	107 ± 14		n,n'
7.420 ± 0.050	11.792	68 ± 4	$(3/2^-)$	n,α
7.609 ± 0.040	11.966	260	$(7/2^-)$	n,n'
7.749 ± 0.010	12.095	80 ± 8	(>7/2)	n,n'
8.100 ± 0.030	12.419	160		α,n
9.049	13.294	5000		γ,n

- TABLE 3 - (continued)

RESONANCE ENERGY E_n (MeV)	^{13}C EXCITATION ENERGY (MeV)	Γ_{total} (keV)	J^{π} ; T	DECAY MODE
9.157	13.394	60		n,n'
9.261 ± 0.010	13.490	500		n,n'α
9.547	13.754	350		n,α
9.948	14.123	200		n,n'
10.230	14.384	260		n,α,n'
10.490	14.623	210		n,n'
10.837	14.943	380		n,α
11.016	15.1087 ± 0.002	5.9	$3/2^-$; 3/2	γ,n,n'
11.250	15.324	450		n,n'
11.465	15.523	220		n
11.996	16.013	210		n,n'
12.085 ± 0.030	16.090	230		n,α
13.014	16.952	390		n
13.458	17.361	190		n,n'
13.837	17.711	170		n
14.466	18.291	300		n,α
14.687	18.495		; 3/2	

- TABLE 3 - (continued)

RESONANCE ENERGY E_n (MeV)	^{13}C EXCITATION ENERGY (MeV)	Γ_{total} (keV)	J^{π} ; T	DECAY MODE
14.843	18.639	35	; 3/2	
14.863	18.657		; 3/2	
14.964	18.750	70		n,α,n'
15.357	19.113	35	; 3/2	α
15.766	19.490	460		n,d,n'
16.200	19.891	600		n,p,d
16.578	20.239	200		n,d,α
16.892	20.529	116		n,p,d,α
17.716	21.289	159		n,p,d
18.300	21.828	114		n,d
18.777	22.268	7000		γ,n,p,d
19.557	22.987	1000		n,d

- TABLE 4 -

AUTHORS	REF.	σ_T (barn)	COMMENTS	REMARKS
MARSHALL - 1946	[90]	4.84 ± 0.1	at 1.46 eV nominal uncertainty	Measurement
JONES - 1948	[91]	4.7 ± 0.1	3 - 120 eV nominal uncertainty	
HAVENS et al. - 1949	[92]	4.7 ± 0.05		
EGELSTAFF - 1952	[93]	4.56 ± 0.1	4.27 - 83.2 eV nominal uncertainty	
SAILOR - 1955	[94]	4.74 ± 0.03	1.46 eV B N L crystal spectrometer	
BRUGGER et al. - 1956	[95]	4.71 ± 0.1	averaged	
WALTON - 1961	[96]	4.82 ± 0.1	1.25 - 128 eV nominal uncertainty	
SIMPSON et al. - 1964	[97]	4.7 ± 0.1	above 5 eV nominal uncertainty	
RAYBURN and WOLLAN - 1965	[98]	4.66 ± 0.03	1.46 eV graphite	
	[99]	4.74 ± 0.06	1.46 eV diamond dust	
TRIFTSHAUSER and FEHSENFELD - 1965	[99]	4.743 ± 0.002	33.9 eV	
		4.7264 ± 0.0024	61.1 eV	
KOESTER et al. - 1967	[100]	4.727 ± 0.005	Neutron gravity spectrometer	
DIMENT and UTTLEY - 1968	[101]	4.744 ± 0.047	nominal uncertainty	
HANK and WILSON - 1967	[102]	4.7534 ± 0.0045	0.3 - 200 eV	
KOESTER et al. - 1969	[103]	4.695 ± 0.0042	Neutron gravity spectrometer	
LEONARD - 1970	[12]	4.730 ± 0.008	E N D F /B.II	Evaluation
STORY - 1970	[13]	4.723 ± 0.0125		
This work - 1975		4.728 ± 0.008		

- TABLE 5 -

AUTHORS	REF.	LABORATORY	NEUTRON ENERGY RANGE (MEV)	NUMBER OF MEASUREMENT ENERGIES	MEASUREMENTS ANGLES (deg)	REMARKS
LANE et al.	[19]	A N L	0.05 - 2.30	30	22° - 145°	Ang. Dist. and polarization
MEIER et al.	[17]	Lausanne	2.2 - 3.8	8	35° - 145°	Ang. Dist.
AHMED et al.	[104]	Geel	0.5 - 2.0	46	20° - 160°	Ang. Dist.
WILLS et al.	[18]	O R N L	1.45 - 4.10	12	35° - 145°	Ang. Dist.
KNOX et al.	[22]	Ohio Univ.	2.63	1	17° - 118	Ang. Dist. and polarization
GALATI et al.	[16]	Kentucky Univ.	3.0 - 7.0	32	15° - 160°	Ang. Dist.
HOLT et al.	[7]	A N L	1.8 - 4.0	12	20° - 160°	Ang. Dist. No data

- TABLE 6 -

AUTHORS	REF.	LABORATORY	NEUTRON ENERGY RANGE (MeV)	NUMBER OF MEASUREMENT ENERGIES	MEASUREMENTS ANGLES (deg)	REMARKS
GALATI et al.	[16]	Kentucky Univ.	3.0 - 7.0	32	15° - 160°	Ang. Dist.
WILENZICK et al.	[105]	Duke Univ.	6.0	1	20° - 150°	"
BRALEY et al.	[106]	Convair, San-Diego	5.6	1	30° - 150°	"
HILL	[107]	Westinghouse Research lab.	5.0	1	10° - 150°	"
BEYSTER et al.	[69]	L A S L	7.0	1	15° - 150°	"
HADDAD et al.	[108]		6.0 - 7.0	2	20° - 150°	"
PEREY et al.	[31]	O R N L	4.5 - 8.5	13	15° - 140°	"
			5.2 - 8.7	40	15° - 140°	"
VELKLEY et al.	[30]	Aerospace Research lab.	7.0 - 9.0	5	30° - 150°	"

- TABLE 7 -

AUTHORS	REF.	LABORATORY	NEUTRON ENERGY RANGE (MeV)	NUMBER OF MEASUREMENT ENERGIES	MEASUREMENTS ANGLES (deg)	REMARKS
PEREY et al.	[31]	O R N L	4.5 - 8.5	13	15° - 140°	Ang. Dist.
		O R N L	5.2 - 8.7	40	15° - 140°	
VELKLEY et al.	[30]	Aerospace Research lab	7.0 - 9.0	5	30° - 150°	"
HAOUAT et al.	[32]	Bruyères-le-Châtel	8.5 - 11.0	4	10° - 160°	"
HAOUAT et al.	[3]	Bruyères-le-Châtel	8.0 - 14.5	14	10° - 160°	"
BOUCHEZ et al.	[33]	C E A Grenoble	14.0 - 14.6	2	20° - 150°	"
CLARKE et al.	[34]	Chalk River	14.0	1	10° - 150°	"
GRIN et al.	[87]	Lausanne	14.7	1	15° - 150°	"
SPAARGAREN et al.	[35]	Amsterdam Univ.	15.0	1	30° - 150°	"
PURSER et al.	[36]	T U N L	9.0 - 15.0	14	25° - 160°	" No data

- TABLE 8 -

AUTHORS	REF.	LABORATORY	NEUTRON ENERGY RANGE (MeV)	NUMBER OF MEASUREMENT ENERGIES	MEASUREMENTS ANGLES (deg)	REMARKS
HARLOW et al.	[78]	O R N L	17.0 - 21.0	25	36° - 139°	Ang. dist. for elastic scatt. only.
BORELI et al.	[38]	University of Texas (Austin)	14.0 - 25.0	≥ 30	30° - 90°	Ang. dist. for elastic scatt. only. Integrated elastic and non elastic cross sections.
DECONNINCK et al.	[39]	University of Louvain	17.0 - 20.5	3	15° - 150°	Ang. dist. for elastic and inelastic (4.439 MeV) reactions.
PEREY et al.	[77]	O R N L	15.0 - 20.0	Continuum	129°	Elastic differential cross sections.

- TABLE 9 -

AUTHORS	REF.	ENERGY (MeV)	$\sigma_{int.}$ (mb)	$\sigma_{90°}$ (mb/sr)	$\sigma_{125°}$ (mb/sr)	
HAOUAT et al.	[3]	14.1 ± 0.1	185 ± 8			(n,n')
SINGLETARY et al.	[109]	14.1	203			
GRIN et al.	[87]	14.1	215 ± 15			
JOSEPH et al.	[110]	14.1	216 ± 25			
BOUCHEZ et al.	[33]	14.1	215 ± 40			
CLARKE et al.	[34]	14.1	209 ± 20			
HAOUAT et al.	[3]	14.5	146.4 ± 9			
PURSER et al.	[36]	14.0	206			
ROTURIER	[111]	14.0	200 ± 40			
TESCH	[112]	14.0	220 ± 25			

- TABLE 9 - (continued)

AUTHORS	REF.	ENERGY (MeV)	$\sigma_{int.}$ (mb)	$\sigma_{90°}$ (mb/sr)	$\sigma_{125°}$ (mb/sr)	
ANDERSON et al.	[113]	14.0	220 ± 8			
BATTAT et al.	[114]	14.0	245 ± 35			
MORGAN et al.	[4]	14.087 ± 0.25	181 ± 8	9.71 ± 0.46	14.40 ± 0.60	
				E_n = 13.987		
LACHKAR et al.	[79]	14.1 ± 0.1	215 ± 20	10.6 ± 1.4		
BENVENISTE et al.	[115]	14.1 ± 0.06	249 ± 28	12		
STEWART et al.	[116]	14.1 ± 0.1	232 ± 18	13		
GRENIER et al.	[117]	14.1 ± 0.1	195 ± 25	9.6 ± 1.6		
DRAKE et al.	[81]	14.2	217.1	11.6 ± 1.5	16.1 ± 2.1	(n,xγ)
MORGAN et al.	[4]	14.591 ± 0.25	170 ± 8	8.19 ± 0.5	13.53 ± 0.6	
MORGAN et al.	[82]	14.7	206 ± 30			
ENGESSER et al.	[118]	14.7		13.1 ± 1.3		
SPAARGAREN et al.	[35]	15.0	229 ± 1			
MARTIN et al.	[119]	14.8	207.2		16.5	
ROGERS et al.	[120]	12 - 14	192.3		15.3	
ROGERS et al.	[120]	14 - 17	94.3		7.5	
ROTURIER	[111]	14.0	140 ± 20			

- TABLE 10 -

AUTHORS	REFERENCE IN THE TEXT	LABORATORY	ENERGY RANGE (MeV)	REMARKS
DAVIS et al.	[49]	RICE Inst.	7.8 - 8.7	Data at 13 energies
BRENDLE et al.	[51]	Tübingen	13.9 - 15.6	
GRAVES et al.	[52]	RICE Inst.	14.1	
AL KITAL et al.	[53]	Brown Univ.	14.1	
KITAZAWA et al.	[54]	Tokyo Inst.	14.1	
CHATTERJEE et al.	[56]	Saha Inst.	14.5	
KOPSCH et al.	[121]	K F K	14.1	$\sigma(n,n'3\alpha) + \sigma(n,\alpha_0)$
SALATHE et al.	[58]	Bale Univ.	14.8 - 18.8	Data at 30 energies
HUCK et al.	[57]	Strasbourg	15.0 - 16.0 - 17.0	Relative data

- TABLE 11 -

AUTHORS	REFERENCE IN THE TEXT	LABORATORY	ENERGY RANGE (MeV)	REMARKS
RETZ et al.	[45]	RICE Inst.	7.5 - 10.5	
RISSER et al.	[48]	RICE Inst.	7.7 - 10.0	
VAN DER ZWAN et al.	[47]	N R C	8.09 - 12.08	
		(Ottawa)	7.3 - 12.0	
OBST et al.	[46]	Univ. of Kentucky	9.0 - 11.0	
VERBINSKY et al.	[50]	O R N L	11.3 - 13.7	
DECONNINCK et al.	[59]	Louvain	15.8 - 18.1	
NILSSON et al.	[55]	Stockolm	16.3	

- TABLE 12 -

AUTHORS	REF.	ENERGY RANGE (MEV)	REMARKS
GREEN et al.	[122]	10.6 - 14.6	-
FRYE et al.	[60]	12.85 - 18.80	Decay stars counting
SACKS	[123]	8.0 - 19.0	Proposed empirical formula
VASIL'EV et al.	[61]	9.0 - 19.0	Nuclear emulsion techniques

- TABLE 13 -

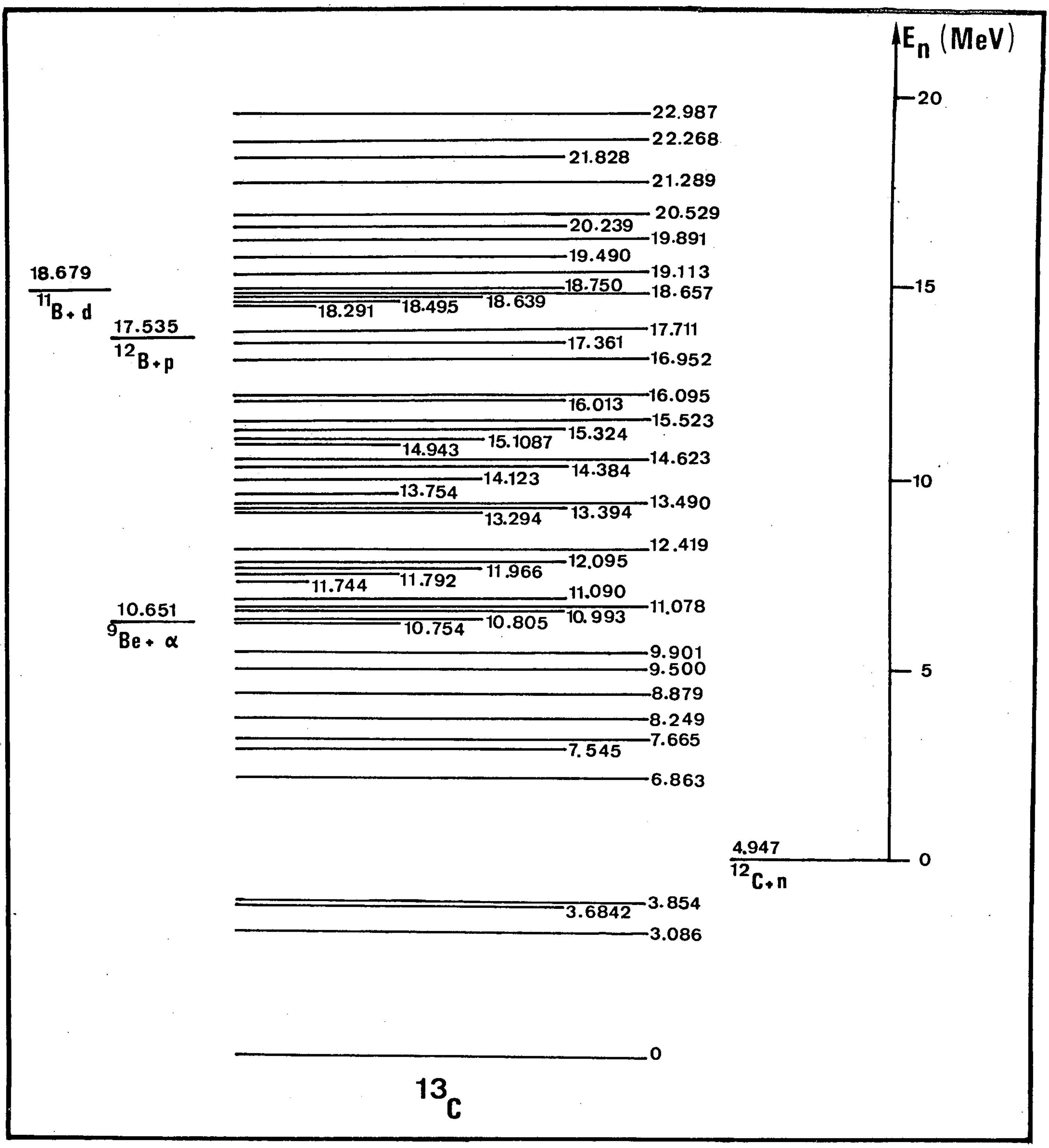
CROSS SECTION	NEUTRON ENERGY				
	THERMAL NEUTRONS	0 - 4.8 MeV	4.8 - 8 MeV	8.0 - 15 MeV	15 - 20 MeV
Total	< 1%	1% ($E \leqslant 2$ MeV) 2% ($2 < E < 4$ MeV)	4%	4%	6%
(n,γ)	10%	20%	20%	20%	20%
Elastic	< 1%	< 4%	5%	5 - 7%	10%
(n,n') (4.439 MeV)			5%($4.8<E_n<6.18$ MeV)	7% ($E_n > 6.18$ MeV)	
(n,α_0)			12%($E_n>6.18$ MeV)	12%	20%
$(n,n'3\alpha)$				20%	25%
(n,p)					15%
(n,d_0)					15%
Non elastic			5%	7%	12%

- TABLE 14 -

AUTHORS	REF.	LABORATORY	NEUTRON ENERGY (MeV)	EXPERIMENTAL METHOD
CHADWICK et al.	[124]	Ruth. lab.	> 8.5	Cloud chamber
SINGLETARY et al.	[109]	North. Univ.	14.1	Nuclear emulsion plates
MÖSNER et al.	[125]	Dresden (Germany)	15.5	Cloud chamber
BARJON et al.	[126]	I E N (Alger)	15.0	Time-of-flight techniques
GRIN et al.	[87]	Lausanne Univ.	14.1	Time-of-flight techniques and scintillating scatterer.
BRINKLEY et al.	[127]	Camberra Univ.	14.1	Nuclear emulsion plates
ANTOLKOVIC et al.	[128]	Zagreb Inst.	14.4	Nuclear emulsion plates
COÇU et al.	[86]	Bruyères-le-Châtel	14.1	Time-of-flight techniques and scintillating scatterer.

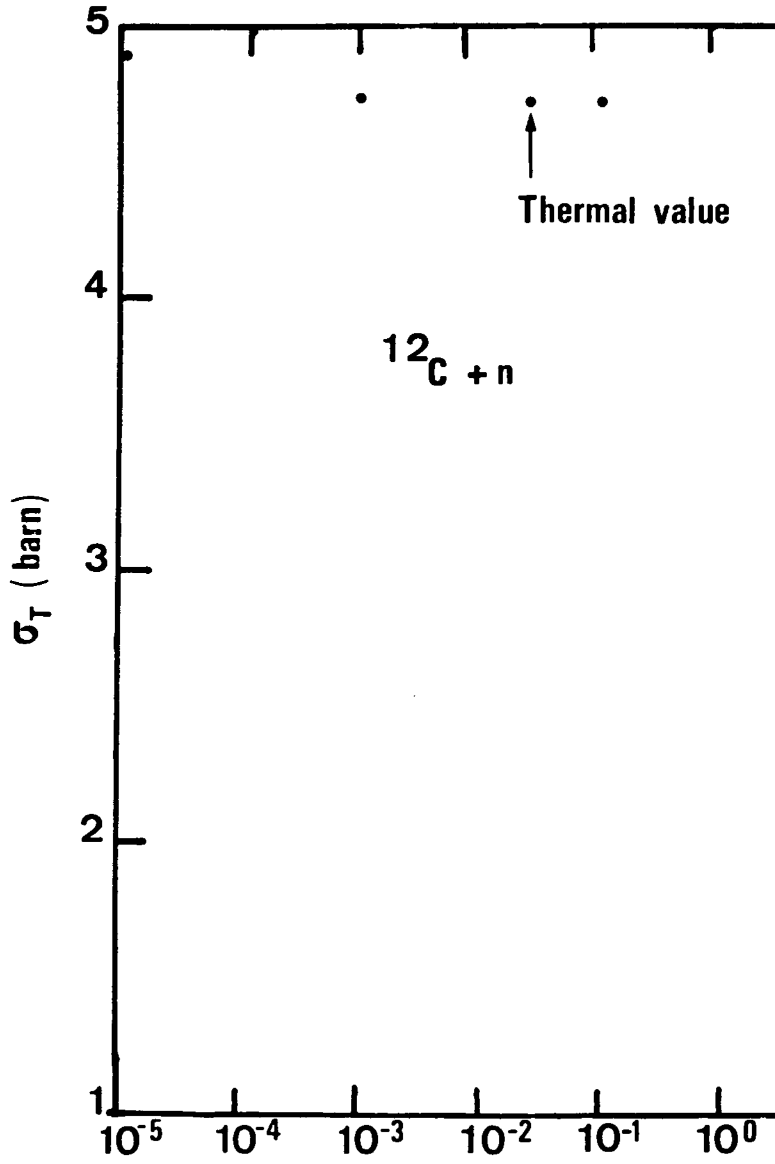
- TABLE 15 -

Q (MeV)	$\Gamma_{tot.}$ (keV)	THRESHOLD (MeV)	E_n (MeV)								
			10	11	12	13	14	15	16	18	20
− 7.653	9.7	8.29	5	10	20	11	10	10	10	5	5
− 9.638	34	10.44		40	70	64	65	83	100	70	45
− 10.3	3000	11.16			10	10	15	15	20	15	5
− 10.84	320	11.75			5	20	35	50	70	45	30
− 11.83	274	12.81				5	20	41	70	80	70
− 12.71	2	13.77					10	30	50	75	80
− 13.35	400	14.46						5	15	30	55
α + ^9Be		7.88	25	80	90	75	80	60	60	40	10
Continuum		7.88	25	80	105	110	160	201	285	285	250
(n,n'3α)		7.88	30	130	195	185	235	294	395	360	300

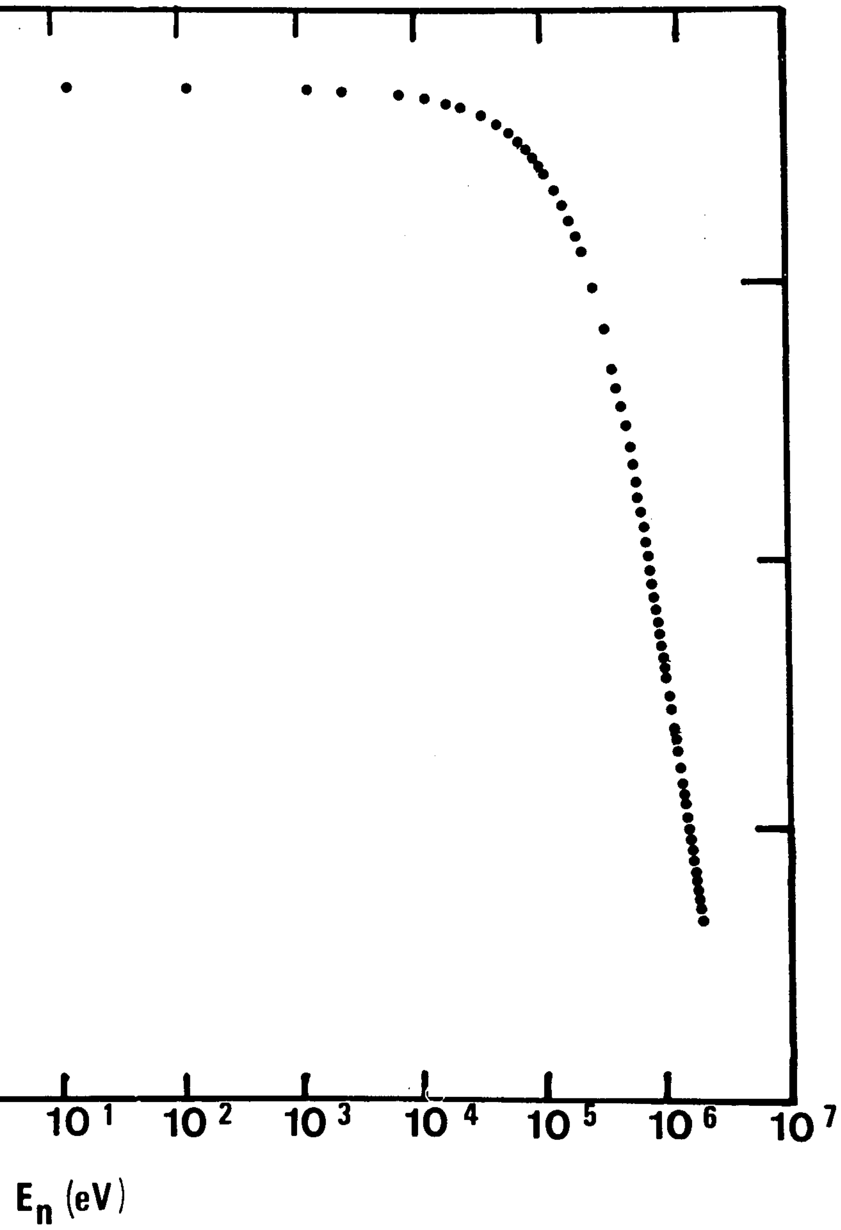


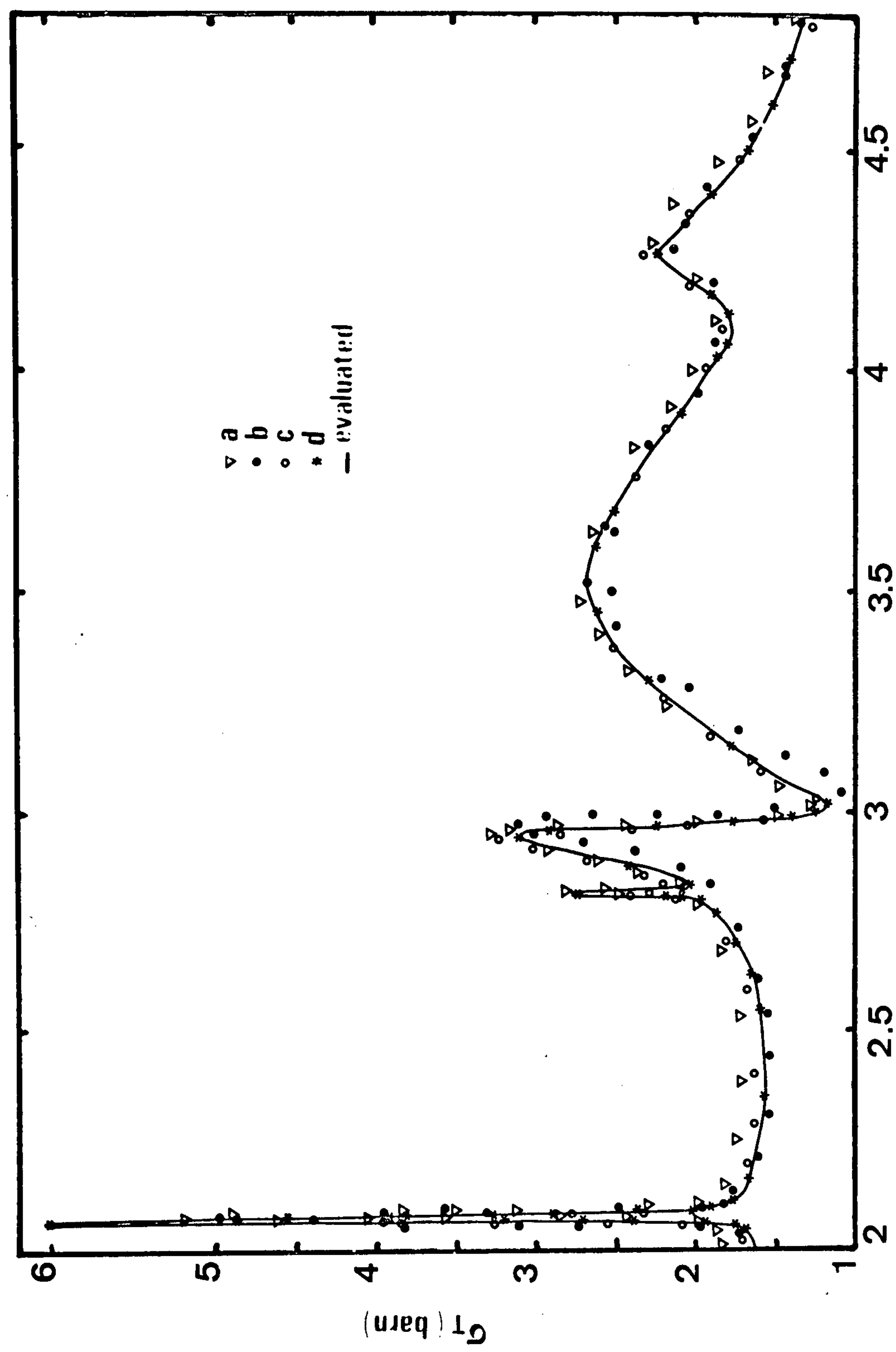
En (MeV)
20
15
10
5
0
22.987
22.268
21.828
21.289
20.529
20.239
19.891
19.490
19.113
18.750
18.657
18.639
18.495
18.291
17.711
17.361
16.952
16.095
16.013
15.523
15.324
15.1087
14.943
14.623
14.384
14.123
13.754
13.490
13.394
13.294
12.419
12.095
11.966
11.792
11.744
11.090
11.078
10.993
10.805
10.754
9.901
9.500
8.879
8.249
7.665
7.545
6.863
3.854
3.6842
3.086
0
18.679
11B+d
17.535
12B+p
10.651
9Be+α
4.947
12C+n
13C

- FIG. 1 -

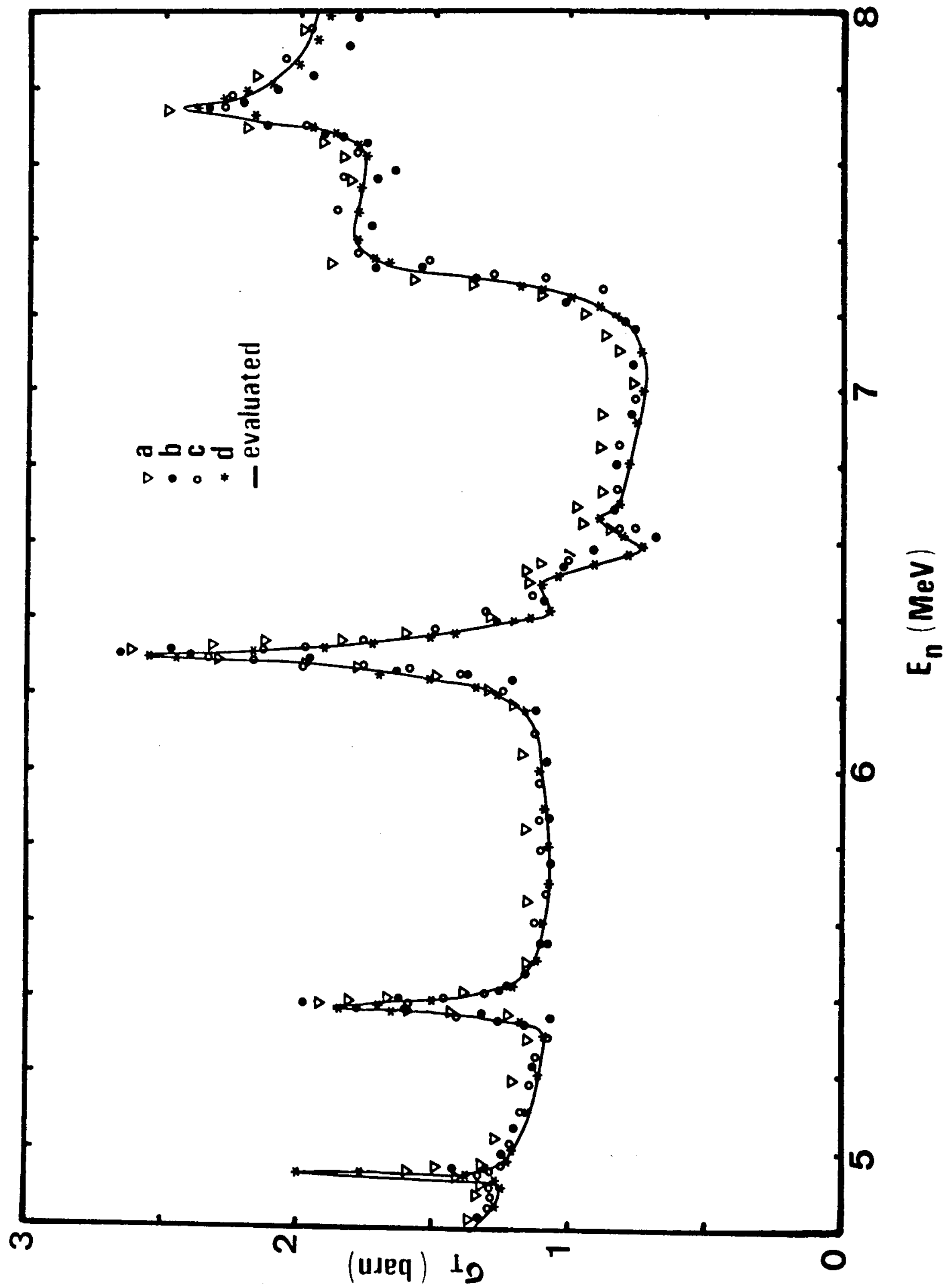


- FIG. 2 -

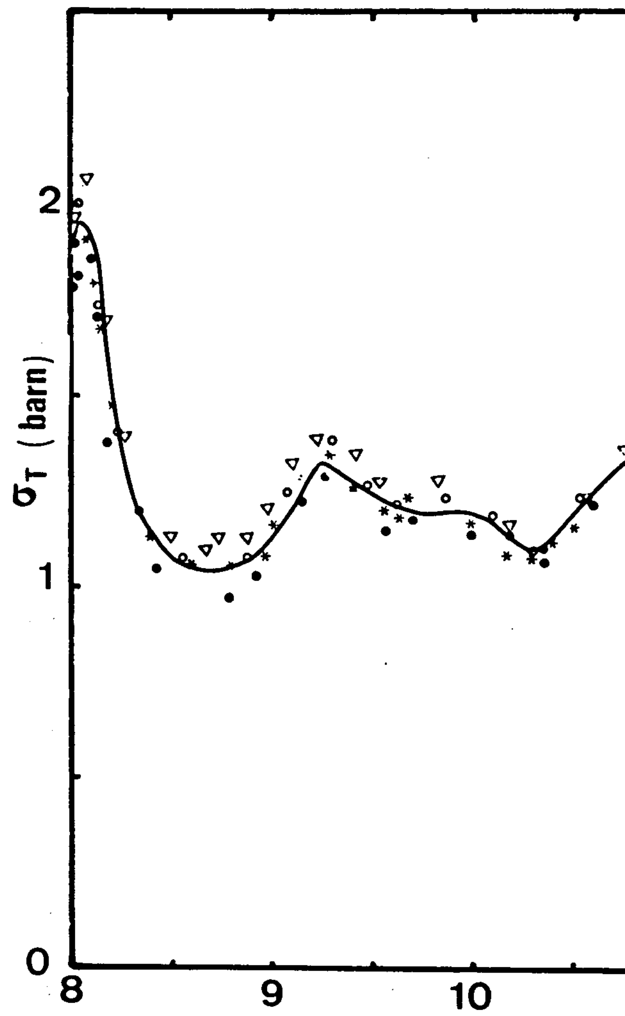

10 1
10 2
10 3
10 4
10 5
10 6
10 7
E_n (eV)



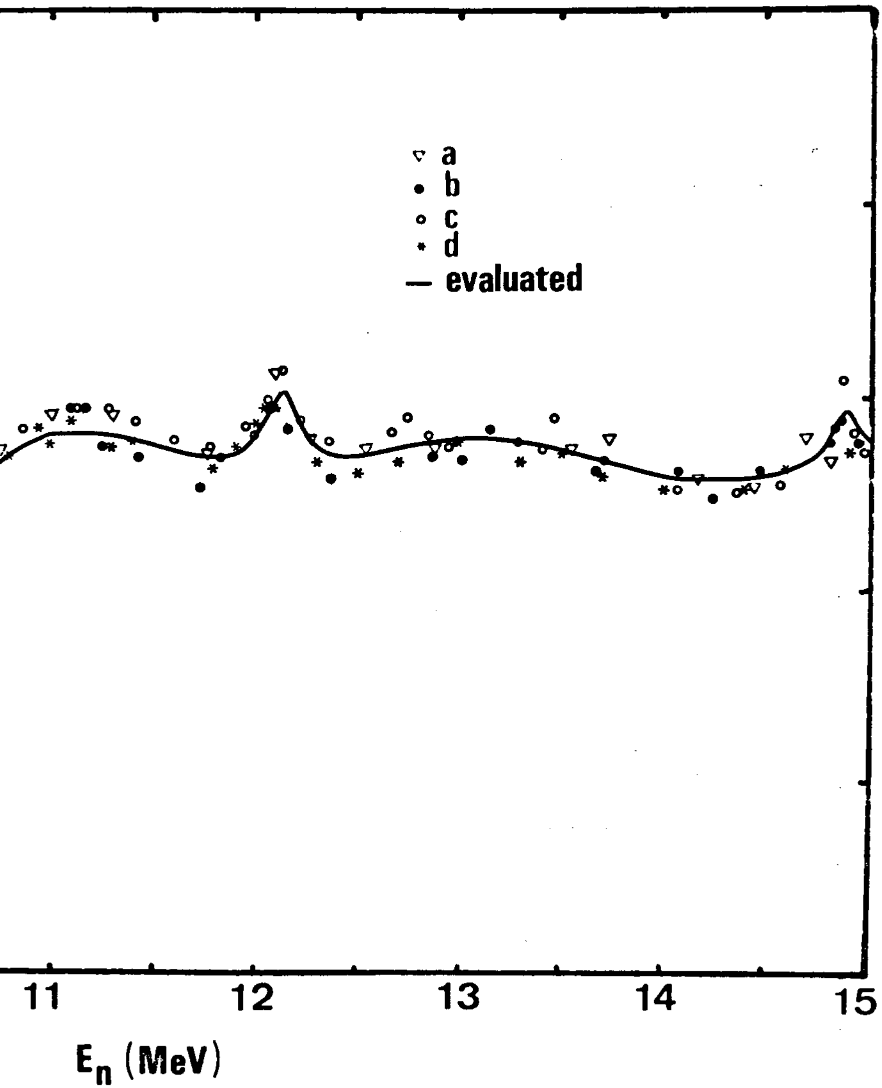
- FIG. 3 -

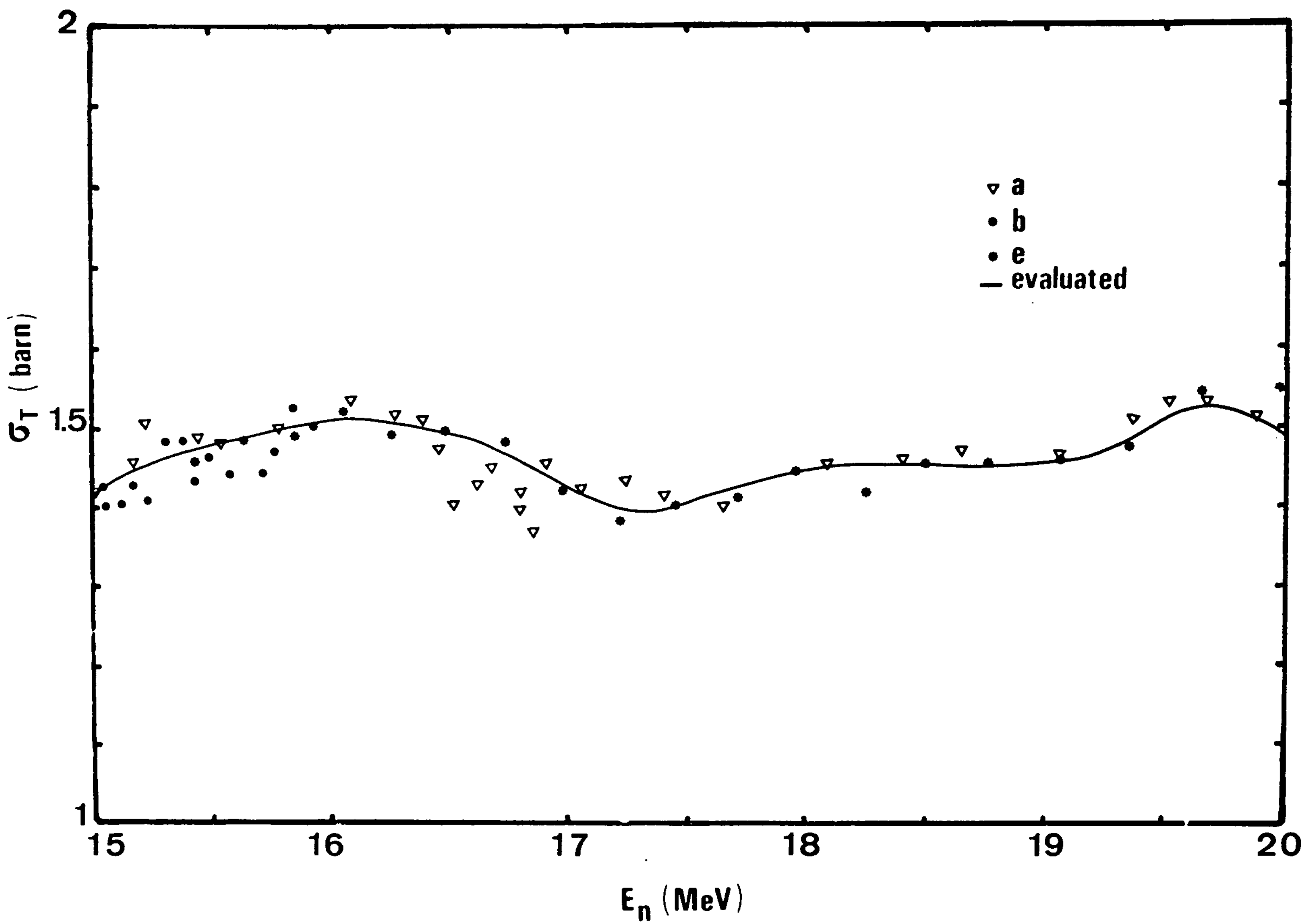


- FIG. 4 -

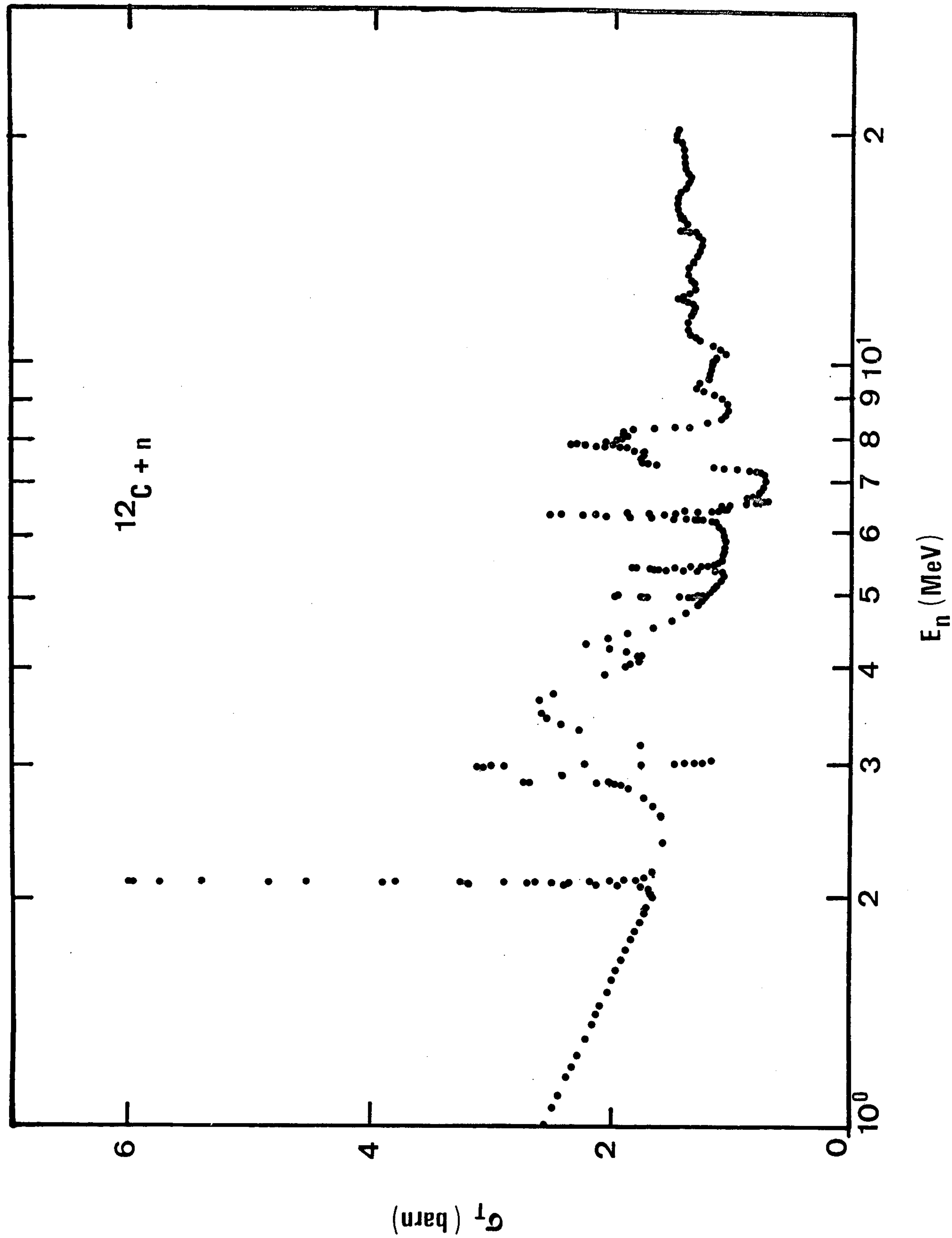


- FIG. 5a -

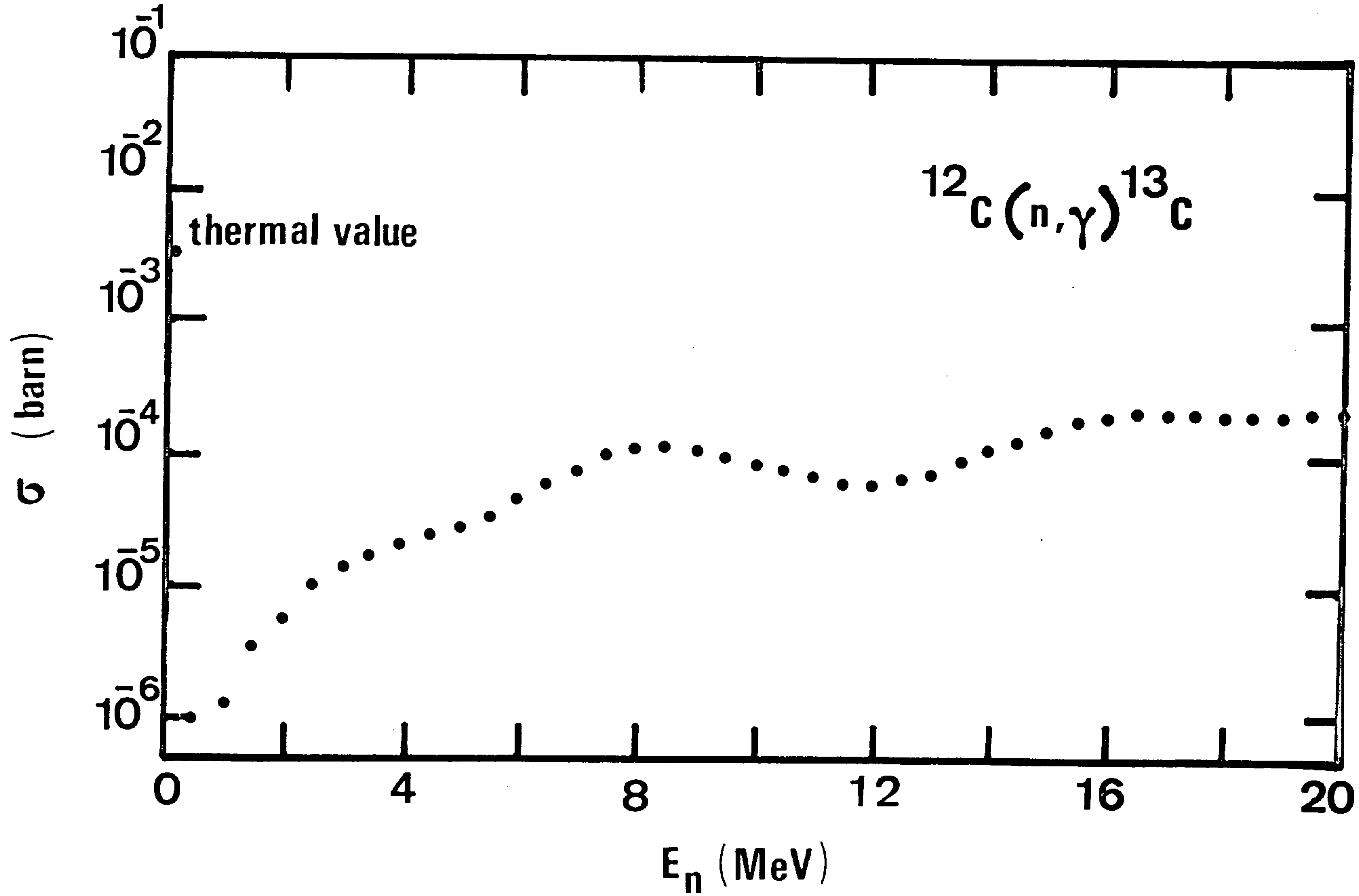

a
b
c
d
evaluated
11
12
13
14
15
E_n (MeV)



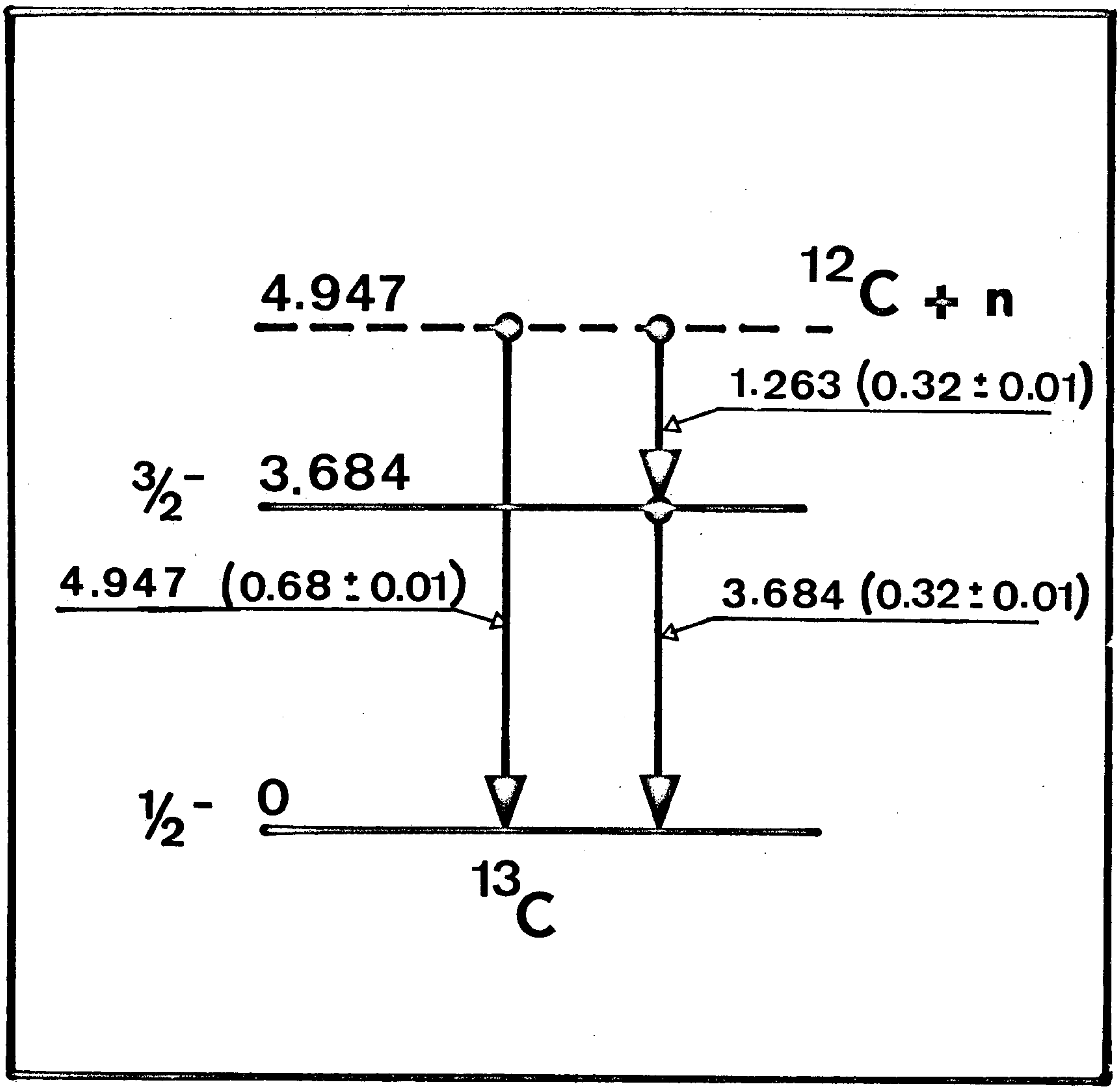
- FIG. 5b -



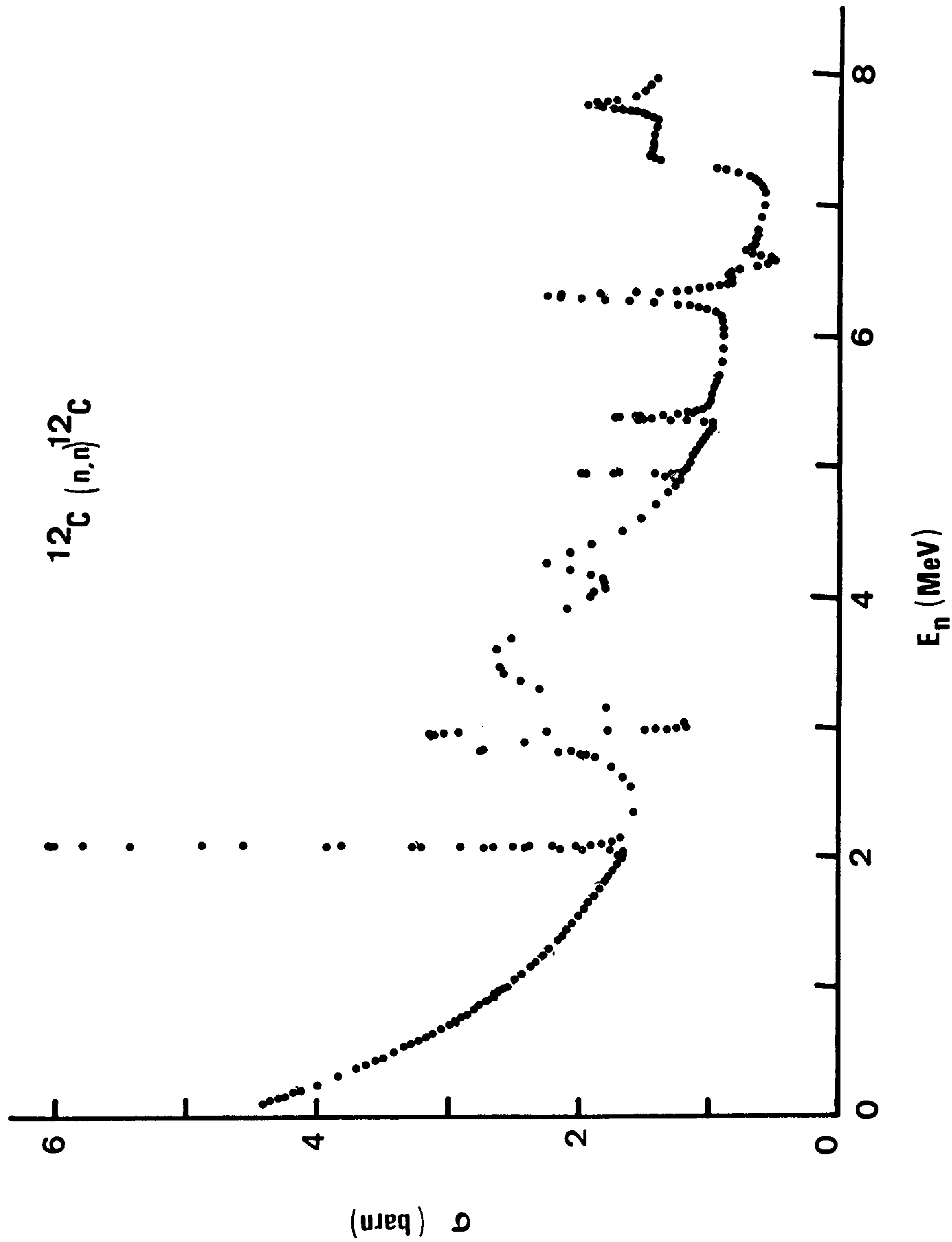
- FIG. 6 -


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ (barn)
thermal value
$^{12}C(n,\gamma)^{13}C$
0
4
8
12
16
20
E_n (MeV)

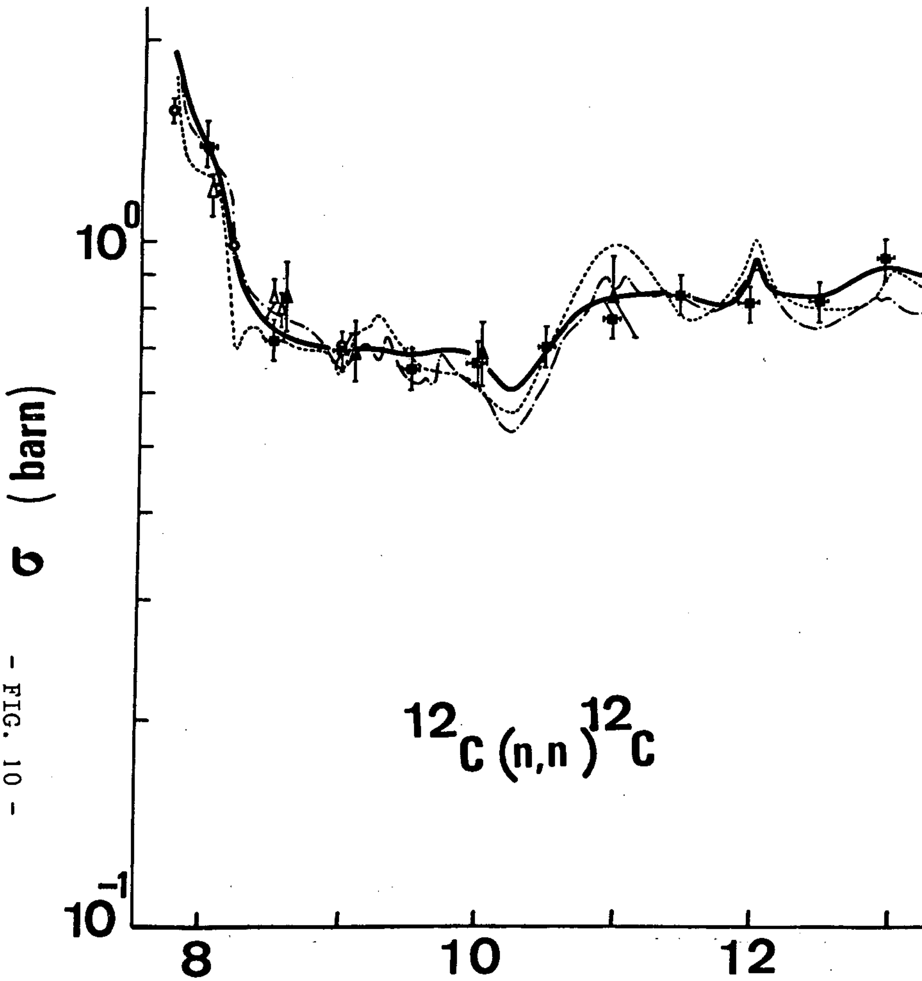
- FIG. 7 -


4.947
$^{12}C + n$
1.263 (0.32 ± 0.01)
3/2- 3.684
4.947 (0.68 ± 0.01)
3.684 (0.32 ± 0.01)
1/2- 0
^{13}C

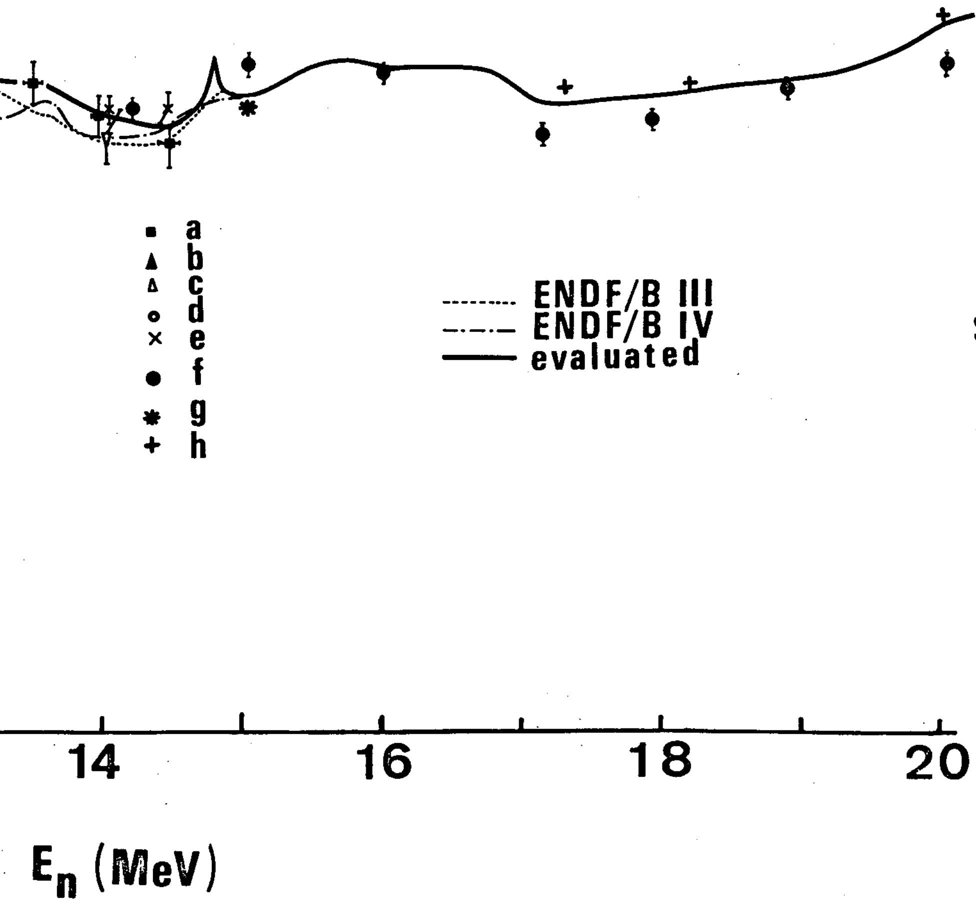
- FIG. 8 -



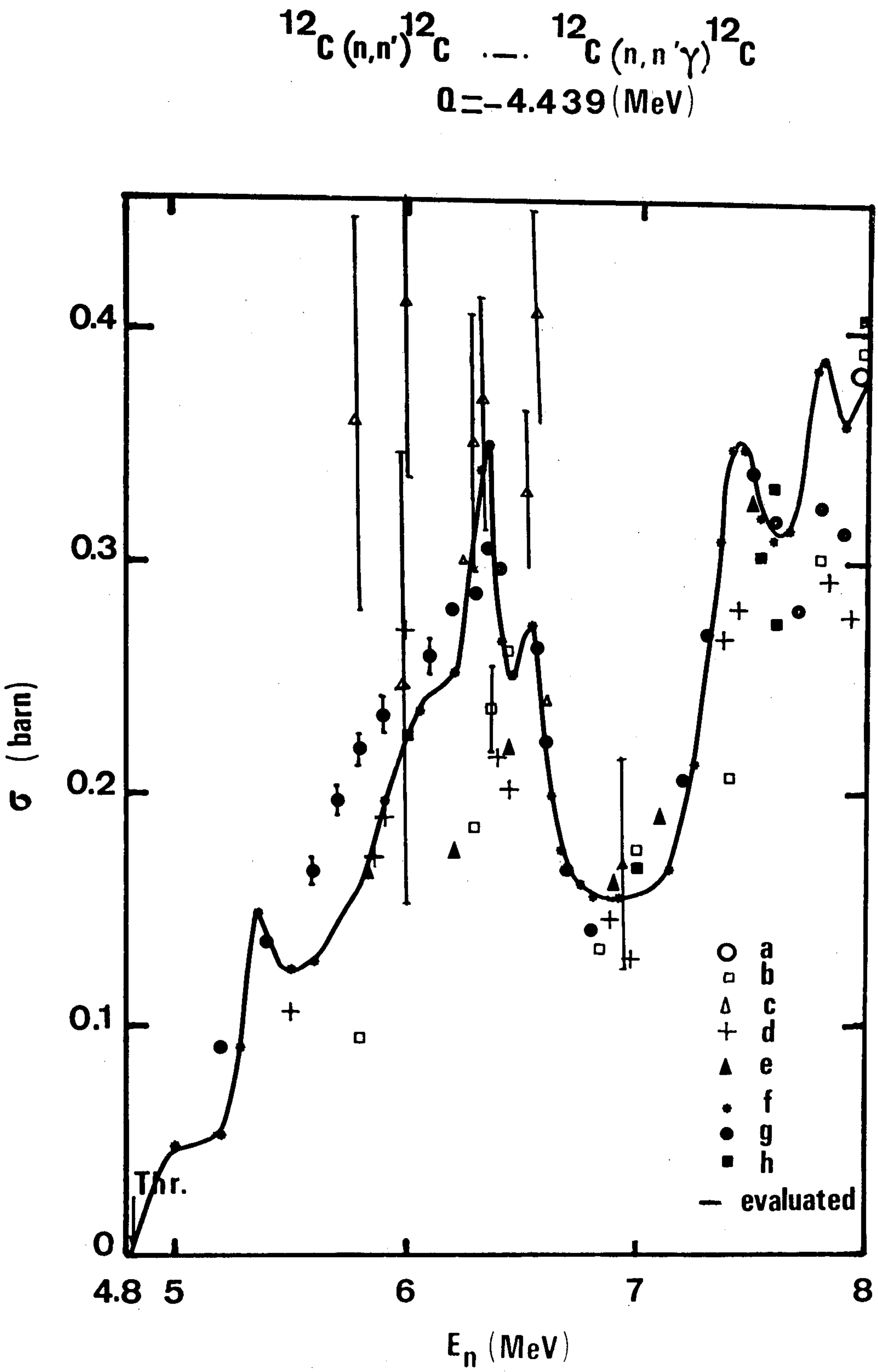
- FIG. 9 -



- FIG. 10 -

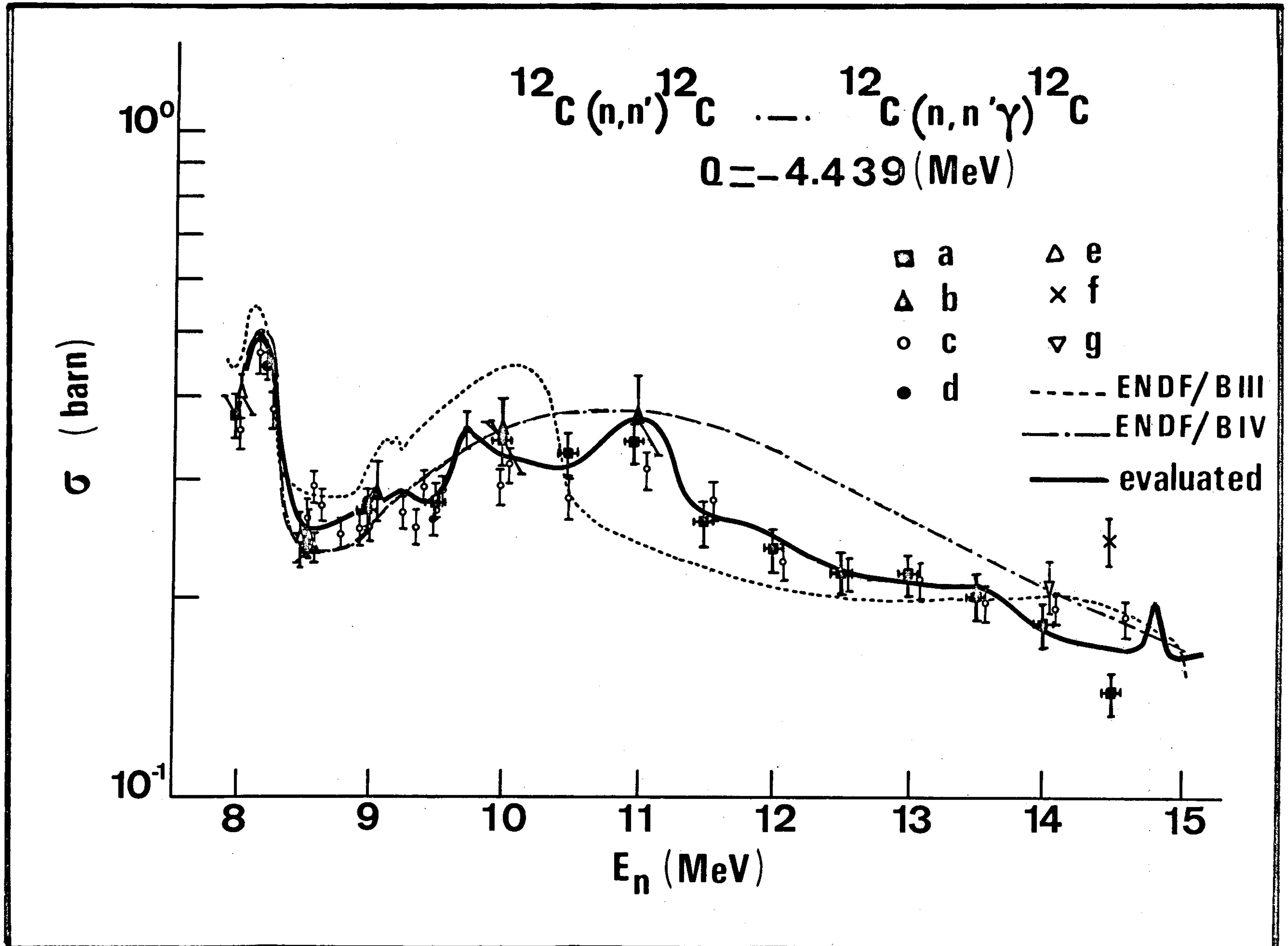


a
b
c
d
e
f
g
h
ENDF/B III
ENDF/B IV
evaluated
14
16
18
20
En (MeV)

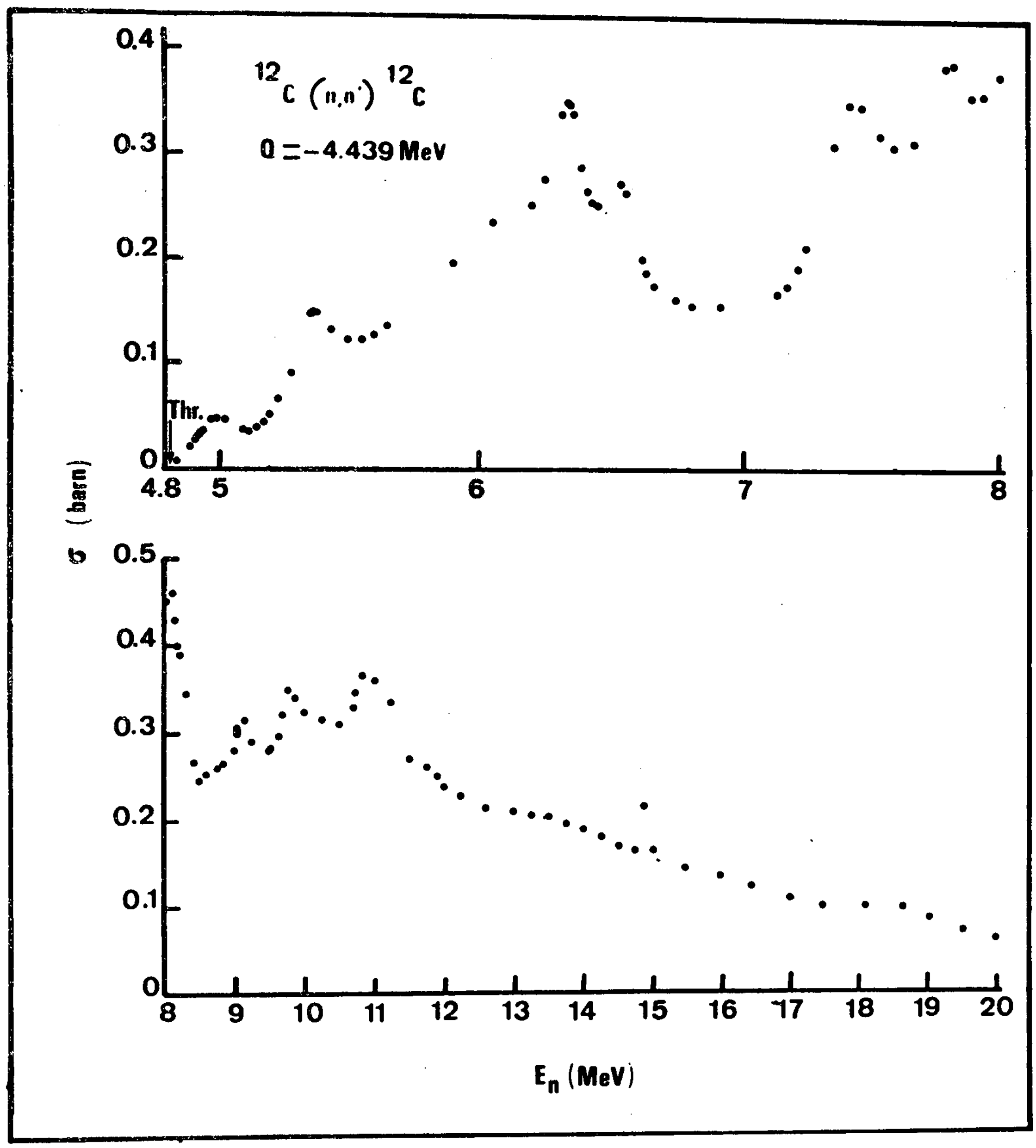


$^{12}C(n,n')^{12}C$.—. $^{12}C(n,n'\gamma)^{12}C$
Q=-4.439 (MeV)
σ (barn)
0.4
0.3
0.2
0.1
0
4.8
5
6
7
8
E_n (MeV)
Thr.
a
b
c
d
e
f
g
h
evaluated

- FIG. 11 -

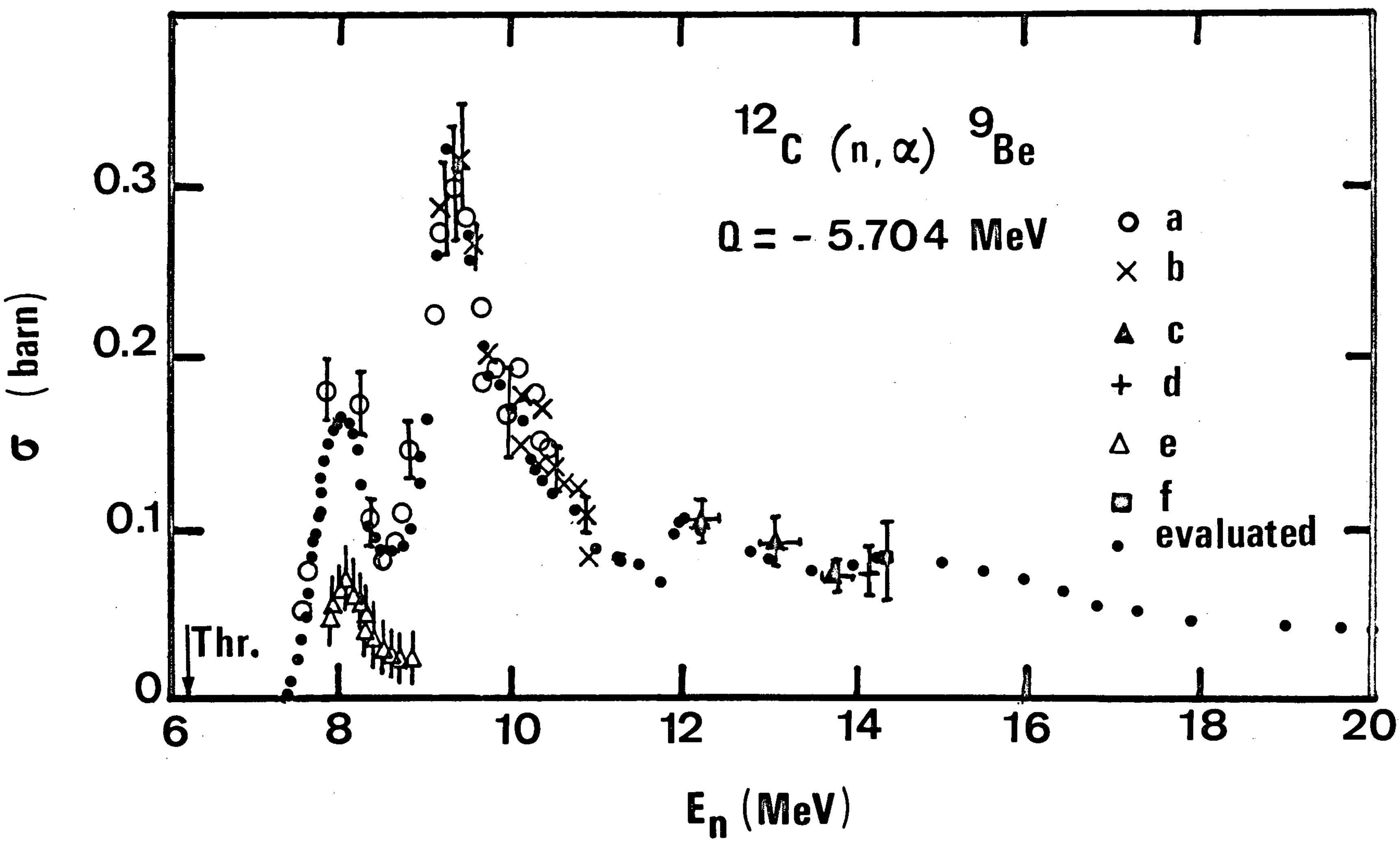

$^{12}C(n,n')^{12}C$.— . $^{12}C(n,n'\gamma)^{12}C$
Q = -4.439 (MeV)
a
b
c
d
e
f
g
ENDF/BIII
ENDF/BIV
evaluated
σ (barn)
10^0
10^{-1}
8
9
10
11
12
13
14
15
E_n (MeV)

- FIG. 12 -



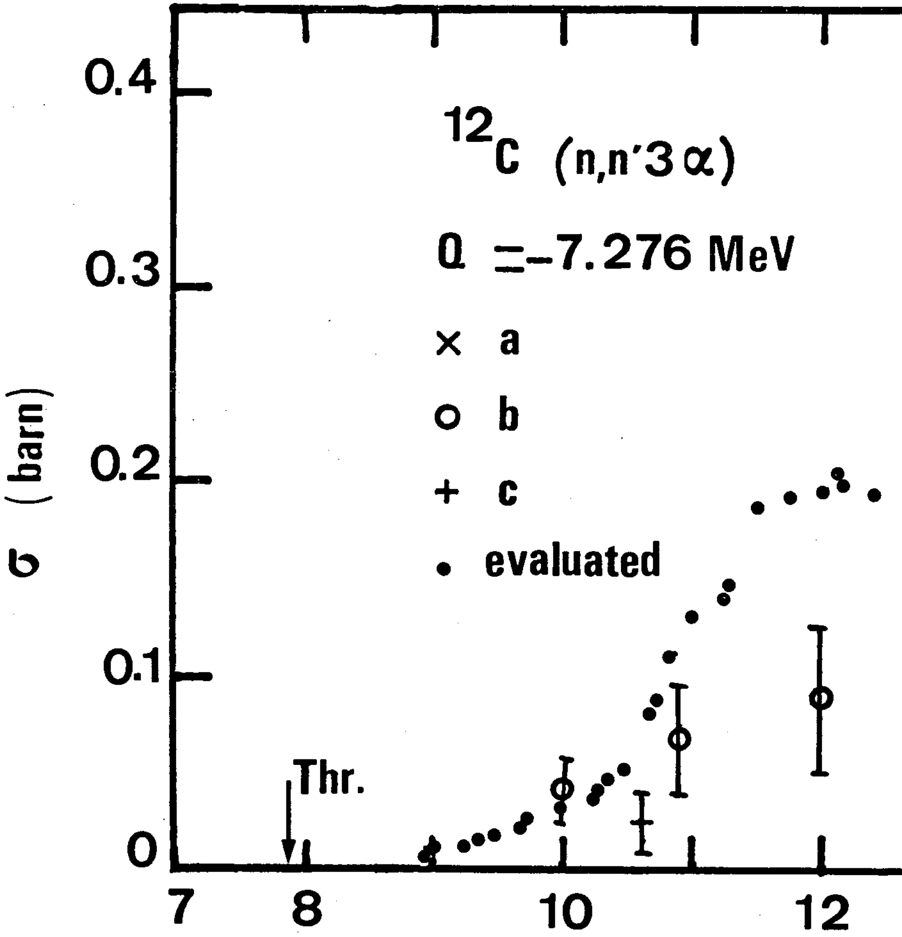
$^{12}C\ (n,n')\ ^{12}C$
Q = -4.439 MeV
Thr.
σ (barn)
0.4
0.3
0.2
0.1
0
4.8
5
6
7
8
0.5
0.4
0.3
0.2
0.1
0
8
9
10
11
12
13
14
15
16
17
18
19
20
E_n (MeV)

- FIG. 13 -

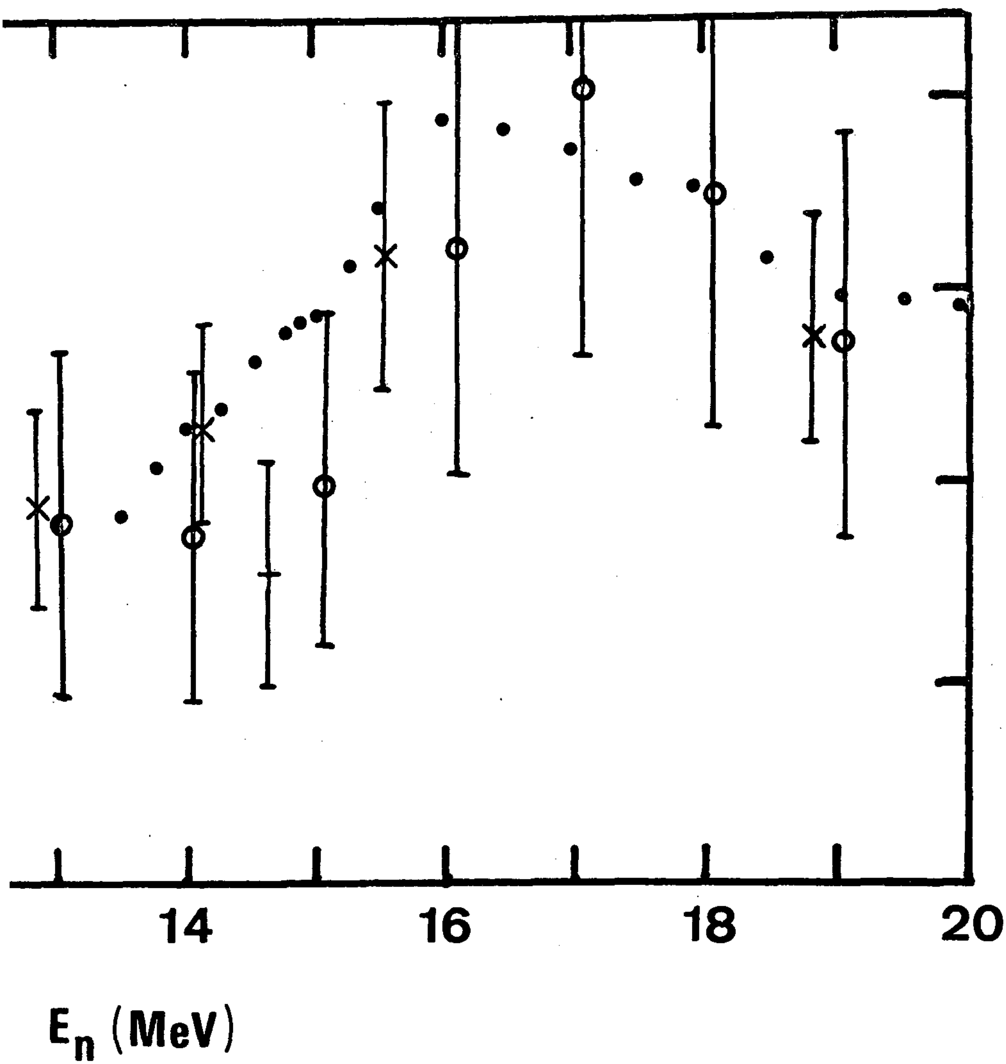

$^{12}C\ (n,\alpha)\ ^{9}Be$
Q = - 5.704 MeV
a
b
c
d
e
f
evaluated
Thr.
σ (barn)
0
0.1
0.2
0.3
6
8
10
12
14
16
18
20
E_n (MeV)

- FIG. 14 -

- FIG. 15 -

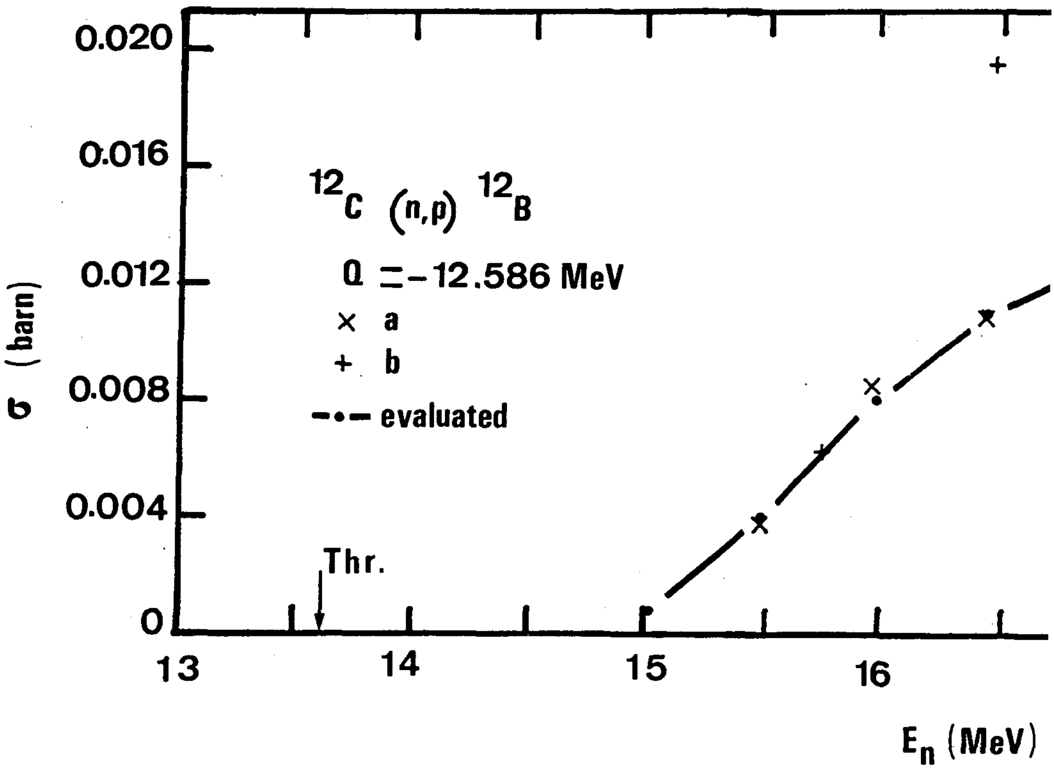


$^{12}C\ (n,n'3\alpha)$
Q = −7.276 MeV
× a
○ b
+ c
• evaluated
Thr.
σ (barn)
0.4
0.3
0.2
0.1
0
7
8
10
12

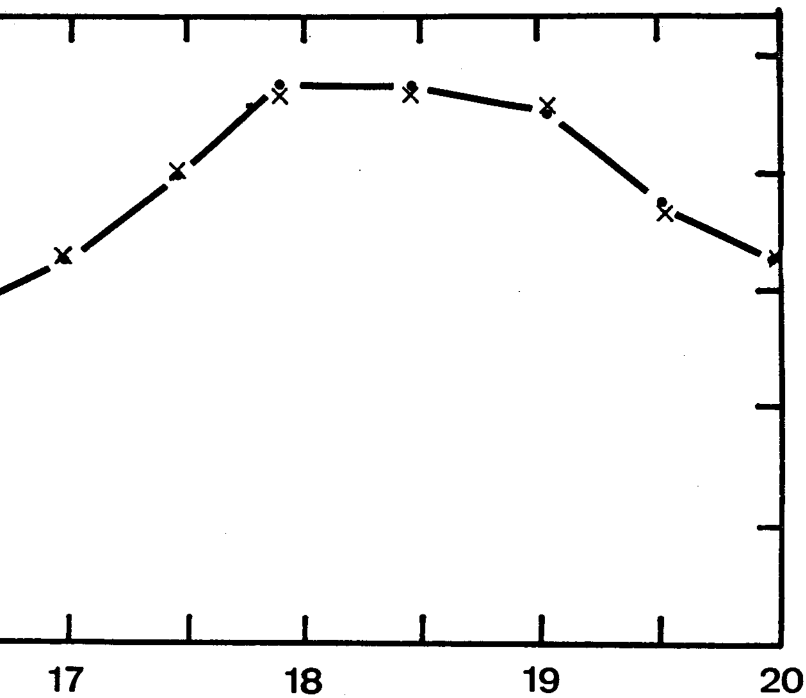


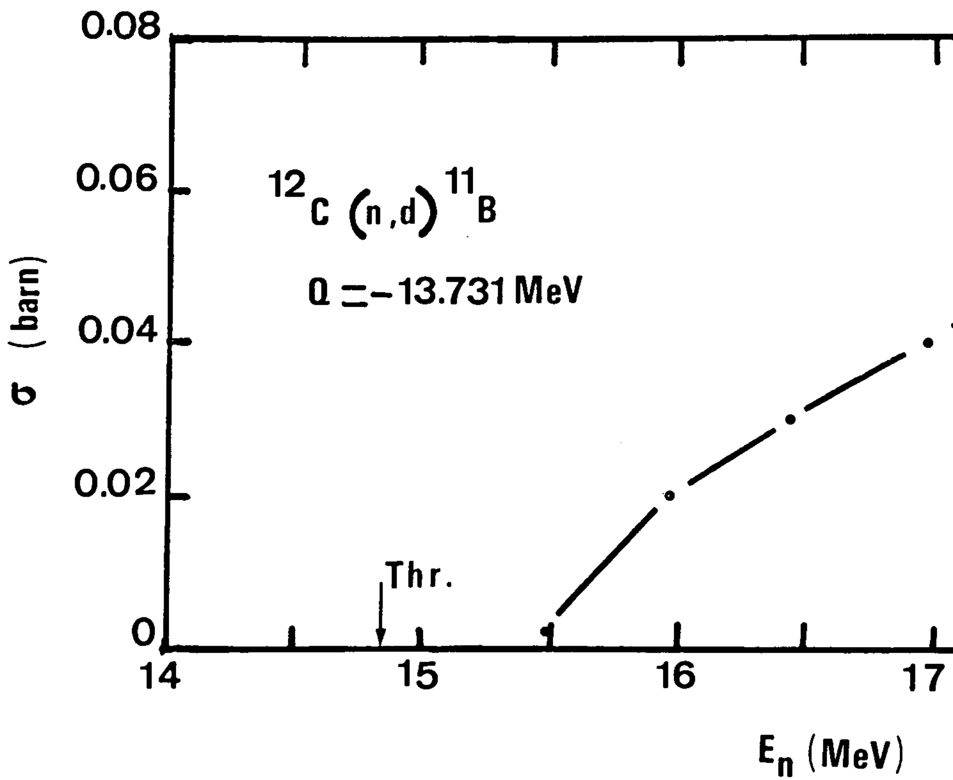
14
16
18
20
E_n (MeV)

- FIG. 16 -

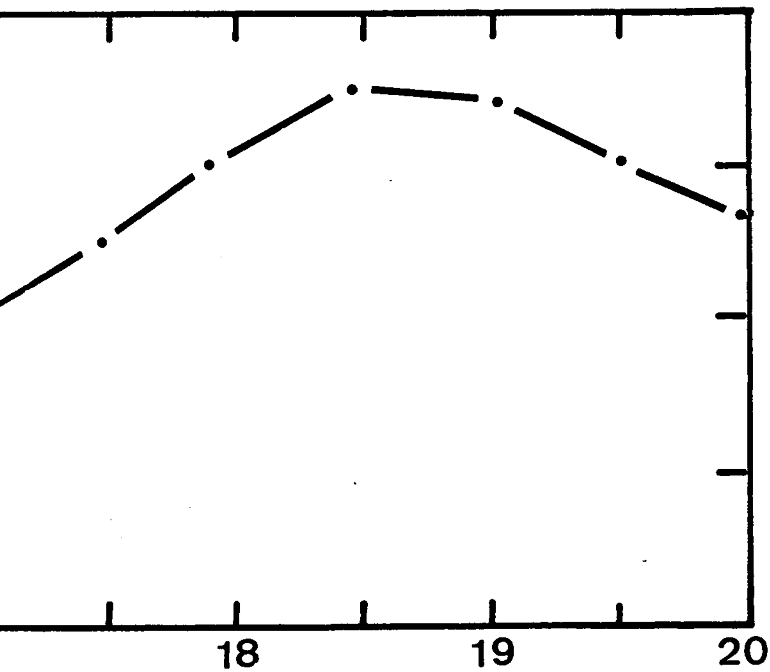


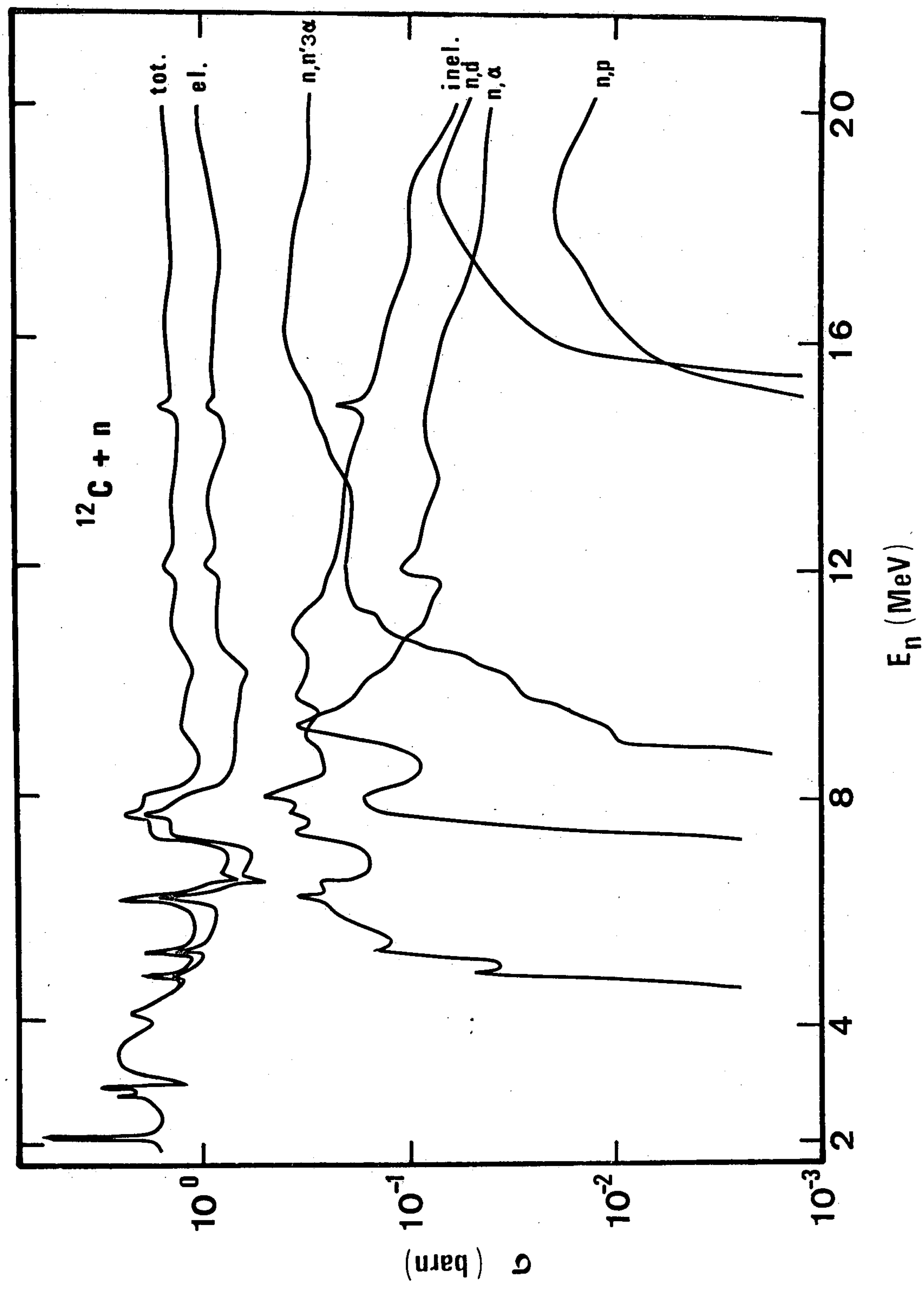
$^{12}C\ (n,p)\ ^{12}B$
Q = −12.586 MeV
× a
+ b
evaluated
Thr.
σ (barn)
0.020
0.016
0.012
0.008
0.004
0
13
14
15
16
E_n (MeV)


17
18
19
20


$^{12}C(n,d)^{11}B$
$Q = -13.731$ MeV
Thr.
σ (barn)
0.08
0.06
0.04
0.02
0
14
15
16
17
E_n (MeV)

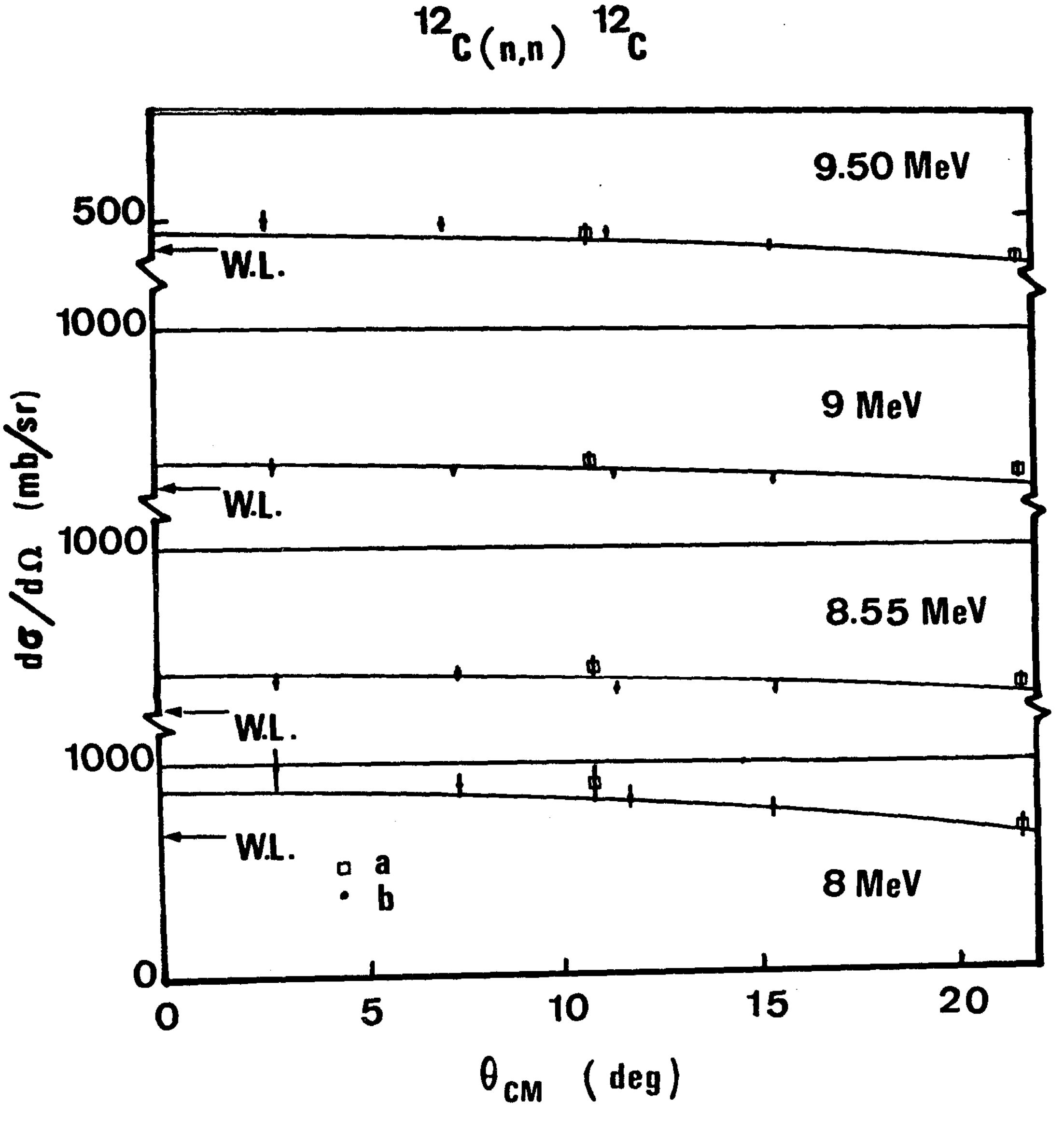
- FIG. 17 -


18
19
20



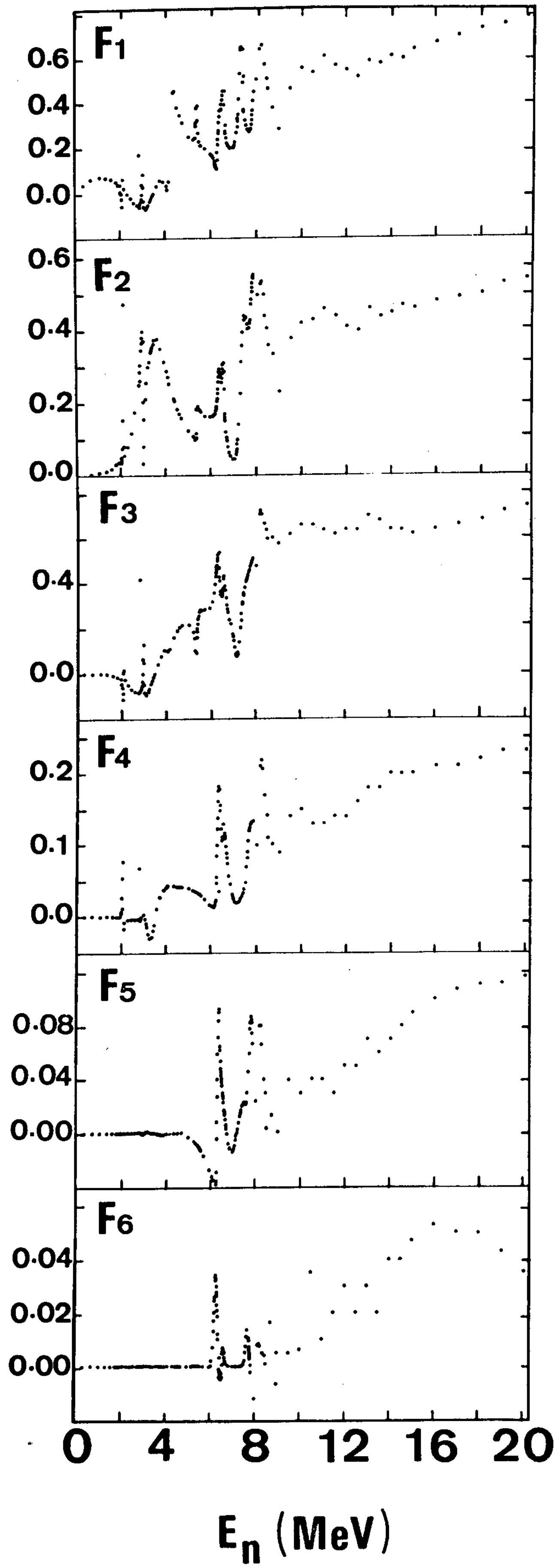
¹²C + n
tot.
el.
n,n'3α
inel.
n,d
n,α
n,p
σ (barn)
10⁰
10⁻¹
10⁻²
10⁻³
2
4
8
12
16
20
E_n (MeV)

- FIG. 18 -

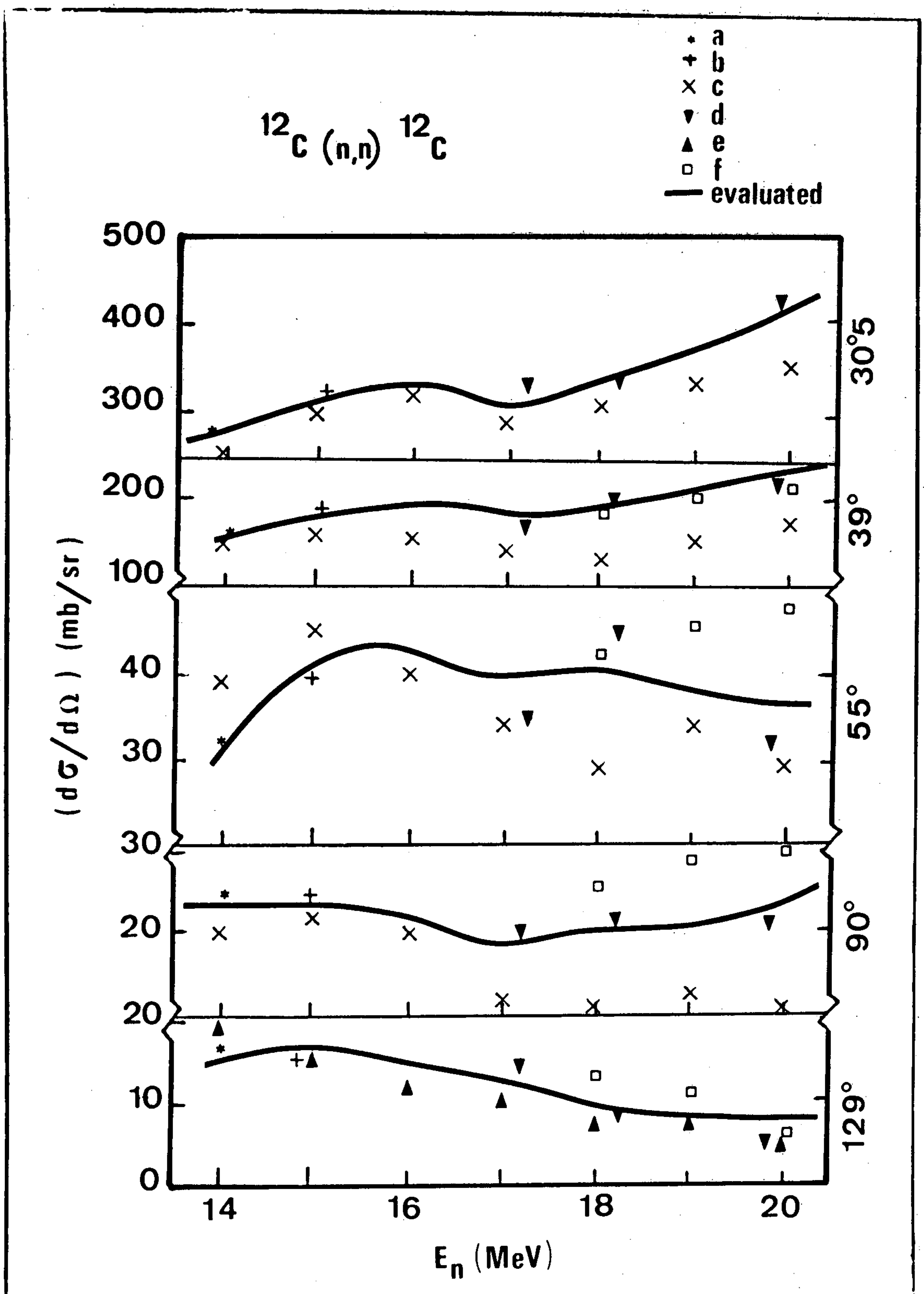


12C (n,n) 12C
9.50 MeV
500
W.L.
1000
9 MeV
W.L.
1000
8.55 MeV
W.L.
1000
W.L.
a
b
8 MeV
0
0
5
10
15
20
θCM (deg)
dσ/dΩ (mb/sr)

- FIG. 19 -

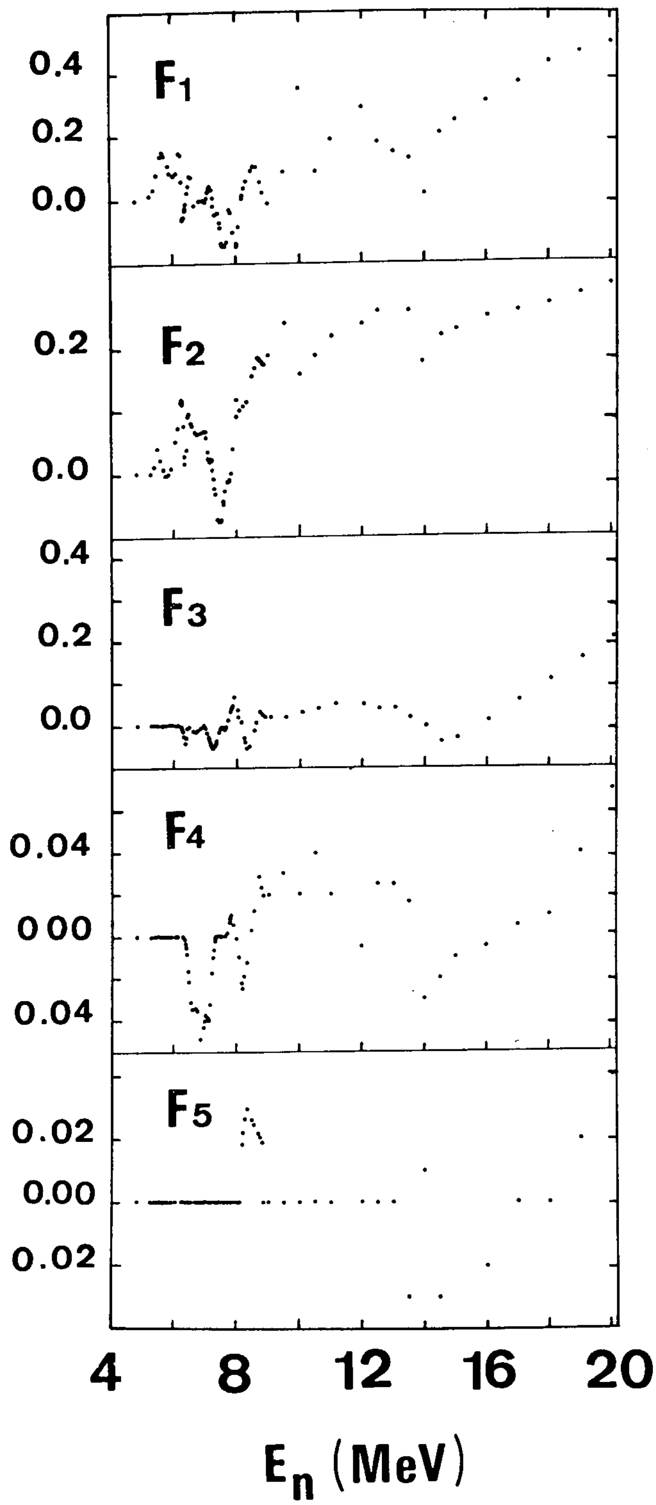

F1
0.6
0.4
0.2
0.0
F2
0.6
0.4
0.2
0.0
F3
0.4
0.0
F4
0.2
0.1
0.0
F5
0.08
0.04
0.00
F6
0.04
0.02
0.00
0
4
8
12
16
20
E_n (MeV)

- FIG. 20 -

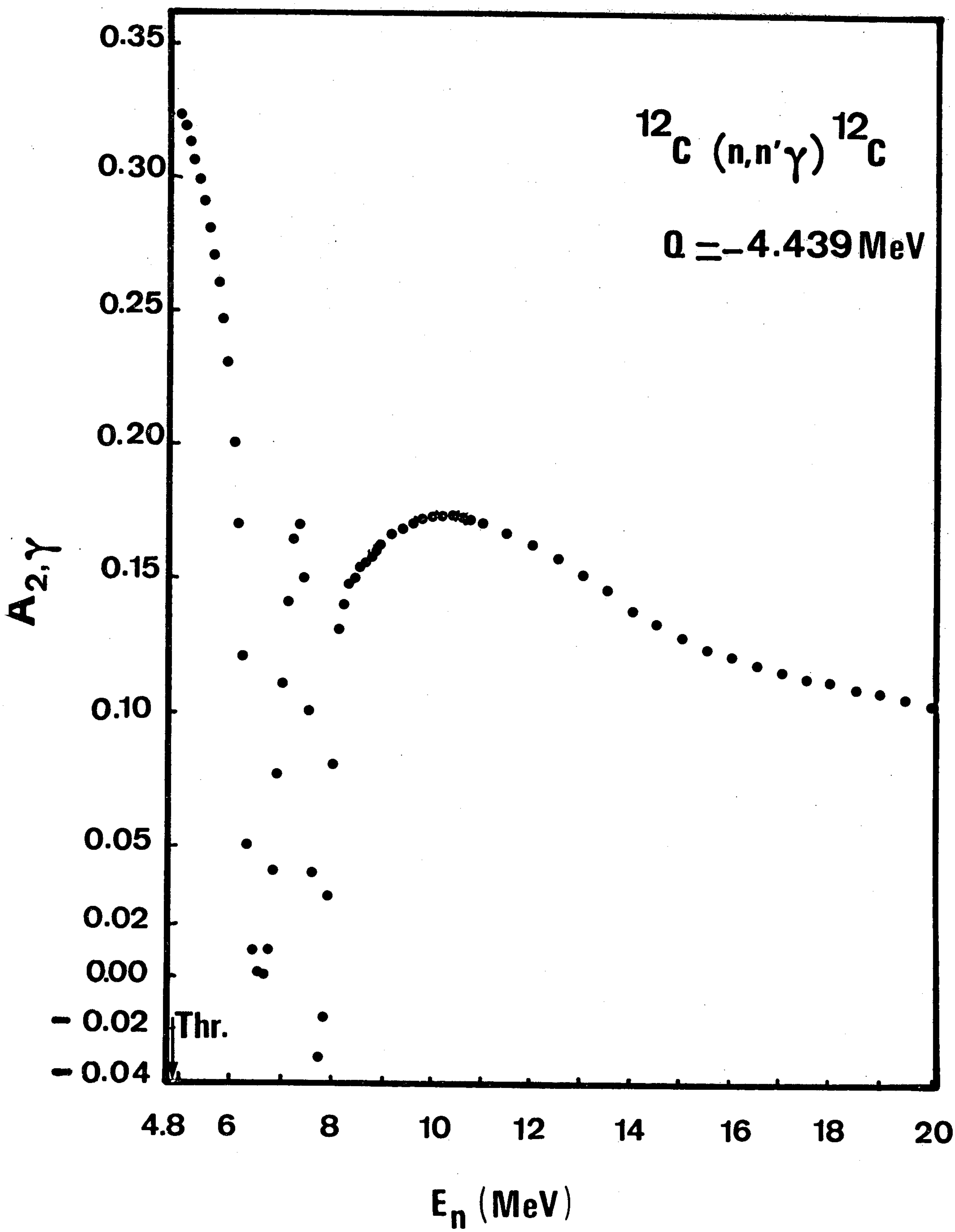


$^{12}C\ (n,n)\ ^{12}C$
a
b
c
d
e
f
evaluated
500
400
300
200
100
40
30
30
20
20
10
0
30°5
39°
55°
90°
129°
$(d\sigma/d\Omega)$ (mb/sr)
14
16
18
20
E_n (MeV)

- FIG. 21 -

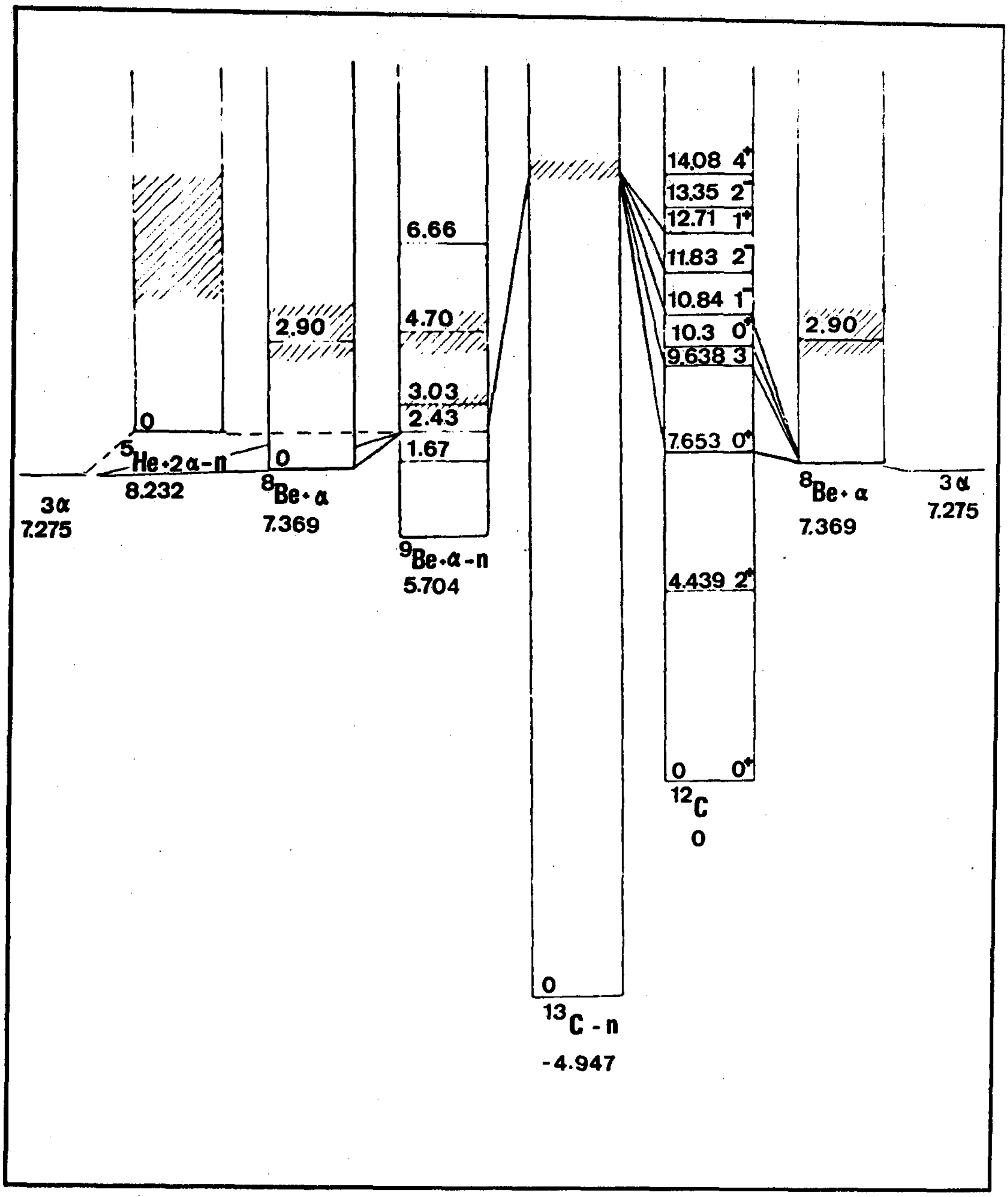

F1
F2
F3
F4
F5
0.4
0.2
0.0
0.2
0.0
0.4
0.2
0.0
0.04
0 00
0.04
0.02
0.00
0.02
4
8
12
16
20
En (MeV)

- FIG. 22 -

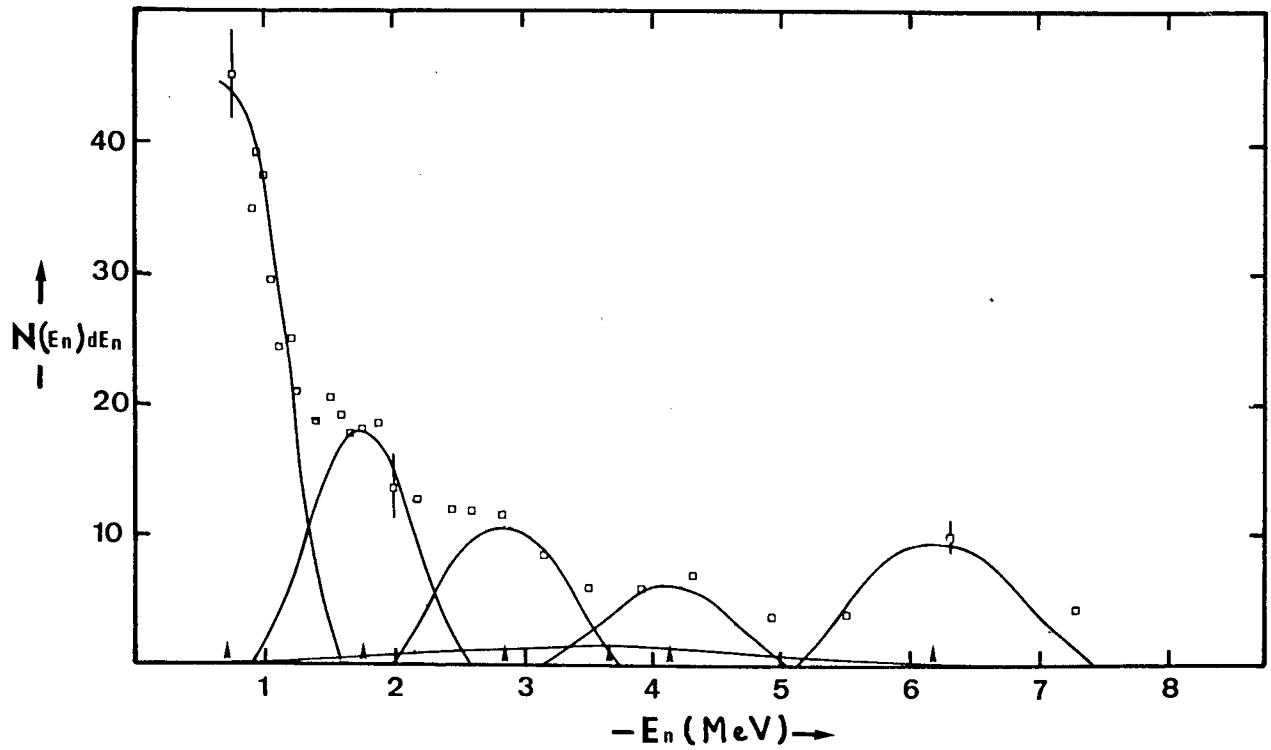


$^{12}C\ (n,n'\gamma)\ ^{12}C$
Q = −4.439 MeV
$A_{2,\gamma}$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.02
0.00
− 0.02
− 0.04
Thr.
4.8
6
8
10
12
14
16
18
20
E_n (MeV)

- FIG. 23 -


14.08 4+
13.35 2−
12.71 1+
11.83 2−
10.84 1−
10.3 0+
9.638 3−
7.653 0+
4.439 2+
0 0+
12C
0
6.66
4.70
3.03
2.43
1.67
9Be+α-n
5.704
2.90
0
8Be+α
7.369
0
5He+2α-n
8.232
3α
7.275
0
13C-n
-4.947
2.90
8Be+α
7.369
3α
7.275

- FIG. 24 -



- FIG 25 -