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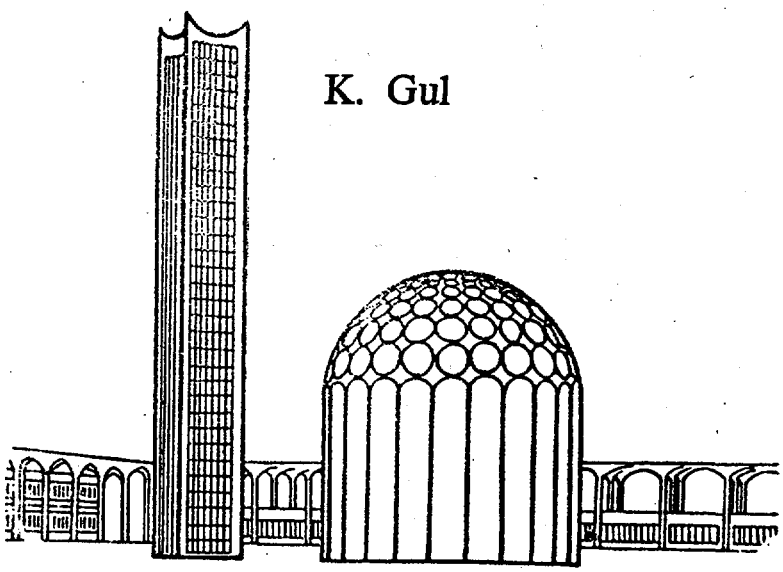
K. Gul



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Pakistan Institute of Nuclear Science & Technology
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K. Gul

Abstract

Calculations of cross sections of neutron induced reactions for ^{52}Cr in 6-20 MeV energy range have been performed using Hauser-Feshbach code developed by the author. The calculations include cross sections of (n,n'), (n,np), (n,2n), (n,p), (n,pn), (n,pγ), (n,α), (n,αγ) and (n,αn) reactions induced in ^{52}Cr. The calculations have been compared with measurements and evaluations.

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Table of Contents

1. Introduction

The present report describes calculations performed using Hauser-Feshbach code developed by the author and presented in an earlier report along with calculations of neutron scattering cross sections to the bound states of nuclei [1]. The present calculations have been carried out with a view to testing the code for calculations of the neutron-induced threshold reaction cross sections. ^{52}Cr was chosen for this purpose in view of its importance in fusion technology and the availability of the desired cross section measurements, calculations and evaluations. Established nuclear structure and nuclear reaction databases have been used in the present calculations.

2. Details of Calculations

Hauser-Feshbach calculations require information on nuclear structure of nuclei involved in nuclear reactions and knowledge of relevant optical model parameters for computation of particle transmission coefficients. The gamma-ray transmission coefficients were calculated on the basis of single particle model as reported earlier [1]. The information on levels, spins and parities of ^{52}Cr, ^{51}Cr, ^{52}V, ^{51}V, ^{49}Ti and ^{48}Ti was taken from nuclear data sheets [2]. The code has an option for determination of level densities using expressions based on back-shifted Fermi gas model [3]; however in the present case formulas recommended by Gilbert and Cameron [4] have been used for level density calculations. Several global optical model parameters have been reported in the literature [5-9]. Optical model parameters reported by Becchetti and Greenless [5] have been used for protons in all exit channels and for neutrons in exit channels occurring in the first step of emission. For the incident channels of neutrons and the neutrons emitted in the second step, optical model parameters recommended by Uhl et al [10] have been used. These optical model parameters are shown in table I. Three different sets of optical model parameters [11-13] have been used for emitted alpha particles for studying their suitability. These optical model parameters are listed in table II. Reaction channels involving emission of deuterons and helions have not been included in the present calculations.

3. Results and Discussion

Several excitation functions as well as proton and alpha particle emission spectra for 15 MeV neutrons have been calculated. The different types of excitation functions include cross sections such as $\sigma_{n,n'}$, $\sigma_{n,p}$, $\sigma_{n,p\gamma}$, $\sigma_{n,pn}$, $\sigma_{n,\alpha}$, $\sigma_{n,\alpha\gamma}$, $\sigma_{n,\alpha n}$, $\sigma_{n,2n}$, $\sigma_{n,np}$, σ_{pem} and σ_{nem}. Emission of two particles are considered in a sequential decay requiring two steps of calculations. The total neutron emission cross section, σ_{nem}, and proton emission cross section, σ_{pem}, were calculated using the following expressions:

$$\sigma_{nem} = \sigma_{n,n} + 2\sigma_{n,2n} + \sigma_{n,np} + \sigma_{n,pn} + \sigma_{n,\alpha n}$$
$$\sigma_{pem} = \sigma_{n,p\gamma} + \sigma_{n,pn} + \sigma_{n,np}$$

The details of calculated cross sections of different types of reactions and their comparison with measurements and evaluations are given in the following sections.

3.1 $^{52}Cr(n,2n)^{51}Cr$ reaction cross sections

$^{52}Cr(n,2n)^{51}Cr$ reaction (Q = -12.01 MeV) is the only reaction which has been studied starting from its threshold to 20 MeV induced neutron energy rather thoroughly, and serves as a good test for model calculations. Calculations for this reaction are shown in figure 1 and compared with measurements. Only data of experiments covering a wide energy range have been included for comparison [14-18]. There are several measurements around 14 MeV which have been represented for comparison by inclusion of the evaluated cross section value recommended by Vonach et al [19]. The data of Bormann et al [16] and Ghorai et al [17] are considerably lower than the calculated values for neutron above 16 MeV energy which agree very well with the recent measurements and calculations reported by Liskien et al [14].

3.2 Neutron emission cross sections

The calculations of double differential neutron emission cross sections at 103^0 for 14 MeV neutrons are given in figure 2 and compared with the corresponding measurements reported by Takahashi et al [20]. The experimental data shown for comparison are those which have not been corrected for multiple scattering events. The higher experimental values in 6-8 MeV and 10.5 - 11.5 MeV emitted energy range could be attributed to the contributions from preequilibrium and direct reaction mechanisms which have not been included in the present calculations.

3.3 Neutron energy differential scattering cross sections

The calculations for 14 MeV neutron energy differential scattering cross sections are shown in figure 3 and are compared with the measurements of Palvik and Vonach [21]. The data of Takahashi et al [20] taken at 103^0 have been included for comparison on the assumption of its isotropy.

3.4 Inelastic neutron scattering cross sections

The calculations for total neutron inelastic scattering cross sections as a function of incident neutron energy are shown in figure 4. The figure also shows the evaluation of Vonach et al [19] and measurement of Salinikov and Lochikova [22] referred by Prince [23] for 14 MeV neutrons. The measurements of inelastic scattering cross sections based on the yield of 1.434 MeV gamma-rays and TNG calculations reported by Larson [24] have also been included for comparison. The higher values of measurements compared with Hauser-Feshbach calculations above 15 MeV incident neutron energy indicate the gradual increase in the contributions from the direct and pre-equilibrium reaction mechanisms. The TNG calculations include contributions of direct and pre-equilibrium reaction mechanisms.

3.5 Total neutron emission cross sections

The calculations of total neutron emission cross sections are shown in figure 5. The calculations reported by Hetrick et al [25] for total neutron emission cross sections

(not shown in the figure) show a constant value of about 1.3 b in the entire 13-19 MeV neutron energy whereas the present calculations give a value of 1.3 b at 13 MeV which increases to 1.8 b at 19 MeV. This may be compared with ENDF-B/V recommended value of about 1.3 b at 13 MeV which rises to about 1.9 b at 19 MeV (not shown in the figure) and thus being in good agreement with the present calculations.

3.6 Proton emission energy spectrum

The calculated energy spectrum of emitted protons on bombardment with 15 MeV neutrons is shown in figure 6. The figure also shows the corresponding measurements of Grimes et al [26]. The calculated spectrum includes protons emitted in (n,p) and (n,np) reaction processes. The higher measured values of cross sections for emitted protons with energy above 8 MeV are possibly due to the contributions from the direct and preequilibrium reaction mechanisms which have not been included in the present calculations.

3.7 ^{52}Cr (n,pγ)^{52}V reaction cross sections

The excitation function for ^{52}Cr(n,pγ)^{52}V reaction is shown in figure 7. The figure also includes for comparison the reported measurements of cross sections [17,27]. Only recent measurements employing high energy resolution gamma-ray detectors have been included for comparison. The agreement between the measurements and calculations is satisfactory though at higher energies the calculations under-estimate the measurements of Ghorai et al [17] which again could be attributed to the neglect of contributions from the direct and preequilibrium reaction mechanisms. Data from ENDF-B/VI have also been included for comparison

3.8 Total proton production cross sections

The total proton production cross sections as a function of incident neutron energy are shown in figure 8 and compared with the measurement of Grimes et al [26] for 15 MeV neutrons for which all the three reactions (n,pγ), (n,pn) and (n,np) contribute.

3.9 Alpha particle emission cross sections

The calculated energy spectrum of emitted alpha particles from ^{52}Cr on bombardment with 15 MeV neutrons is shown in figure 9. It is compared with the measured spectrum of alpha particles reported by Grimes et al [26]. The calculations for ^{52}Cr (n, $\alpha\gamma$)^{49}Ti excitation function are shown in figure 10. The calculations based on three different optical model parameter sets are shown for comparison. Measurements reported by Paulsen et al [28] and Grimes et al [26] are shown for comparison. The recommended evaluated value by Vonach et al [19] and the predictions based on systematics [29,30] are also shown. The calculations based on optical model parameters of Perey and Perey [11] and those based on the global optical model parameters of emitted alpha particles recommended by Avrigeanu et al [12] are in good agreement with each other but differ from calculations based on optical model

parameters of Bredbacka et al [13]. Data from ENDF/B-VI have also been included for comparison. The total alpha particle emission cross sections are given in figure 11 and are based on the optical model parameters of Perey and Perey [11].

4. Summary

The present calculations were carried out with a purpose to test the Hauser-Feshbach code developed by the author. There has been a satisfactory agreement of the calculations with measurements for several reaction channels in 6-20 MeV neutron energy range keeping in view the fact that contributions from direct and pre-equilibrium reaction mechanisms have not been included in the present work.

Acknowledgment

The author is thankful to the Nuclear Data Section of IAEA for providing data used in the present report designated as ENDF/B-VI.

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Table I. Optical model parameters for neutrons in the incident channel and exit channel of the second stage of the reaction

Channel	V (MeV)	r_V (fm)	a_V (fm)	W_V (MeV)	W_S (MeV)	r_W (fm)	a_W (fm)	V_{SO} (MeV)	W_{SO} (MeV)	r_{SO} (fm)	a_{SO} (fm)
Incident	47.8	1.198	0.63	0.0	7.4	1.295	0.53	6.2	0.0	1.01	0.75
Second Stage Exit	52.0	1.198	0.63	0.0	7.3	1.37	0.37	6.2	0.0	1.01	0.75

Table II. Optical model parameters for emitted alpha particles. No spin orbit potential was used.

Reference	V (MeV)	r_V (fm)	a_V (fm)	W_V (MeV)	W_S (MeV)	r_W (fm)	a_W (fm)	r_C (fm)
Perey and Perey [11]	48.0	1.617	0.64	12.9	0.0	1.617	0.51	1.4
Avrigeanu et al [12]	138.0	1.245	0.785	8.3	0.0	1.57	0.64	1.4
Bredbacka et al [13]	83.1	1.55	0.56	15.4	0.0	1.55	0.60	1.4

List of Figures

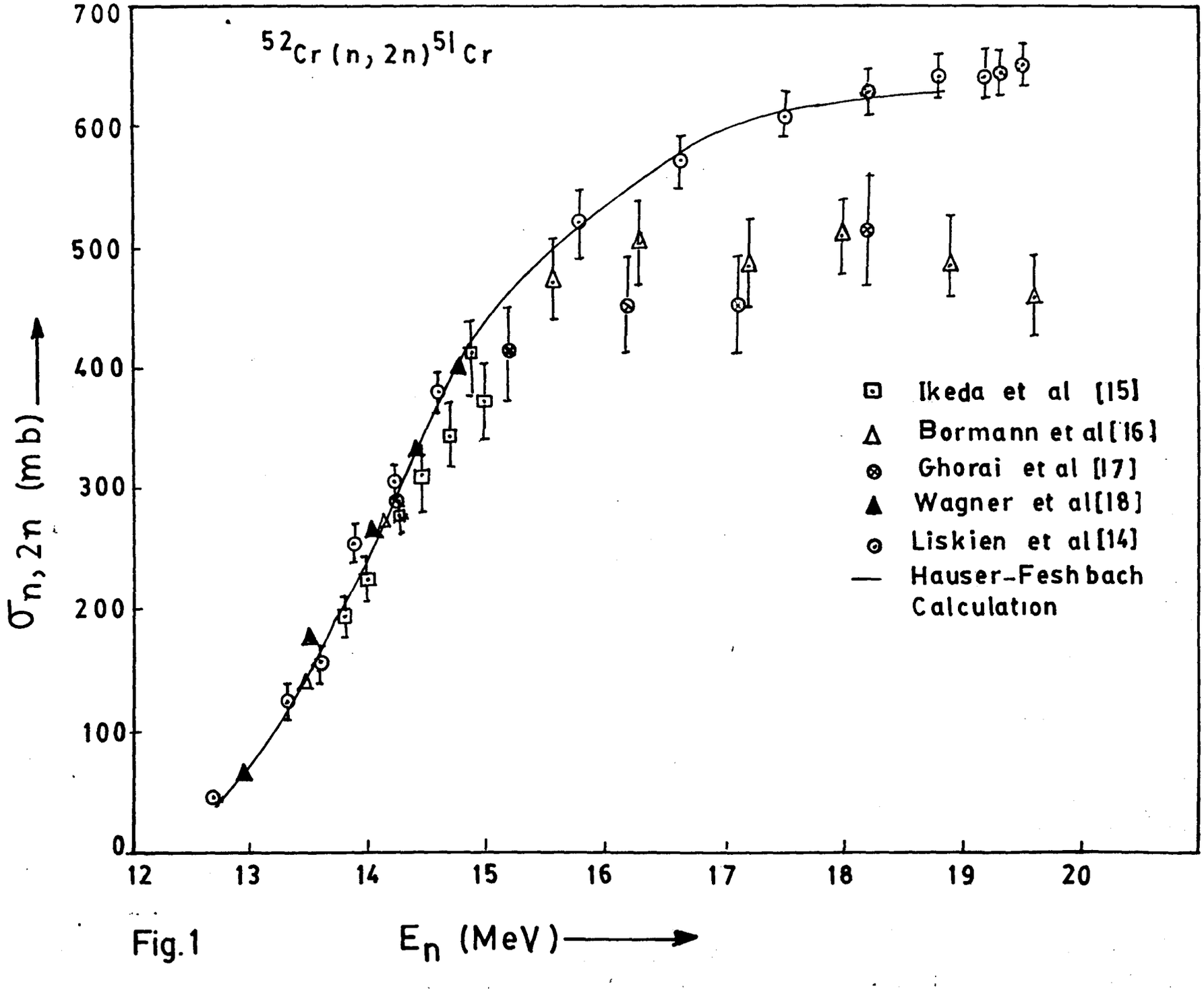
$^{52}Cr(n,2n)^{51}Cr$
700
600
500
400
300
200
100
0
12
13
14
15
16
17
18
19
20
$\sigma_{n,2n}$ (mb)
E_n (MeV)
Ikeda et al [15]
Bormann et al [16]
Ghorai et al [17]
Wagner et al [18]
Liskien et al [14]
Hauser-Feshbach Calculation

Fig.1

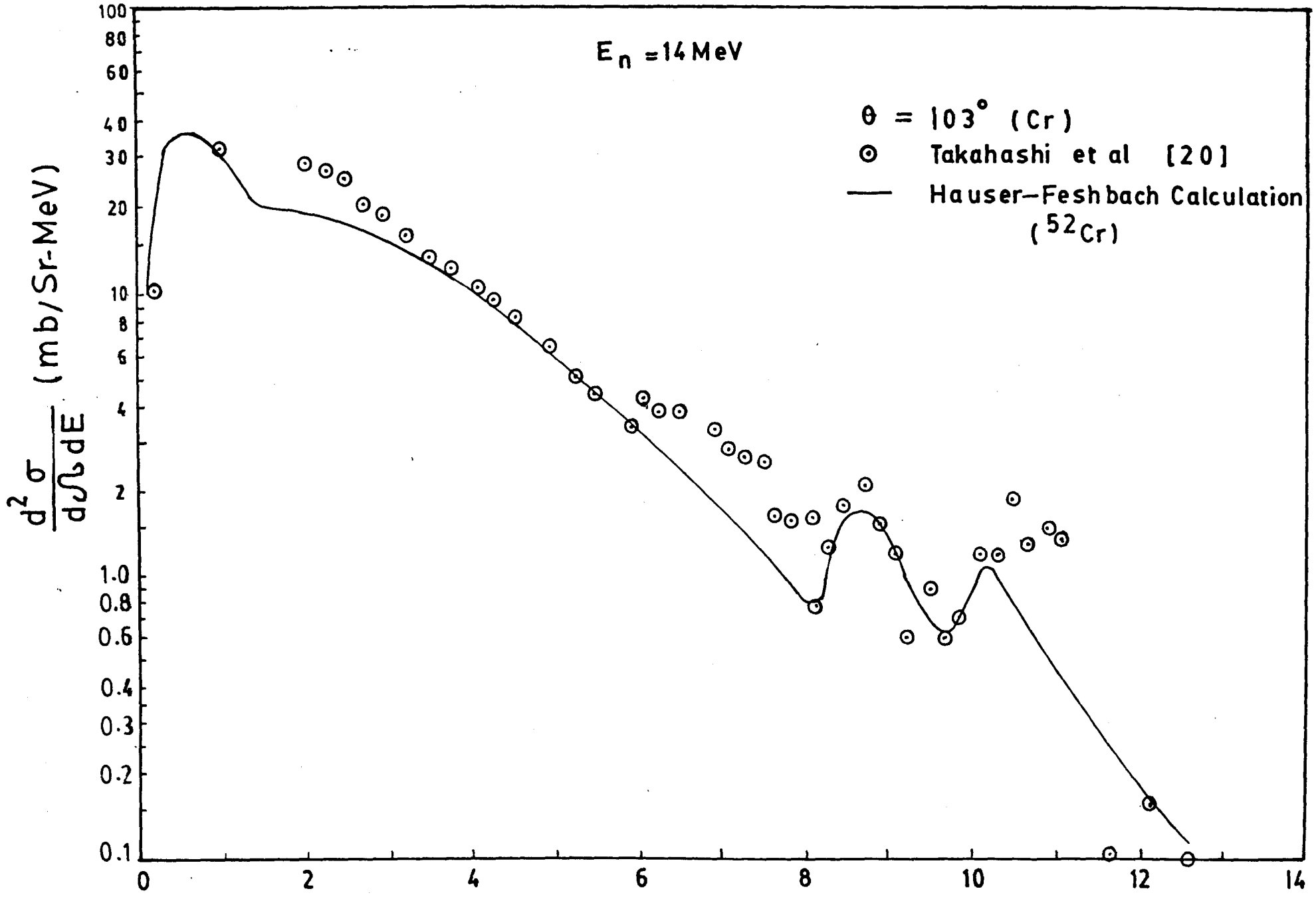
E_n = 14 MeV
θ = 103° (Cr)
Takahashi et al [20]
Hauser–Feshbach Calculation (^{52}Cr)
$\frac{d^2\sigma}{d\Omega dE}$ (mb/Sr-MeV)
NEUTRON EMISSION ENERGY (MeV)
100
80
60
40
30
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
14

Fig. 2

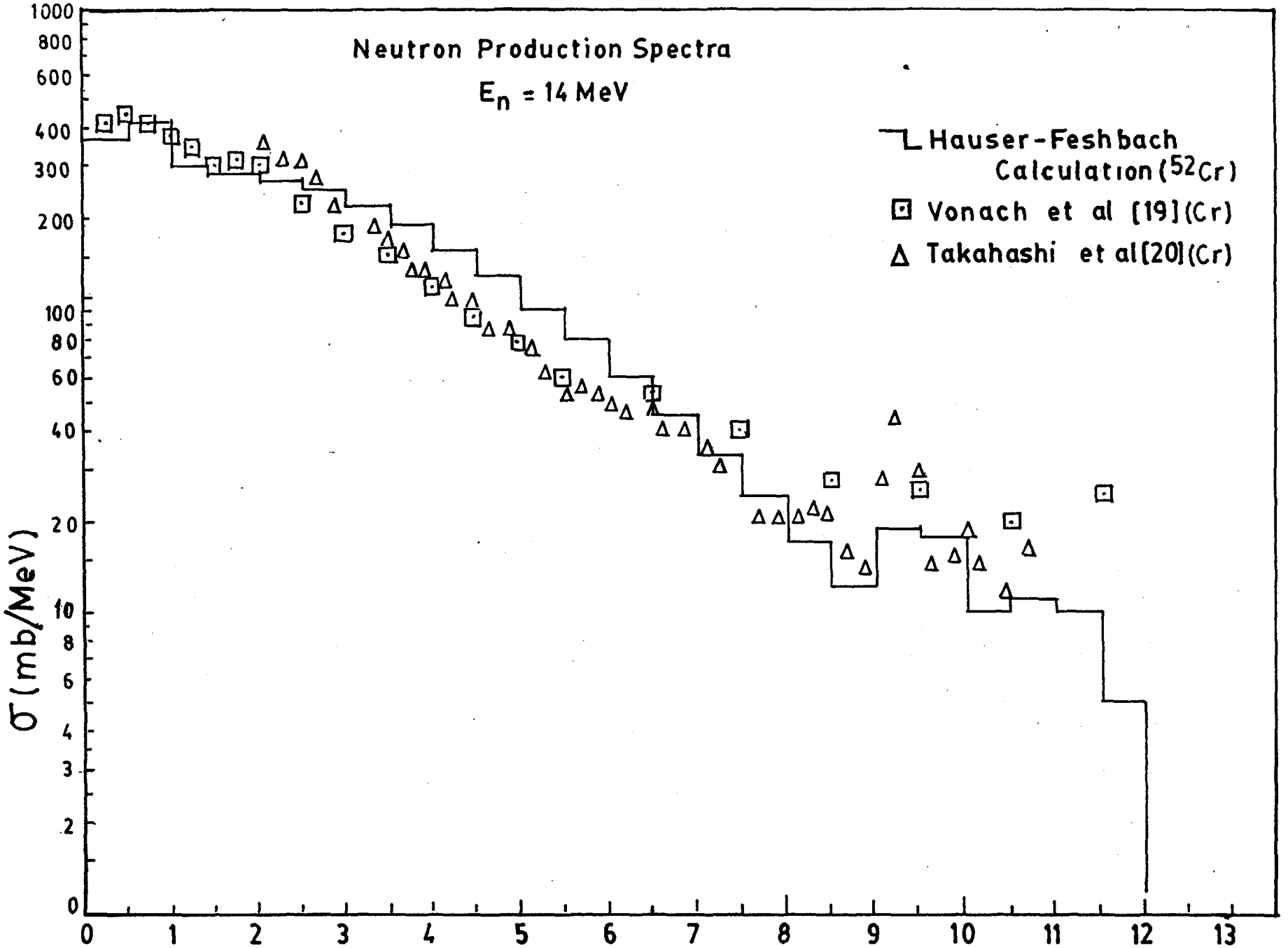
Neutron Production Spectra
E_n = 14 MeV
Hauser-Feshbach Calculation (^{52}Cr)
Vonach et al [19] (Cr)
Takahashi et al [20] (Cr)
σ (mb/MeV)
EMITTED NEUTRON ENERGY (MeV)
1000
800
600
400
300
200
100
80
60
40
20
10
8
6
4
3
2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13

Fig.3

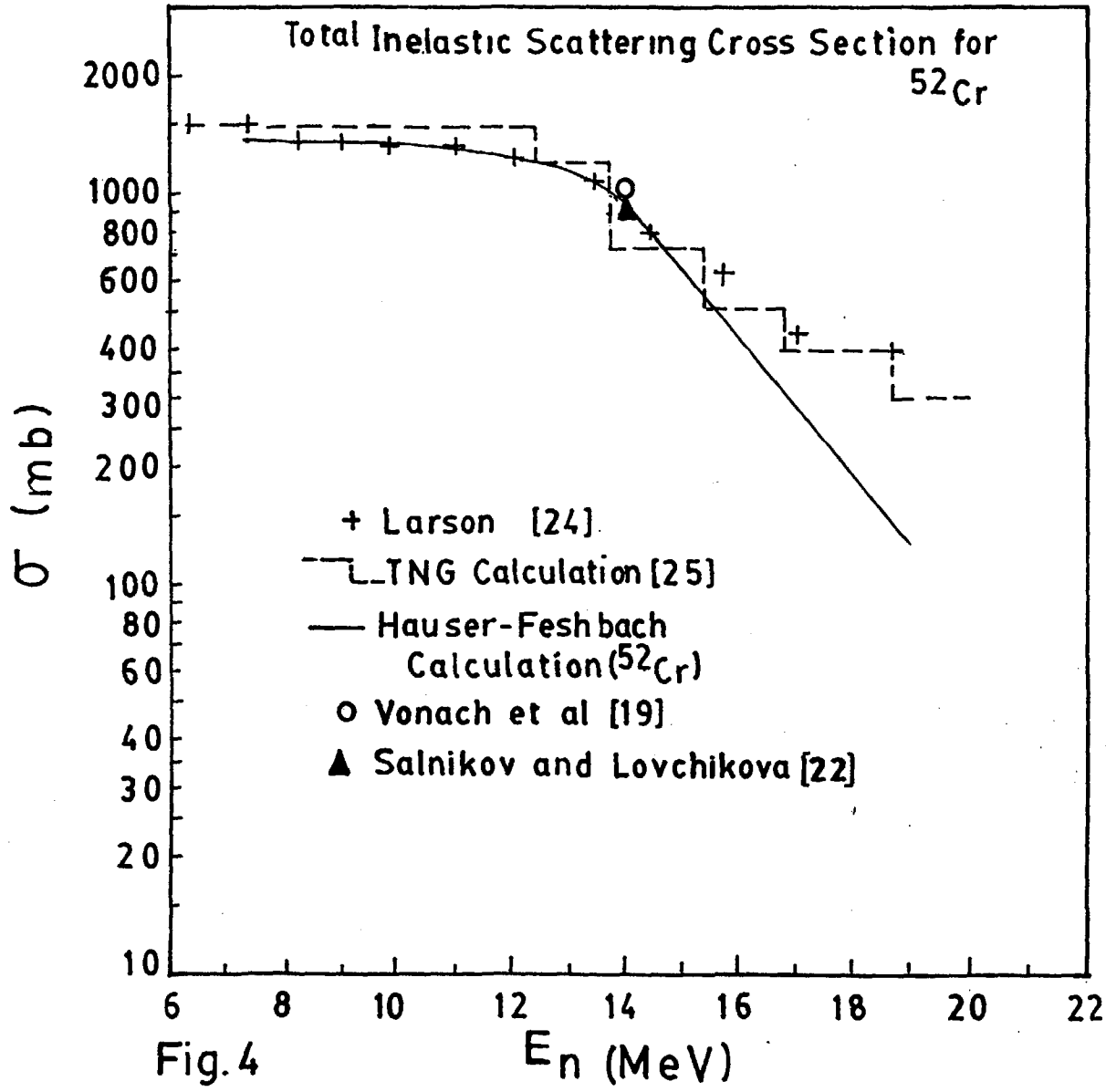
Total Inelastic Scattering Cross Section for ^{52}Cr
2000
1000
800
600
400
300
200
100
80
60
40
30
20
10
σ (mb)
6
8
10
12
14
16
18
20
22
E_n (MeV)
+ Larson [24]
TNG Calculation [25]
Hauser-Feshbach Calculation (^{52}Cr)
o Vonach et al [19]
▲ Salnikov and Lovchikova [22]

Fig. 4

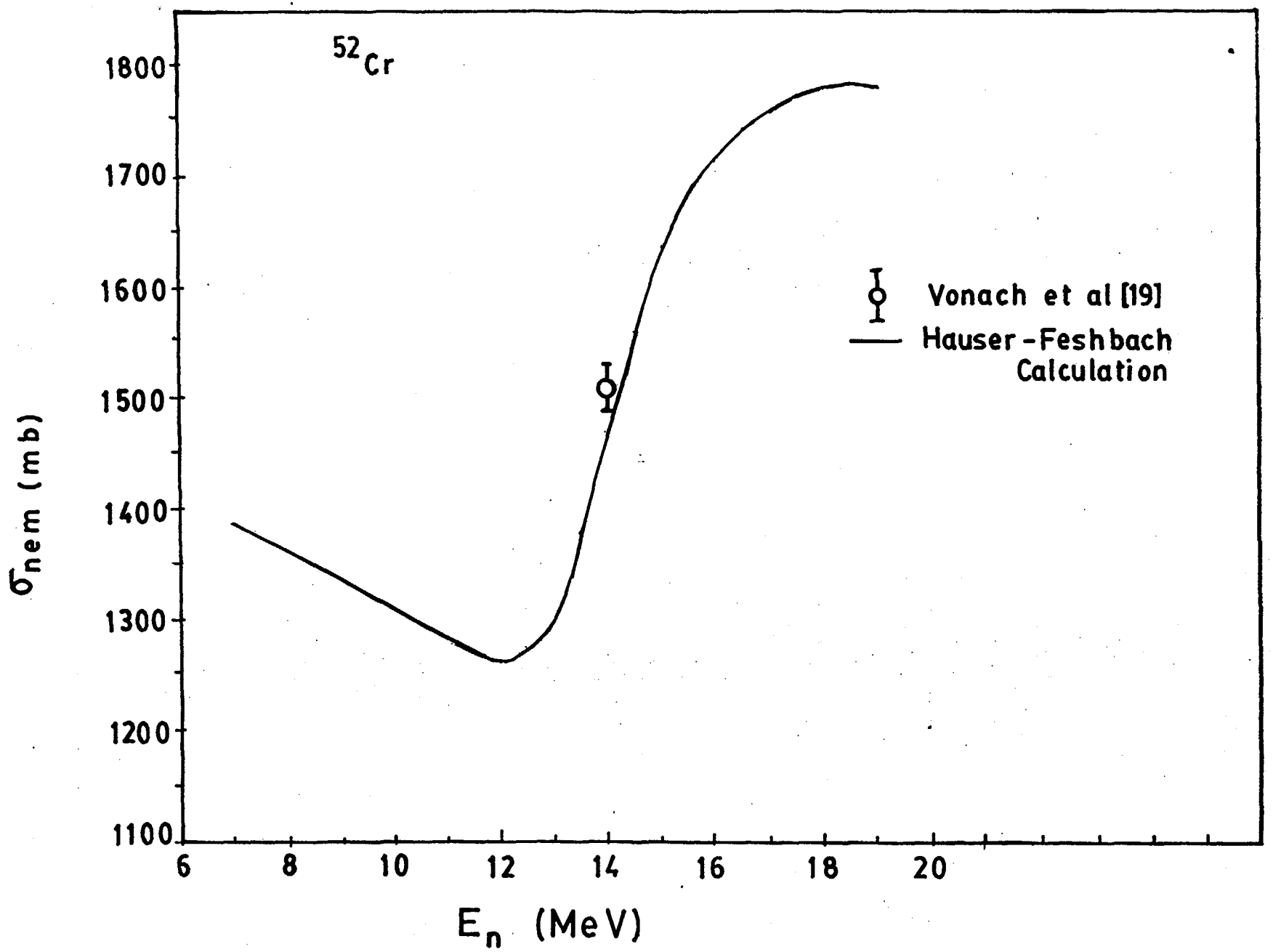

Fig.5 (Secondary Neutron Production Cross Section)

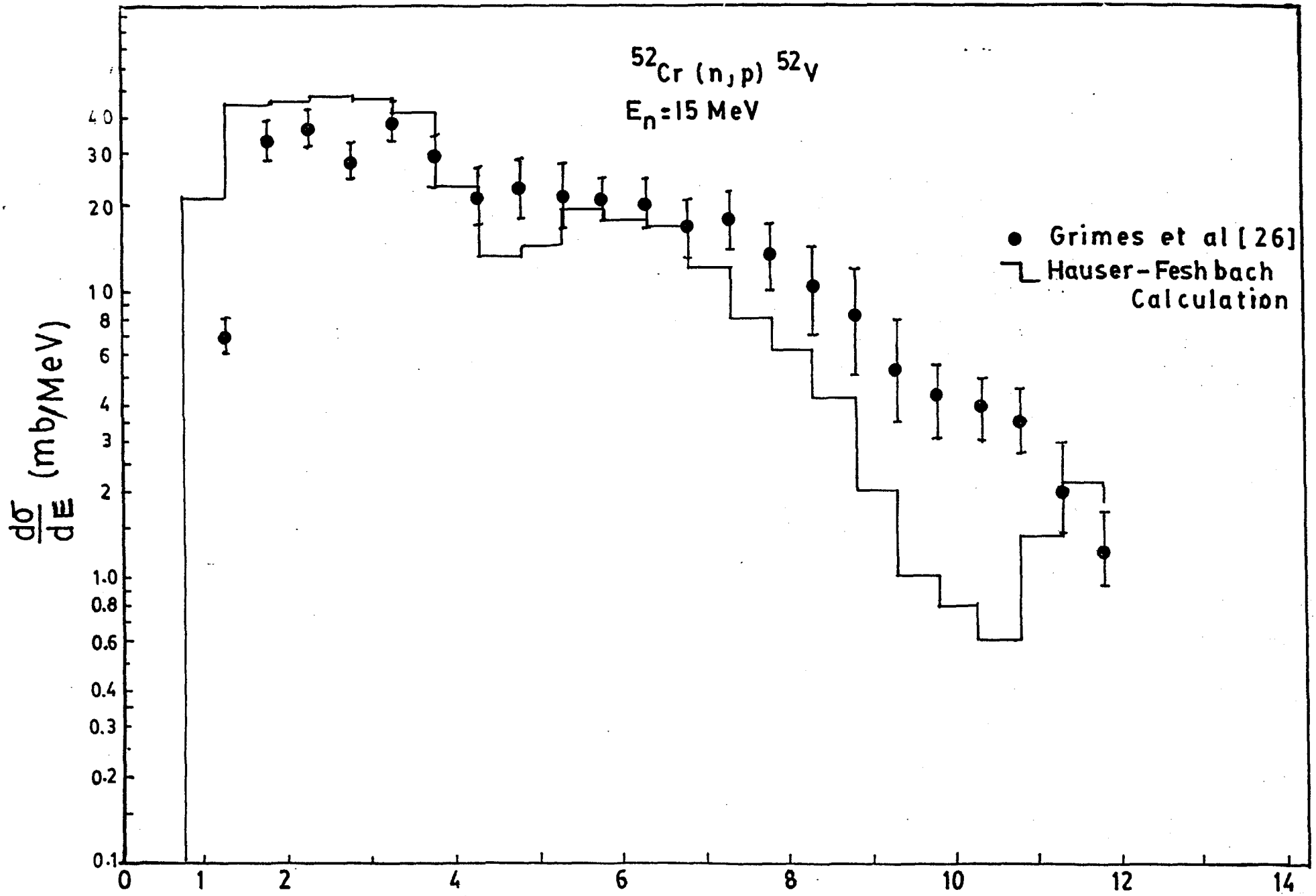

Fig. 6 Emitted Proton Energy .

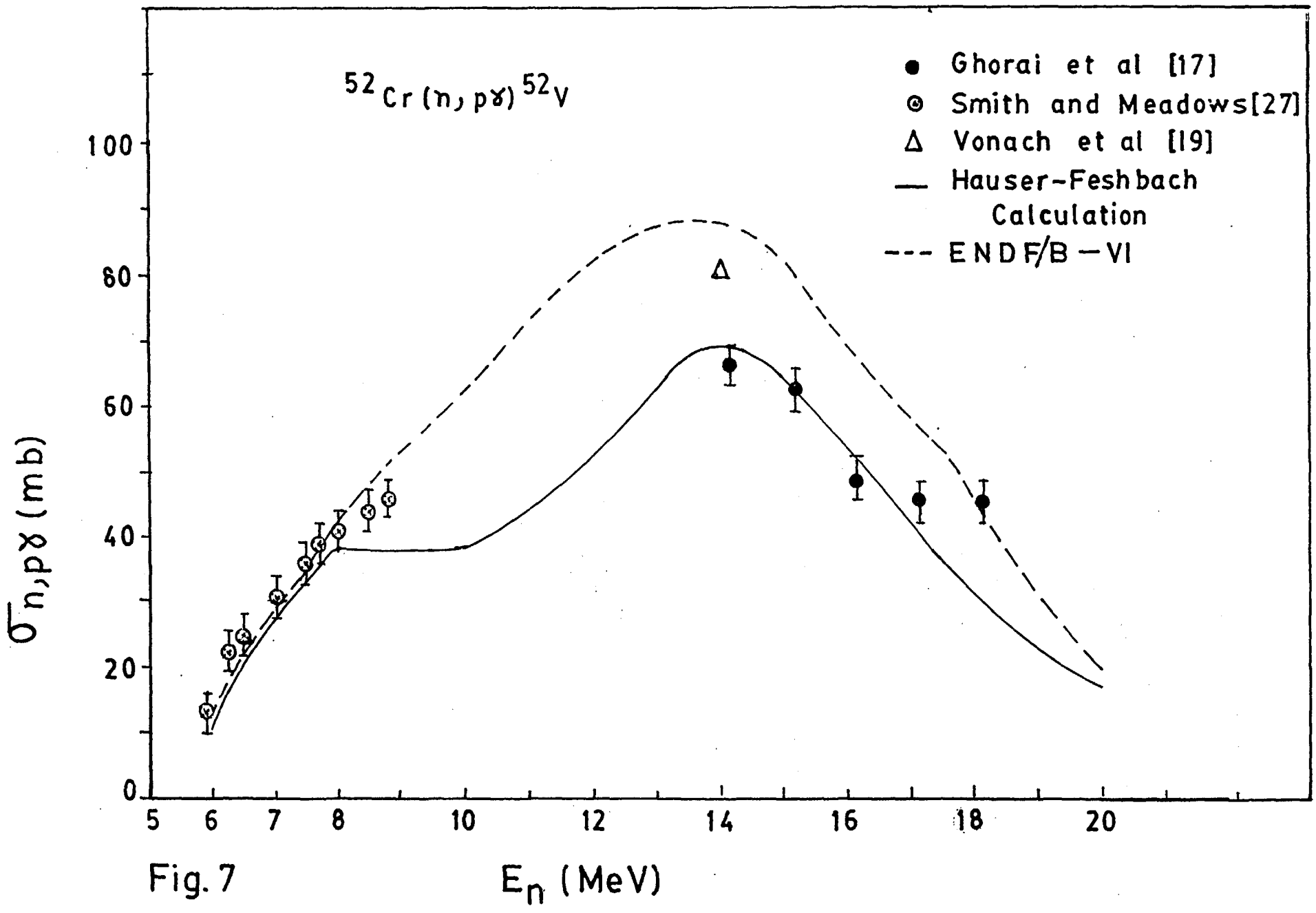
$^{52}Cr(n,p\gamma)^{52}V$
Ghorai et al [17]
Smith and Meadows[27]
Vonach et al [19]
Hauser-Feshbach Calculation
ENDF/B-VI
$\sigma_{n,p\gamma}$ (mb)
E_n (MeV)
0
20
40
60
80
100
5
6
7
8
10
12
14
16
18
20

Fig. 7

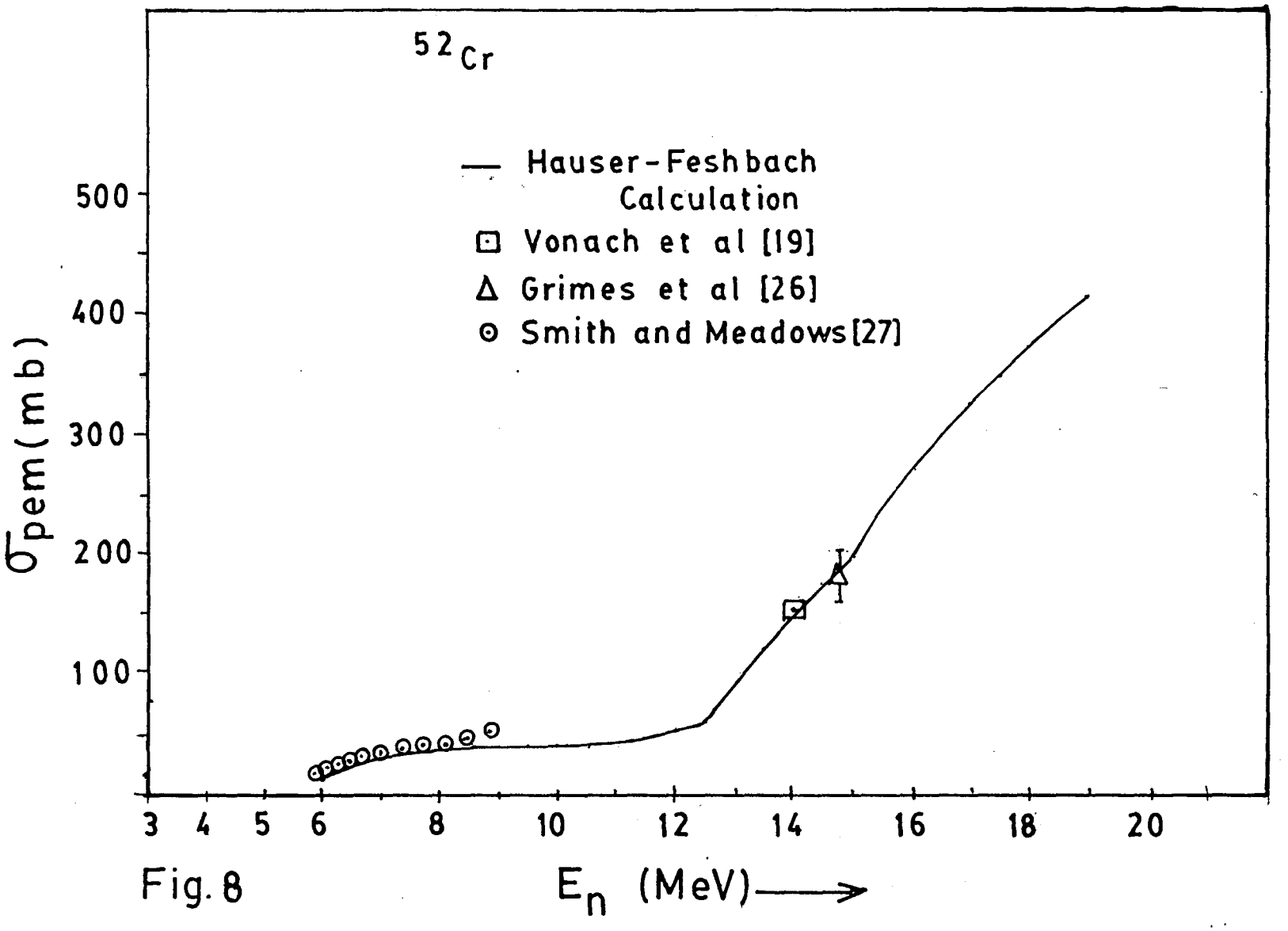
52Cr
Hauser-Feshbach Calculation
Vonach et al [19]
Grimes et al [26]
Smith and Meadows [27]
500
400
300
200
100
σpem (mb)
3
4
5
6
8
10
12
14
16
18
20
En (MeV)

Fig. 8

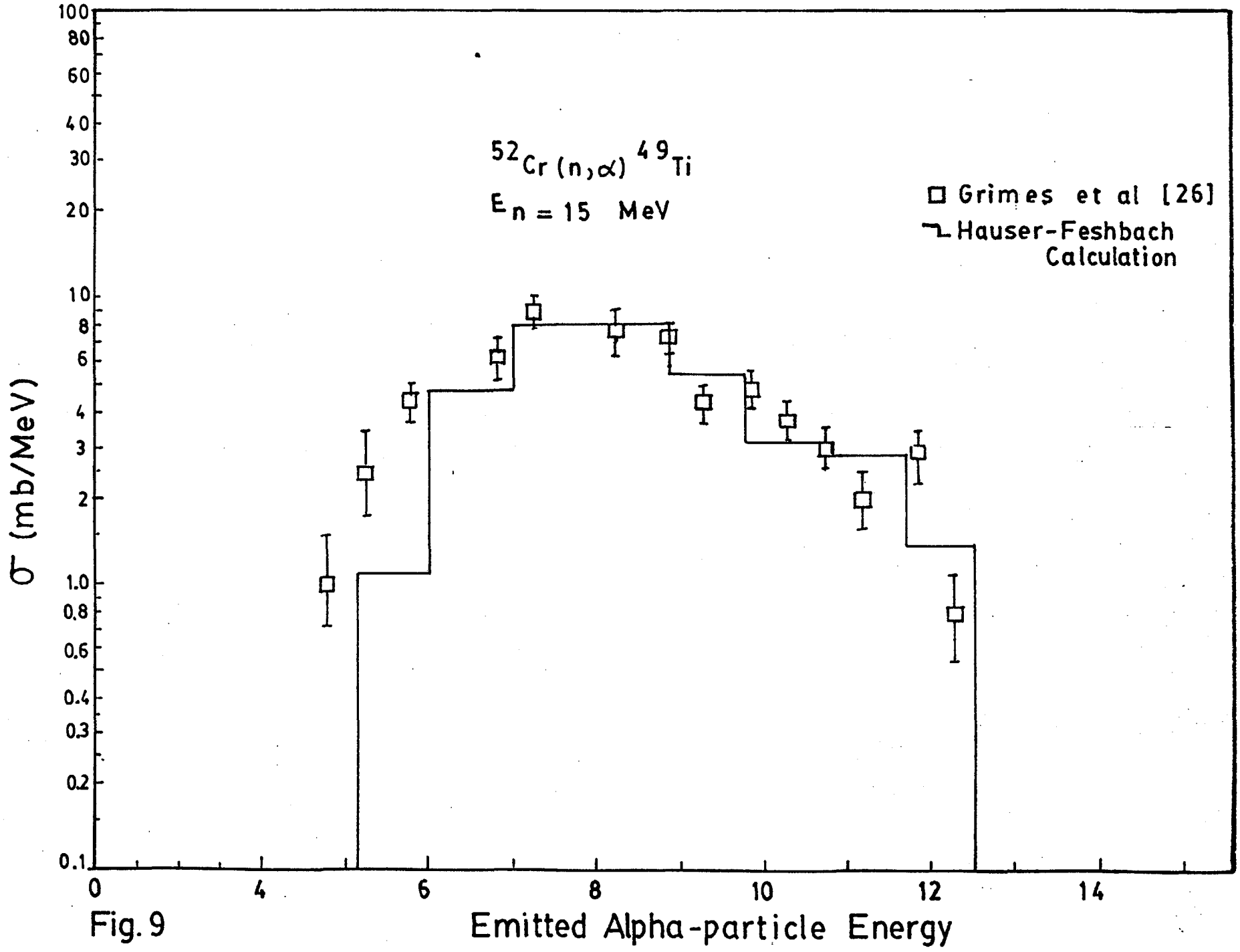
$^{52}Cr(n,\alpha)^{49}Ti$
$E_n = 15$ MeV
Grimes et al [26]
Hauser-Feshbach Calculation
σ (mb/MeV)
Emitted Alpha-particle Energy
100
80
60
40
30
20
10
8
6
4
3
2
1.0
0.8
0.6
0.4
0.3
0.2
0.1
0
4
6
8
10
12
14

Fig. 9

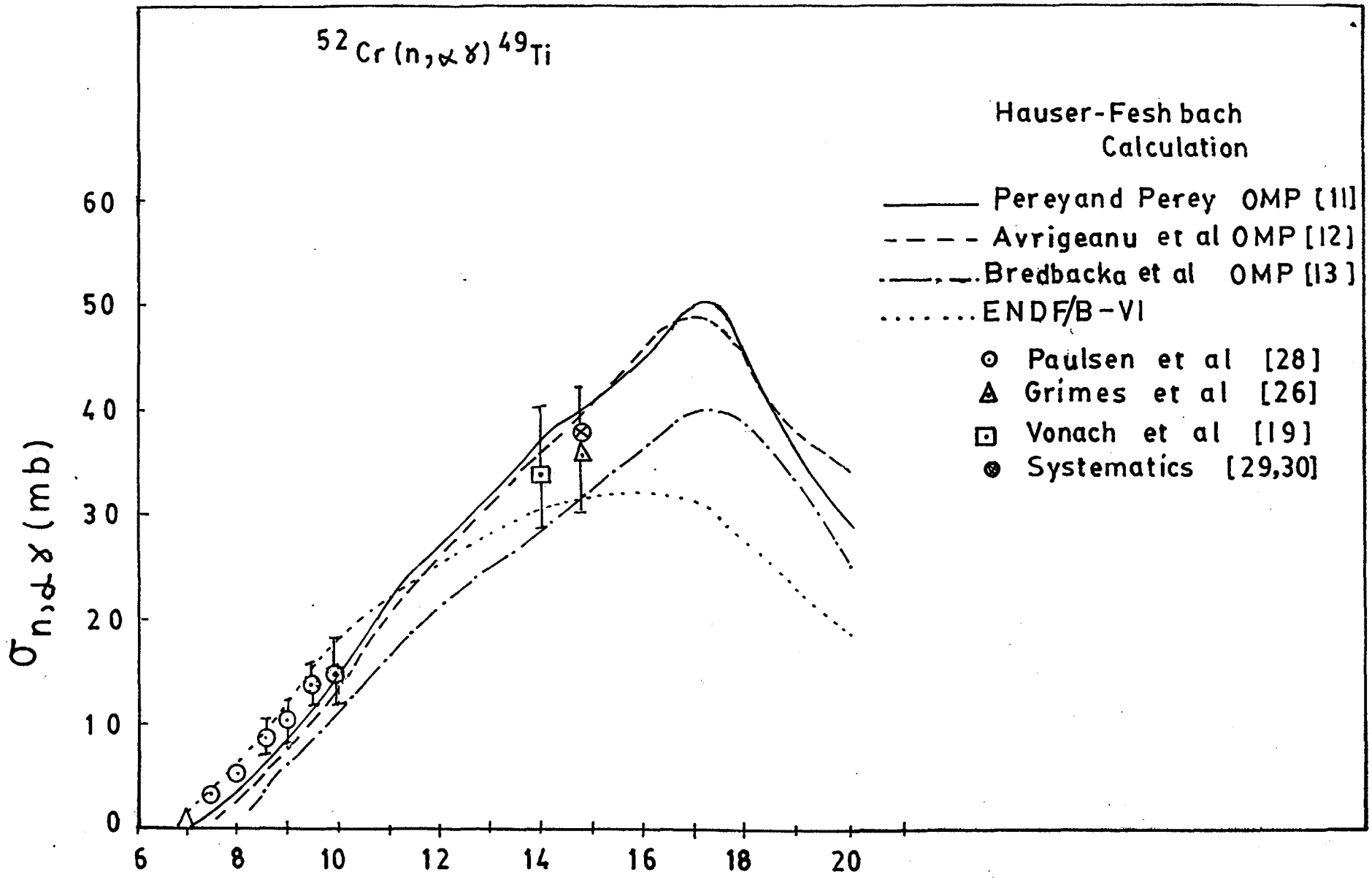
$^{52}Cr(n,\alpha\gamma)^{49}Ti$
Hauser-Feshbach Calculation
Pereyand Perey OMP [11]
Avrigeanu et al OMP [12]
Bredbacka et al OMP [13]
ENDF/B-VI
Paulsen et al [28]
Grimes et al [26]
Vonach et al [19]
Systematics [29,30]
$\sigma_{n,\alpha\gamma}$ (mb)
0
10
20
30
40
50
60
6
8
10
12
14
16
18
20
E_n (MeV)

Fig.10

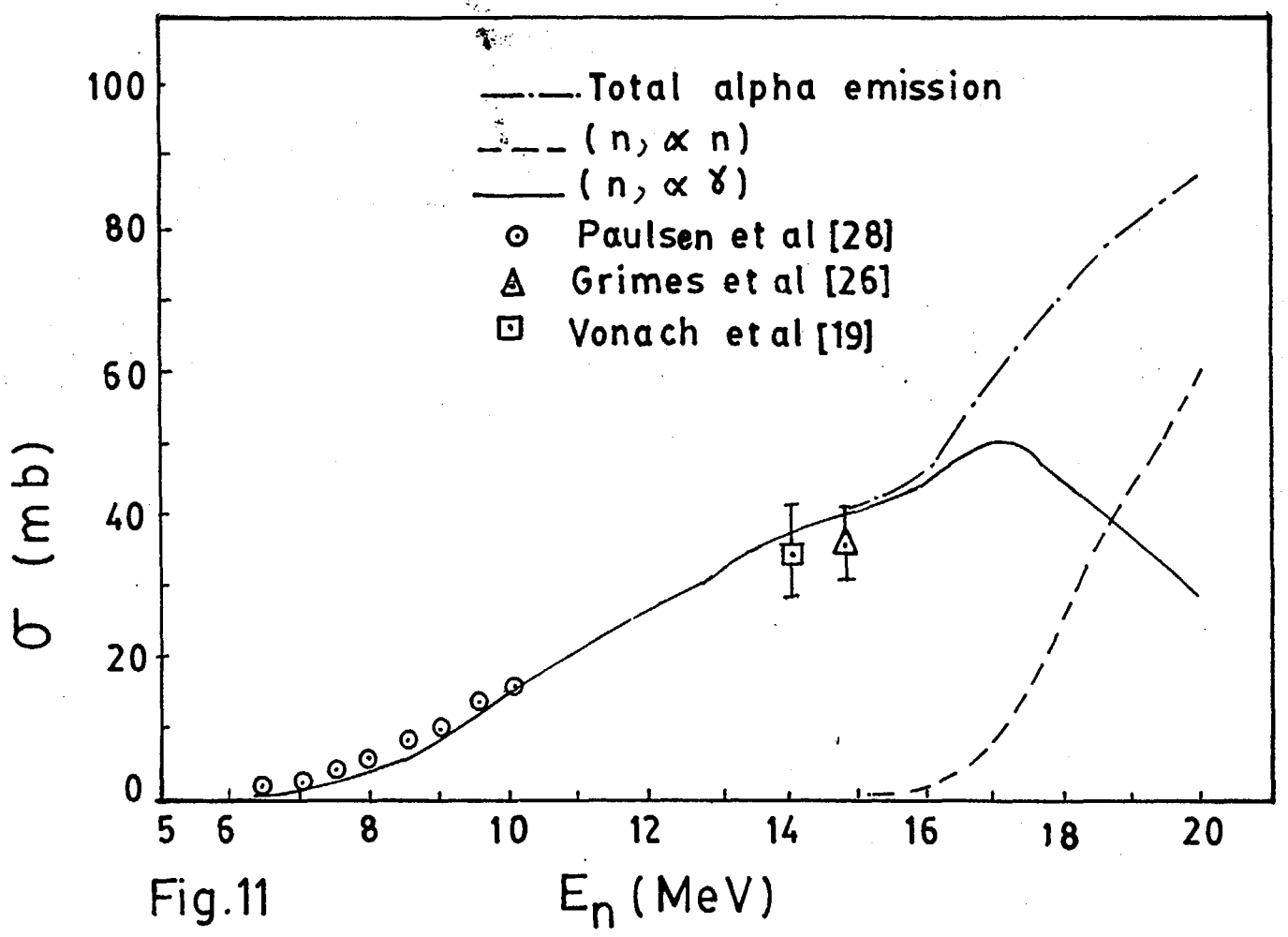
Total alpha emission
(n, α n)
(n, α γ)
Paulsen et al [28]
Grimes et al [26]
Vonach et al [19]
σ (mb)
100
80
60
40
20
0
5
6
8
10
12
14
16
18
20
E_n (MeV)

Fig.11

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