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EVALUATION OF NEUTRON NUCLEAR DATA FOR ^{3}He AND ^{4}He

February 1990

Keiichi SHIBATA

日本原子力研究所
Japan Atomic Energy Research Institute

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編集兼発行　日本原子力研究所
印　　刷　いばらき印刷㈱

Evaluation of Neutron Nuclear Data for ^{3}He and ^{4}He

Keiichi SHIBATA

Department of Physics
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

(Received January 31, 1990)

Neutron-induced cross sections of ^{3}He and ^{4}He have been evaluated for JENDL-3 in the energy range from 10^{-5} eV to 20 MeV. Evaluated quantities are the total and elastic scattering cross sections of ^{4}He and the total, elastic scattering, (n,p) and (n,d) reaction cross sections of ^{3}He. The total and elastic scattering cross sections of ^{4}He were analyzed with the R-matrix theory in the overall energy region. In the ^{3}He evaluation, the R-matrix calculation was performed below 1 MeV by considering the total, elastic scattering and (n,p) reaction cross sections, and above 1 MeV the evaluation was based on available experimental data. The evaluated data have been compiled in the ENDF-5 format.

Keywords: Evaluation, Neutron Nuclear Data, Helium-3, Helium-4, Cross Section, JENDL-3

^{3}He及び^{4}Heの中性子核データ評価

日本原子力研究所東海研究所物理部
柴田 恵一

（1990年1月31日受理）

^{3}He及び^{4}Heの中性子核データが，10^{-5}eVから20MeVのエネルギー範囲でJENDL-3のために評価された。評価された量は，^{4}Heの全断面積，弾性散乱断面積及び^{3}Heの全断面積，弾性散乱断面積，(n，p)，(n，d)反応断面積である。^{4}Heの全断面積及び弾性散乱断面積は，全エネルギー領域にわたって，R行列理論により解析された。^{3}Heの評価に於いては1MeV以下では全断面積，弾性散乱断面積，(n，p)反応断面積を考慮したR行列理論の計算が行われ，一方1MeV以上では，実験値に基づいて評価が行われた。評価済みデータは，ENDF-5フォーマットで編集された。

東海研究所：〒319-11 茨城県那珂郡東海村白方字白根2-4

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1. Introduction

Neutron-induced cross sections of helium isotopes are important not only for nuclear engineering but also for the studies on few-nucleon systems. Unfortunately, they were not contained in the second version of Japanese Evaluated Nuclear Data Library (JENDL-2), which was released in 1982. Thus, it was decided to evaluate the neutron nuclear data of ^{3}He and ^{4}He for JENDL-3.

Concerning ^{3}He, evaluated are the total, elastic scattering, (n,p) and (n,d) reaction cross sections. According to the experimental data[1-3], the ^{3}He(n,γ) reaction cross section is less than 50 μb in the energy range from thermal to 17 MeV. Thus, we neglected the (n,γ) reaction in this work. The (n,p) reaction cross section is considered as a standard from thermal to 50 keV. The ENDF/B-V data on ^{3}He were carried over without any changes from ENDF/B-III of which evaluation was performed in 1968.

The present evaluation of the (n,p) cross section took account of the new measurements and the accuracy was much improved, particularly for 0.3 - 100 keV. The (n,p) cross section was analyzed with the R-matrix theory below 1 MeV as well as the total and elastic scattering cross sections.

For ^{4}He, the open channels are the elastic scattering and (n,γ) reaction up to 20 MeV. The (n,γ) reaction, however, has a negative Q-value (-893.6 keV) and its cross section is expected to be negligible in the energy range concerned. In fact, no capture measurement has been reported. Thus, we considered only the total and elastic scattering cross sections which were assumed to be equal to each other in this work.

The essence of the present evaluation was already published[4]. This report is intended to provide more complete information for users of JENDL-3. The status of the presently evaluated quantities is listed in Table 1.

2. Helium-3

2.1 Total Cross Section

There are several measurements available for the evaluation:

Battat et al.	(1959)[5],	0.2 - 20 MeV,
Als-Nielsen and Dietrich	(1964)[6],	0.0003 - 11 eV,
Goulding et al.	(1973)[7],	0.7 - 30 MeV,

Alfimenkov et al. (1981)[8], 1 - 200 keV,

Haesner et al. (1983)[9], 1 - 40 MeV.

Below 1 MeV, the total, elastic scattering and (n,p) reaction cross sections were analyzed with the R-matrix theory. The R-matrix parameters used in the analysis are given in Table 2. The calculated results are shown in Figs. 1 and 2, together with ENDF/B-V and the experimental data. It should be noted that the ENDF/B-V data give small cross sections as compared with the present evaluation and the experimental data of Alfimenkov et al.[8]

Above 1 MeV, the evaluated curve was obtained by the least-squares fitting to the experimental data of Goulding et al.[7] and Haesner et al.[9] Figures 3 and 4 show the evaluated results.

2.2 Elastic Scattering Cross Section

Available experimental data are listed as follows:

Seagrave et al. (1960)[10], 1 - 6 MeV,

Sayres et al. (1961)[11], 0.95 - 17.5 MeV,

Curtis (1973)[12], 14 MeV,

Drosg et al. (1974)[13], 7.9 - 23.7 MeV,

Alfimenkov et al. (1977)[14], 0.02 - 2 eV,

Alfimenkov et al. (1981)[8], 1 - 200 keV,

Haesner (1982)[15], 1 - 30 MeV.

Below 1 MeV, the evaluation was based on the R-matrix calculation. The calculated thermal cross section is 3.13 barns, in good agreement with a value of 3.10 ± 0.13 barns recommended by Mughabghab et al.[16] The results are illustrated in Figs. 5 and 6. A large difference is seen between the present evaluation and ENDF/B-V. ENDF/B-V assumed a value of 1.0 barn for the elastic scattering cross section from 10^{-5} eV to 10.8 keV, but the assumption is obviously inconsistent with the measurements of Alfimenkov et al.[8,14]

Above 1 MeV, the present evaluated cross section was obtained by subtracting the reaction cross section ((n,p) + (n,d)), which is discussed in the following sections, from the total cross section. The results are shown in Figs. 7 and 8.

Angular distributions of elastically scattered neutrons were determined on the basis of the experimental data[10,15] above 1 MeV. Isotropic distributions in the center-of-mass system were assumed in the energy range from 10^{-5} eV to 1 MeV.

2.3 (n,p) Reaction Cross Section

Available experimental data are given as follows:

Coon and Nobles	(1949)[17],	thermal,
Coon	(1950)[18],	0.4 - 3 MeV,
Batchelor et al.	(1955)[19],	0.12 - 1.2 MeV,
Gibbons and Macklin	(1959)[20],	8.65 keV - 4.2 MeV,
Sayres et al.	(1961)[11],	1 - 8 MeV,
Als-Nielsen and Dietrich	(1964)[6],	thermal,
Macklin and Gibbons	(1965)[21],	4 - 300 keV,
Antolkovic et al.	(1967)[22],	14.4 MeV,
Costello et al.	(1970)[23],	0.3 - 1.16 MeV,
Drosg	(1978)[24],	7.9 - 23.7 MeV,
Haesner	(1982)[15],	1 - 30 MeV,
Borzakov et al.	(1982)[25],	0.27 - 137 keV.

Below 1 MeV, the evaluated data were obtained from the R-matrix calculation. The calculated thermal cross section is 5328 barns, in good agreement with a value of 5333 ± 7 barns recommended by Mughabghab et al.[16] The evaluated data are shown in Figs. 9 - 13. It should be noted that the present evaluation is in good agreement with the measurement of Borzakov et al.[25] in the energy range of 0.3 to 130 keV. The ENDF/B-V data are larger than the present evaluation in this region.

In the ENDF/B-V evaluation[26], the thermal cross section of 5327 barns was derived from the measurement by Als-Nielsen and Dietrich[6] of the total cross section up to an energy of 11 eV, and the cross section was assumed to follow 1/v up to 1.7 keV. From 1.7 keV to 100 keV, the ENDF/B-V evaluation was based on the measurements of Gibbons and Macklin[20,21]. The present evaluation shows that the deviation from the 1/v law is 1.5% at 100 eV and 4.8% at 1 keV. The 1/v behavior below 100 eV was well described by the ^1S resonance in the R-matrix calculation. The resonance corresponds to the first excited state ($J^\pi = 0^+$) of ^4He at an excitation energy of 20.1 MeV. This result is consistent with the spin dependence of the (n,p) cross section measured by Passell and Shermer[27].

Above 1 MeV, the evaluation was made on the basis of the least-squares fitting to the measurements of Haesner[15] and Drosg[24]. The results are seen in Figs. 14 and 15.

2.4 (n,d) Reaction Cross Section

The evaluated (n,d) reaction cross section was obtained from the least-squares fitting to the experimental data of Haesner[15] and Drosg.[24] The present evaluation is almost consistent with the ENDF/B-V data, as seen in Fig. 16.

3. Helium-4

In the present evaluation, the (n,γ) reaction was neglected and thus the total cross section is equivalent to the elastic scattering cross section. A smooth curve was obtained from the least-squares fitting to the experimental data on the total cross section. The measurements used in the fitting are listed as follows:

Battat et al.	(1959)[5]	0.94 - 20 MeV,
Vaughn et al.	(1960)[28]	0.12 - 19.8 MeV,
Austin et al.	(1962)[29]	7 - 12 MeV,
Rorer et al.	(1969)[30]	0.2 - 6 eV,
Goulding et al.	(1973)[7]	0.7 - 29 MeV,
Lamaze et al.	(1979)[31]	15 - 28 MeV,
Haesner et al.	(1983)[9]	1 - 40 MeV.

Furthermore, the curve thus obtained was considered as a set of experimental data with accuracy of 5% and was analyzed with the R-matrix theory in the overall energy region. Initial values for the R-matrix parameters were taken from the work of Bond and Firk[32]. The parameters were automatically adjusted by using the RESCAL code[33], and the final values are given in Table 3. The calculated thermal cross section is 0.759 barn, and agrees with a value of 0.76 ± 0.01 barn recommended by Mughabghab et al.[16] The R-matrix calculation was adopted as the evaluated data in the overall energy region. Figures 17 - 19 show the evaluated data. Angular distributions of elastically scattered neutrons were calculated with the R-matrix theory up to 20 MeV, and are illustrated in Figs. 20 - 25.

4. Concluding Remarks

Neutron nuclear data of ^{3}He and ^{4}He were evaluated for JENDL-3 in the energy range from 10^{-5} eV to 20 MeV.

The total, elastic scattering and (n,p) reaction cross sections of

^{3}He were analyzed with the R-matrix theory below 1 MeV. The 1/v behavior in the (n,p) cross section was well reproduced by taking account of the ^{1}S resonance. Above 1 MeV, these cross sections were evaluated on the basis of the experimental data. The evaluated data on the ^{3}He(n,d) reaction were obtained by the least-squares fitting to the experimental data.

Concerning ^{4}He, the elastic scattering is the only reaction channel to be evaluated, which means that the total cross section is assumed to be equivalent to the elastic scattering one. The experimental data on the total cross section were analyzed with the R-matrix theory in the overall energy region. Angular distributions of elastically scattered neutrons were also obtained from the R-matrix calculation.

Acknowledgment

The author would like to thank T. Fukahori for reviewing the present evaluated data. He is also indebted to S. Igarasi, Y. Kikuchi and T. Nakagawa for their valuable discussion during the course of this work.

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Table 1 Status of presently evaluated quantities.

Quantities	Energy range (eV)* min.	max.	Comments
(1) ^{3}He			
a) Cross section			
Total	1.0 -5	2.0 +7	Figs. 1-4
Elastic scattering	1.0 -5	2.0 +7	Figs. 5-8
Nonelastic scattering	1.0 -5	2.0 +7	
(n,p)	1.0 -5	2.0 +7	Figs. 9-15
(n,d)	4.36+6	2.0 +7	Fig. 16
b) Angular distributions of secondary neutrons			
Elastic scattering	1.0 -5	2.0 +7	
(2) ^{4}He			
a) Cross section			
Total	1.0 -5	2.0 +7	Figs.17-19
Elastic scattering	1.0 -5	2.0 +7	
b) Angular distributions of secondary neutrons			
Elastic scattering	1.0 -5	2.0 +7	Figs.20-25

* 2.0+7 denotes 2.0×10^{7}.

Table 2 R-matrix parameters used in the n+^{3}He analysis.

$J\pi$	ℓ	$E_\lambda^{J\pi}$(MeV)	$\gamma_{\lambda n}^{J\pi}$(MeV$^{1/2}$)	$\gamma_{\lambda p}^{J\pi}$(MeV$^{1/2}$)	$B_{\lambda n}^{J\pi}$	$B_{\lambda p}^{J\pi}$	$R_{n0}^{\infty J\pi}$
0-	1	0.423	2.000	1.900	-0.830	-0.721	0.0
0+	0	-0.477	1.014	1.014	0.0	-0.034	0.2
1-	1	1.523	2.400	2.100	-0.628	-0.575	0.0

Channel radii: $a_n = a_p = 3.55$ fm.

The R-matrix is given by

$$R_{c',c}^{J\pi} = R_{c0}^{\infty J\pi}\delta_{c',c} + \sum_\lambda \gamma_{\lambda c'}^{J\pi}\gamma_{\lambda c}^{J\pi}/(E_\lambda^{J\pi} - E).$$

The symbol $B_{\lambda c}^{J\pi}$ denotes the real boundary condition.

Table 3 R-matrix parameters used in the n+^{4}He analysis.

$J\pi$	ℓ	$E_\lambda^{J\pi}$(MeV)	$\gamma_{\lambda n}^{J\pi}$(MeV$^{1/2}$)	$R_{n0}^{\infty J\pi}$	$B_{\lambda n}^{J\pi}$
1/2+	0	22.375	1.809	0.120	0.0
1/2-	1	5.758	2.768	0.289	-0.286
3/2-	1	0.964	2.198	0.310	-0.706
3/2+	2	35.575	3.498	0.0	-0.220
5/2+	2	30.840	3.074	0.0	-0.256

Channel radius: a = 3.35 fm.

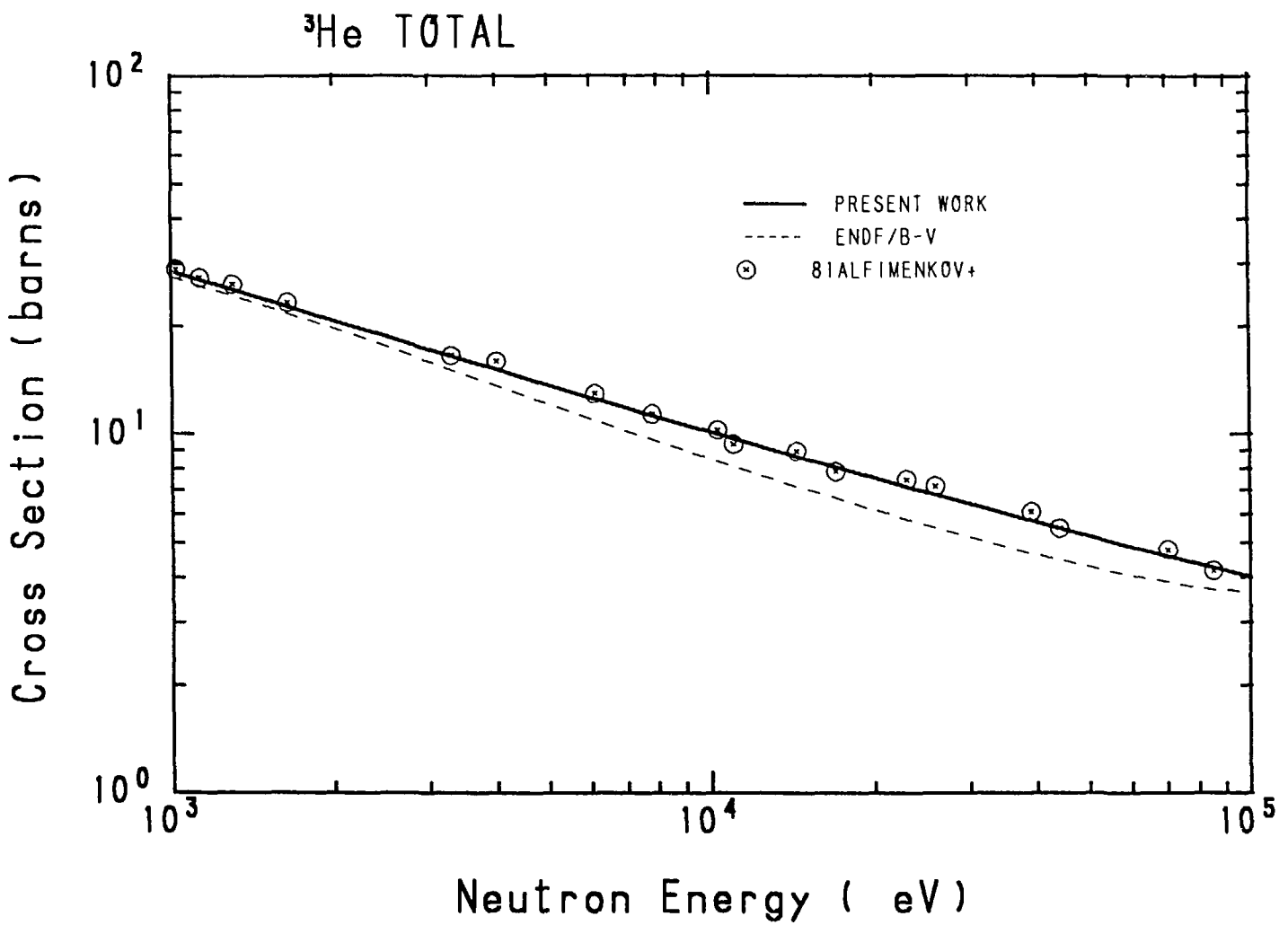

Fig. 1 Total cross section of ^{3}He in the energy range from 1 keV to 100 keV.

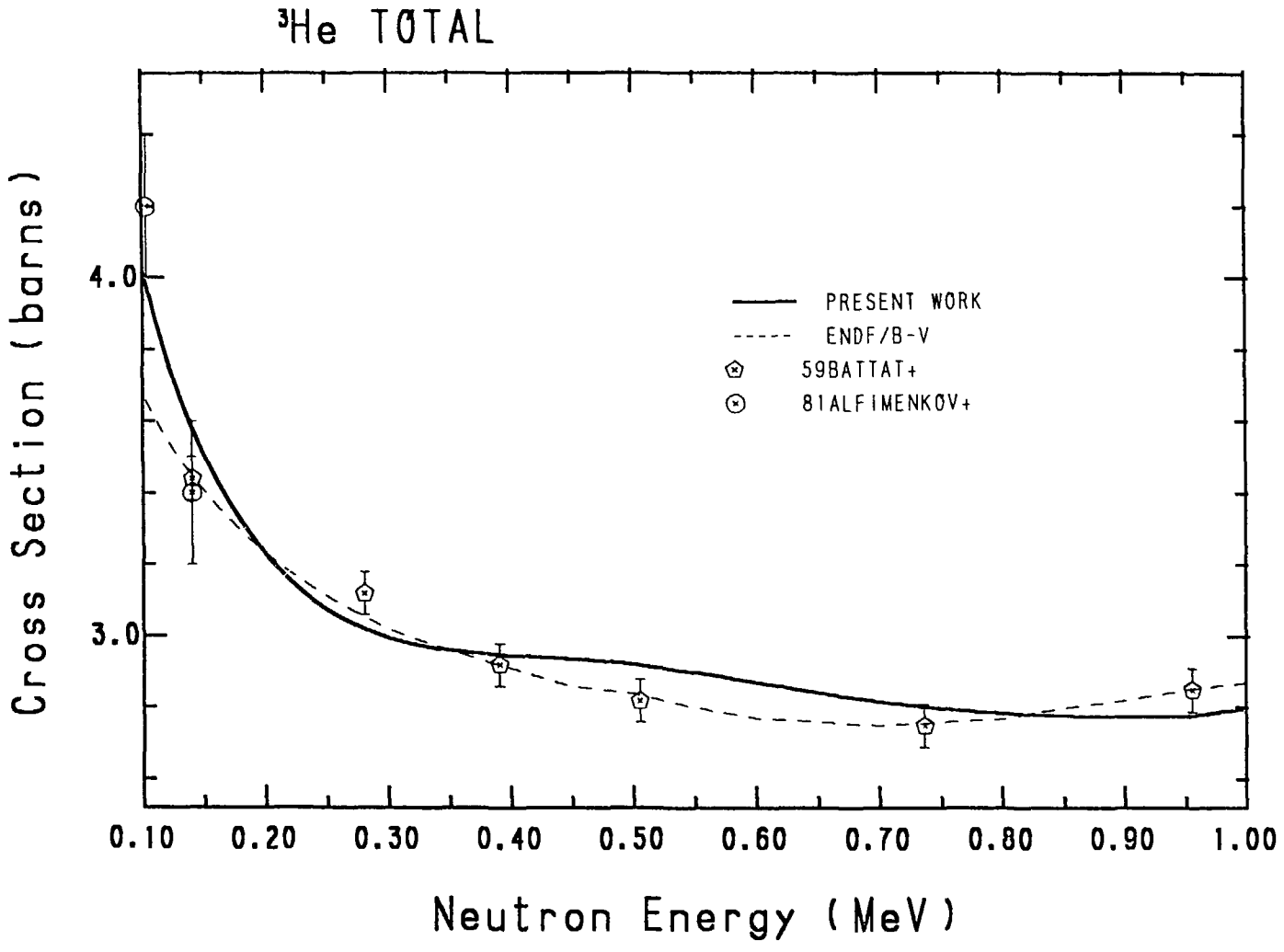

Fig. 2 Total cross section of ^{3}He in the energy range from 100 keV to 1 MeV.

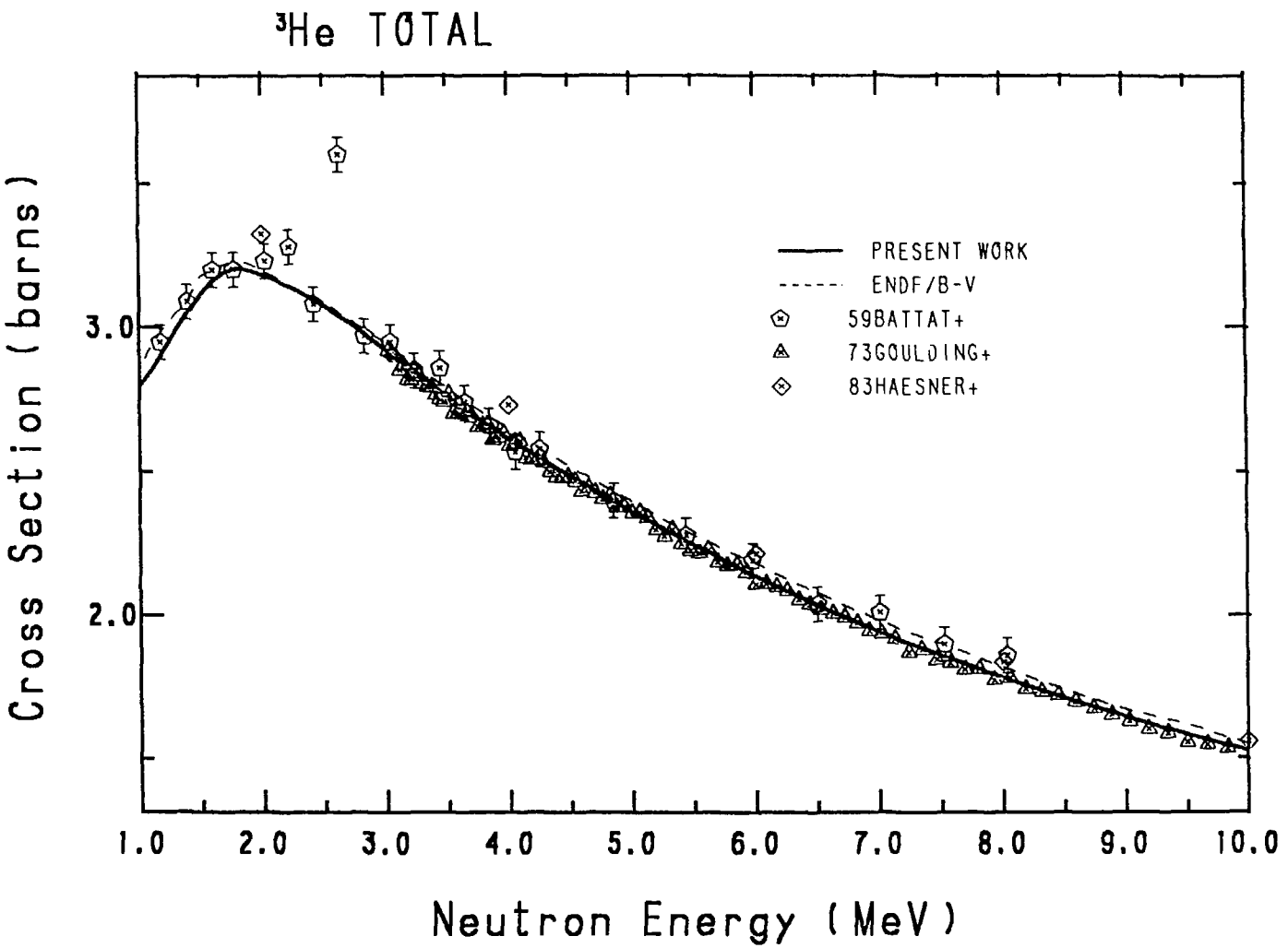

Fig. 3 Total cross section of ^{3}He in the energy range from 1 MeV to 10 MeV.

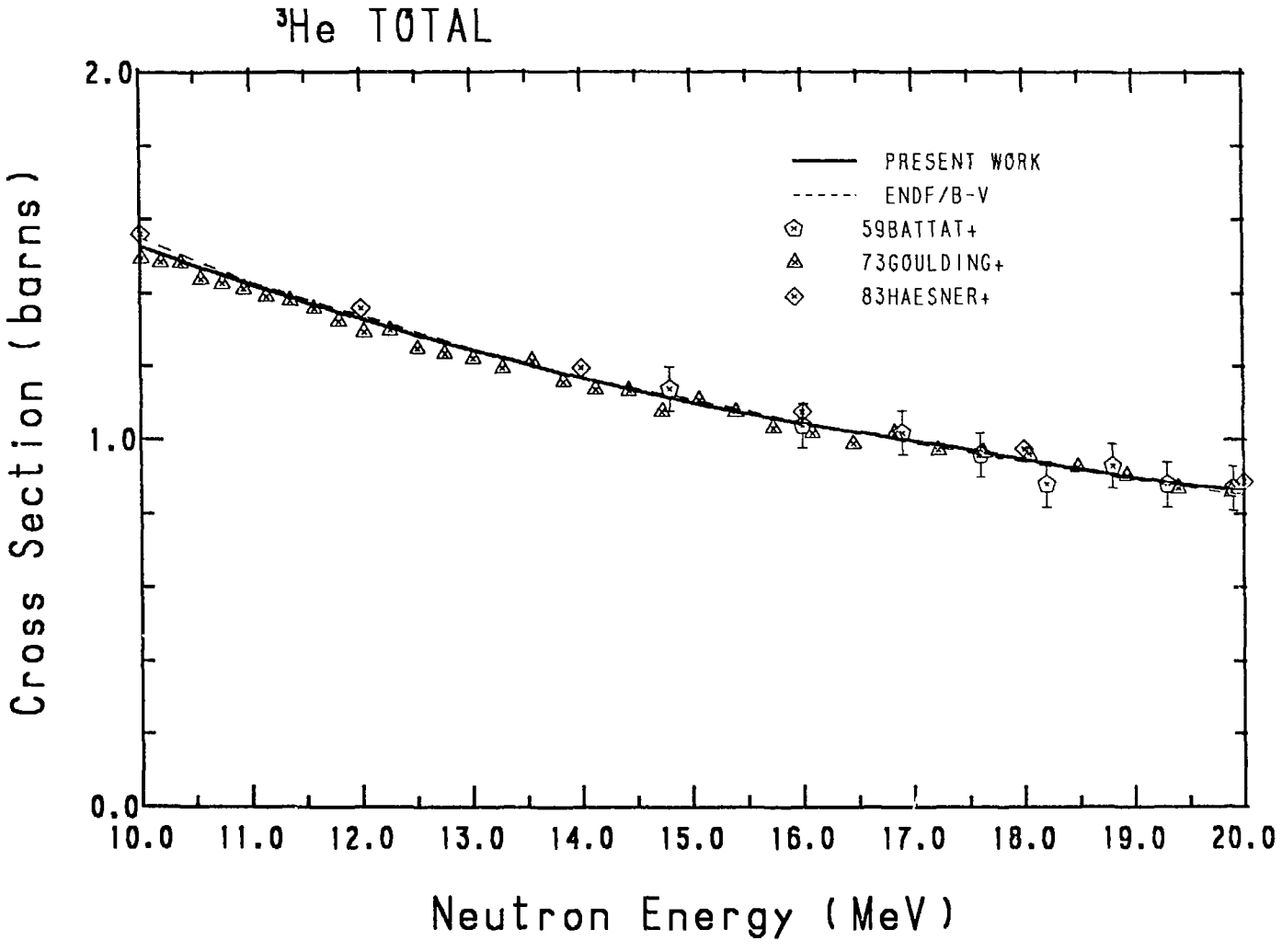

Fig. 4 Total cross section of ^{3}He in the energy range from 10 MeV to 20 MeV.

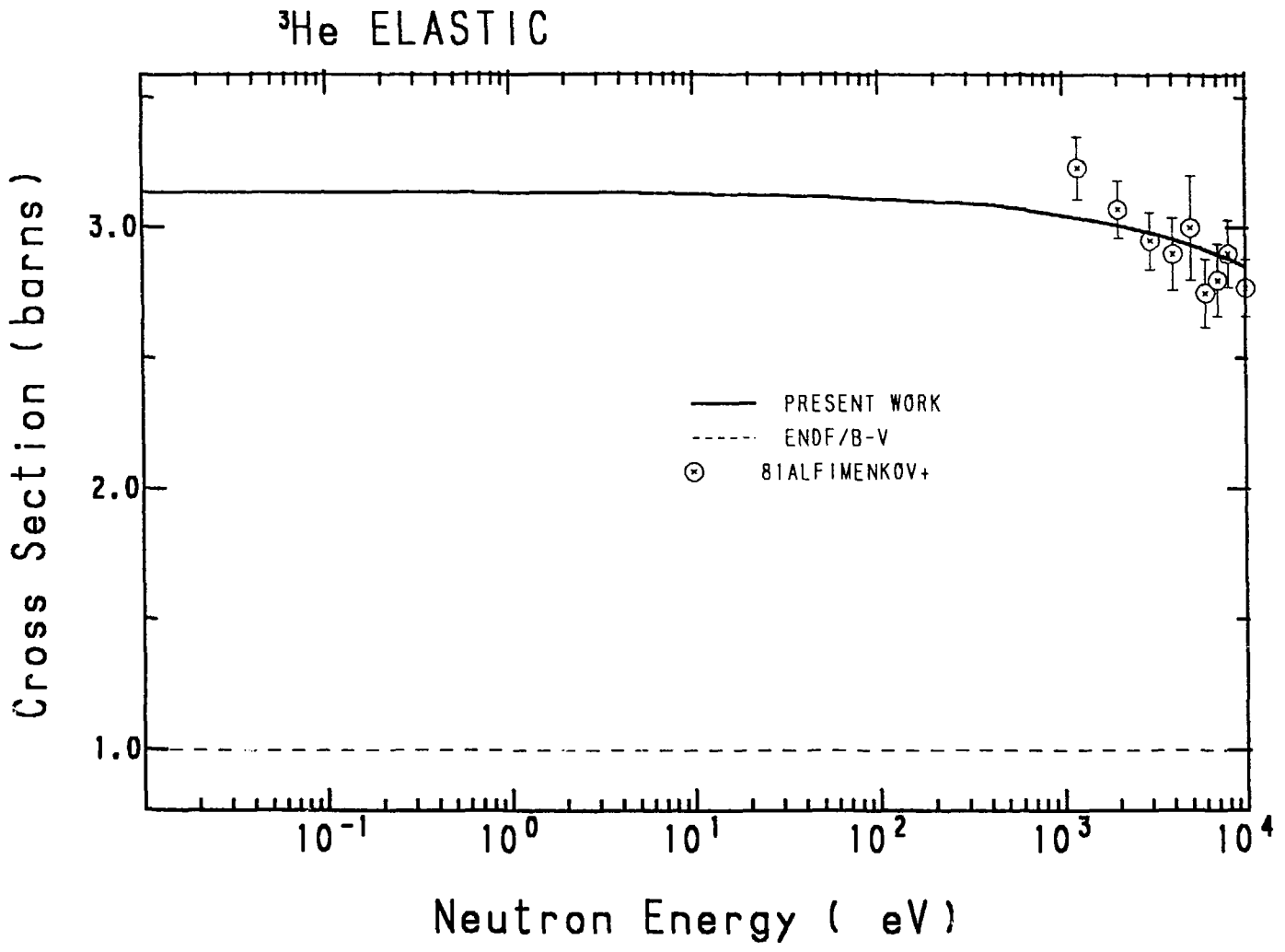

Fig. 5 Elastic scattering cross section of ^{3}He in the energy range from 10^{-2} eV to 10^4 eV.

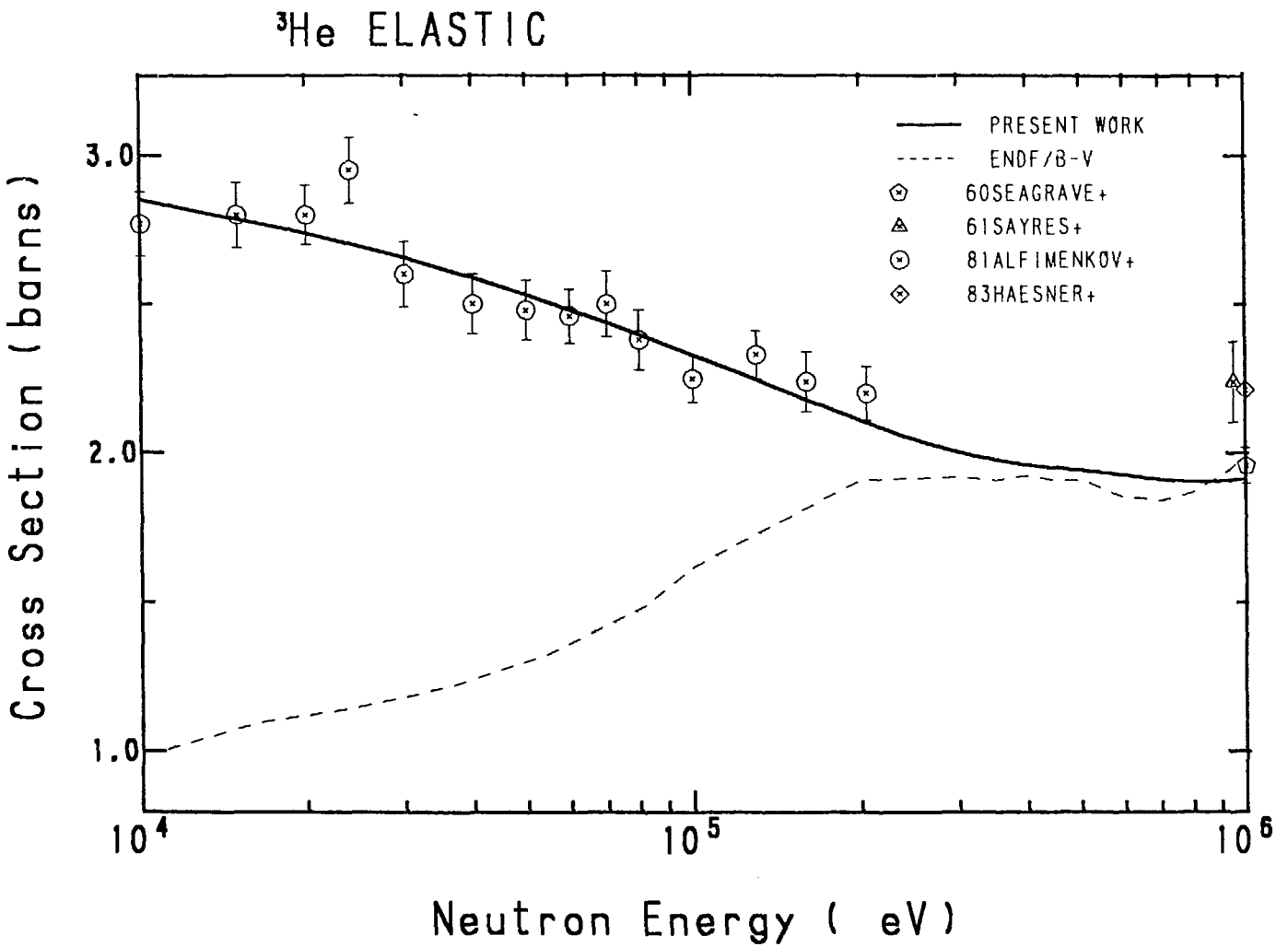

Fig. 6 Elastic scattering cross section of ^{3}He in the energy range from 10 keV to 1 MeV.

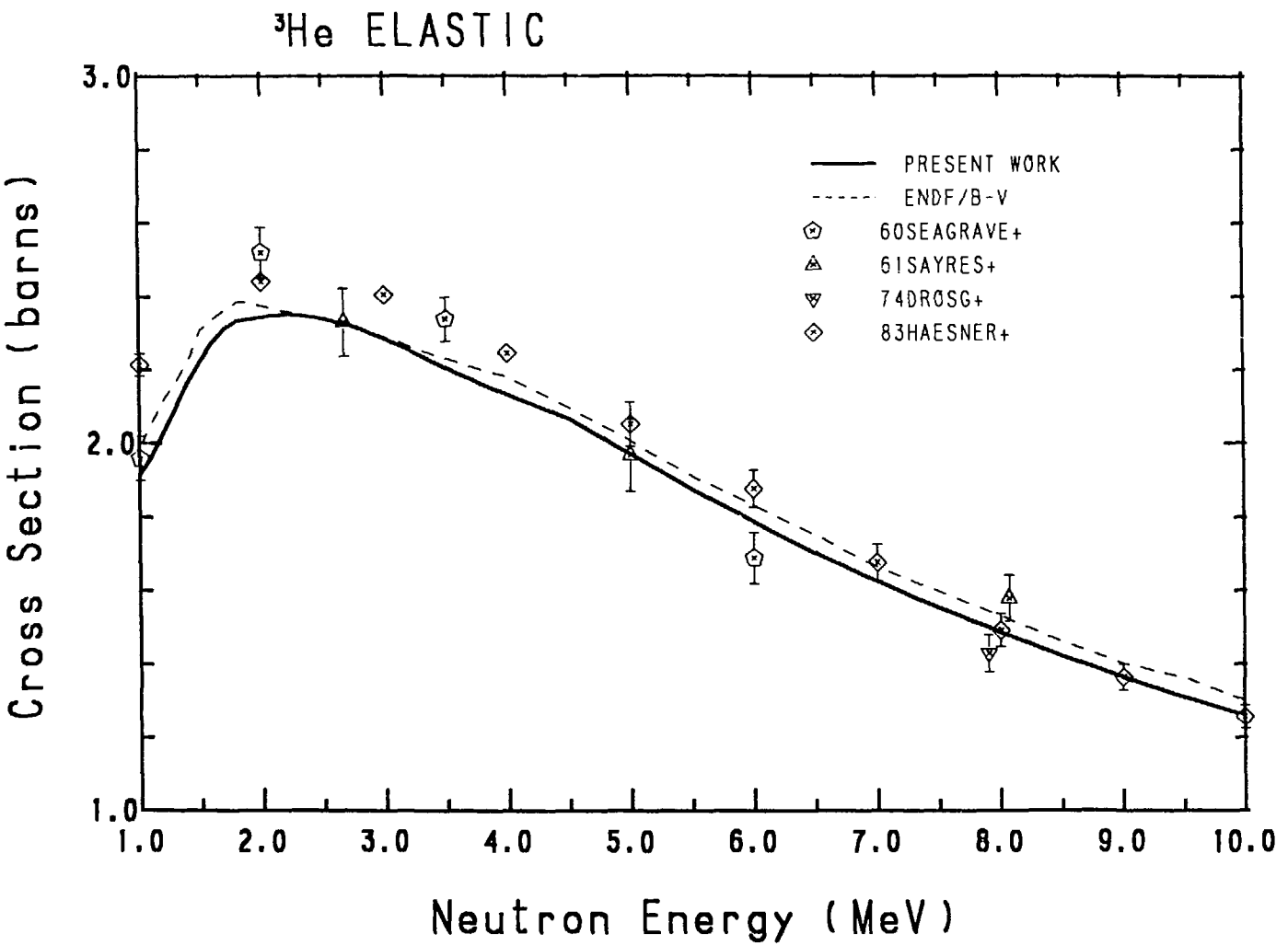

Fig. 7 Elastic scattering cross section of ^{3}He in the energy range from 1 MeV to 10 MeV.

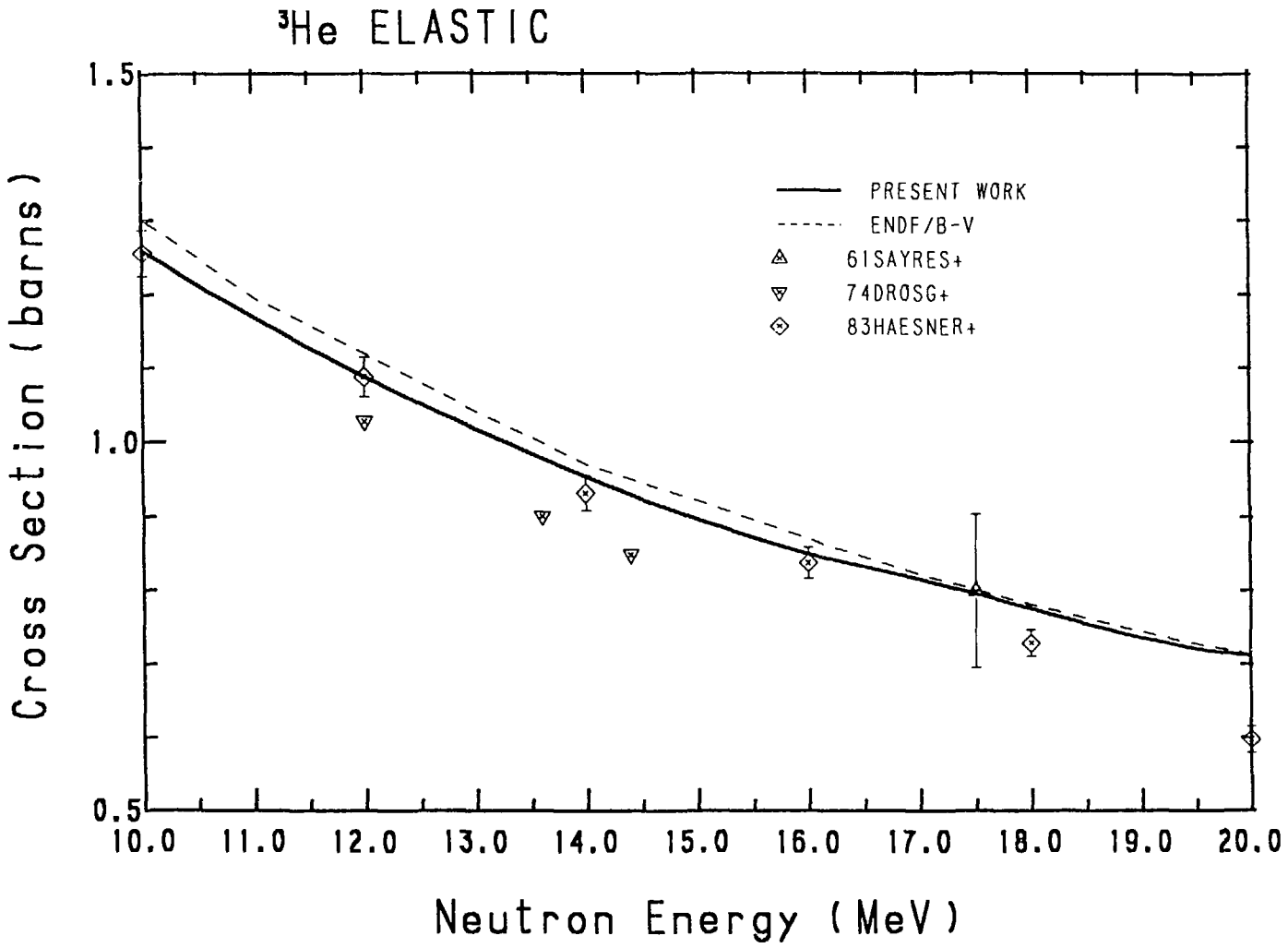

Fig. 8 Elastic scattering cross section of ^{3}He in the energy range from 10 MeV to 20 MeV.

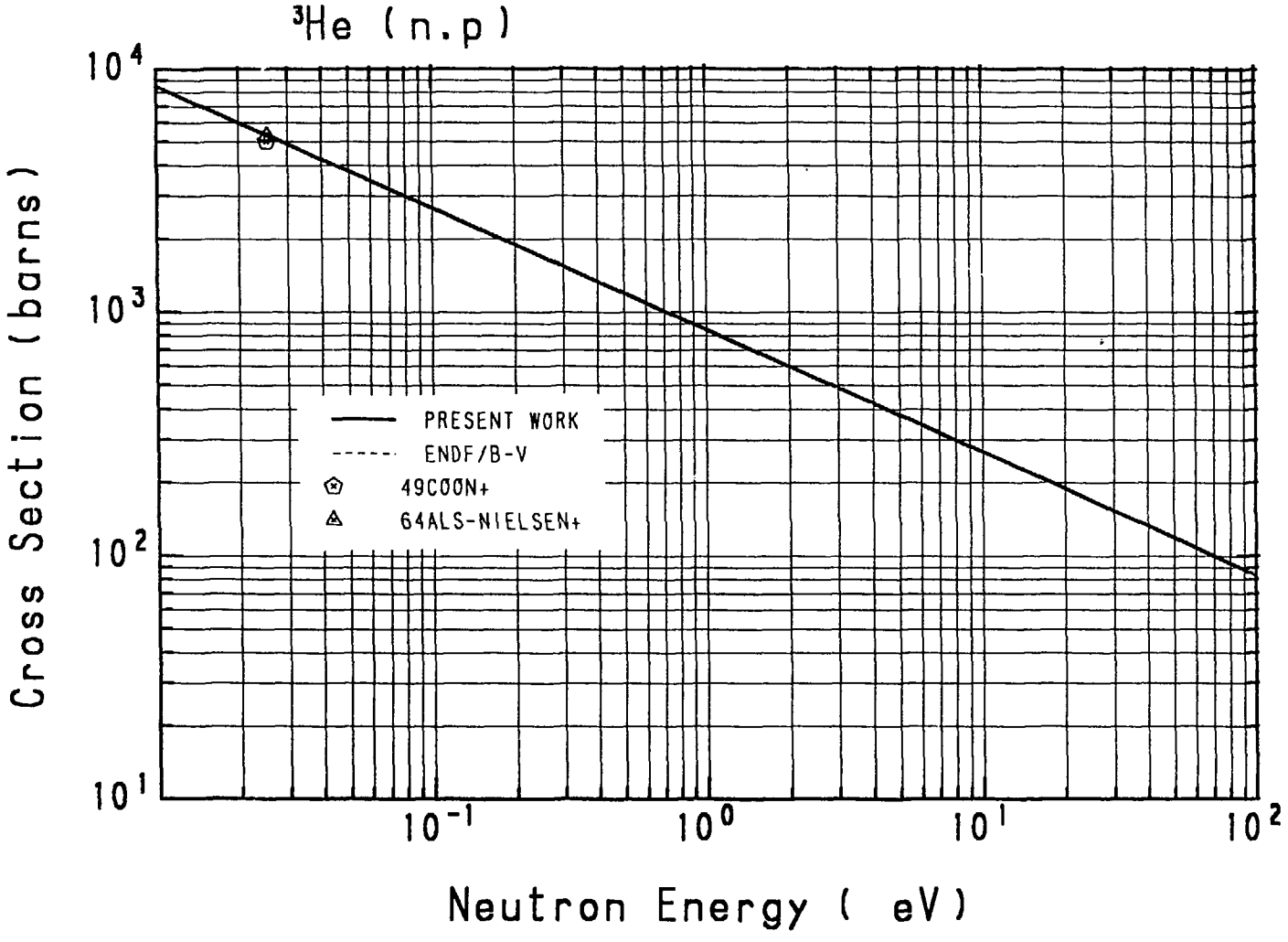

Fig. 9 ^{3}He(n,p) reaction cross section in the energy range from 10^{-2} eV to 10^2 eV.

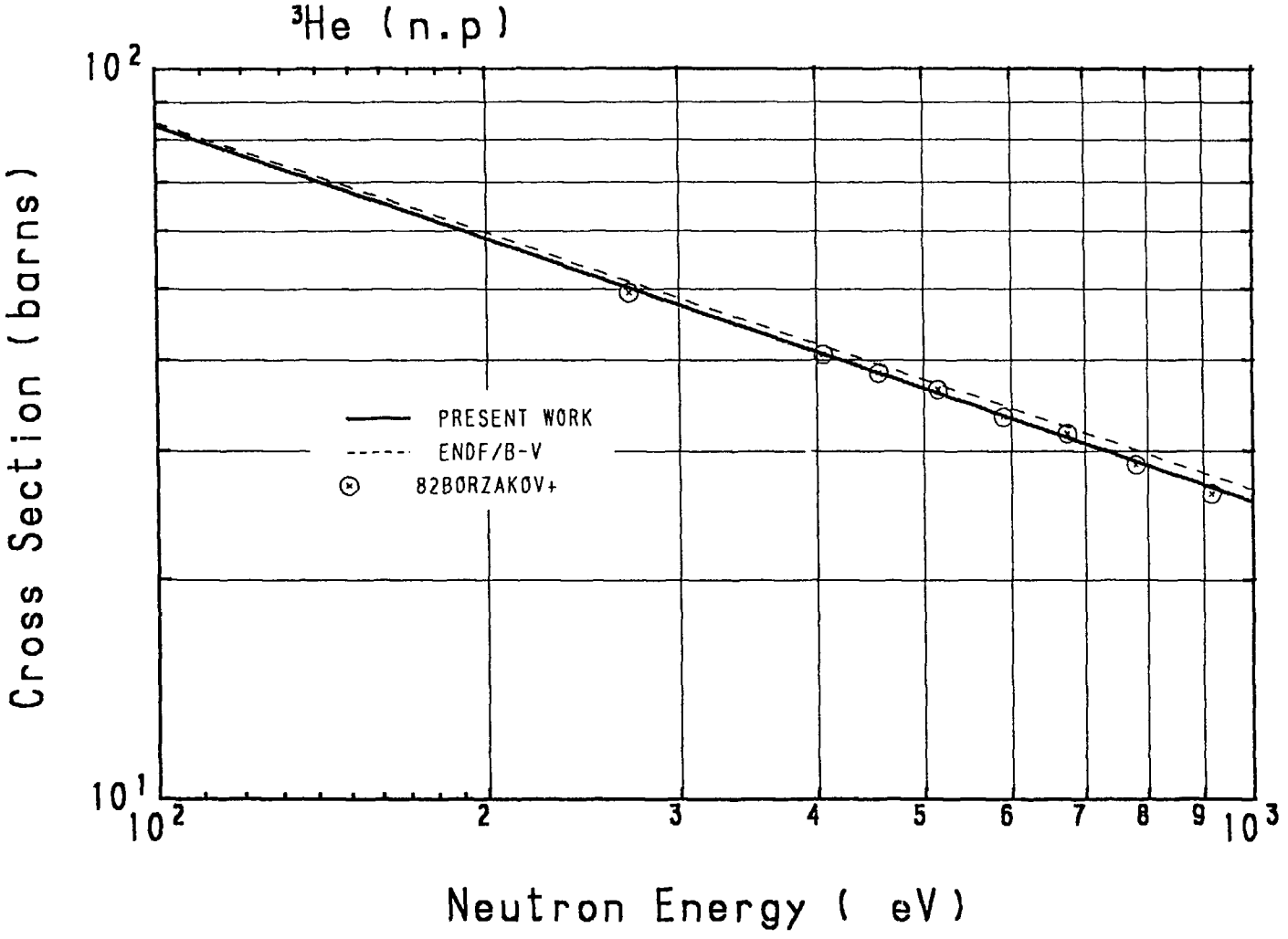

Fig. 10 ^{3}He(n,p) reaction cross section in the energy range from 10^2 eV to 10^3 eV.

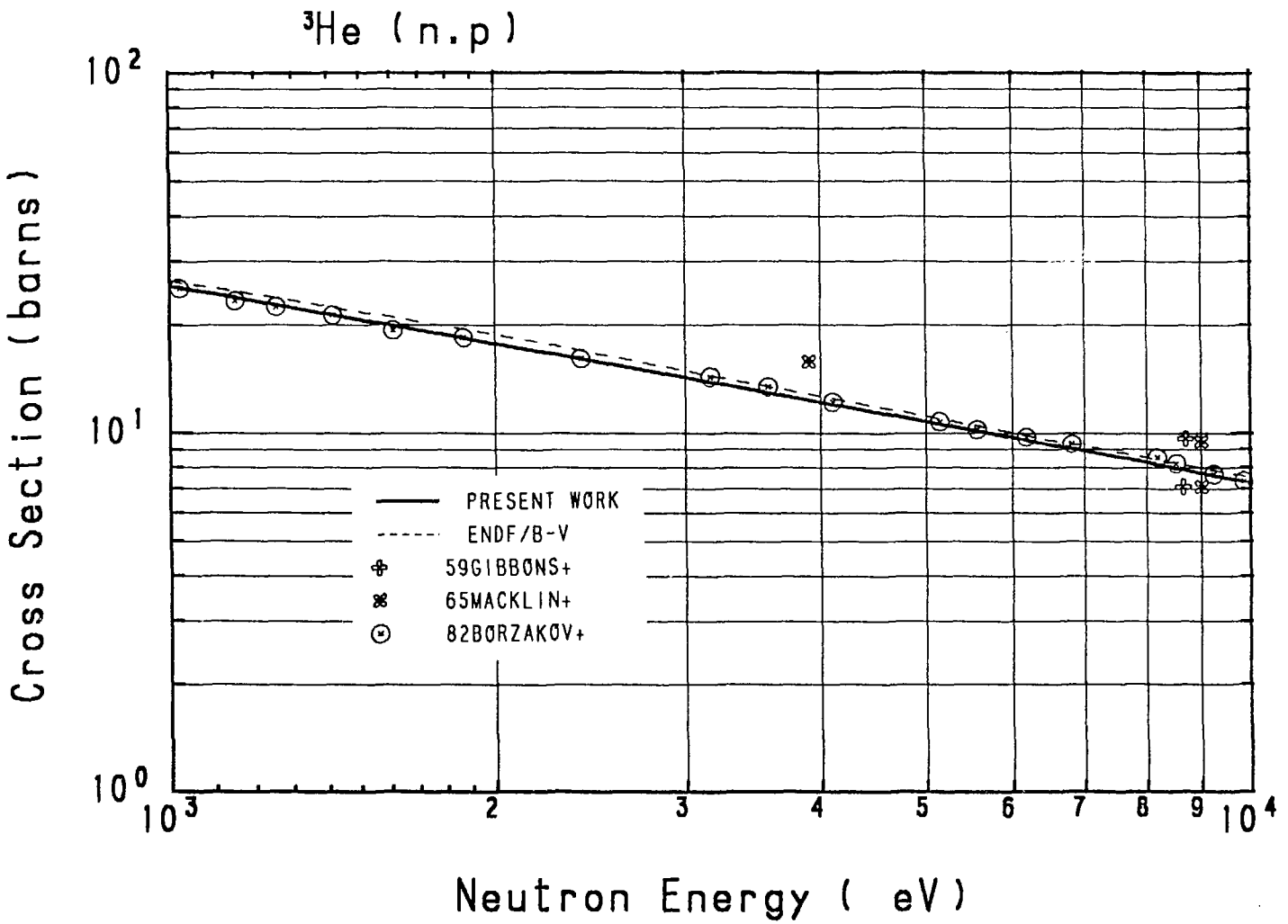

Fig. 11 ^{3}He(n,p) reaction cross section in the energy range from 1 keV to 10 keV.

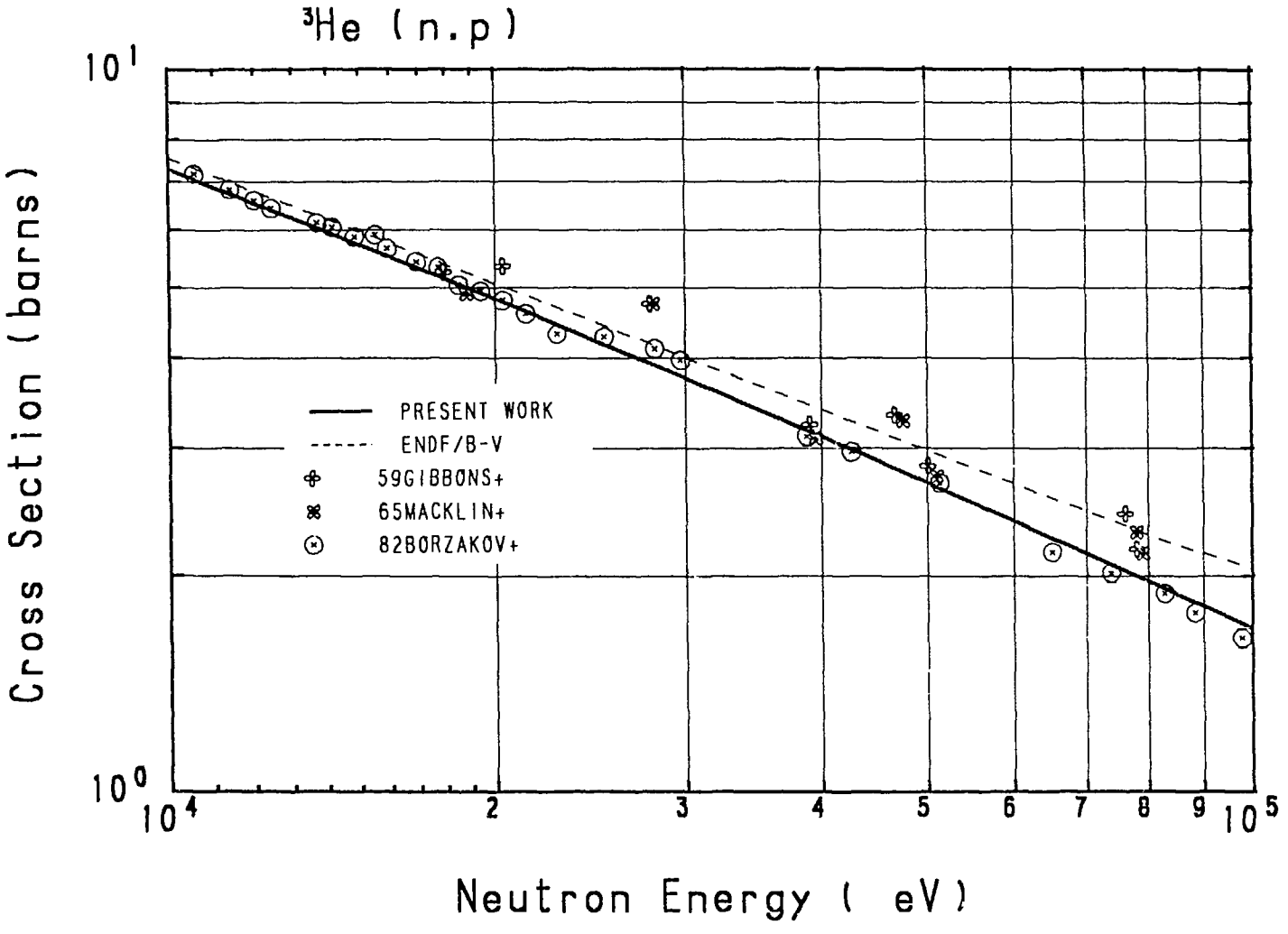

Fig. 12 ^{3}He(n,p) reaction cross section in the energy range from 10 keV to 100 keV.

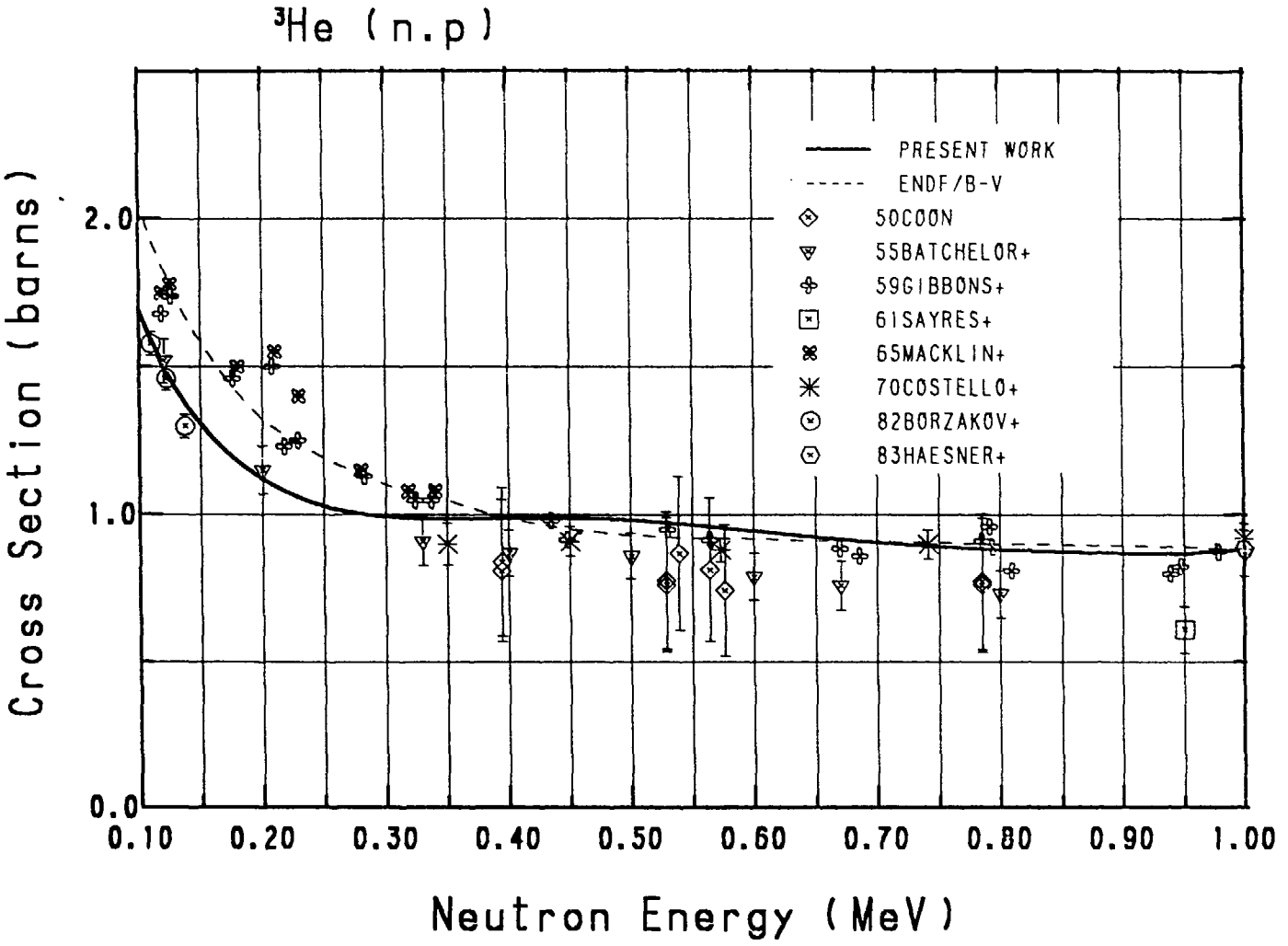

Fig. 13 ^{3}He(n,p) reaction cross section in the energy range from 100 keV to 1 MeV.

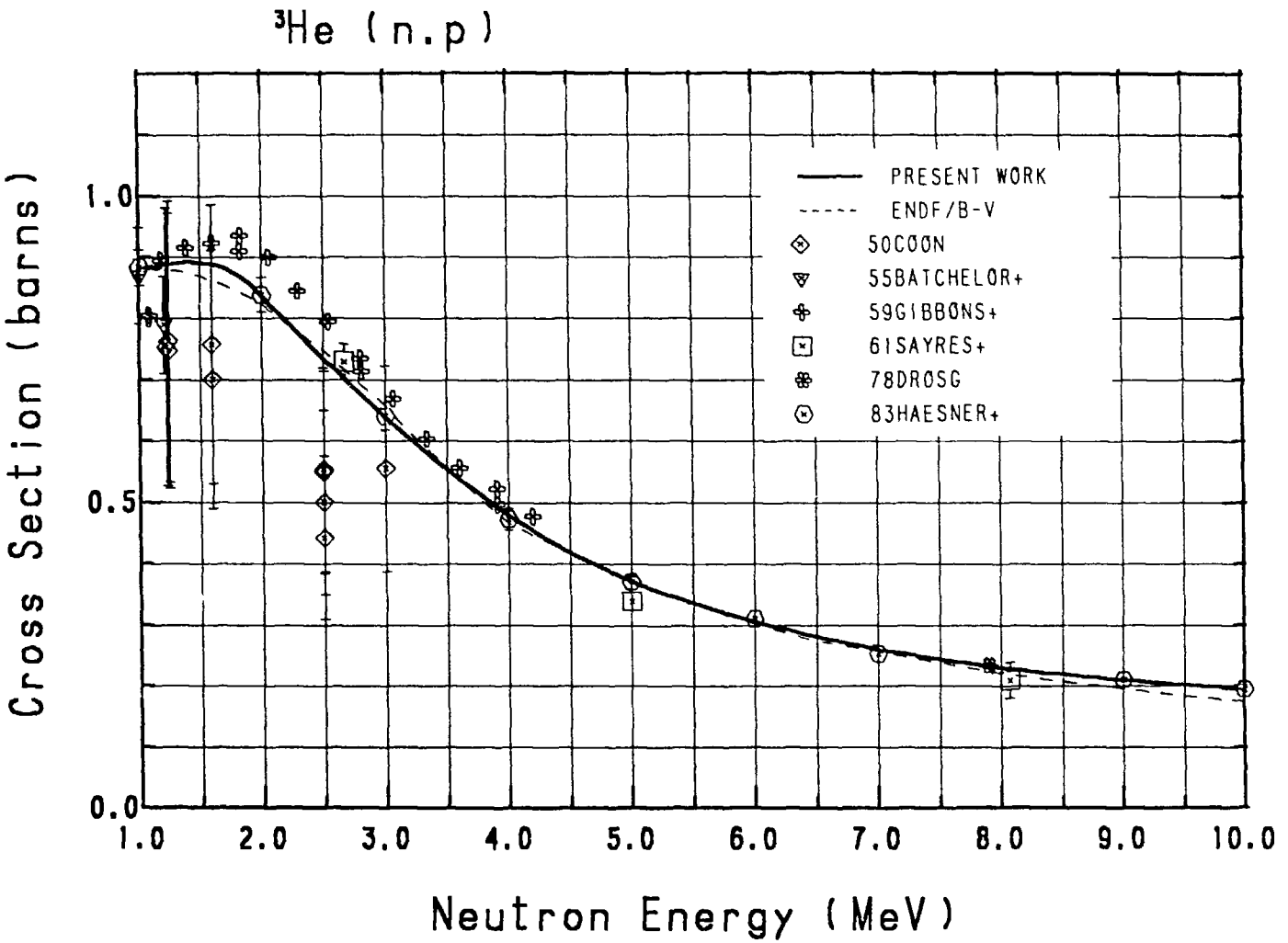

Fig. 14 ^{3}He(n,p) reaction cross section in the energy range from 1 MeV to 10 MeV.

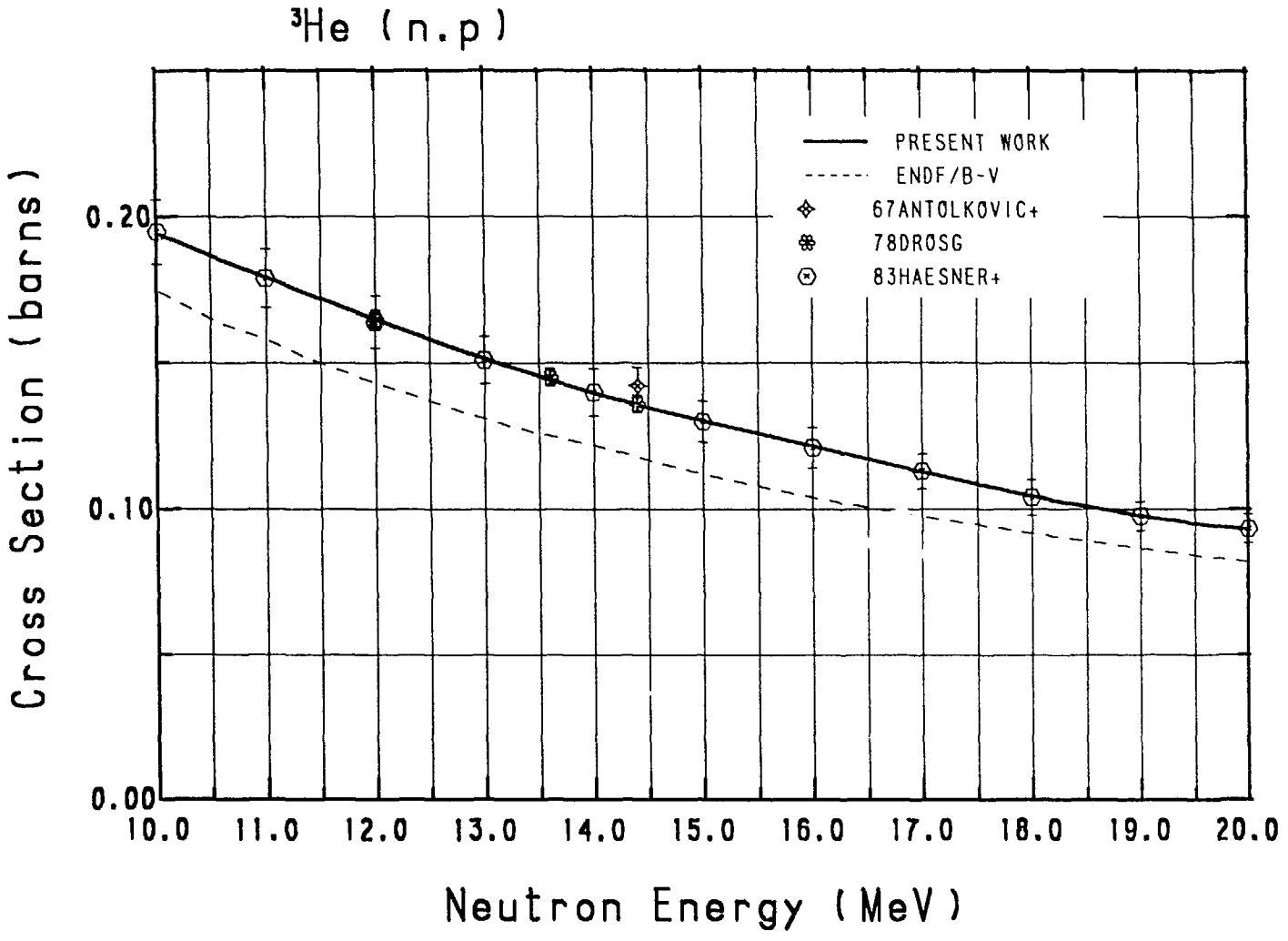

Fig. 15 ^{3}He(n,p) reaction cross section in the energy range from 10 MeV to 20 MeV.

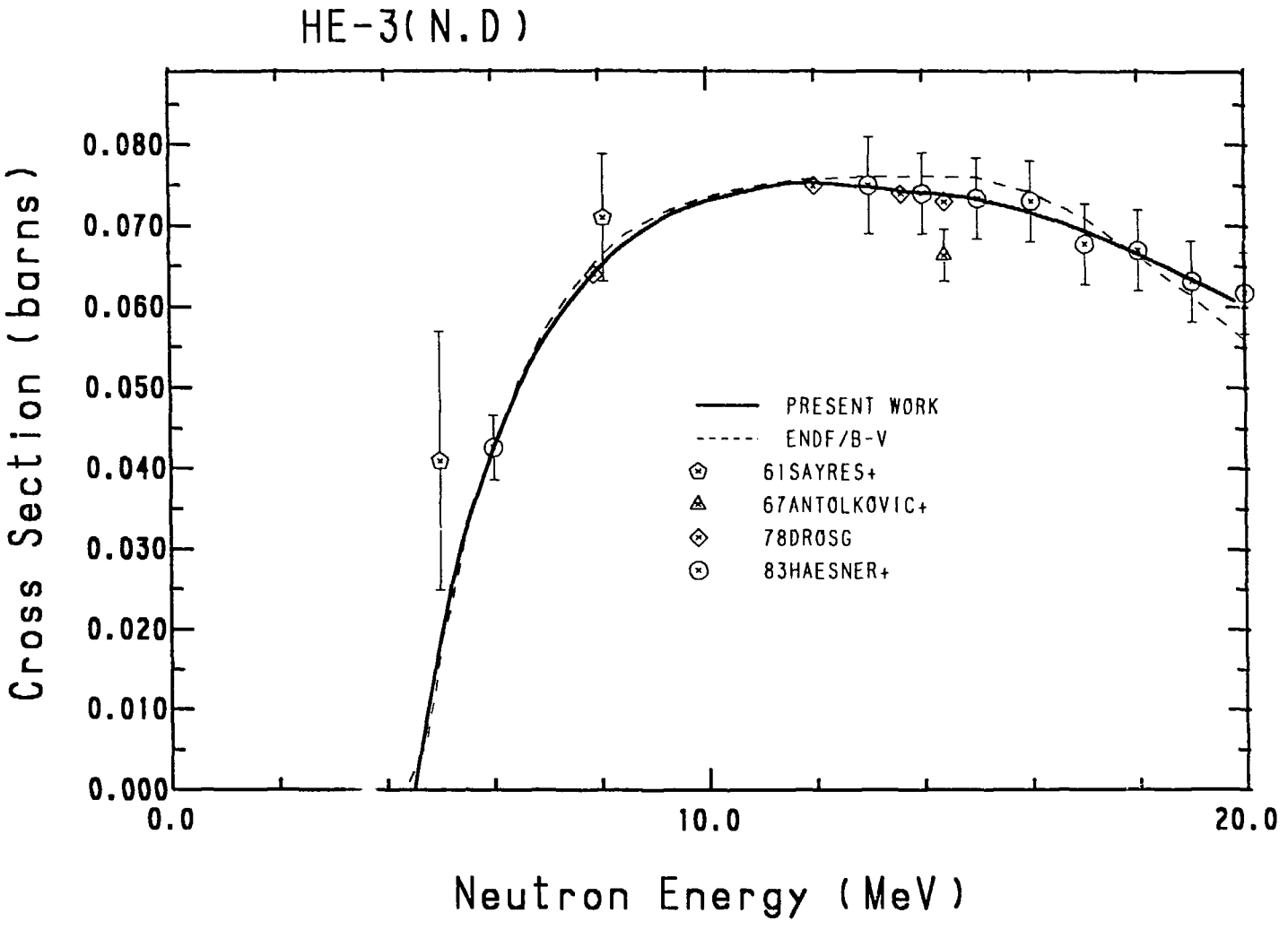

Fig. 16 $^{3}He(n,d)$ reaction cross section.

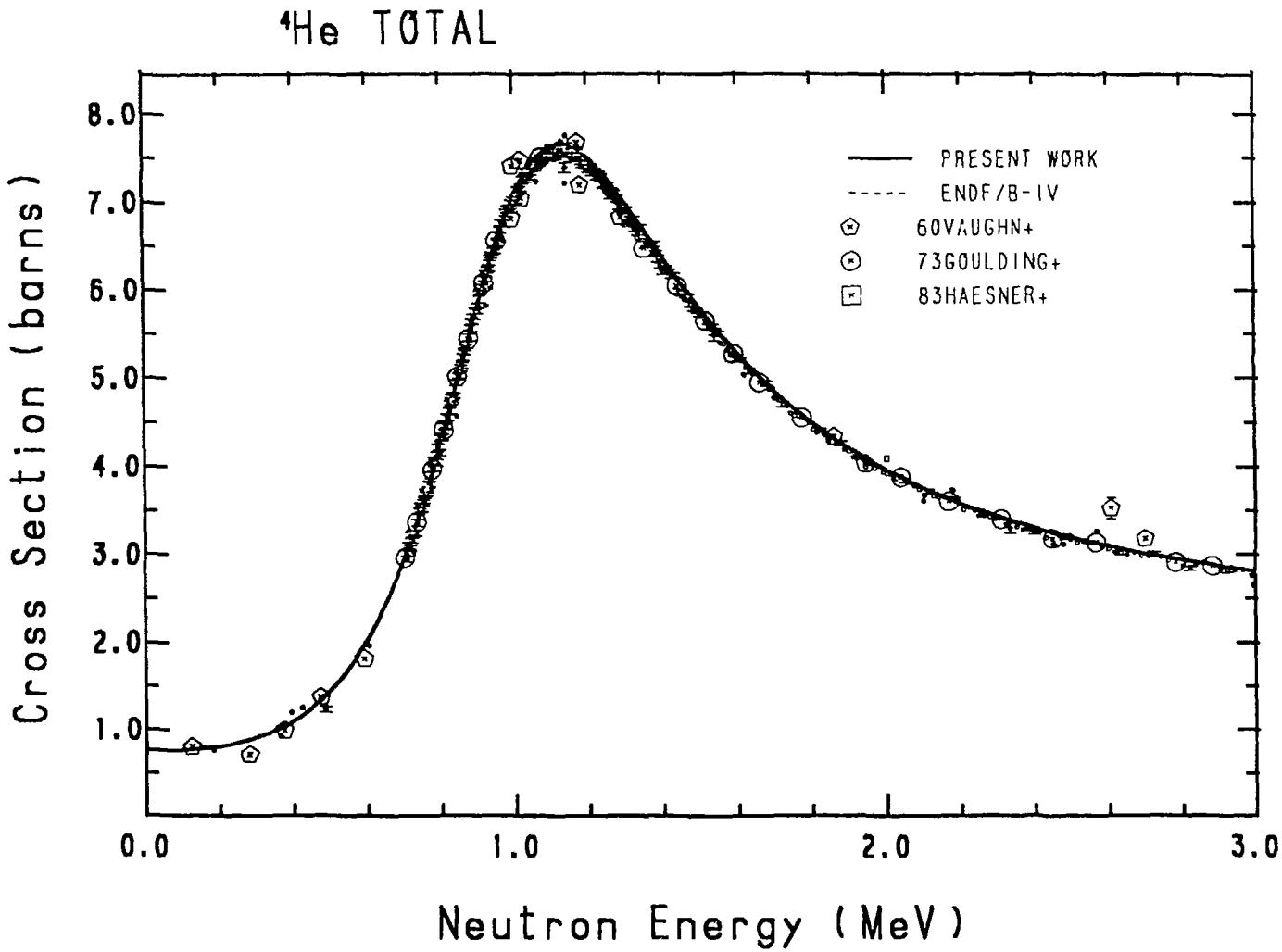

Fig. 17 Total cross section of ^{4}He below 3 MeV.

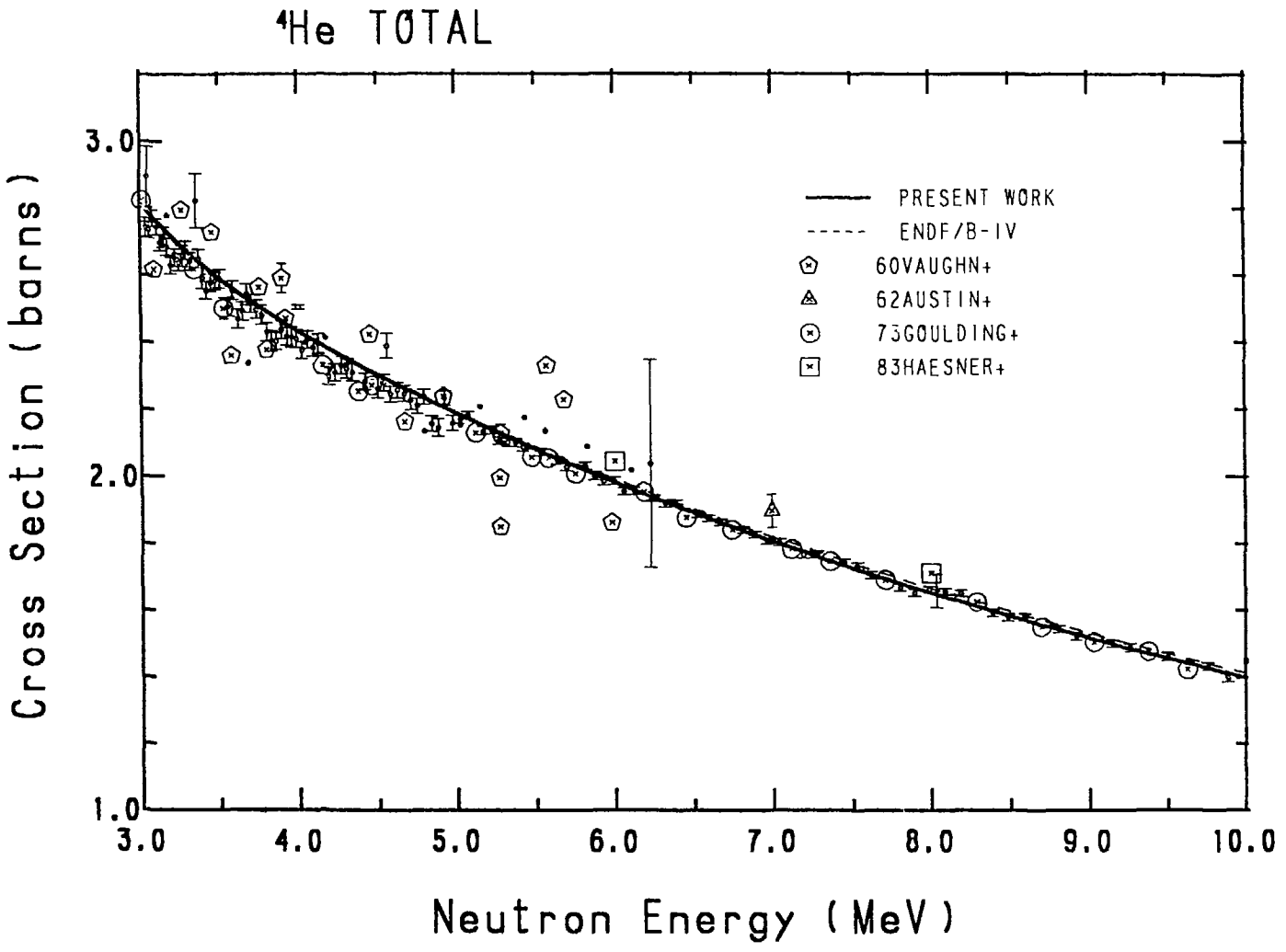

Fig. 18 Total cross section of ^{4}He in the energy range from 3 MeV to 10 MeV.

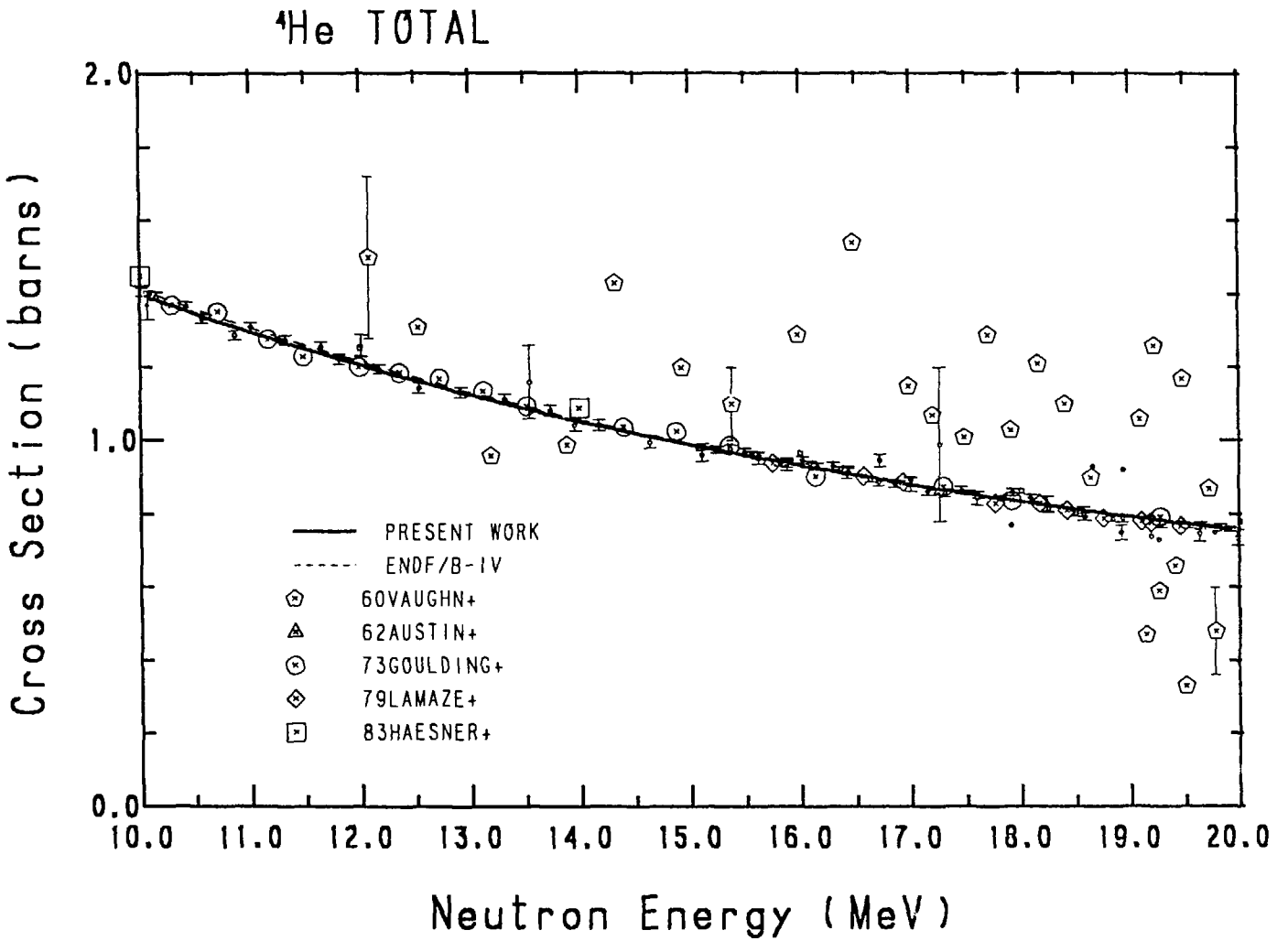

Fig. 19 Total cross section of ^{4}He in the energy range from 10 MeV to 20 MeV.

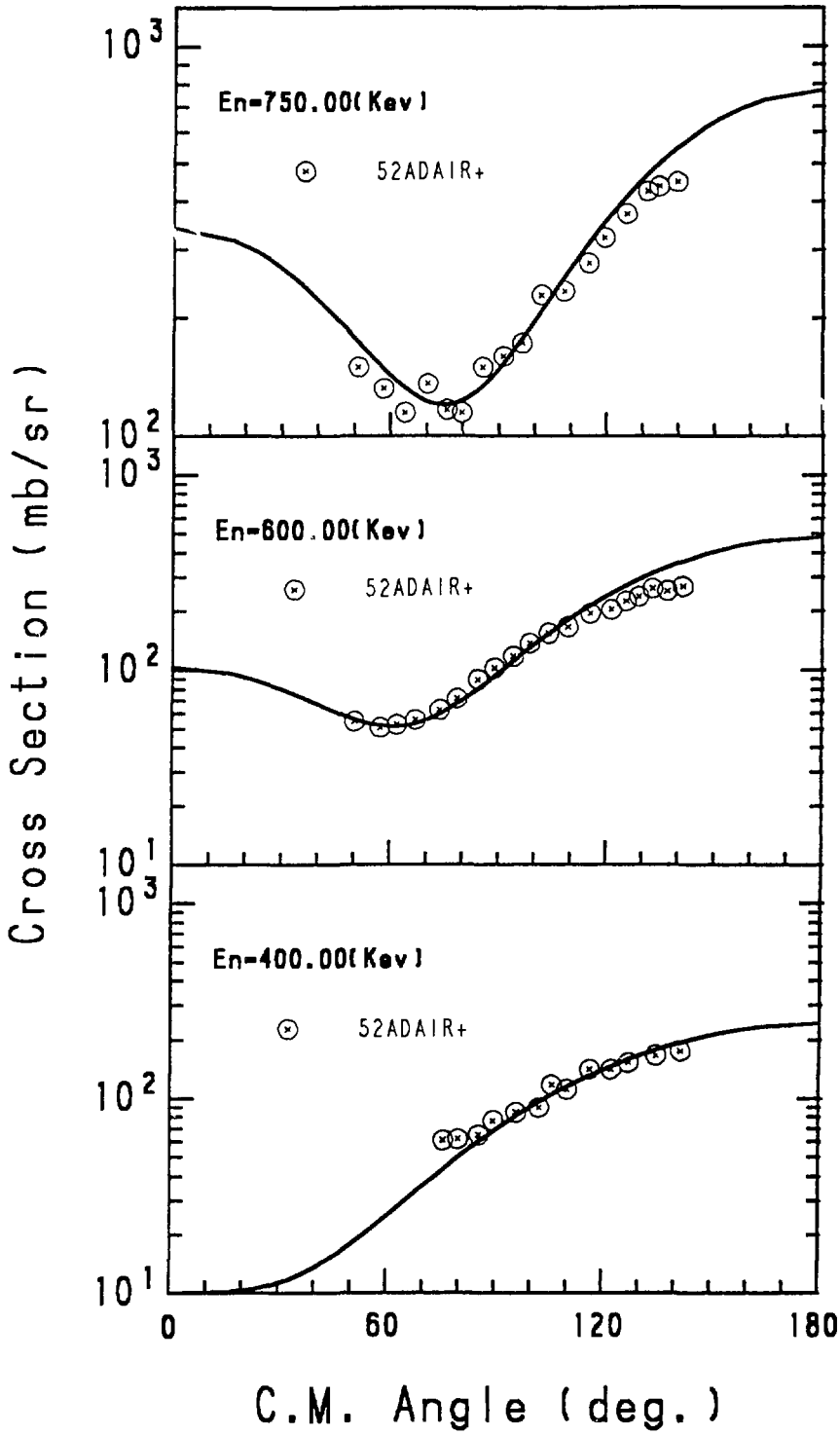

Fig. 20 Angular distributions of neutrons elastically scattered from ^{4}He at 400 ~ 750 keV.

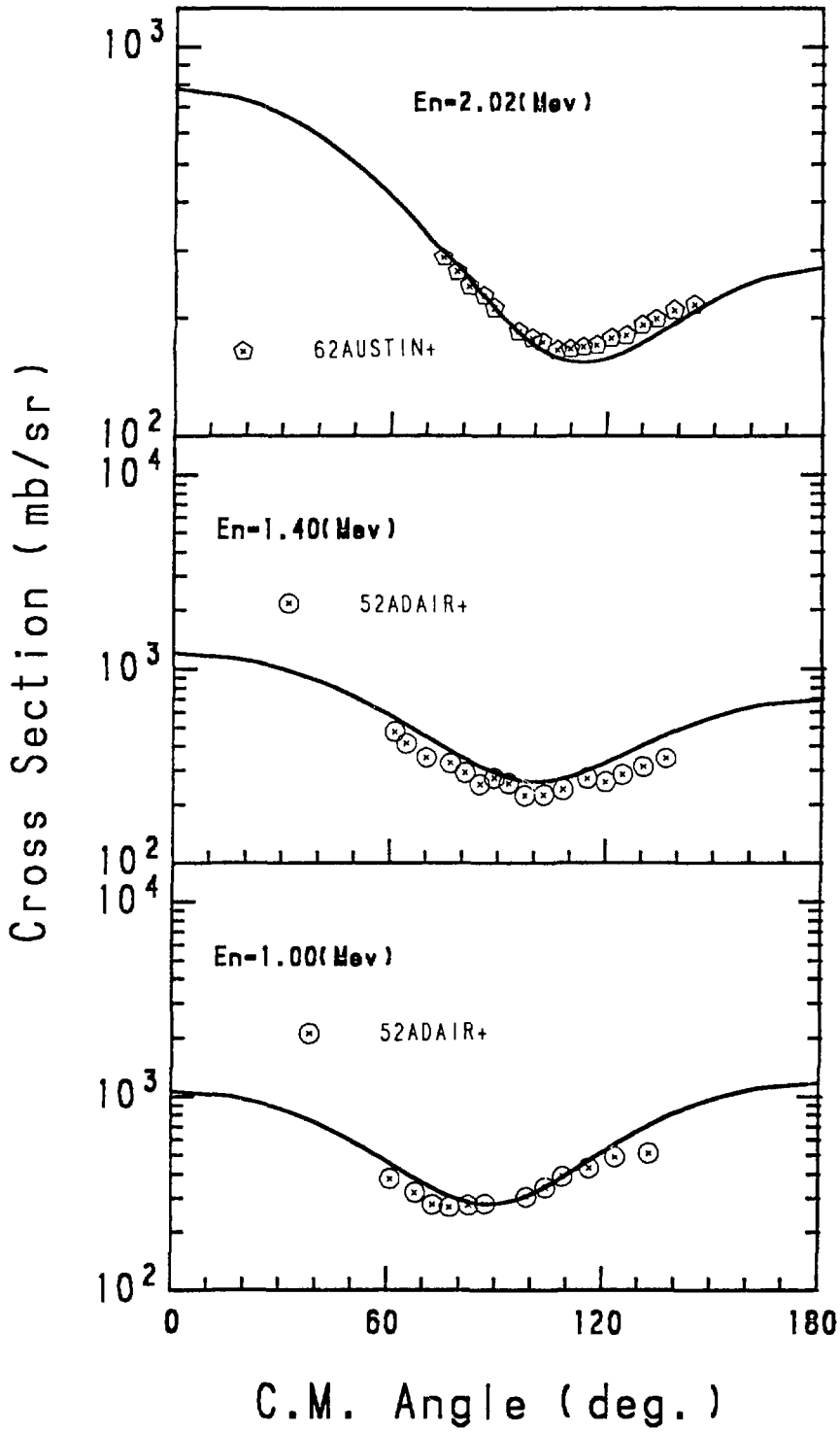

Fig. 21 Angular distributions of neutrons elastically scattered from ^{4}He at 1 ~ 2 MeV.

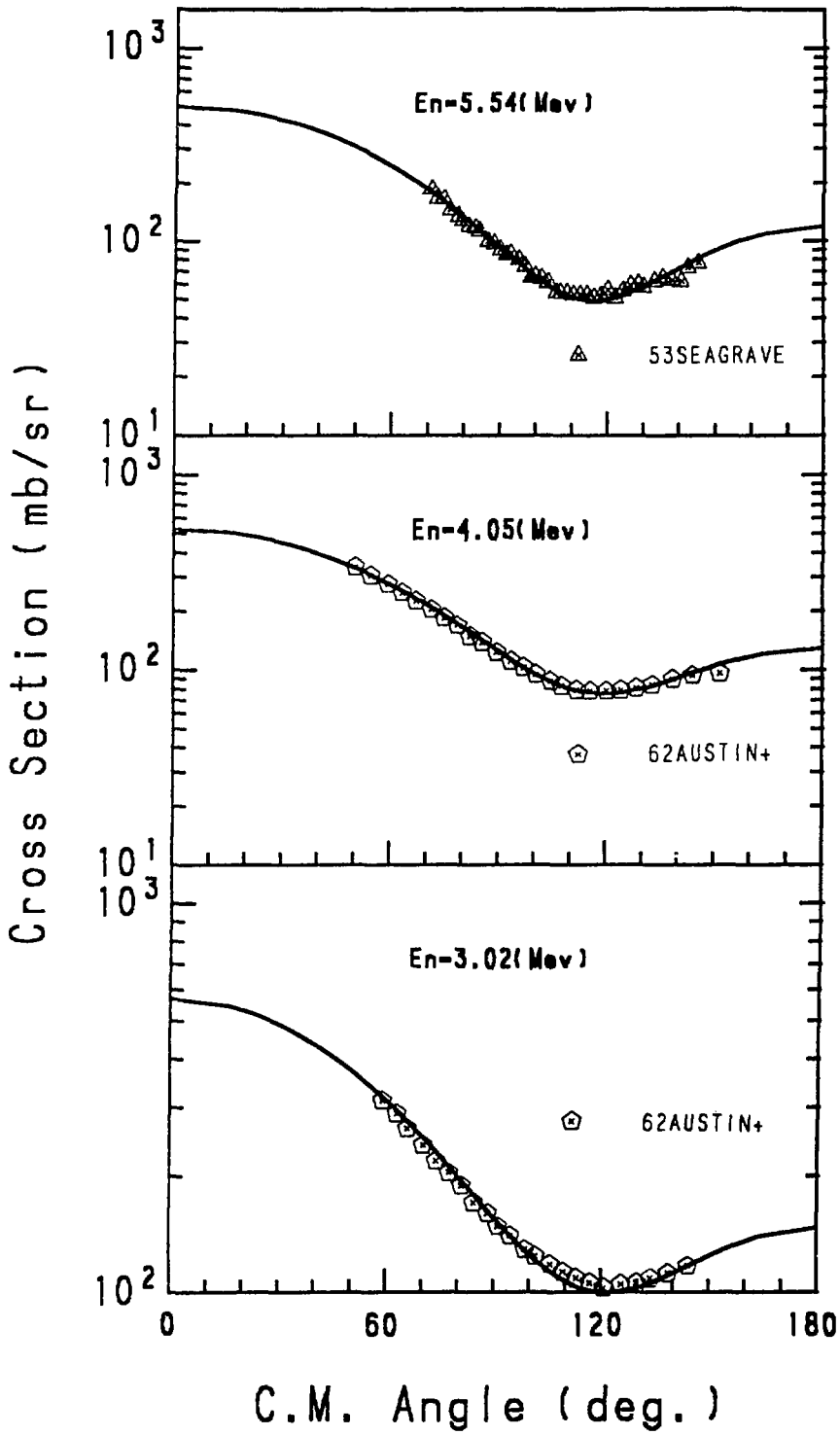

Fig. 22 Angular distributions of neutrons elastically scattered from ^{4}He at 3 ~ 5 MeV.

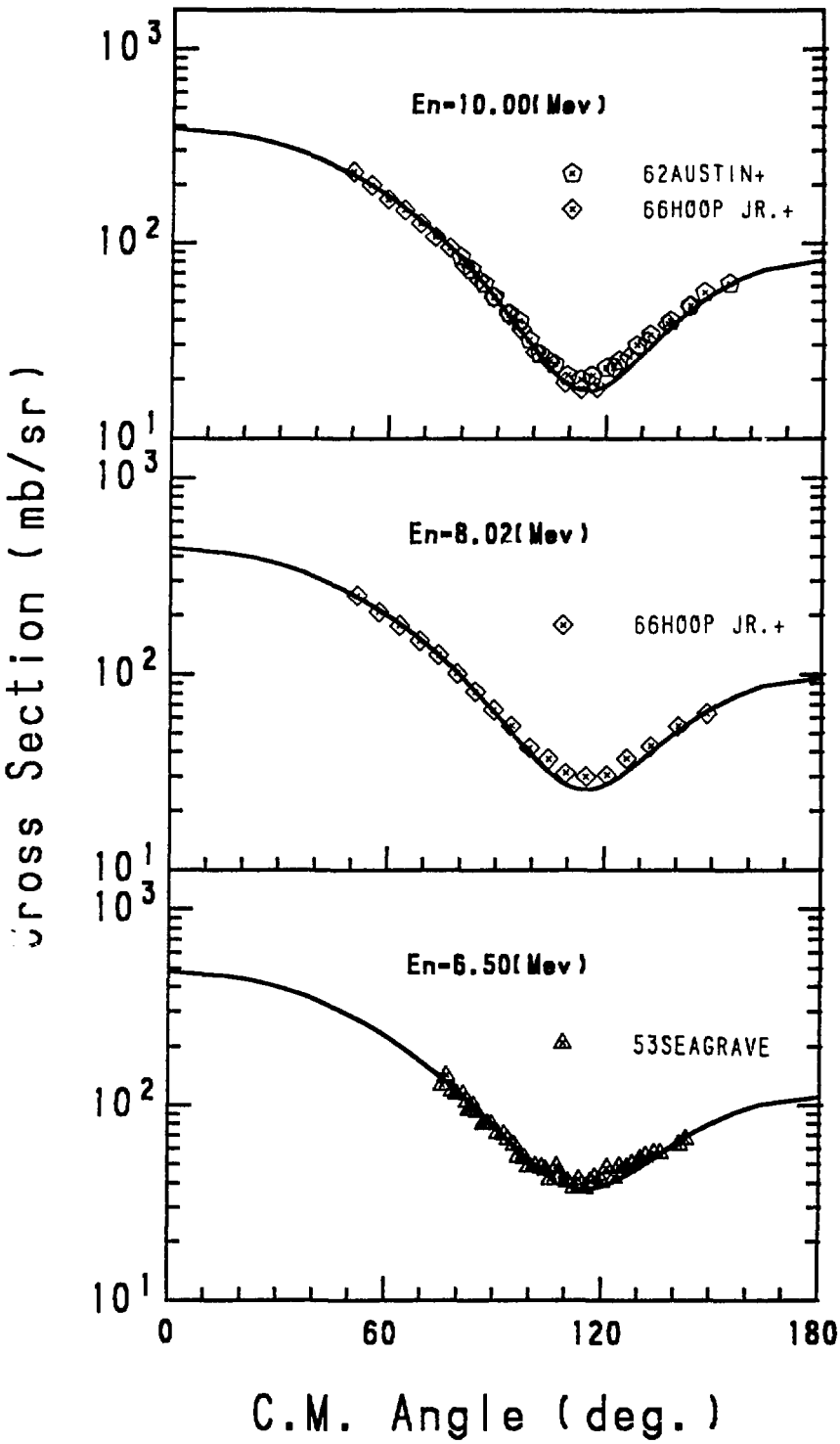

Fig. 23 Angular distributions of neutrons elastically scattered from ^{4}He at 6 ~ 10 MeV.

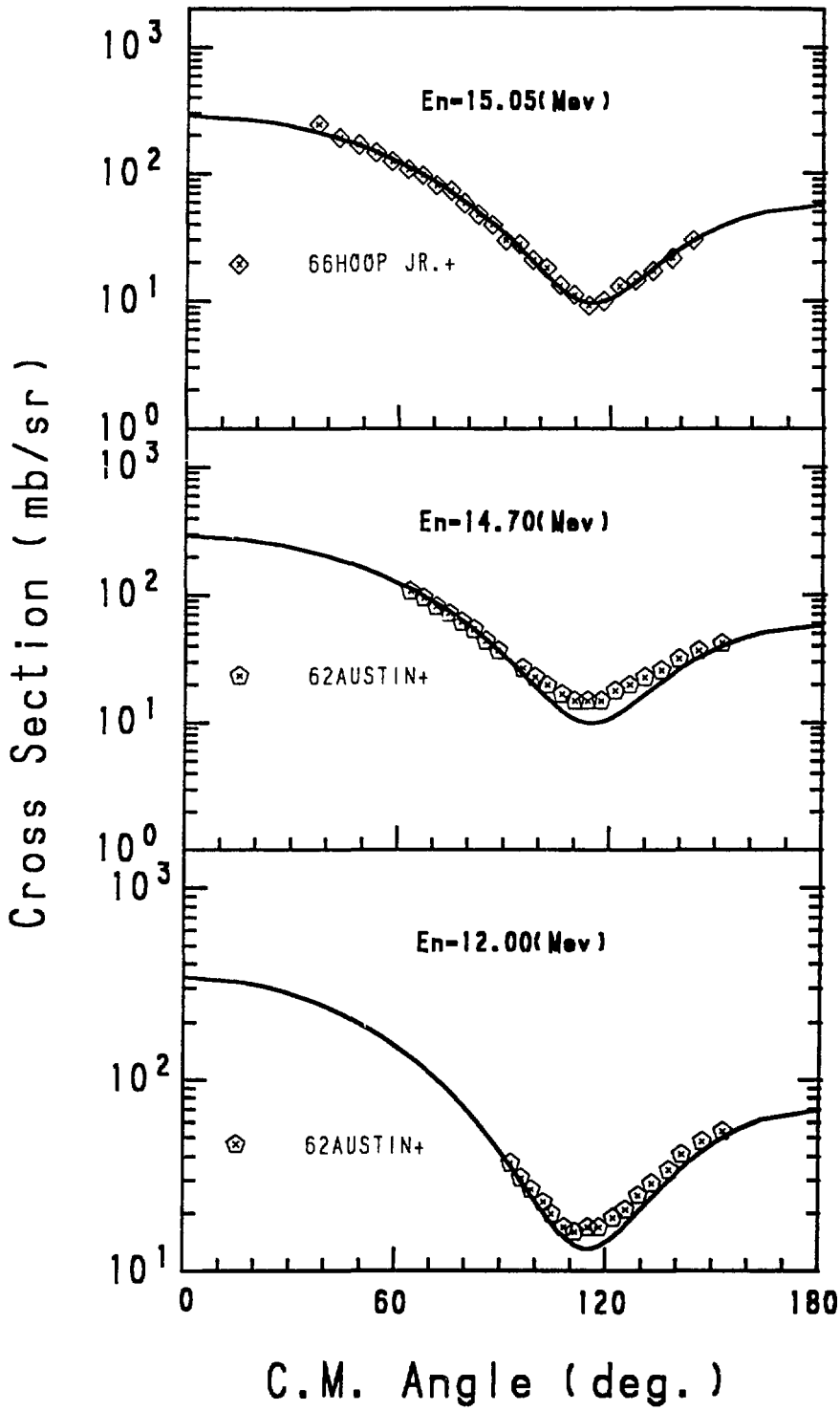

Fig. 24 Angular distributions of neutrons elastically scattered from ^{4}He at 12 ~ 15 MeV.

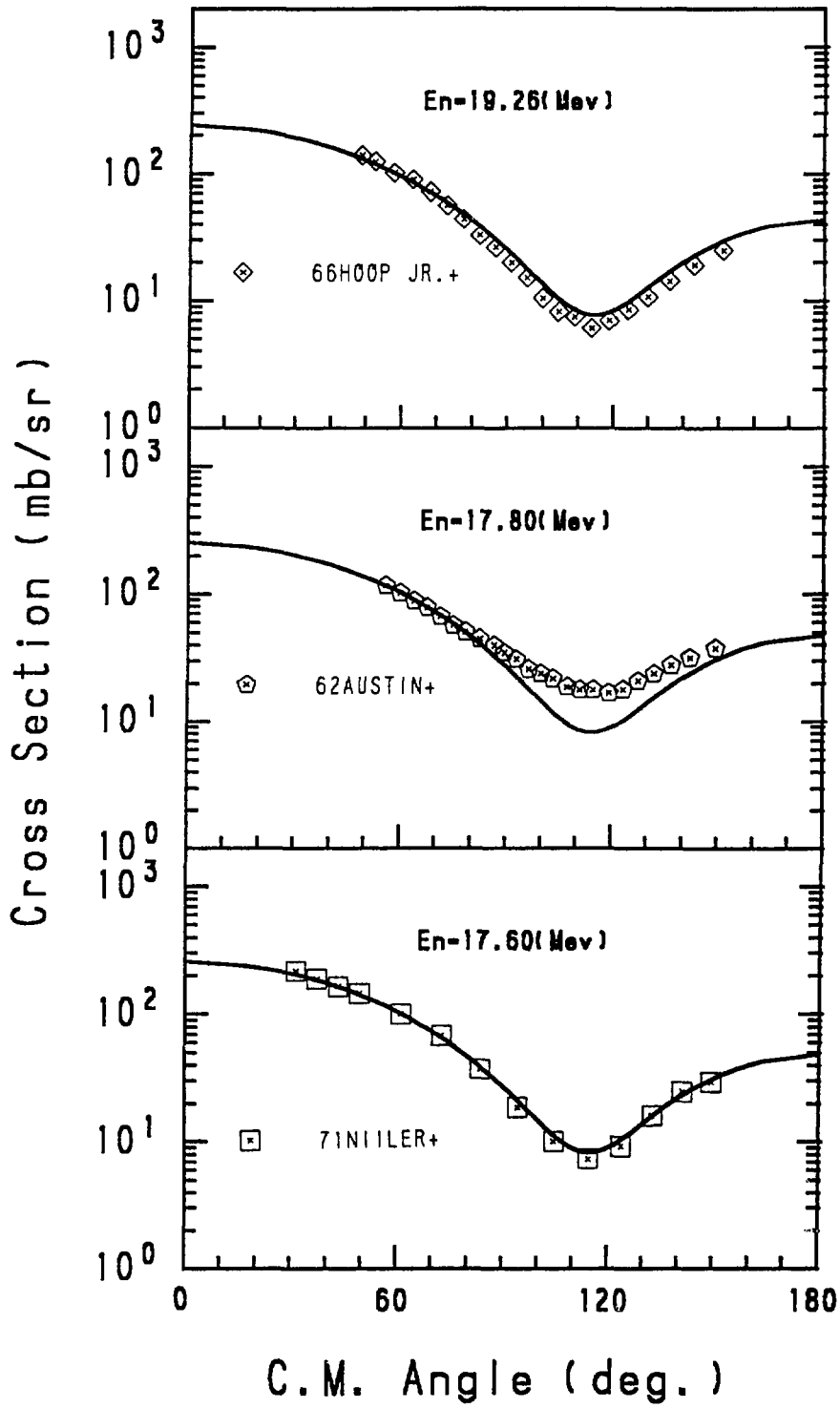

Fig. 25 Angular distributions of neutrons elastically scattered from ^{4}He at 17 ~ 19 MeV.