JAERI-M
89-008

NEANDC(J)-132"U"
INDC(JPN)-119/L

EVALUATION OF NUCLEAR DATA FOR AMERICIUM ISOTOPES

February 1989

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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 Nuclear Data for Americium Isotopes

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(Received January 17, 1989)

The nuclear data of ^{241}Am, ^{242g}Am, ^{242m}Am and ^{243}Am, which are stored in JENDL-2, were compared with recent experimental data. New experimental data of americium isotopes except ^{242g}Am have been reported since the JENDL-2 evaluation was made. The data of these nuclides were reevaluated on the basis of the new experimental data. Mainly revised data are the fission and capture cross sections and resonance parameters. The inelastic scattering cross sections were also re-calculated by adopting new level-scheme data. The data of ^{244g}Am and ^{244m}Am, which were not stored in JENDL-2, were newly evaluated. Only available experimental data for ^{244}Am were thermal cross sections. The shape of the fission cross section was determined to be the same as that of ^{242g}Am, and other data were calculated with CASTHY.

Keywords : Nuclear Data, Americium-241, Americium-242, Americium-243, Americium-244, Evaluation, Cross Section, Resonance Parameters.

This work was performed by Japan Atomic Energy Research Institute under contract with Power Reactor and Nuclear Fuel Development Corporation.

Am核種の核データ評価

日本原子力研究所東海研究所物理部
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（1989年1月17日受理）

JENDL－2に収録されている^{241}Am，^{242g}Am，^{242m}Am，^{243}Amの核データと最近の測定データとの比較を行った。^{242g}Am以外については，JENDL－2以降新たな測定データが報告されていることが分かったので，それらを基にデータの再評価を行った。再評価をした主なデータは，核分裂断面積，中性子捕獲断面積と共鳴パラメータである。さらに，非弾性散乱断面積についても新しい励起レベルのデータを基にした再計算を行った。^{244g}Amおよび^{244m}AmについてはJENDL－2にデータが収録されていないので今回新たにデータ評価を行った。^{244}Amの測定データは熱中性子エネルギーでの核分裂断面積だけなので，^{242g}Amの評価値を基に核分裂断面積の形を決め，他はCASTHYで計算した。

本報告書は，日本原子力研究所が動力炉・核燃料開発事業団の委託により行った研究の成果である。
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1. Introduction

Nowadays many nuclear reactors are in operation, and consequently waste management has become very important. In the nuclear fuel cycle, not only the nuclear data of fuel isotopes but also those of transplutonium isotopes are very important.

Evaluation work of the nuclear data of Am, Cm, Bk, Cf isotopes has been continued in the Nuclear Data Center, JAERI, under contract with Power Reactor and Nuclear Fuel Development Corporation (PNC). By the end of fiscal year 1986, the data of 18 nuclides from ^{241}Am to ^{252}Cf had been evaluated. However, new experimental data have been published for some of those isotopes after our previous evaluation was made, and some discrepancies are found between the experimental data and the evaluated ones. Therefore reevaluation is needed for them.

In the present work, the data of americium isotopes which were the most important among the transplutonium isotopes were investigated. New important experiments have been reported for ^{241}Am, ^{242m}Am and ^{243}Am. The nuclear data of these Am isotopes were reevaluated on the basis of those new experiments. Furthermore, the data of ^{244}Am were newly evaluated.

The review of evaluated data for the nuclides important for fast breeder reactors was also made under the contract with PNC. However, this report describes only the evaluation of nuclear data for americiun isotopes.

In the next section, the evaluation for JENDL-2 is reviewed and new experiments after the JENDL-2 evaluation are shortly described. The present evaluation work will be given in the third section.

2. Present Status of Americium Nuclear Data

The neutron nuclear data for americium isotopes stored in JENDL-2 were evaluated from 1979 to 1982. In this section, outline of JENDL-2 evaluation and new experiments performed after JENDL-2 evaluation are given.

2.1 Americium 241

a. JENDL-2 Evaluation

The data of ^{241}Am were evaluated by Kikuchi[1] in 1982 as follows:

1) Thermal cross sections

The following recommended cross sections by Lynn et al.[2] were adopted and represented with resonance parameters.

Total = 615 ± 20 barns (614.7 barns),

Capture = 600 ± 20 barns (600.4 barns),

Fission = 3.1 ± 0.2 barns (3.02 barns),

Elastic scattering = 11.9 ± 2 barns (11.26 barns).

The values in the parentheses are those calculated from the resonance parameters, and are in good agreement with the recommendation of Lynn et al.

2) Resolved resonance parameters

The parameters measured by Derrien and Lucas[3], by Weston and Todd[4], by Gayther and Thomas[5] and Knitter and Budtz-Jørgensen[6] were taken into consideration. Then those by Derrien and Lucas were adopted to JENDL-2. However the cross sections calculated from their parameters in the thermal energy region were not satisfactory. Therefore, five negative resonances were newly added to improve the thermal cross sections. The upper boundary of the resolved resonance region was determined to be 150 eV. The total spin J of 2.5 which was the same as ground state spin was assumed to the levels whose J was not experimentally determined, and the multilevel Breit-Wigner formula was adopted. Therefore, to treat properly the resolved resonance parameters of ^{241}Am, special processing codes such as RESENDD[7] have to be used.

3) Unresolved resonance parameters

The unresolved resonance parameters were determined with ASREP[8] in the energy range from 150 eV to 30 keV to reproduce well the fission and capture cross sections evaluated as is described below.

4) Cross sections above resonance region

The data for JENDL-1 were evaluated on the basis of the data by Seeger et al.[9], Bowman et al.[10] and Shpak et al.[11] After then, new data were published by Gayther and Thomas,[5] Cance et al.[12], Kupriyanov et al.[13], Knitter and Budtz-Jørgensen,[6] Wisshak and Käppeler,[14] Behrens and Browne,[15] and Hage et al.[16] The fission cross section for JENDL-2 was determined on the basis of the data by Knitter and Budtz-Jørgensen below 10 keV, those of Wisshak and Käppeler from 10 to 300 keV and those of Behrens and Browne above 300 keV.

Phillips and Howe[17] measured the ^{241}Am total cross section. The spherical optical potential parameters given in Table 1 were determined to reproduce their data. The total cross section calculated from this set of parameters was adopted to JENDL-2.

The capture cross section measured by Gayther and Thomas[5] was taken in the energy range below 350 keV, and the values above 350 keV were calculated with CASTHY[19].

The cross sections of (n,2n), (n,3n) and (n,4n) reactions were calculated with the evaporation model. The inelastic scattering cross sections were obtained from calculation with CASTHY by adopting discrete level information from the Table of Isotopes (7th ed.)[20].

b. Experimental data

The major experimental data published after JENDL-2 evaluation are as follows;

1) Dabbs et al.[21]

The fission cross section was measured by using LINAC at ORNL (ORELA), in the very wide energy range from 0.02 eV to 20 MeV. The thermal cross section of 3.06 ± 0.19 barns and the resonance integral of 14.1 ± 0.9 barns were obtained.

2) Vanpraet et al.[22]

The radiative capture cross section was measured with the Geel 150 MeV LINAC (GELINA), in the energy range from 600 eV to 200 keV. Their result is smaller than the data by Gayther and Thomas[5] adopted in JENDL-2 and by Wisshak and Käppeler.[14]

3) Gul et al.[23]

They measured the fission cross section and reported the value of 3.0 ± 0.2 barns at 14.7 MeV.

4) Vorotnikov and Otroshchenko[24]

The ratio of ^{242}Am isomer production cross section by neutron capture to ^{241}Am fission cross section was measured at the energies from 0.2 to 1.3 MeV.

5) Wisshak et al.[25]

They also measured the isomer production by ^{241}Am neutron capture at 14.75 meV and 30 keV. The measured ratios of the ground state production to the total ^{242}Am production are as follows:

R = 0.92 ± 0.06 at 14.75 meV,

R = 0.65 ± 0.05 at 30 keV.

These experimental data are shown in Figs. 1 to 6 comparing with evaluated data. In the resonance region, JENDL-2 is in very good agreement with the experimental data. The total cross section measured by Phillips and Howe is also well reproduced with the JENDL-2 evaluation. However, new evaluation is needed for the fission and capture cross sections because of discrepancies among JENDl-2 and the recent experimental data.

2.2 Americium 242g

At the time of JENDL-2 evaluation,[26] existing experimental data were only the fission cross sections measured by Hanna et al.[27] and Bak et al.[28], and the capture cross section by Hanna et al.[27] at the thermal neutron energy. Therefore, the evaluation for JENDL-2 was made on the basis of these old experimental data and the data of ^{242m}Am evaluated for JENDL-2.

Since the JENDL-2 evaluation was made, no experimental data have been reported.

2.3 Americium 242m

a. JENDL-2 Evaluation

The data stored in JENDL-2 were evaluated by Nakagawa and Igarasi[26] in 1979.

1) Thermal cross sections

An average thermal fission cross section of experimental data published by 1978 was 6740 ± 400 barns. In JENDL-2, the cross sections in this energy region were represented with the resolved resonance parameters which gave the following thermal cross sections;

Total = 7969 barns,
Capture = 1342 barns,
Fission = 6620 barns,
Elastic Scattering = 6.7 barns.

2) Resonance parameters

The resonance parameters of 6 levels obtained by Bowman et al.[29] up to the 3.25 eV level were adopted. The upper boundary of the resolved resonance region was set at 3.5 eV. No unresolved resonance parameters were given.

3) Cross sections above resonance region

Above 3.5 eV, experimental data for the fission cross section were available. The following experimental data were taken into account for the JENDL-2 evaluation.

3.5 eV - 20 eV	Bowman et al.[29]
20 eV - 1.5 keV	Seeger et al.[9]
1.5 keV - 100 keV	Seeger et al., Bowman et al.
above 100 keV	Browne et al.[30]

In the energy region above 1.5 keV, a semi-empirical formula was used to reproduce the experimental data.

Other cross sections were calculated with optical, statistical and evaporation models. The optical potential parameters for ^{241}Am were used with slight modification as listed in Table 2. The average radiative capture width of 50 meV and the level spacing of 0.45 eV were assumed for calculation of the capture cross section.

b. Experimental data

Two experiments on the fission cross section have been made in a very wide energy range since the JENDL-2 was released.

1) Dabbs et al.[31)]

They obtained the fission cross section in the energy range from 0.005 eV to 20 MeV by using ORELA. The thermal cross section of 6950 ± 250 barns and the resonance integral of 1800 ± 65 barns were obtained.

2) Browne et al.[32)]

The fission cross section at neutron energies from 0.001 eV to 20 MeV was measured with LINAC at LLNL. Three separate experiments were performed. In the low energy experiment, ratio to the ^{235}U fission cross section was measured below 3 eV, and transformed to the cross section by adopting the ENDF/B-V ^{235}U fission cross section. The thermal fission cross section obtained and the resonance integral calculated from the measured fission cross section were 6328 ± 320 barns and 1553 ± 78 barns, respectively.

In the resonance region, the 48 resonances up to 20 eV were analysed. Average resonance parameters were as follows,

$<\Gamma_f> = 363$ meV,

$<D> = 0.4$ eV,

$So = (1.07 \pm 0.22) \times 10^{-4}$,

$<\Gamma_\gamma> = 50$ meV (assumed value).

In the high energy region, the cross section was also measured relatively to the ^{235}U fission cross section. The final results were given as the weighted averages of their two series of experiments.[30,32)] A separate experiment was also made at 14.1 MeV with monoenergetic neutrons at LLNL Insulated Core Transformer (ICT) accelarator. The cross section of 2.412 barns was obtained by using the ENDF/B-V ^{235}U fission cross section of 2.074 barns.

Figures 7 to 11 shows the experimental data together with the evaluated ones. It is seen that the fission cross sections measured by Dabbs et al. are systematically larger by about 20 % than those by

Browne et al. Relatively large discrepancies are found among evaluated capture cross sections.

It seems that reevaluation is needed on the basis of these recent experiments. In particular, the resolved resonance parameters in JENDL-2 should be updated by those of Browne et al. and unresolved resonance parameters are needed up to several 10 keV.

2.4 Americium 243

a. JENDL-2 evaluation

Evaluation was made by Kikuchi[1].

1) Thermal cross sections

The recommended cross sections in BNL 325 (3rd)[33] were adopted, then resolved resonance parameters were improved to reproduce well the thermal cross sections. The cross sections calculated from the resonance parameters are as follows,

Total = 86.2 barns (85 ± 4 barns),

capture = 78.5 barns (79.3 ± 2.0 barns),

fission = 0.225 barns (0.228 barns),

where the values in parentheses are the recommended cross sections in BNL 325 (3rd).

2) Resolved resonance parameters

Evaluation by Igarasi and Nakagawa[34] which was based on the experiment of Simpson et al.[35] was adopted after slight modifications which were a change of an average fission width to 0.12 meV and improvement of neutron widths of the negative resonances to reproduce well the thermal cross sections as mentioned above. The upper boundary of the resolved resonance region is 215 eV.

3) Unresolved resonance region

The unresolved resonance parameters were given in the energy region from 215 eV to 30 keV. S- and p-wave strength functions were calculated with the optical model and other parameters were obtained from the resolved resonance parameters.

4) Cross sections above resonance region

The fission cross section measured by Behrens and Browne[15] was adopted above 200 keV. In the energy range below 200 keV, the experimental data by Seeger[36] were abandoned because they seemed to be less reliable, and the smooth curve connecting the cross sections at 30 and 200 keV was given by eye-guiding.

Since no experimental data had been measured for the other cross sections, the calculations with optical and statistical models were adopted to JENDL-2.

b. Experimental data

1) Wisshak and Käppeler[37]

They obtained the capture and fission cross sections with the 3 MV Van de Graaff at Karshule in the energy range from 5 to 250 keV. The $^{6}Li(p,n)$ and T(p,n) reactions were utilized as neutron sources, and the ^{197}Au capture and ^{235}U fission cross sections as standard cross sections.

Their capture cross section is in good agreement with KEDAK-4. On the other hand, JENDL-2 is somewhat larger and ENDF/B-V is much lower than their data. The fission cross section is also in good agreement with KEDAK-4, but on the contrary to the capture cross section, JENDL-2 is lower, and ENDF/B-V is higher.

2) Weston and Todd[38]

The capture cross section was measured with ORELA in the energy region from 258 eV to 92 keV, and normalized to the ENDF/B-V evaluation of 74.8 barns at 0.0253 eV. The experiment was carried out down to the thermal region. However the results in a lower energy range than 258 eV were not published because of some problems on treatment of self shielding effects.

The p-wave strength function of $(2.6 \pm 0.3) \times 10^{-4}$ was obtained by fitting to the measured data on the assumption that $S_0 = 0.98 \times 10^{-4}$, $\Gamma_\gamma = 39$ meV and D = 0.75 eV below 100 keV.

3) Fursov et al.[39]

They measured the ratio of the fission cross section to that of ^{239}Pu from 0.135 to 7.4 MeV, and obtained the cross section by adopting the ^{239}Pu fission cross section of ENDF/B-V.

4) Goverdovsky et al.[40]

They also measured the fission cross section at neutron energies from 4 to 11 MeV by using EGP-10 tandem accelerator at FEI.

5) Knitter and Budtz-Jørgensen[41]

The Van de Graaff and LINAC (GELINA) at Geel were used to measure the fission cross section. GELINA was used in a lower energy region from 1 eV to 1.4 MeV and Van de Graaff in a higher energy range from 0.35 to 4 MeV.

Fission areas of 31 resonances from 1.358 eV to 55.65 eV were determined from the low energy experiment. As a result, it was pointed out that the peak cross section of the first resonance at 1.358 eV was 1/5 of the JENDL-2 evaluation. Their result is in good agreement with Wisshak and Käppeler[37] in the energy range from 10 to 250 keV, and Seeger[36] above 1 MeV.

6) Kanda et al.[42]

They measured the fission cross section at energies from 1.1 to 6.8 MeV by using the 4.5 MV Dynamitron at the Tohoku University. Their result is smaller than the JENDL-2 evaluation.

These experimental data are compared with evaluated ones in Figs. 12 to 15. The total cross section of JENDL-2 reproduces well the experimental data in the resonance region. The fission cross section is larger than the experiments in the MeV region. The capture cross section is in very good agreement with Weston and Todd.

2.5 Americium 244

No evaluated data are available. Vandenbosch et al.[43] reported the fission cross section at the thermal energy. The following fission cross sections were recommended by Mughabghab.[44)]

2300 ± 300 barns for ^{244g}Am,

1600 ± 300 barns for ^{244m}Am,

3. Evaluation of Americium Nuclear Data

Since some discrepancies were found between the recent experimental data and the evaluated data in JENDL-2, reevaluation was made mainly for fission and capture cross sections and resonance parameters. In addition, the data of ^{244}Am and ^{244m}Am were newly evaluated.

3.1 Americium 241

1) Resolved resonance parameters

No new analysis has not been made since JENDL-2 evaluation. The experimental data by Dabbs et al.[21)] cover the wide range from thermal to fast neutron energies, and their thermal fission cross section of 3.06 ± 0.19 barns is in agreement with JENDL-2 within the experimental error. The measured resonance integral of the fission cross section of 14.1 ± 0.9 barns above 0.55 eV is also almost the same as JENDL-2 of 14.7 barns. Therefore, reevaluation of the resolved resonance parameters is not needed.

The parameters of the JENDL-2 evaluation were adopted in the present work after modification of total spin values with a computer program JCONV[45)].

2) Unresolved resonance parameters

The capture cross section of JENDL-2 is smaller than the experimental data of Vanpraet et al.[22)] at lower energies than 3 keV, and larger at higher energies. The shape of the fission cross section measured by Dabbs et al.[21)] does not have such structure as JENDL-2 shown in Fig. 5.

In the present evaluation, considering these facts, the unresolved resonance parameters were determined in the energy range from 150 eV to 30 keV to reproduce the capture cross section of Vanparet et al. and the fission cross section of Dabbs et al. by using ASREP.[8)]

3) Cross sections above resonance region

Fission cross section

The measured values of Dabbs et al.[21] are systematically lower by about 10 % than those of Behrens and Browne[15] which were adopted in JENDL-2 in the energy region above 1 MeV. The data of Dabbs et al. are in good agreement with other experimental data as shown in Fig. 5. At 14.7 MeV, there is a large discrepancy between the data of 2.62 ± 0.14 barns measured by Dabbs et al. and that of 3.0 ± 0.2 barns measured by Gul et al. It seems that the value of Gul et al. might be too large in comparison with others.

In the present work, the data by Dabbs et al. were adopted in the whole energy range. Below 1 MeV, their experimental data were smoothed with spline-fitting to obtain a cross-section curve. The result of present evaluation is shown in Figs. 16 and 17 together with the experimental data and other evaluated ones.

Capture cross section

JENDL-2 is about 10 - 20 % larger than the recent experiment by Vanpraet et al.[22] in the keV region. In the JENDL-2 evaluation, the capture cross section was normalized to 0.83 barns at 350 keV. In the present work, the capture cross section was calculated with the optical- and statistical-model code CASTHY so that the cross section at 60 keV might be 1.7 barns, and the result was adopted above 30 keV. The obtained gamma-ray strength function (Γ_γ/D) is 0.055.

The present result is compared with experimental data and other evaluated data in Fig. 18. In the whole energy region including the unresolved resonance region, the present result is in good agreement with the experimental data.

Other cross sections

The same values as JENDL-2 were adopted for the (n,2n) and (n,3n) reaction cross sections. The (n,4n) reaction was not considered because of a high threshold energy of 19.78 MeV.

The total, elastic and inelastic scattering cross sections were calculated with CASTHY. Optical model parameters are listed in Table 1, which are the same as those used in JENDL-2 evaluation because the total cross section has not been measured after the previous evaluation. Level density parameters were determined by means of LEVDENS,[46] by taking account of level spacings recommended by Mughabghab[44] and excited level information in ENSDF.[47] The level density parameters determined for americium isotopes are shown in Table 3. In Figs. 19 to 22, for ^{241}Am, ^{242}Am, ^{243}Am and ^{244}Am, cumulative numbers of excited levels calculated with the constant temparature model are compared with staircase plots of levels which are taken from ENSDF.

For a calculation of the inelastic scattering cross sections, data of excited levels were adopted from the Nuclear Data Sheets.[48] Discrete levels up to 682 keV were taken into consideration and those above 732 keV were assumed to be overlapping. The levels whose spin was unknown or too large were disregarded. The levels considered in the present evaluation are given in Table 4. All cross sections above 1 keV are shown in Fig. 23.

Angular distributions of emitted neutrons

The resuls of calculation with CASTHY were adopted for the angular distributions of elastically and inelastically scattered neutrons. Isotropic distributions in the laboratory system were assumed for the (n,2n), (n,3n) reaction and fission neutrons.

Number of neutrons per fission

The same values as JENDl-2 were adopted:

$$\nu_p = 3.219 \pm 0.15\ E,$$
$$\nu_d = 0.0045 \text{ for } E < 6.2 \text{ MeV},$$
$$= 0.0031 \text{ for } E > 8 \text{ MeV},$$

and ν_d was linearly connected between 6.2 and 8 MeV. The value of ν_p is in very good agreement with the evaluated value of 3.22 ± 0.04 of Holden and Zucker[49].

3.2 Americium 242g

As described in Section 2.2, no new experimental data are available. Therefore, the data in JENDL-2 were adopted without any modification.

3.3 Americium 242m

Resolved resonance parameters

The six resonances were adopted for JENDL-2 on the basis of experimental data by Bowman et al.[29] Resently, Browne et al.[32] measured the fission cross section and deduced the parameters of 48 resonances up to 19.7 eV, which were listed in Table 5.

The fission cross section calculated from the resonance parameters in Table 5 was compared with experimental data. This set of parameters reproduces well the fission cross section measured by Browne et al. as shown in Fig. 24. The data of Browne et al. are about 20% lower than the experimental data by Dabbs et al.[31] Although the reason of this discrepancy was unknown, the resonance parameters obtained by Browne et al. were adopted in the present work.

Unresolved resonance parameters

Unresolved resonance parameters were given in the energy region from 20 eV to 30 keV. The parameters were determined to reproduce the smoothed fission cross sections of Browne et al. by means of ASREP. At the low energies, since the number of resonances is not so large, large resonance structure is still observed in the average cross section. Such structure was taken into consideration by giving background cross sections. Figure 25 shows the comparison between the fission cross section calculated from the unresolved resonance parameters and the averaged cross sections of Browne et al. The differences between them were compensated with the background cross section. The present evaluation is compared with the experimental data and the other evaluated data in Fig. 26.

Cross sections above resonance region

The fission cross section was determined by spline fitting to the experimental data by Browne et al. The (n,2n) and (n,3n) reaction cross sections were taken from JENDL-2. The total, capture, elastic and inelastic scattering cross sections were calculated with CASTHY by using the optical potential parameters in Table 2, the level density parameters in Table 3 and the level scheme[50] in Table 6. Gamma-ray strength function was calculated by assuming $<\Gamma_\gamma>$ = 50 meV and Dobs = 0.4 eV which were obtained from the resolved resonance parameters.

In Figs. 27 and 28, the fission and capture cross sections are shown together with the experimental data and other evaluated ones.

Other data

The angular distributions of elastically and inelastically scattered neutrons were calculated with CASTHY. The isotropic distributions in the laboratorv system were assumed for the neutrons due to the fission, (n,2n) and (n,3n) reactions. The energy distributions of the emitted neutrons, and ν_p and ν_d were taken from JENDL-2.

3.4 Americium 243

1) Resolved resonance parameters

After the JENDL-2 evaluation which was based on the experiment by Simpson et al.[35], Knitter and Budtz-Jørgensen[41] measured fission area of 31 resonances from 1.358 to 55.65 eV. In the present evaluation, the fission widths of the 31 resonances were modified on the basis of the results of Knitter and Budtz-Jørgensen. The average value of the fission widths is 0.19 meV which is larger than that of 0.12 meV adopted in JENDL-2. However, the mean value of 0.12 meV was adopted for the other resonances above 56 eV.

The thermal fission cross section calculated from the resonance parameters is 0.116 barn which is much smaller than the recommended value of 0.1983 ± 0.0043 barn by Mughabghab.[44] A negative resonance was taken into account and the fission widths of the negative resonance and low-lying positive resonances were modified a little to obtain the fission cross section of 0.2 barn at 0.0253 eV.

2) Unresolved resonance parameters

In the unresolved resonance region from 215 eV to 30 keV, the same parameters as JENDL-2 were adopted.

3) Cross sections above resonance region

Fission cross section

Four experiments have been made above 100 keV recently. These results except Ref. 40 are systematically smaller by 10 - 20% than those of Behrens and Browne[15] which were adopted in JENDL-2. Therefore, the smaller cross section than JENDL-2 was adopted in the present evaluation by spline-fitting the recent results in the energy region from 100 keV to 10 MeV. Below 100 keV, the data of JENDL-2 were adopted. Above 10 MeV, the shape of the cross section was determined on the basis of the results of Behrens and Browne. The present evaluation is shown in Figs. 29 and 30 together with experimental data and other evaluated ones.

Capture cross section

Since the previous evaluation for JENDL-2 was in very good agreement with the recent experiment by Weston and Todd,[38] the same way of calculation with CASTHY was adopted. The result was normalized to 2.2 barns at 30 keV. A comparison between the present calculation and others is shown in Fig. 31. Small discrepancies between present and previous results are found above 30 keV because the level density parameters and level scheme are slightly different from those of JENDL-2.

Other cross sections

The (n,2n), (n,3n) and (n,4n) reaction cross sections were taken from JENDL-2. The total, elastic and capture cross sections were calculated with CASTHY. The level scheme[51] used in the calculation is listed in Table 7.

4) Other data

The angular distributions of elastically and inelastically scattered neutrons were calculated with CASTHY. The isotropic distributions in the laboratory system were assumed for the neutrons emitted from fission, (n,2n) and (n,3n) reactions. The energy distributions of the emitted neutrons and number of neutrons per fission were taken from JENDL-2.

3.5 Americium 244g

Since no experimental data were available, the data were estimated from the data of ^{242g}Am as follows.

1) Cross sections

Neither resolved nor unresolved resonance parameters were given because no experimental data existed for the resonances. The fission cross section of 2300 ± 300 barns[44] at 0.0253 eV was adopted and the 1/v shape was assumed below 0.07 eV which is a half value of the level spacing of 0.13 eV calculated from the adopted level density parameters. In this energy region, the capture cross section was also assumed to be in the 1/v shape and normalized to 600 barns at 0.0253 eV which was estimated by assuming that the ratios of fission and capture cross sections were almost the same at thermal and high energies. The elastic scattering cross section was obtained with the CASTHY calculation.

Above 0.07 eV, the fission cross section was assumed to be the same as that of ^{242g}Am. The (n,2n), (n,3n) and (n,4n) reaction cross sections were calculated from the evaporation model by assuming that the neutron emission cross section was equal to the difference between the compound nucleus formation cross section calculated with the optical model and the fission cross section.

Other cross sections were calculated with CASTHY. The optical model parameters in Table 2 were used. The level scheme taken from Nuclear Data Sheets[52] is listed in Table 8. The gamma-ray strength function for the capture cross section was calculated from Γ_γ = 50 meV and Dobs = 0.13 eV.

The obtained cross sections are shown in Fig. 32.

2) Other data

The number of prompt neutrons per fission was obtained from Howerton's empirical formula[53]:

$$\nu_p = 3.188 + 0.184E \text{ (MeV)}.$$

For delayed neutrons, Tuttle's empirical formula[54] was applied.

$$\nu_d = 0.0138, \quad E < 6 \text{ MeV},$$
$$= 0.00946, \quad E > 8 \text{ MeV}$$

The angular distributions of elastically and inelastically scattered neutrons were calculated with CASTHY. Those of the (n,2n), (n,3n), (n,4n) reactions and fission were assumed to be isotropic in the laboratory system.

Evaporation spectra were assumed for the energy distributions of emitted neutrons, and their nuclear temperatures were estimated from the level density parameters with EVAPSPEC.[55] Fission neutron spectrum was determined from systematics by Smith et al.[56]

3.6 Americium 244m

The data were evaluated with the same way as ^{244g}Am. The fission cross section of 1600 ± 300 barns at 0.0253 eV was adopted. Energies of excited levels were shifted by 88 keV as shown in a right hand side of Table 8.

The evaluated cross sections are shown in Fig. 33.

4. Concluding Remarks

In the present work, the JENDL-2 evaluations and recent experimental data for americium isotopes were investigated, and the data of ^{241}Am, ^{242m}Am and ^{243}Am were reevaluated. In particular, previous evaluations were modified on the basis of these new experimental data for the fission and capture cross sections. In addition to the reevaluation, the data of ^{244g}Am and ^{244m}Am were newly evaluated.

The data of heavy actinides are important from the view point of the nuclear fuel cycle. In order to make an accurate data base for it, many experiments should be curried out. For americium isotopes, the fission and capture cross sections could be determined on the basis of the recent experimental data. However, no experimental data are available for the inelastic scattering and (n,2n) reactions. Therefore, large discrepancies exist among evaluated data for these quantities. It is needed to improve the heavy actinide data both experimentally and theoretically.

Acknowledgement

The author thanks to members of the Nuclear Data Center, JAERI, for their help to the present work. This work was performed under contract with Power Reactor and Nuclear Fuel Development Corporation (PNC). The anther thanks also to Dr. K. Shirakata of PNC for his advice to the present work.

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Table 1 Optical potential parameters

(MeV and fm)

V	$= 43.4 - 0.107\ E_n$	
W_s	$= 6.95 - 0.339\ E_n + 0.0531\ E_n^2$	
V_{so}	$= 7.0$	
r_0	$= r_{so}$	$= 1.282$
r_s	$= 1.29$	
a	$= a_{so}$	$= 0.60$
b	$= 0.5$	

for ^{241}Am, ^{243}Am

Table 2 Optical potential parameters

(MeV and fm)

V	$= 42.0 - 0.107\ E_n$	
W_s	$= 9.0 - 0.339\ E_n + 0.0531\ E_n^2$	
V_{so}	$= 7.0$	
r_0	$= r_{so}$	$= 1.282$
r_s	$= 1.29$	
a	$= a_{so}$	$= 0.60$
b	$= 0.5$	

for ^{242}Am, ^{244}Am

Table 3 Level density parameters

Nuclide	a(MeV^{-1})	T(MeV)	C(MeV^{-1})	E_x(MeV)	α_M(MeV$^{-1/2}$)	Δ(MeV)
^{239}Am	28.4	0.372	8.005	3.189	29.97	0.49
^{240}Am	25.8	0.371	13.96	2.304	28.64	0.0
^{241}Am	29.0	0.367	9.95	3.122	30.45	0.43
^{242}Am	29.6	0.342	22.98	2.323	30.85	0.0
^{243}Am	31.3	0.355	11.71	3.278	31.81	0.50
^{244}Am	30.3	0.340	26.47	2.373	31.39	0.0
^{245}Am	31.3	0.360	18.06	3.265	31.98	0.39

Table 4 Level scheme of ^{241}Am[48)]

No.	Energy(keV)	Spin-Parity	
GR	0.0	5/2	-
1	41.176	7/2	-
2	93.65	9/2	-
3	158.0	11/2	-
4	205.883	5/2	+
5	235.0	7/2	+
6	272.0	9/2	+
7	320.0	11/2	+
8	471.81	3/2	-
9	504.448	5/2	-
10	549.0	7/2	-
11	623.10	1/2	+
12	636.861	3/2	-
13	652.089	1/2	-
14	653.23	3/2	+
15	670.24	3/2	+
16	682.0	11/2	-

Levels above 732 keV were assumed to be overlapping.

Table 5 Breit-Wigner resonance parameters[29] (a value of Γ_γ=50 meV and an average g factor of 0.5 were used for all resonances) for ^{242m}Am up to 20 eV.

E_0 (eV)	Γ_n (meV)	Γ_f (meV)	E_0 (eV)	Γ_n (meV)	Γ_f (meV)
0.178	0.213	240	10.30	0.025	250
0.615	0.108	200	10.62	0.105	400
1.10	0.385	999	10.87	0.120	300
1.71	0.060	250	11.25	0.110	225
2.11	0.196	330	11.43	0.090	100
2.95	0.075	230	11.79	0.140	325
3.18	0.298	310	11.92	0.230	325
3.39	0.220	260	12.62	0.790	360
4.013	0.290	220	13.04	0.470	300
4.27	0.255	215	13.41	0.940	400
4.55	0.210	600	13.90	0.280	400
5.37	0.470	422	14.42	0.280	350
5.70	0.040	250	14.68	0.375	400
5.95	0.440	350	15.15	0.100	350
6.15	0.065	300	15.67	0.680	550
6.65	0.220	170	16.06	0.195	300
6.84	0.050	70	16.48	0.470	380
7.00	0.035	80	16.92	0.950	500
7.21	0.100	380	17.50	0.475	525
8.07	0.155	500	17.82	0.285	400
8.60	0.080	500	18.47	0.610	400
9.03	0.375	850	19.07	0.800	500
9.43	0.070	220	19.31	0.900	550
9.88	0.140	420	19.70	0.450	450

Table 6 Level scheme of ^{242m}Am[50)]

No.	Energy (keV)	Spin-Parity
1	- 49.0	1^-
2	- 5.0	0^-
3	0.0	3^-
GR	0.0	5^-
4	25.0	2^-
5	64.0	6^-
6	99.0	4^-
7	99.0	5^-
8	141.0	7^-
9	193.0	3^-
10	214.0	6^-
11	214.0	7^-
12	239.0	4^-
13	239.0	2^-
14	276.0	3^-
15	292.0	5^-
16	323.0	4^-
17	361.0	6^-
18	381.0	5^-
19	439.0	7^-
20	451.0	6^-
21	532.0	7^-
22	630.0	8^-

Levels above 632 keV were assumed to be overlapping.

Table 7 Level scheme of ^{243}Am[51]

No.	Energy (keV)	Spin-Parity
GR	0.0	5/2 -
1	42.2	7/2 -
2	84.0	5/2 +
3	96.4	9/2 -
4	109.3	7/2 +
5	143.5	9/2 +
6	189.3	11/2 +
7	266	3/2 -
8	300	5/2 -
9	345	7/2 -

Levels above 383 keV were assumed to be overlapping.

Table 8 Level scheme of ^{244}Am[52]

No.	Energy (keV)	Spin-Parity	Energy (keV) of $^{244}Am^{m}$
GR	0.0	6 -	- 88.0
1	88.0	1 +	0.0
2	100.309	2 +	12.309
3	123.281	3 +	35.281
4	148.283	4 +	60.283
5	175.657	1 -	87.657
6	183.511	5 -	95.511
7	197.295	2 -	109.295
8	228.299	3 -	140.299
9	261.696	2 -	173.696
10	272.202	4 -	184.202
11	289.212	1 -	201.212
12	296.658	3 -	208.658
13	322.751	5 -	234.751
14	335.575	0 -	247.575
15	342.650	3 -	254.650
16	343.658	4 -	255.658
17	348.405	3 +	260.405
18	361.838	2 -	273.838
19	377.057	0 +	289.057
20	390.028	4 +	302.028
21	398.743	5 -	310.743
22	414.689	2 +	326.689
23	418.957	2 +	330.957
24	420.131	2 +	332.131
25	421.204	3 -	333.204

Levels above 435 keV were assumed to be overlapping.

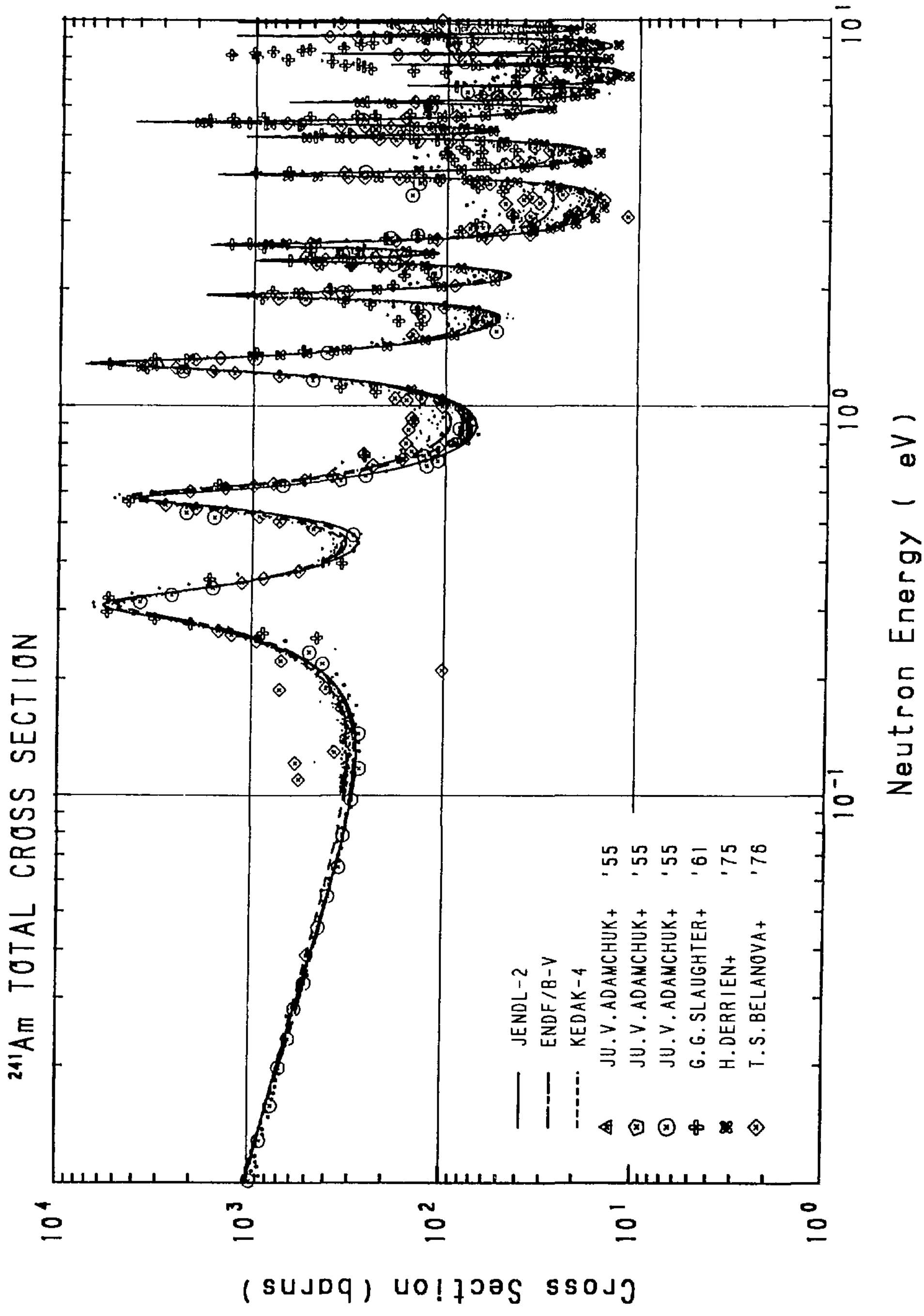

Fig. 1 Total cross section of ^{241}Am in the energy range from 0.01 to 10 eV.

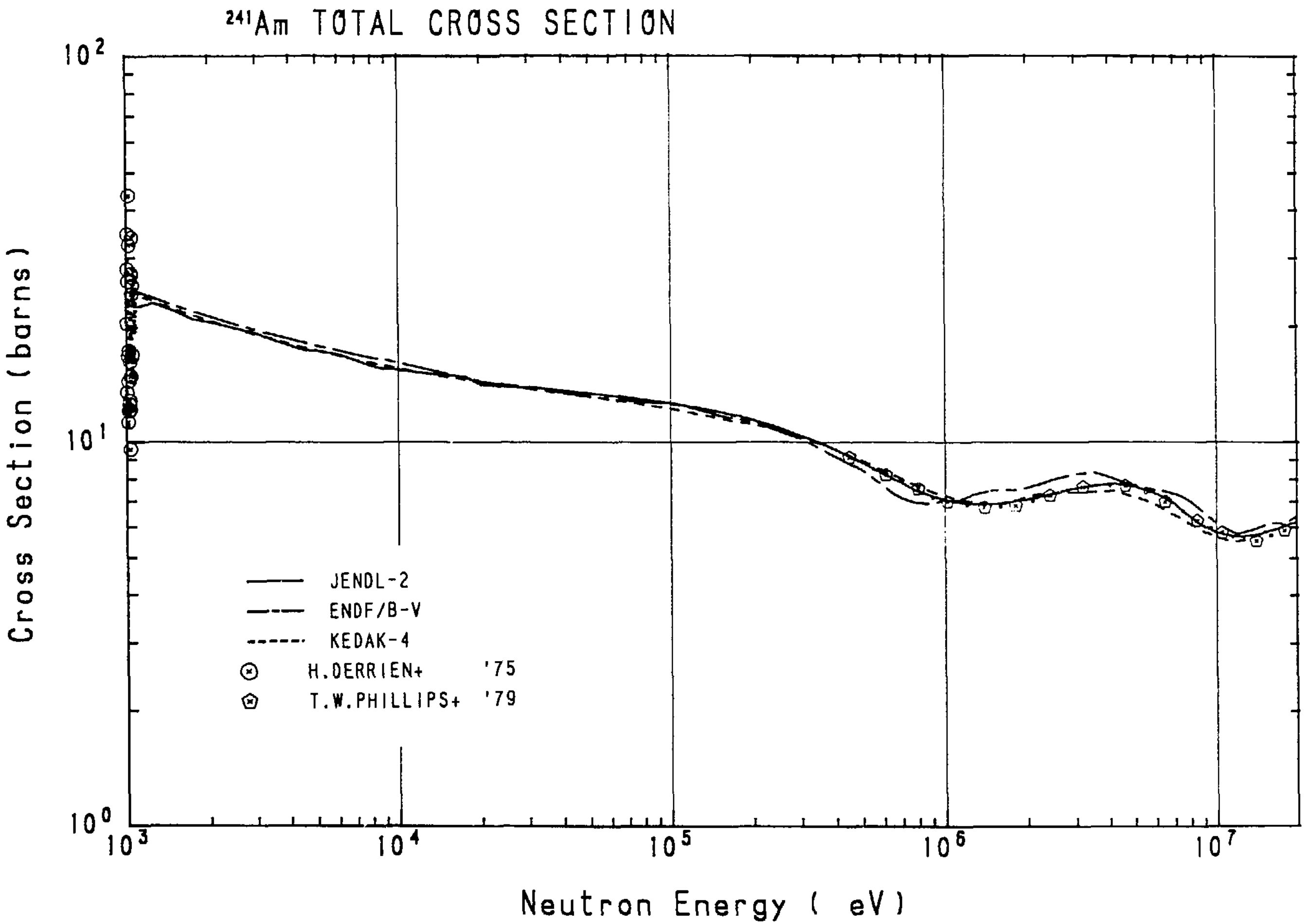

Fig. 2 Total cross section of ^{241}Am in the energy range from 1 keV to 20 MeV.

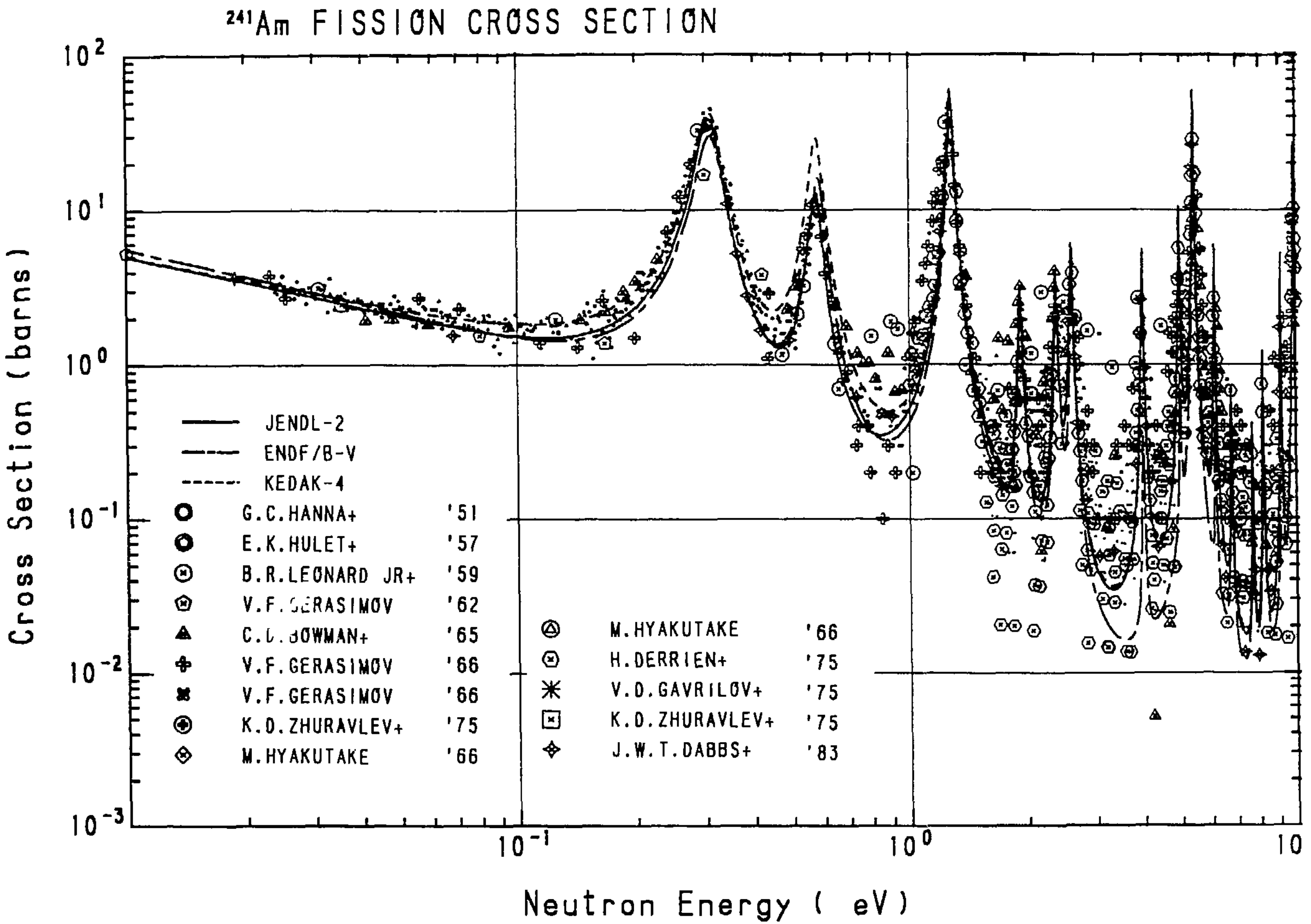

Fig. 3 Fission cross section of ^{241}Am in the energy range from 0.01 to 10 eV. All the available experiments are compared with evaluated data.

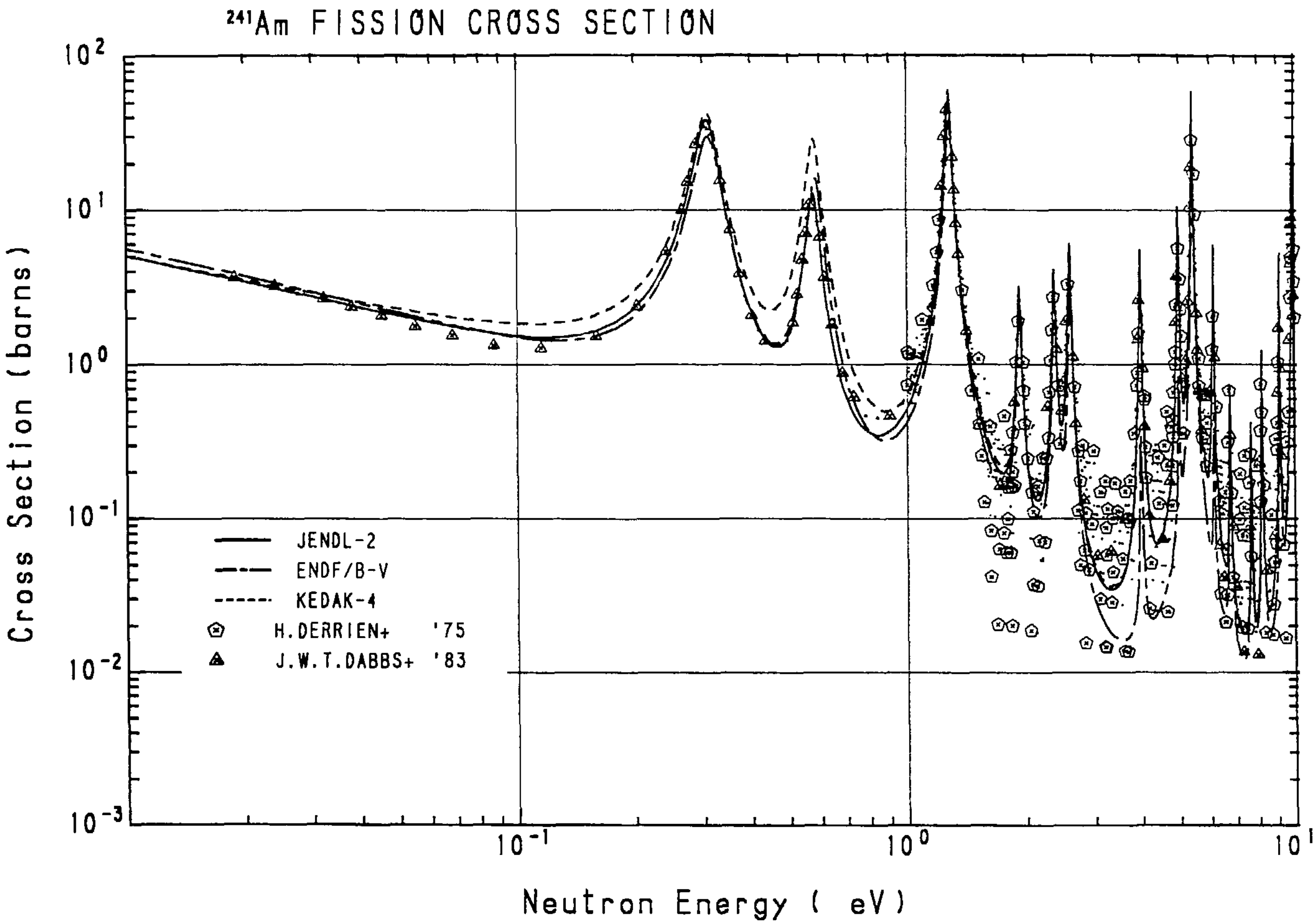

Fig. 4 Fission cross section of ^{241}Am in the energy range from 0.01 eV to 10 eV. Only recent two experiments are compared with evaluated data.

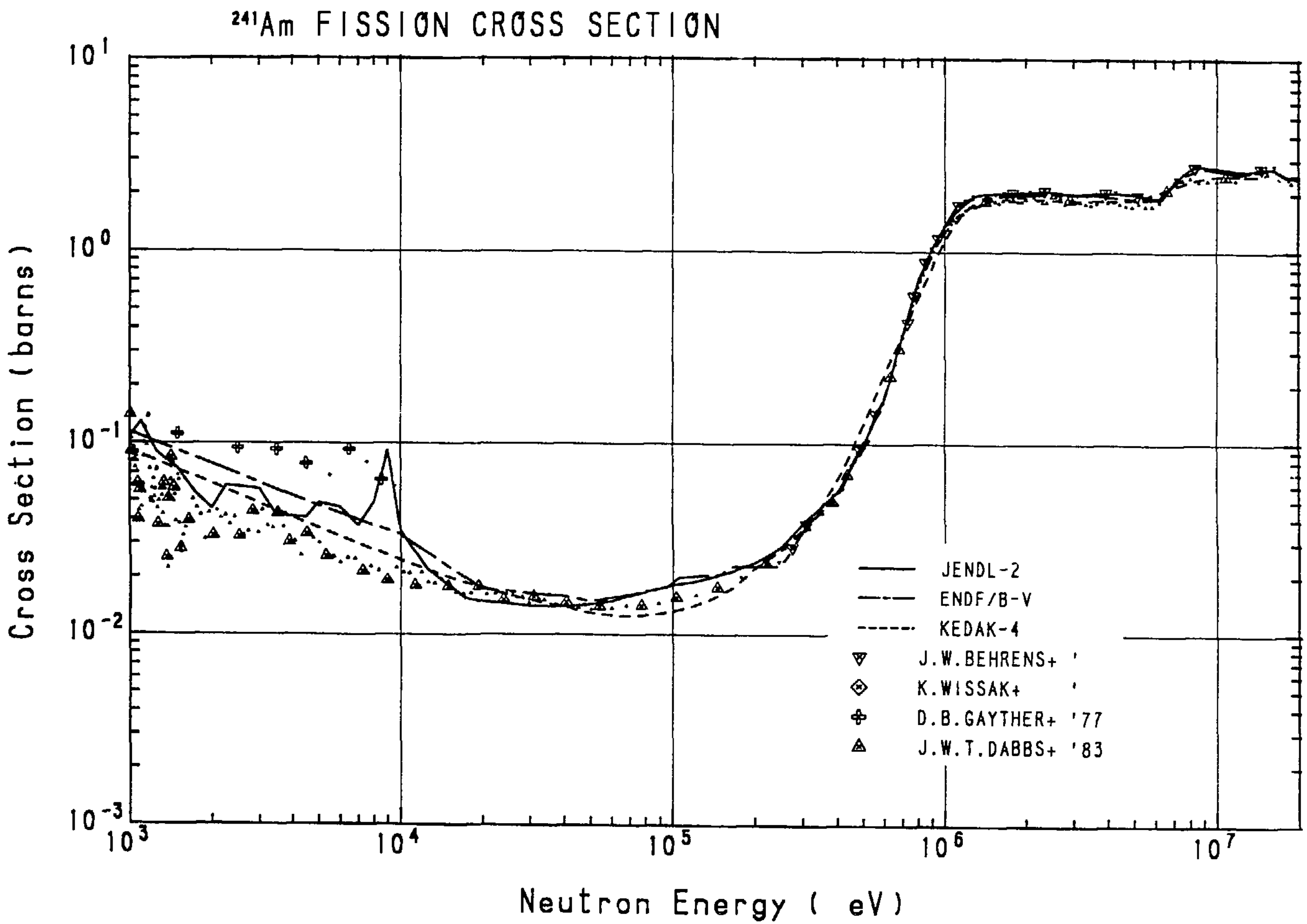

Fig. 5 Fission cross section of ^{241}Am in the energy range from 1 keV to 20 MeV.

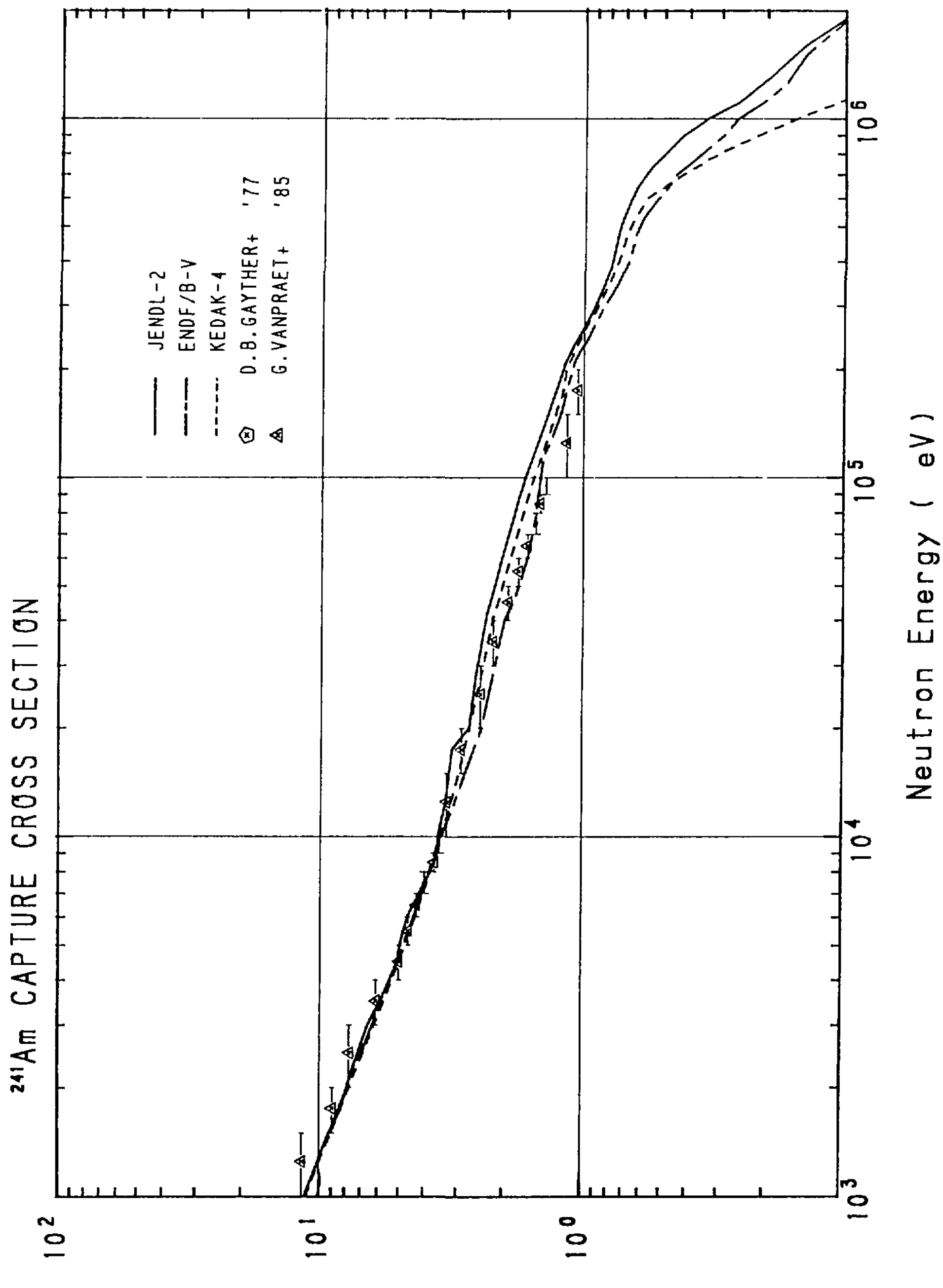

Fig. 6 Capture cross section of ^{241}Am.

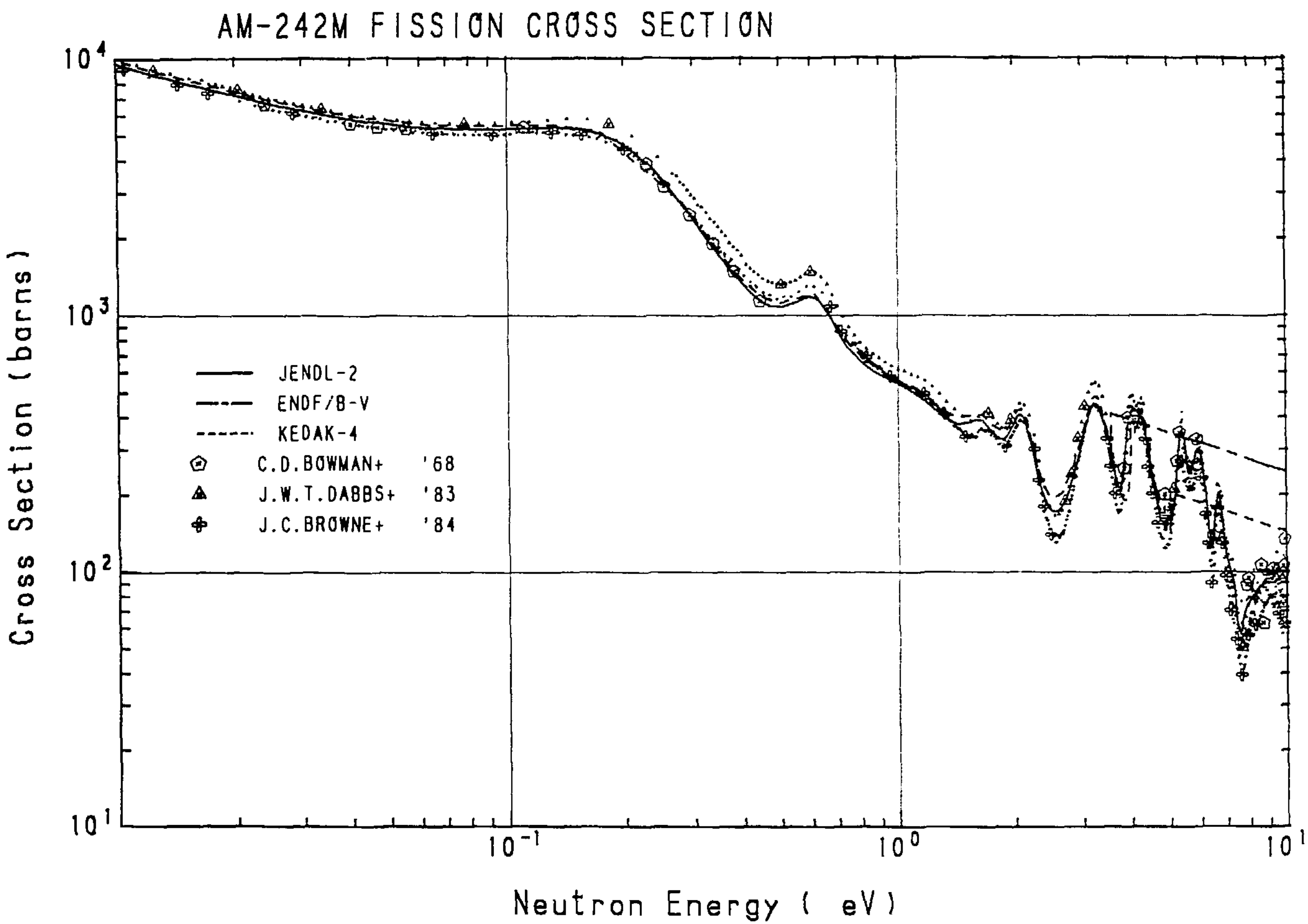

Fig. 7 Fission cross section of ^{242m}Am in the energy range from 0.01 to 10 eV.

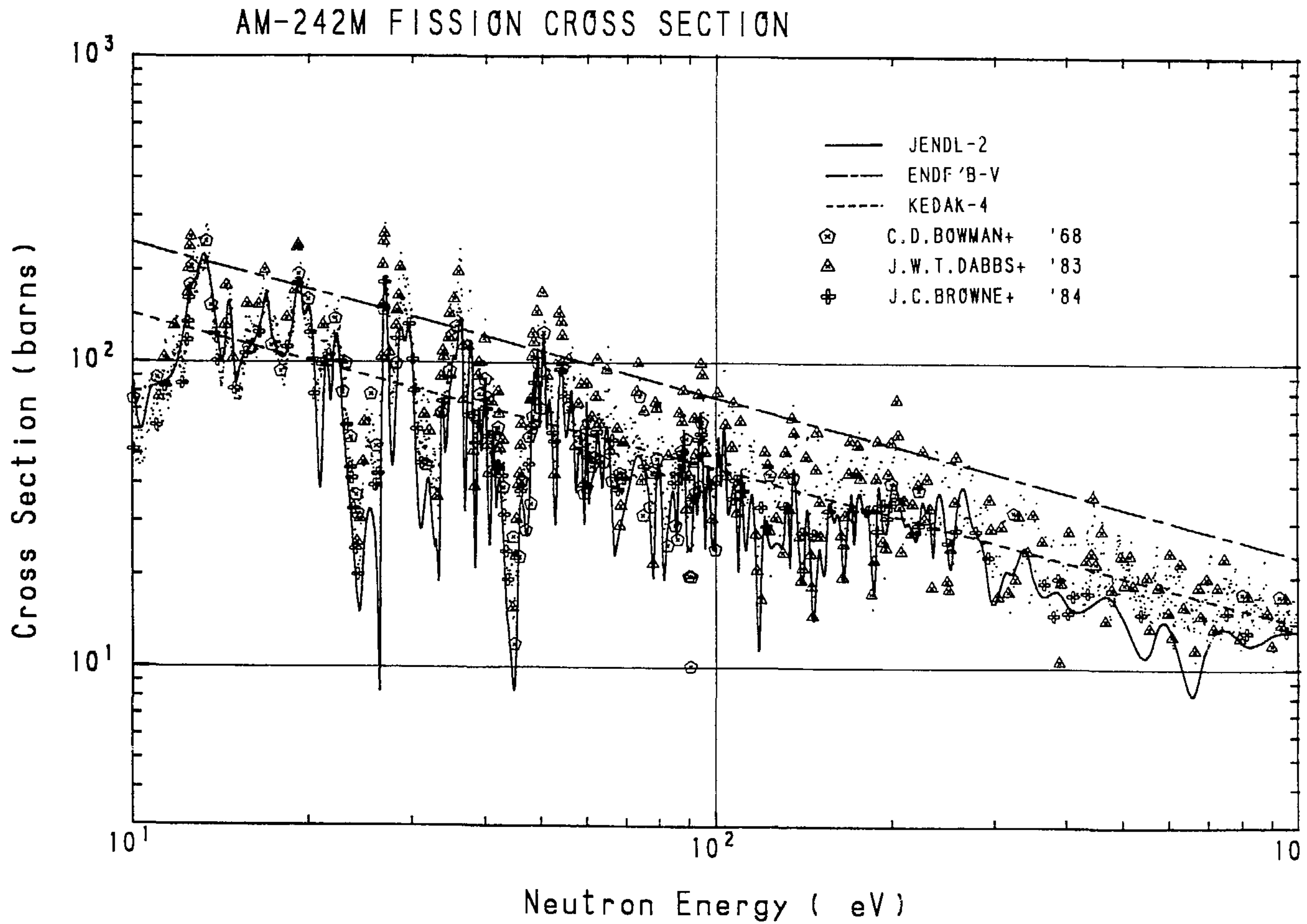

Fig. 8 Fission cross section of ^{242m}Am in the energy range from 10 eV to 1 keV.

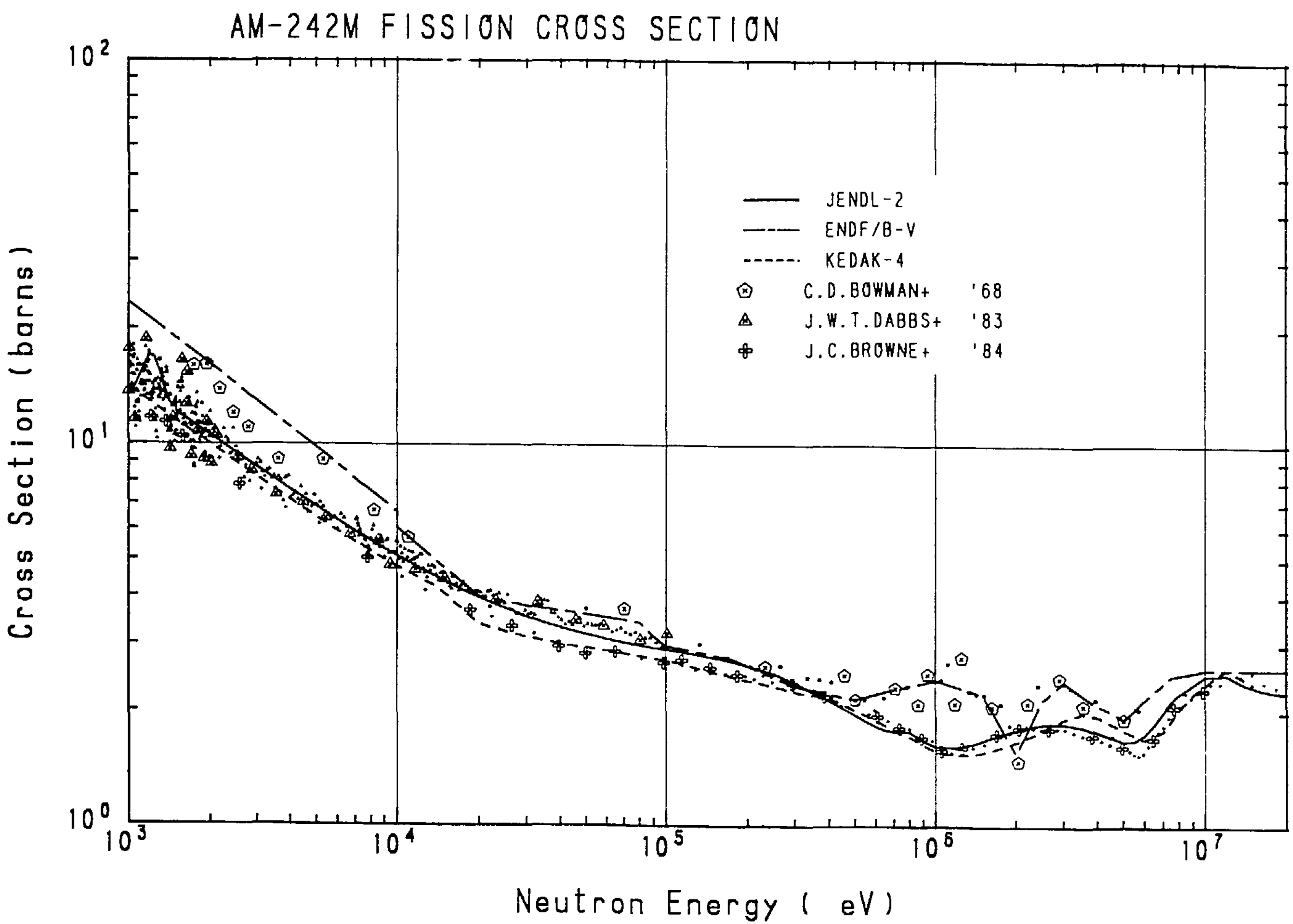

Fig. 9 Fission cross section of ^{242m}Am in the energy range from 1 keV to 20 MeV.

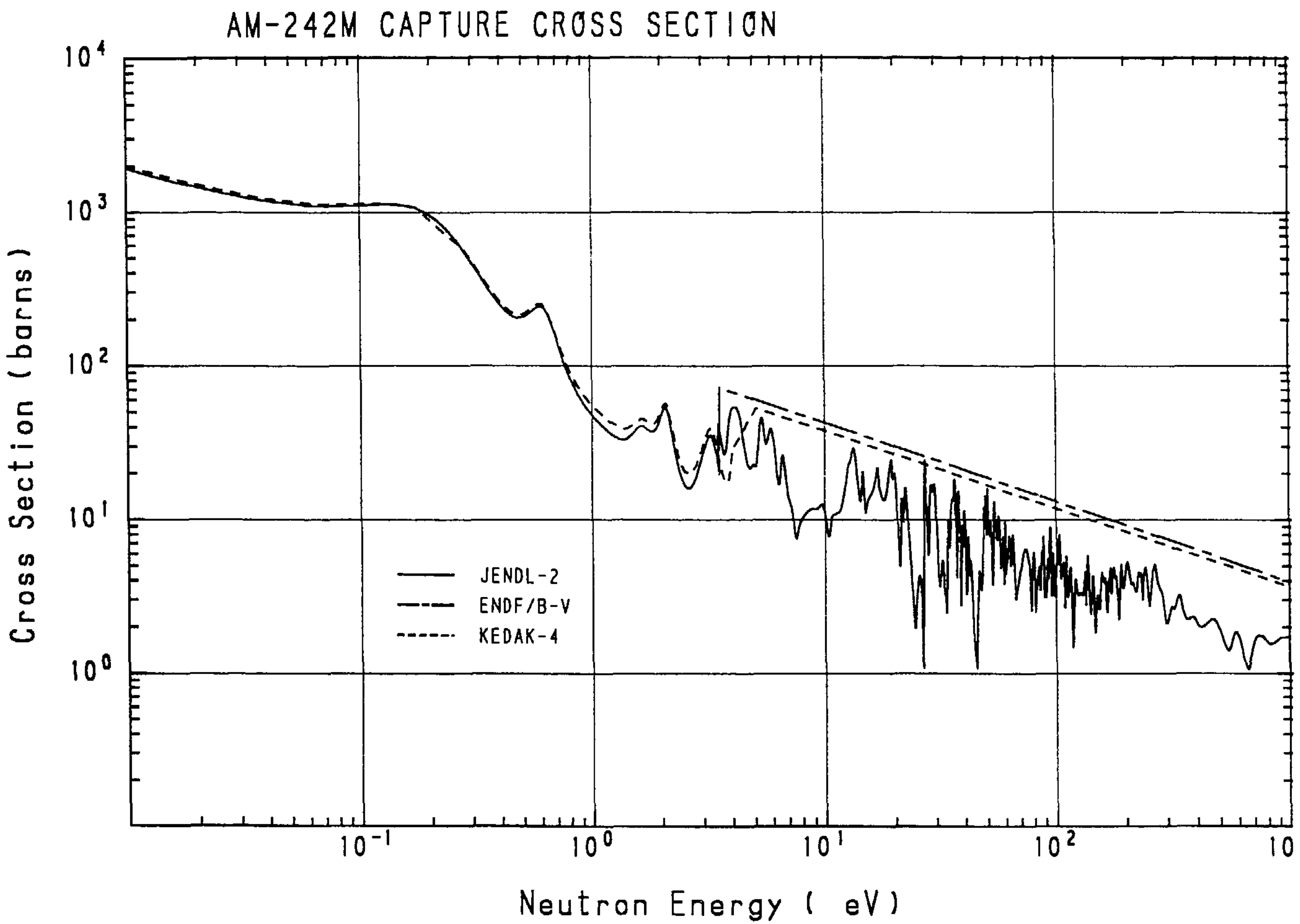

Fig. 10 Capture cross section of ^{242m}Am in the energy range from 0.01 eV to 1 keV.

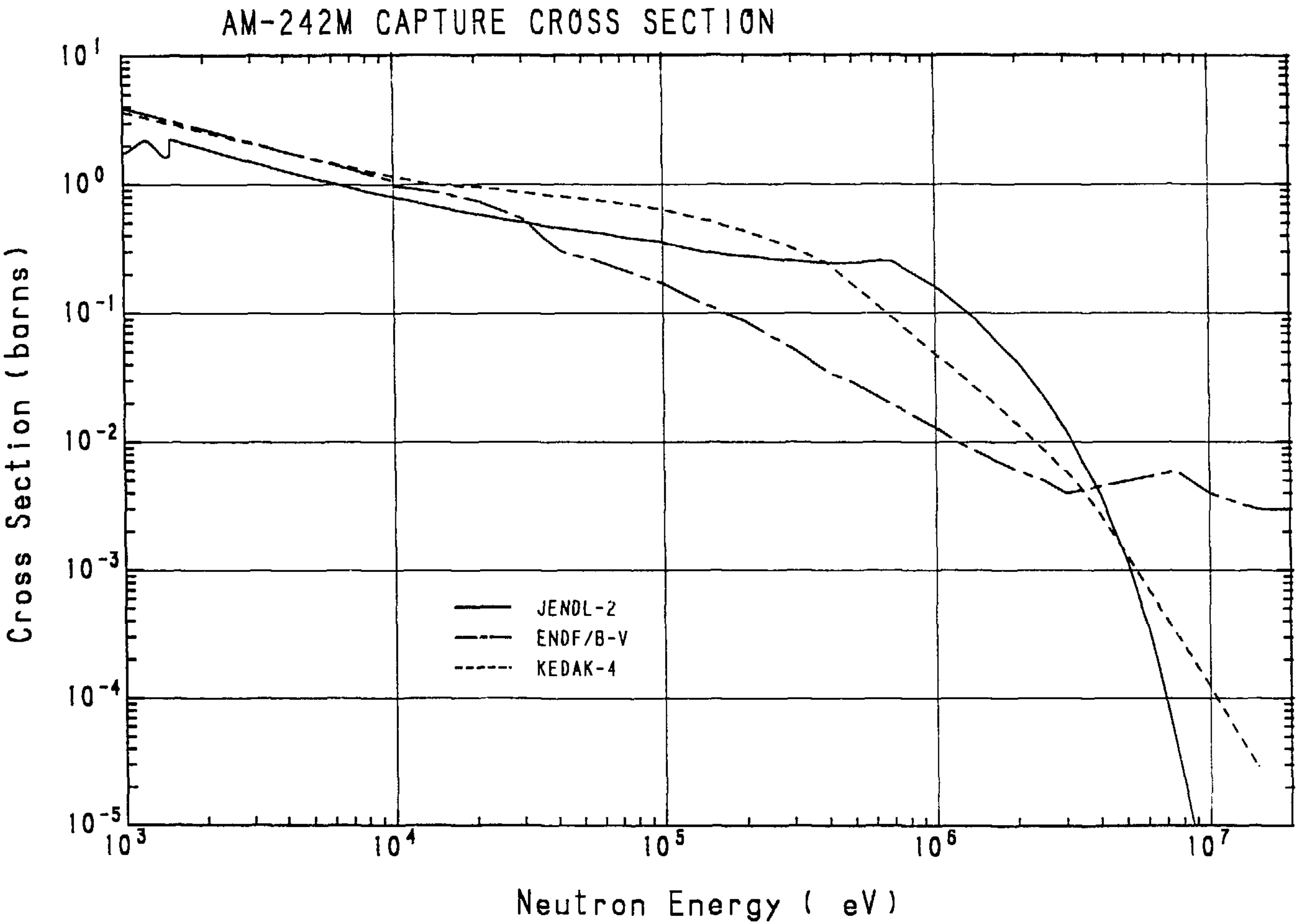

Fig. 11 Capture cross section of ^{242m}Am in the energy range from 1 keV to 20 MeV.

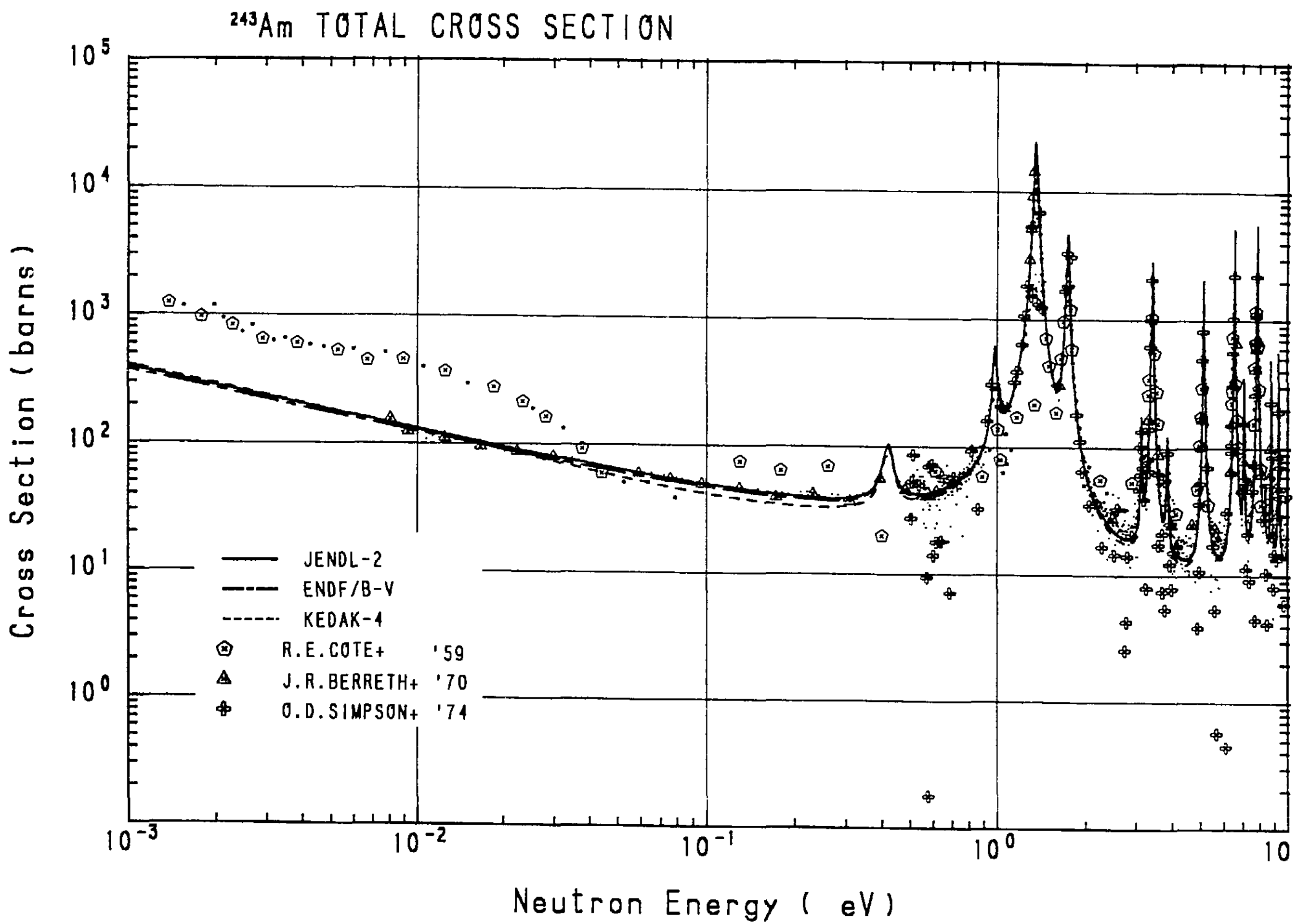

Fig. 12 Total cross section of ^{243}Am in the energy range from 0.01 to 10 eV.

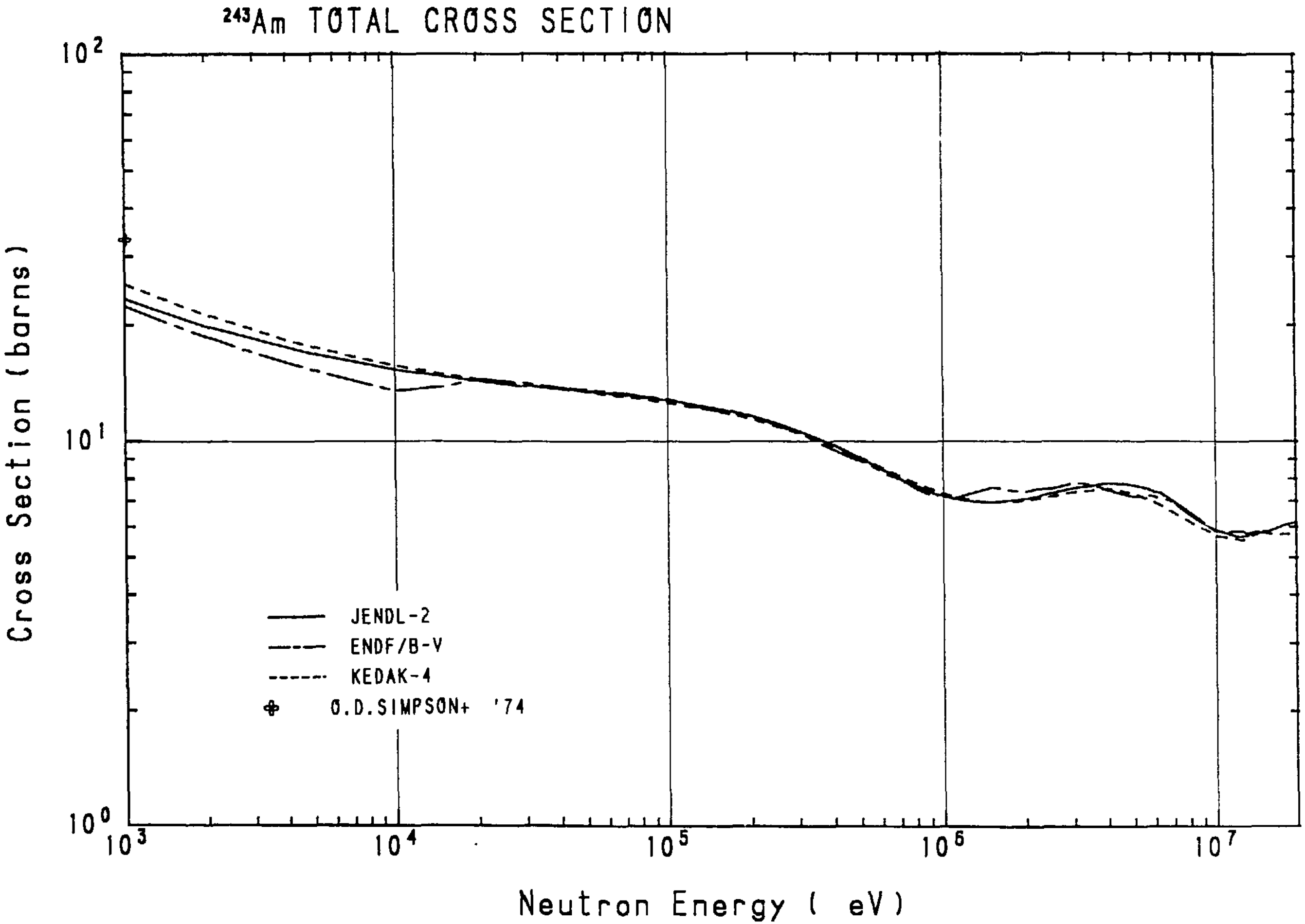

Fig. 13 Total cross section of ^{243}Am in the energy range from 1 keV to 20 MeV.

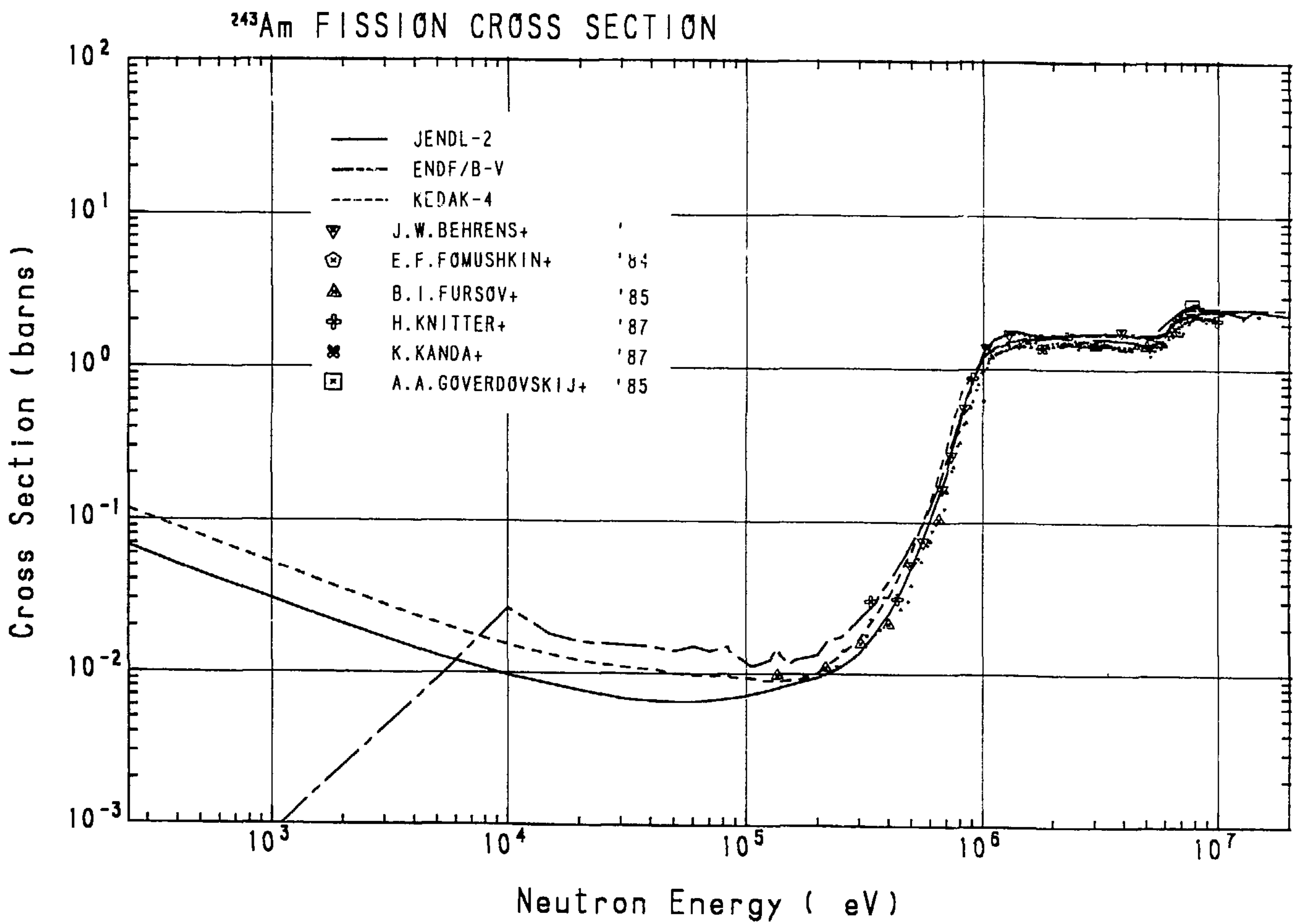

Fig. 14 Fission cross section of ^{243}Am in the energy range above 250 eV.

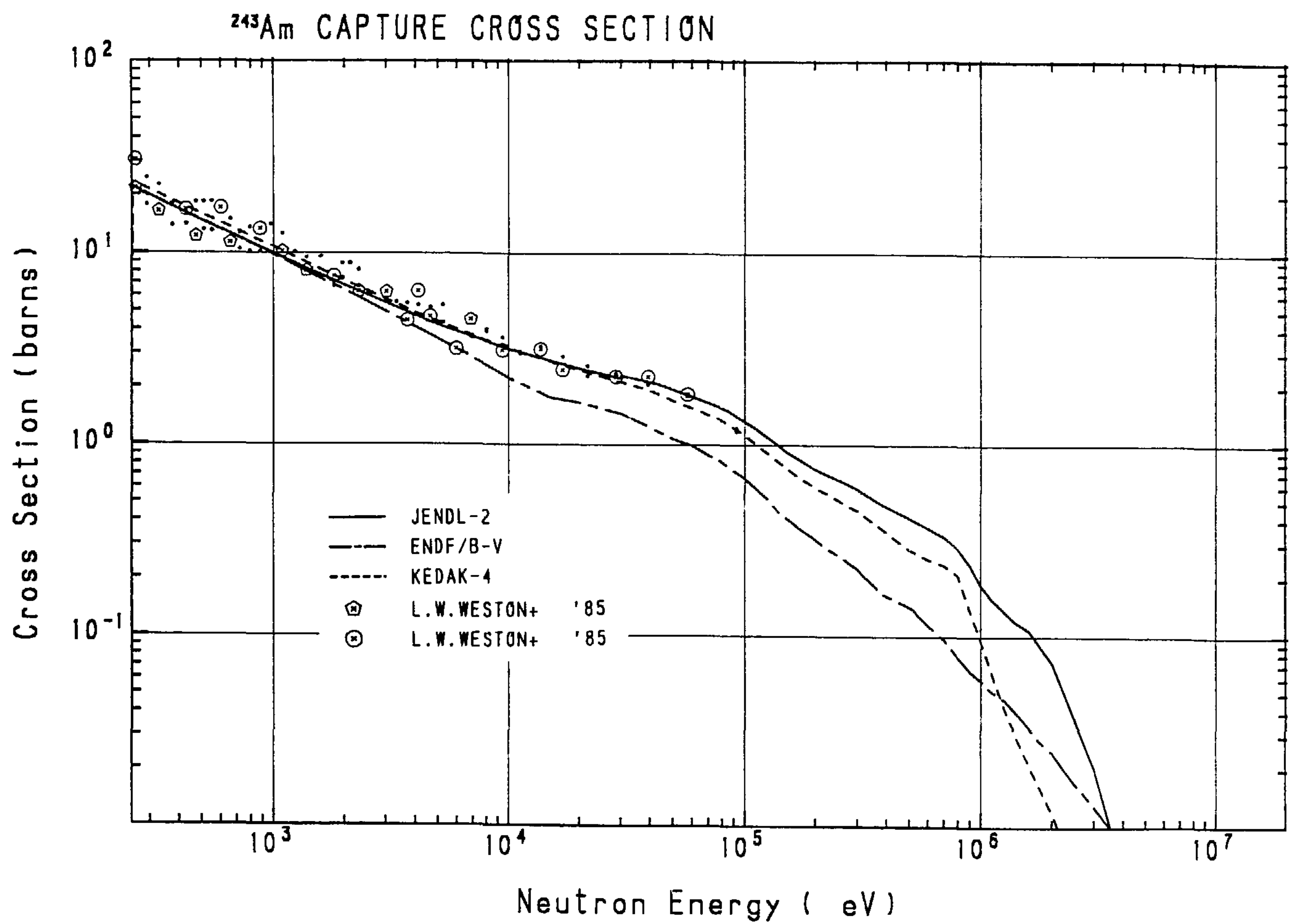

Fig. 15 Capture cross section of ^{243}Am in the energy range above 250 eV.

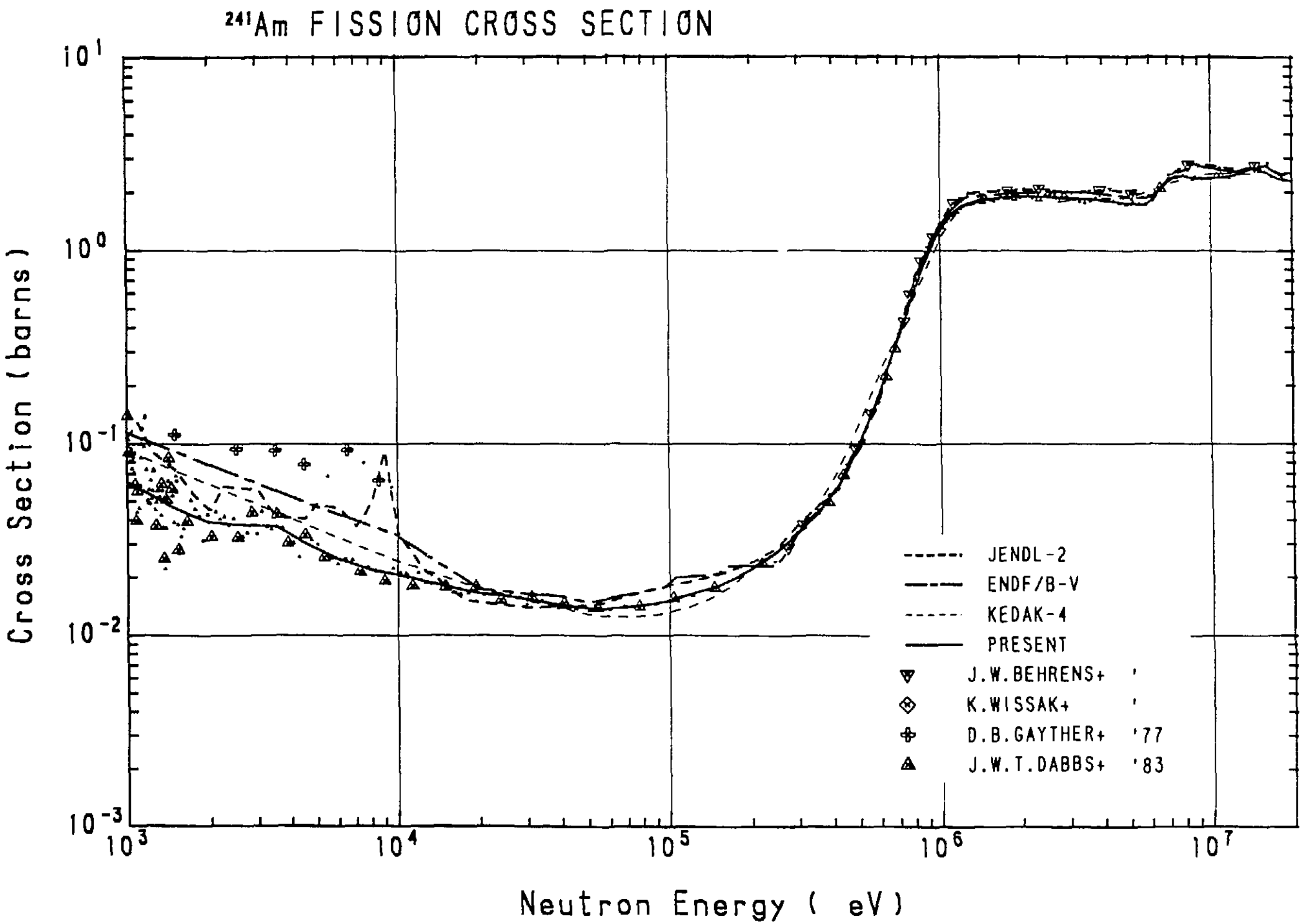

Fig. 16 Fission cross section of ^{241}Am in the energy range from 1 keV to 20 MeV.

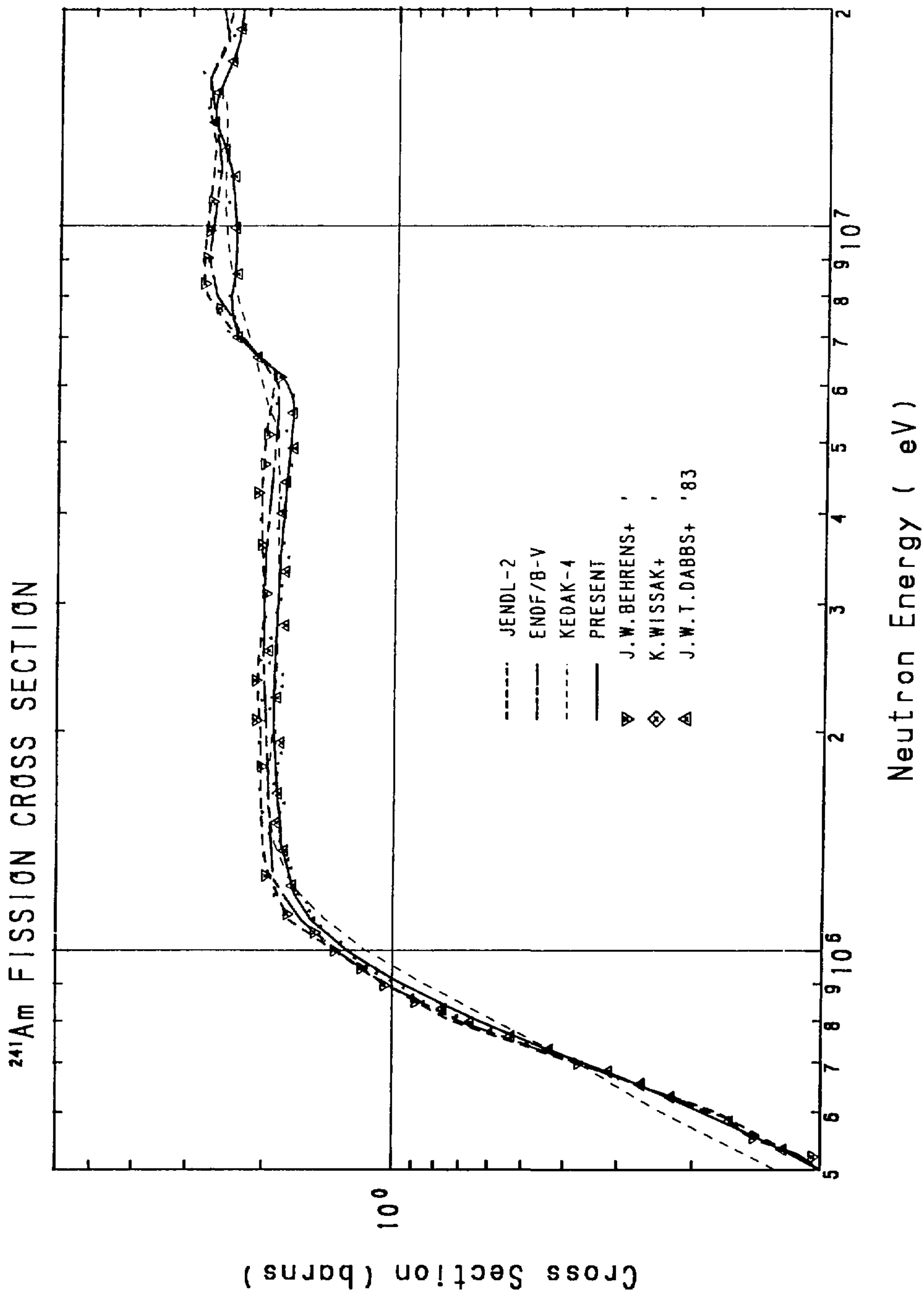

Fig. 17 Fission cross section of ^{241}Am in the energy range from 500 keV to 20 MeV.

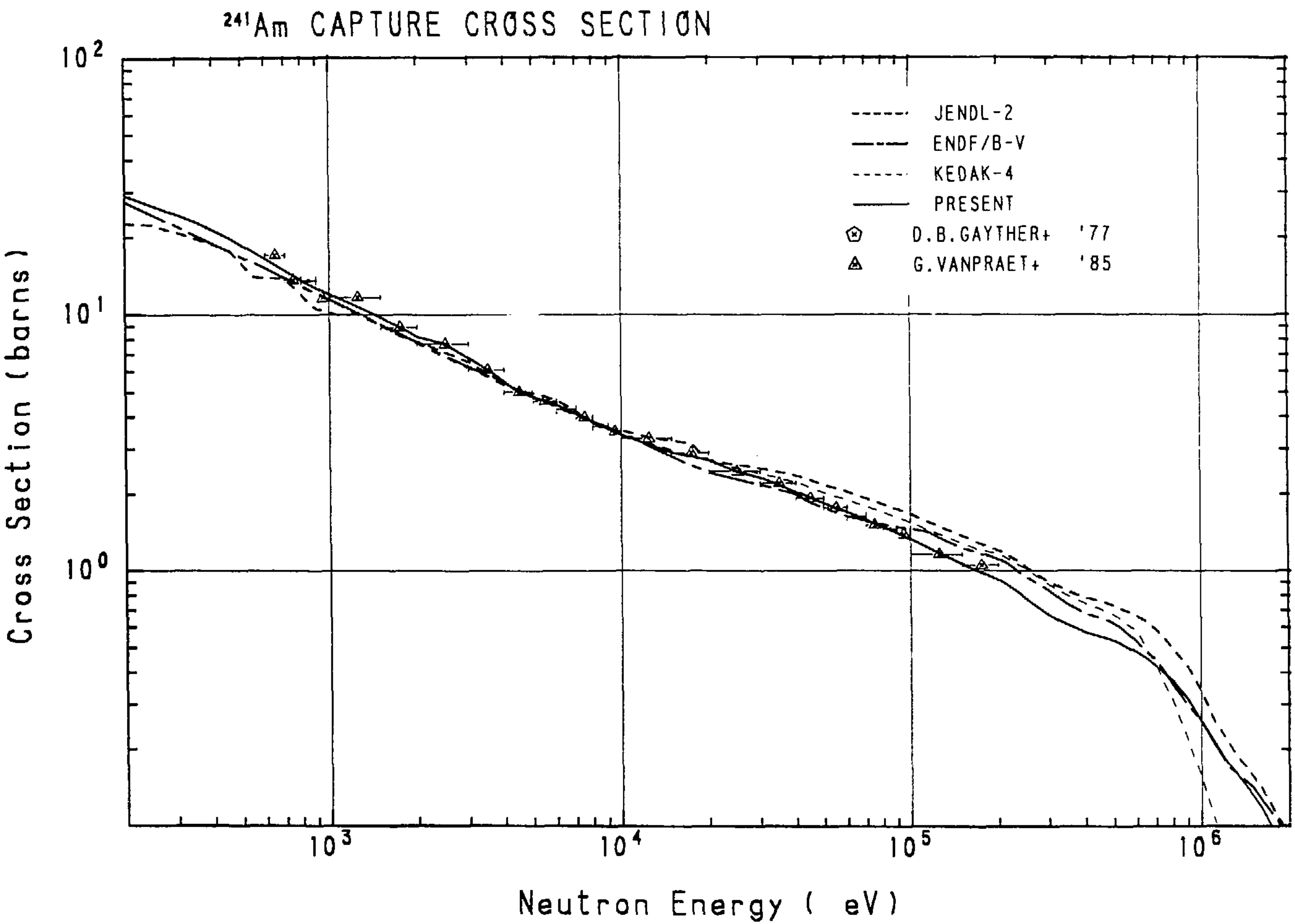

Fig. 18 Capture cross section of ^{241}Am in the energy range from 200 eV to 2 MeV.

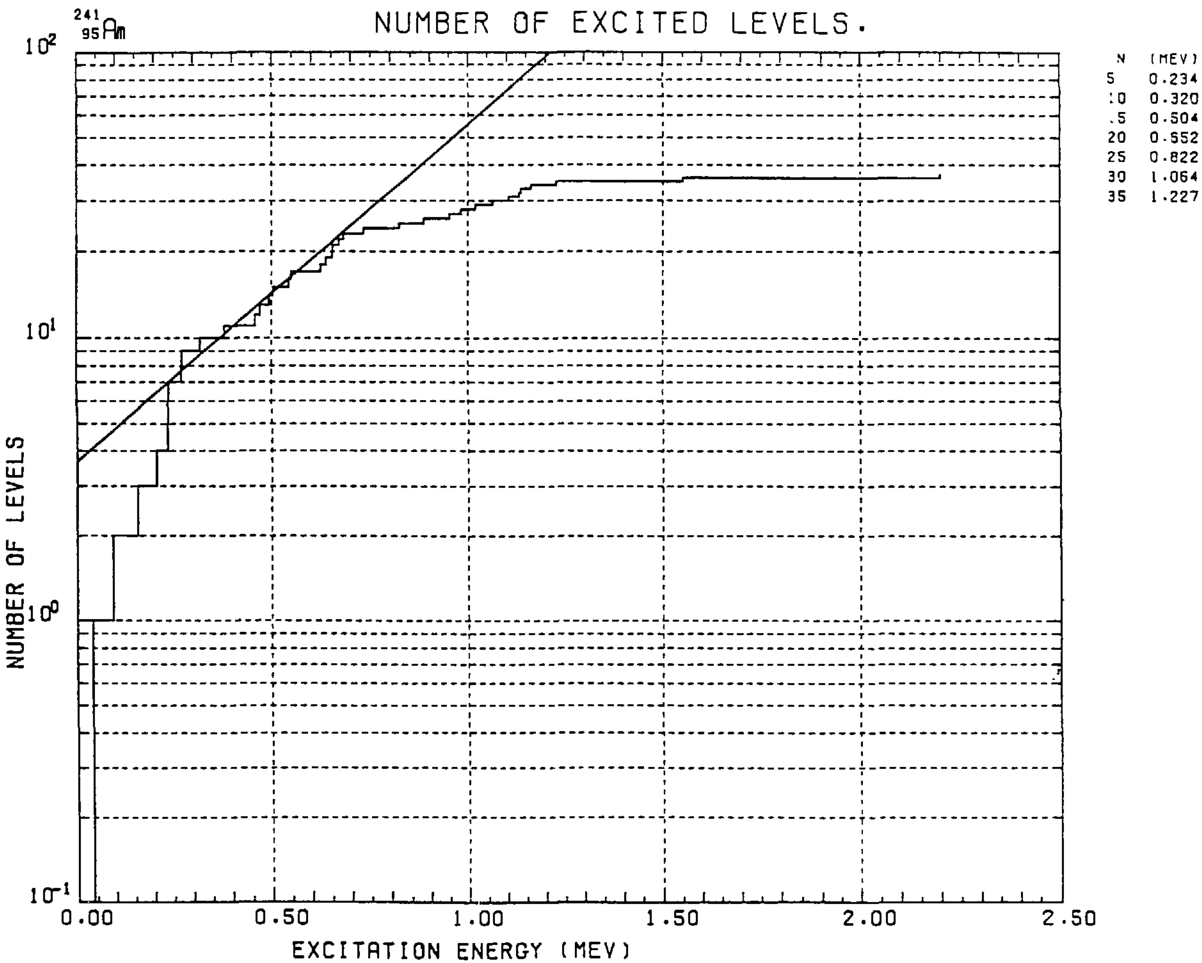

Fig. 19 Staircase plot of ^{241}Am excited levels.

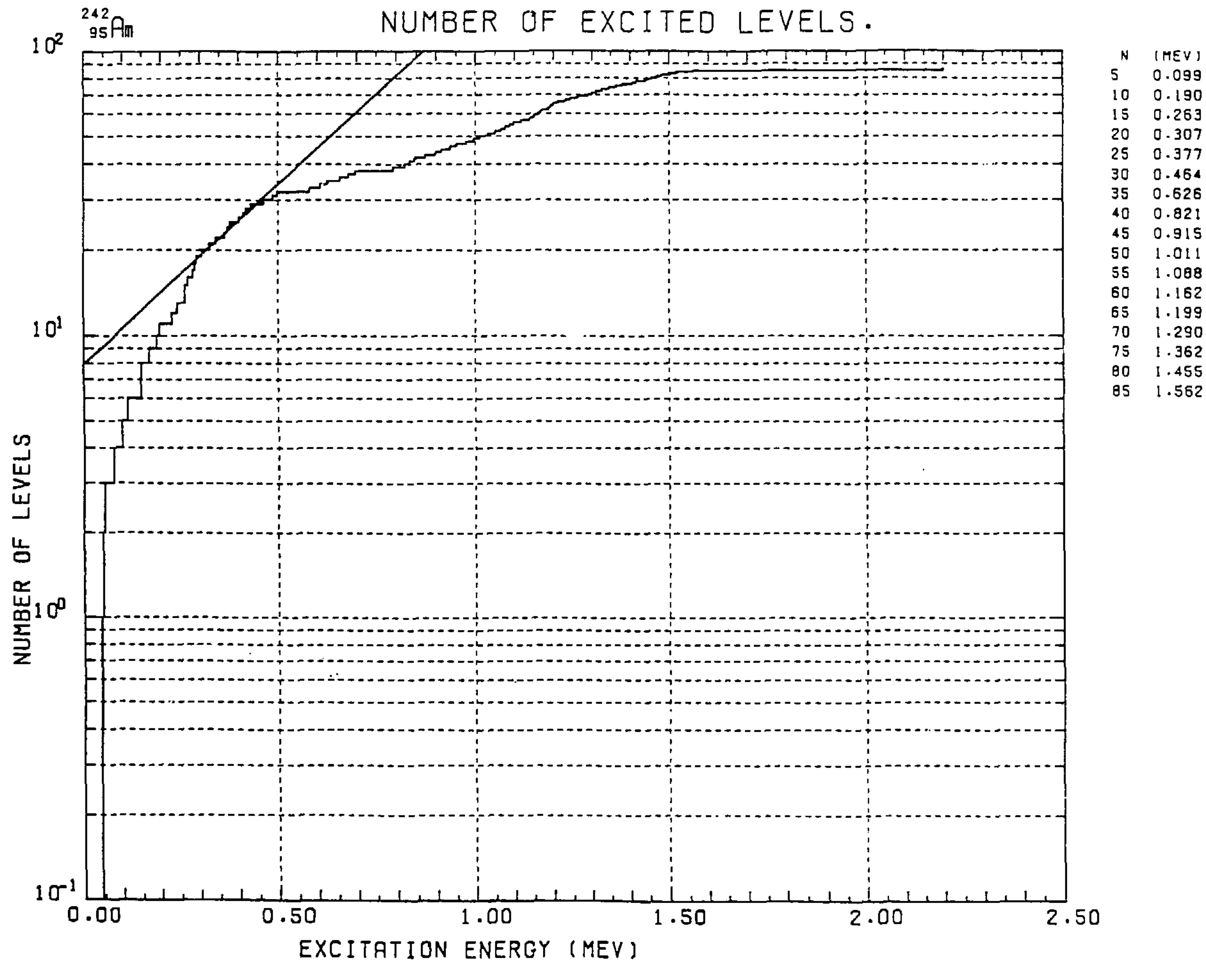

Fig. 20 Staircase plot of ^{242}Am excited levels.

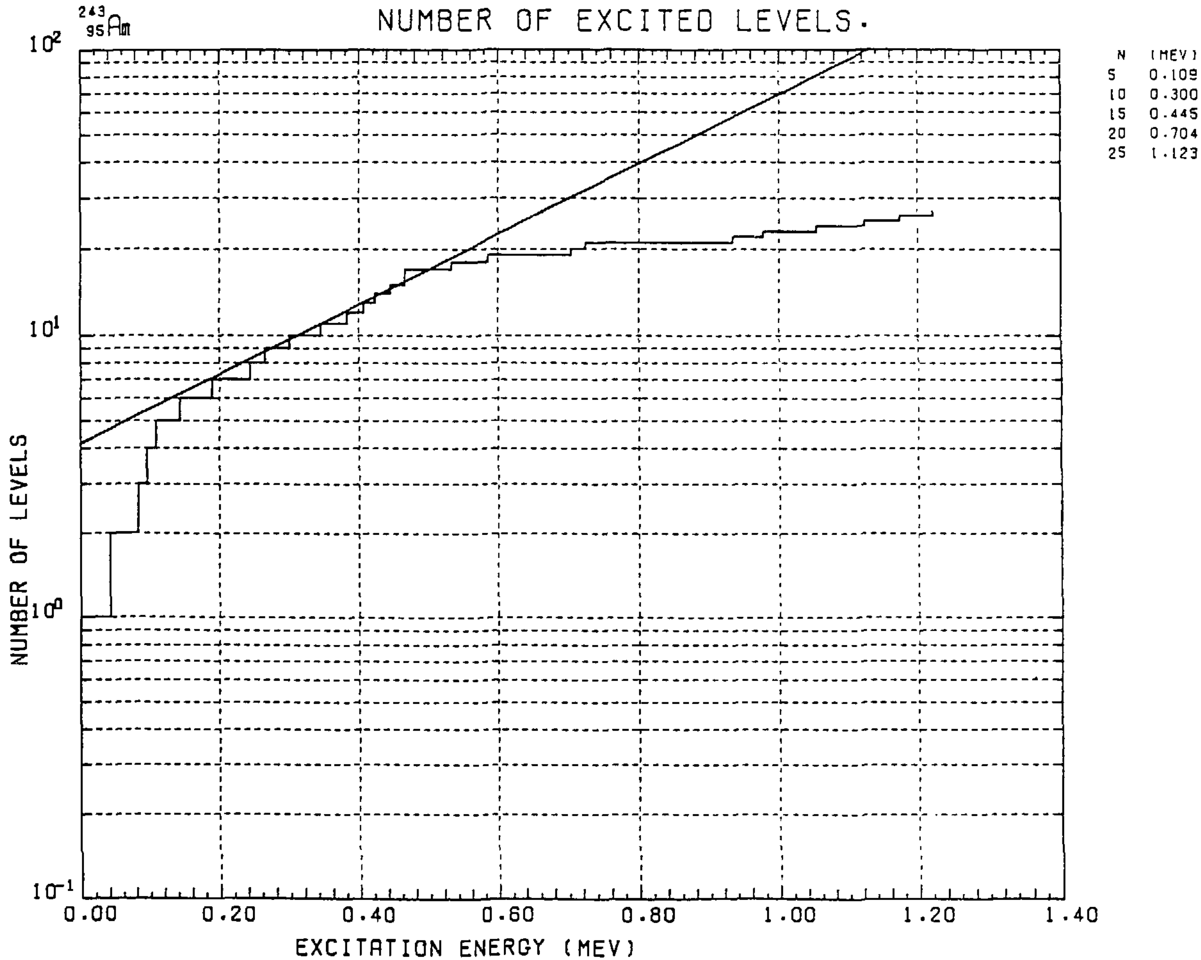

Fig. 21 Staircase plot of ^{243}Am excited levels.

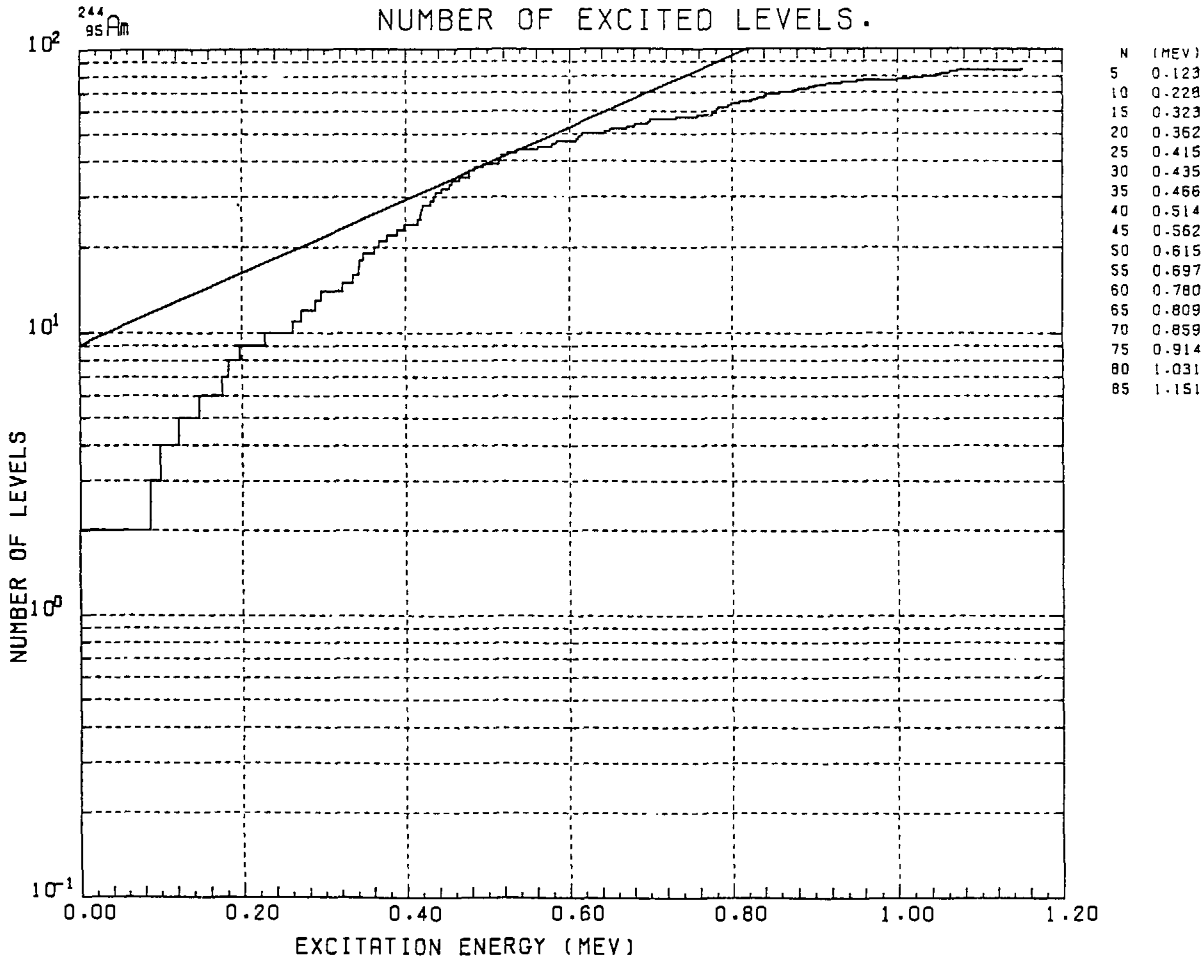

Fig. 22 Staircase plot of ^{244}Am excited levels.

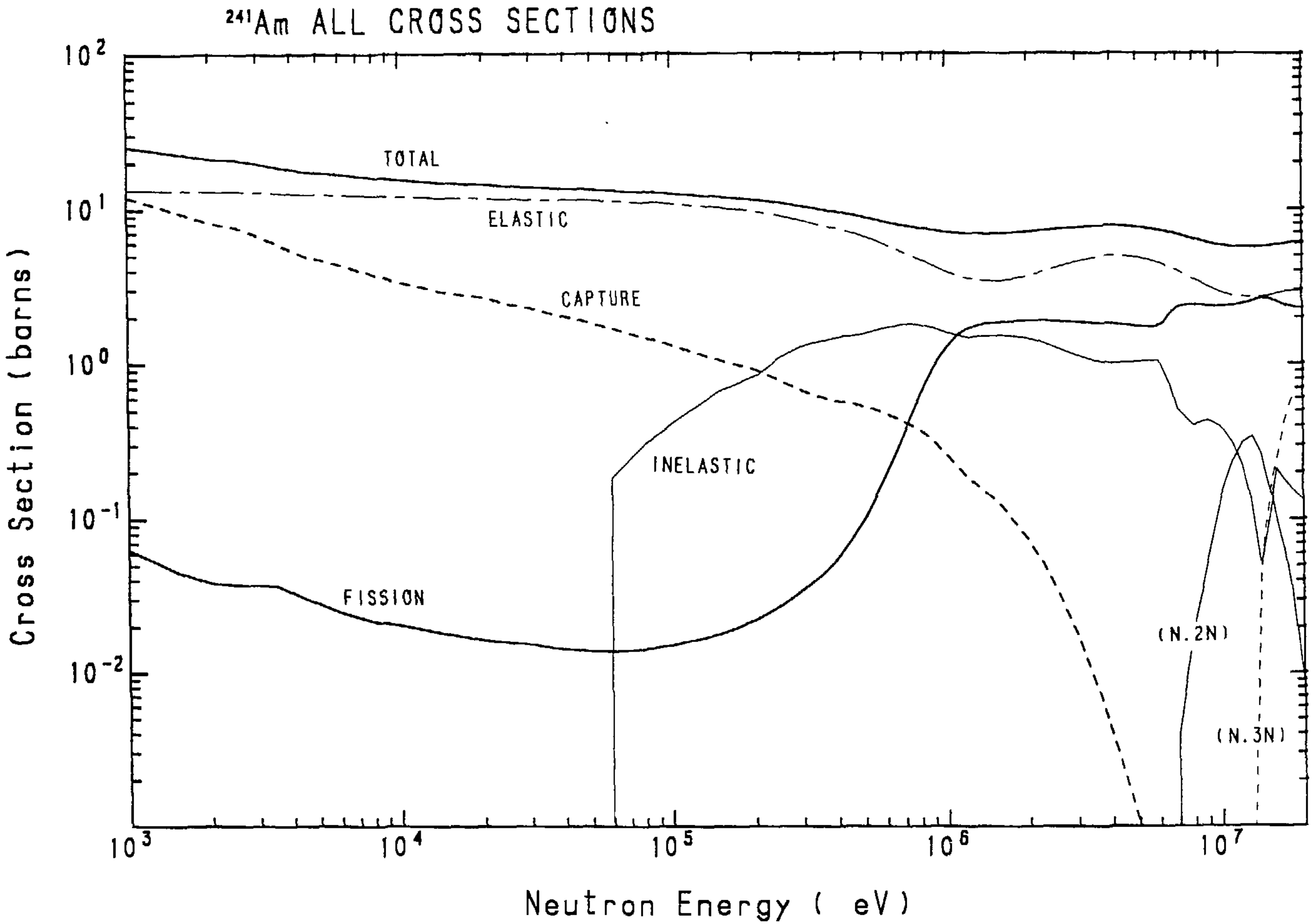

Fig. 23 Cross sections of ^{241}Am.

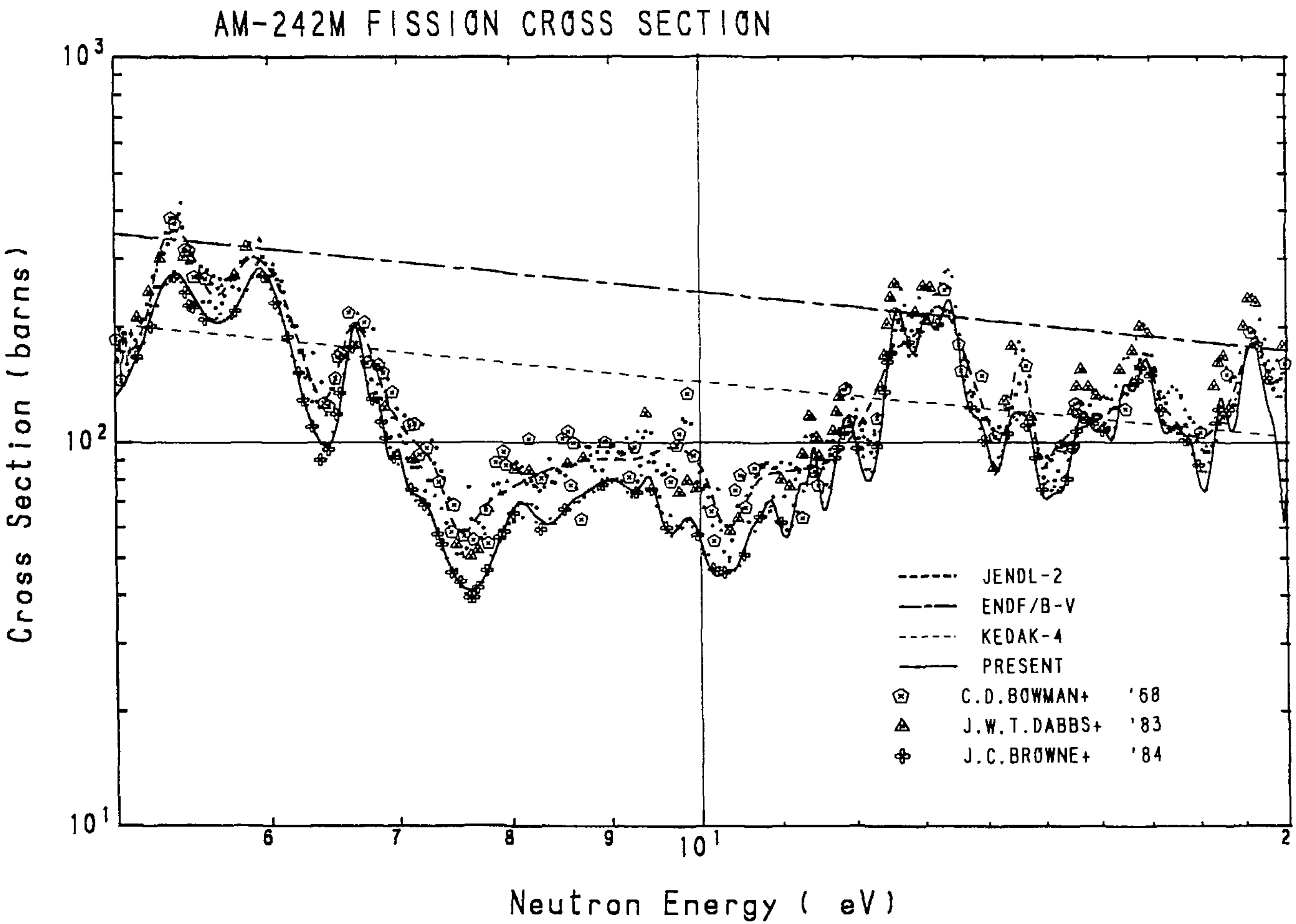

Fig. 24 Fission cross section of ^{242m}Am in the energy range from 5 to 20 eV.

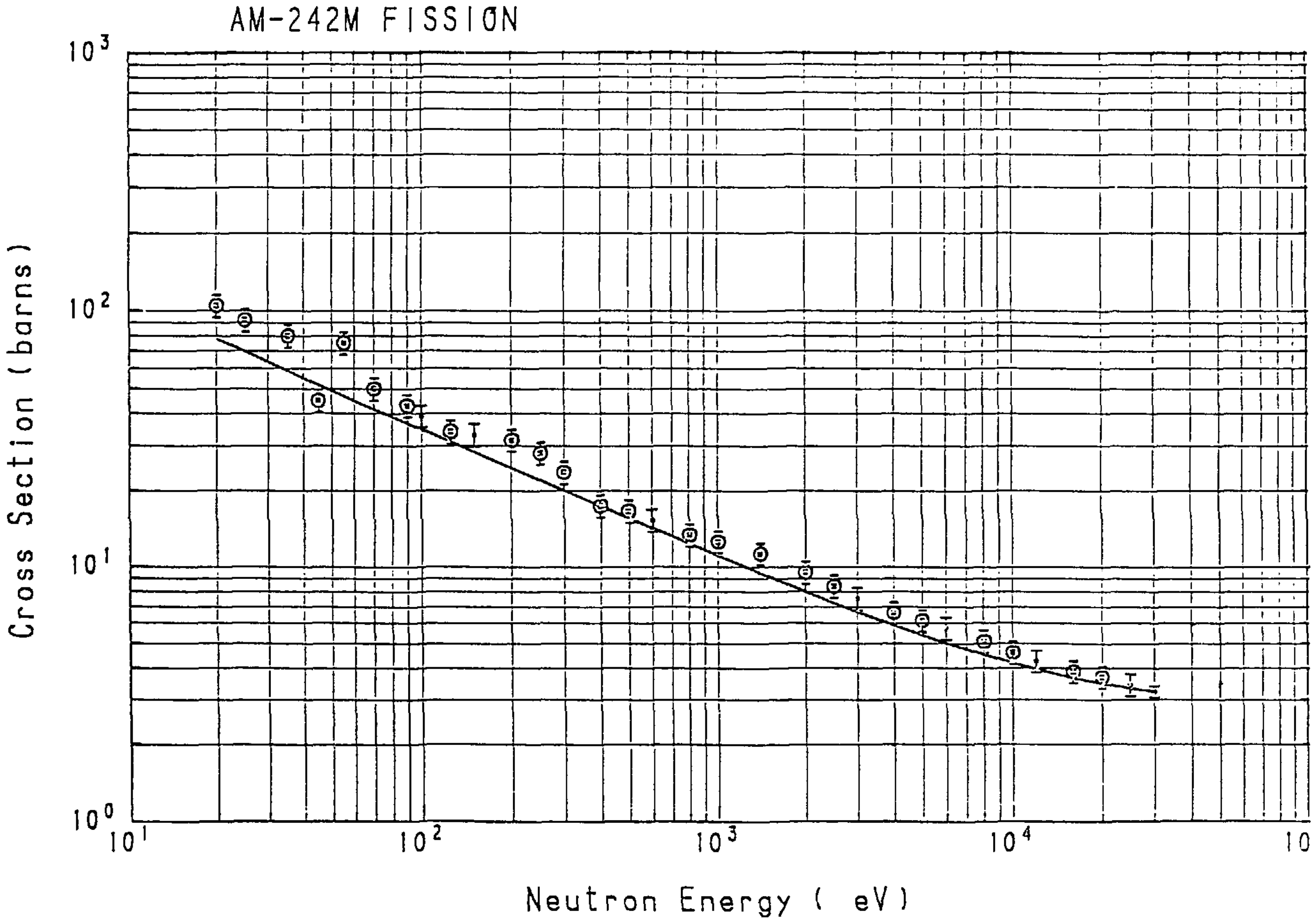

Fig. 25 Fission cross section of ^{242m}Am in the unresolved resonance region. Open circles show the average fission cross section to be reproduced with the unresolved resonance parameters. The solid line is calculated from the present unresolved resonance parameters. Differences between them were compensated with background cross sections.

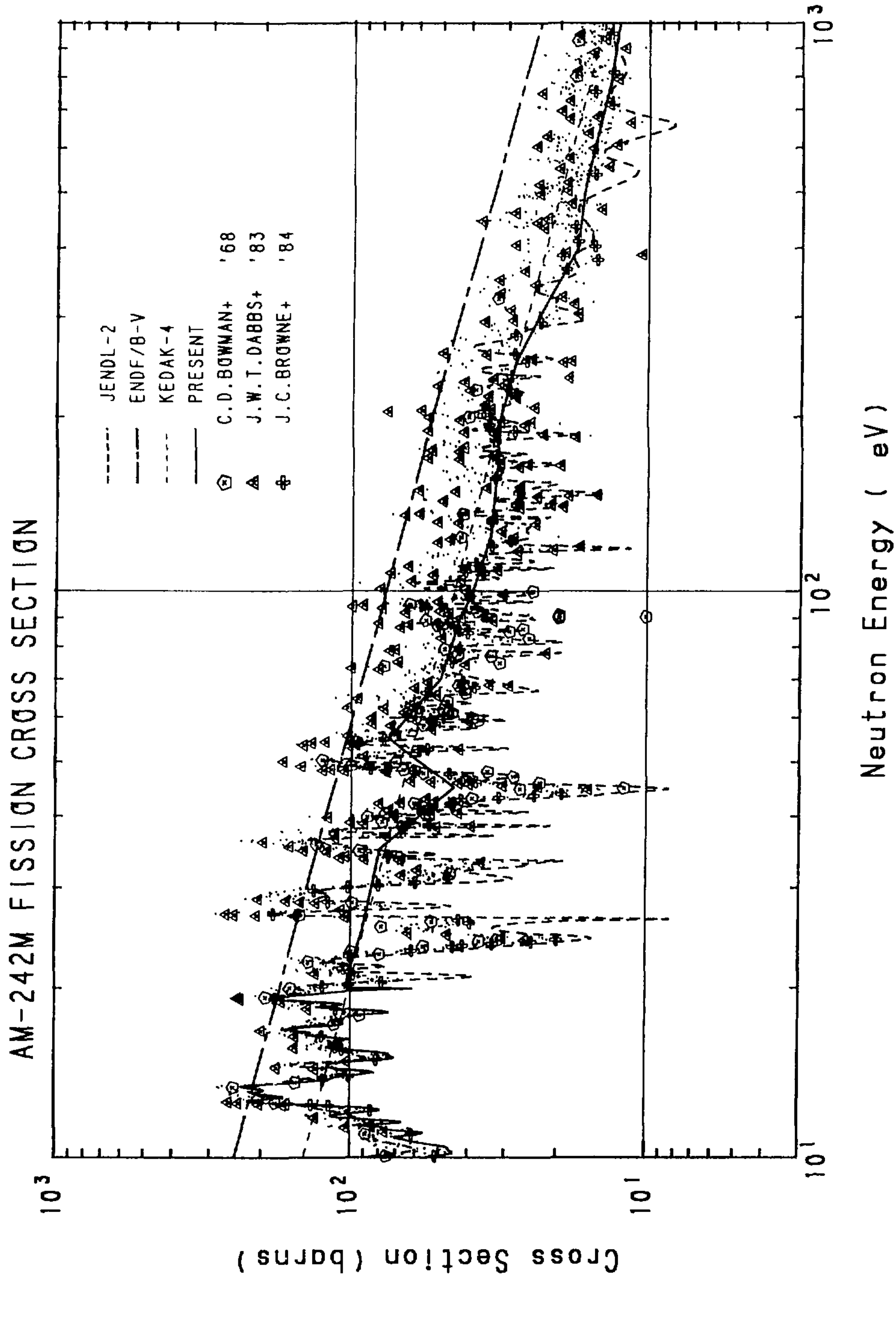

Fig. 26 Fission cross section of ^{242m}Am in the unresolved resonance region.

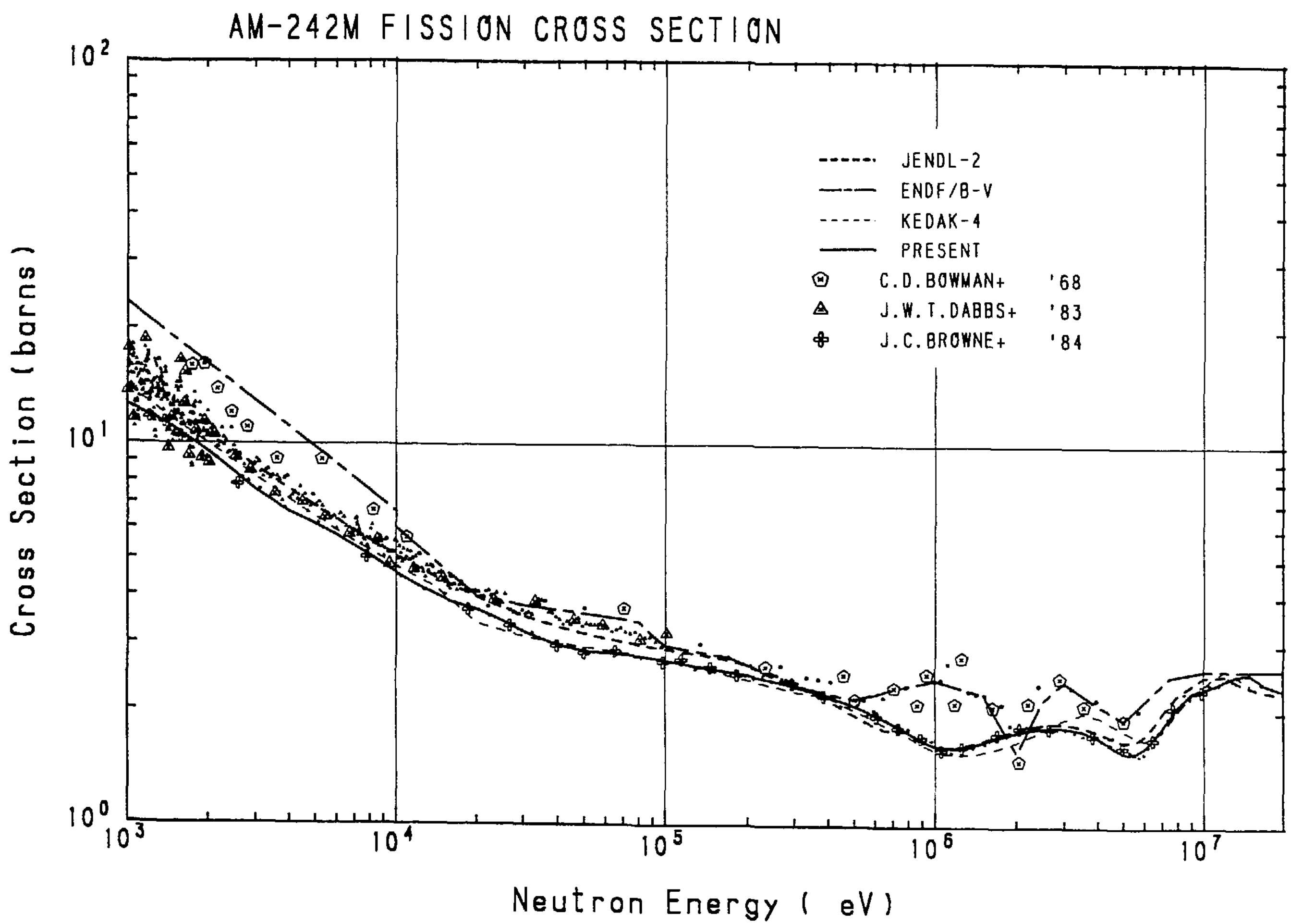

Fig. 27 Fission cross section of ^{242m}Am in the energy range from 1 keV to 20 MeV.

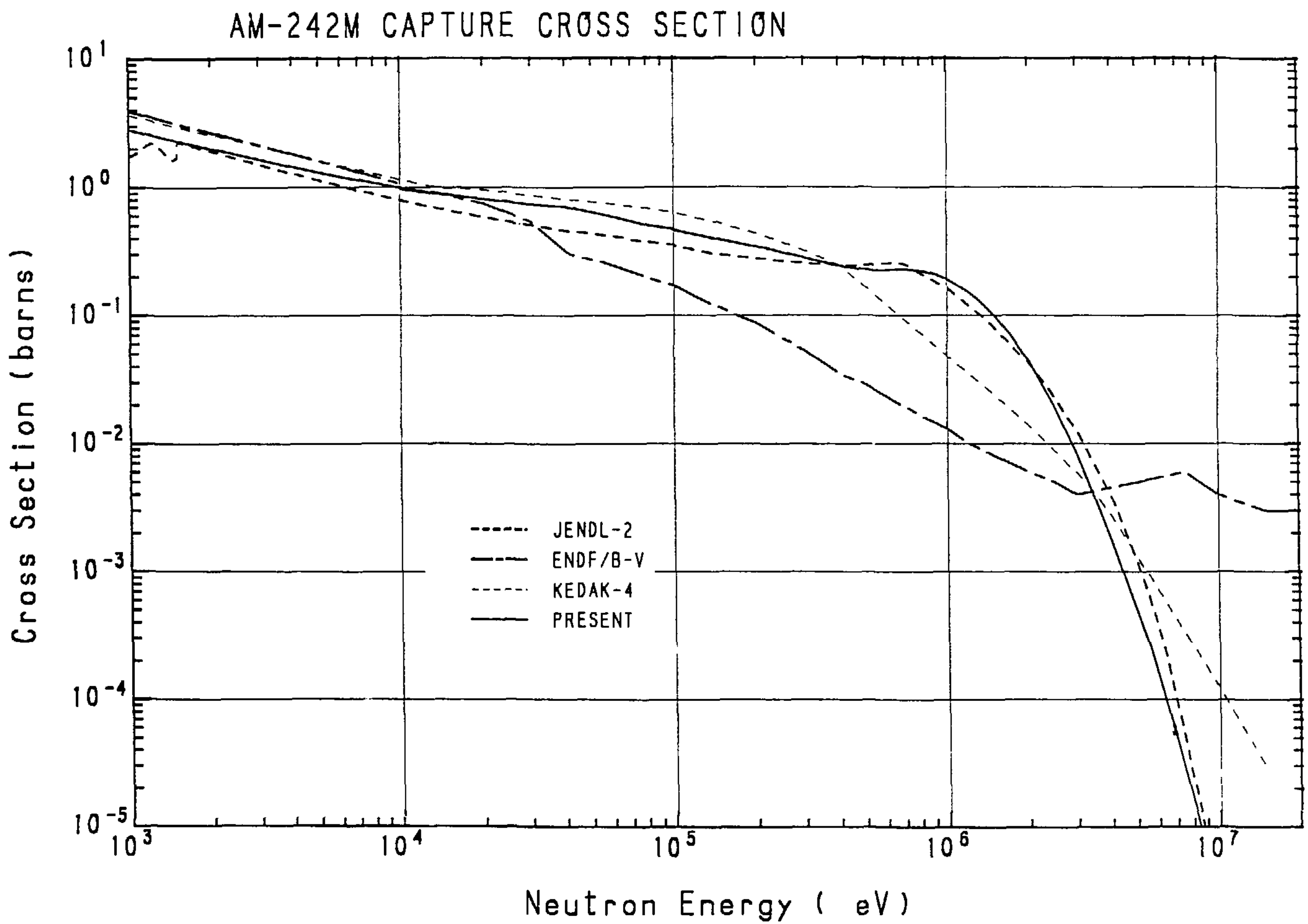

Fig. 28 Capture cross section of ^{242m}Am.

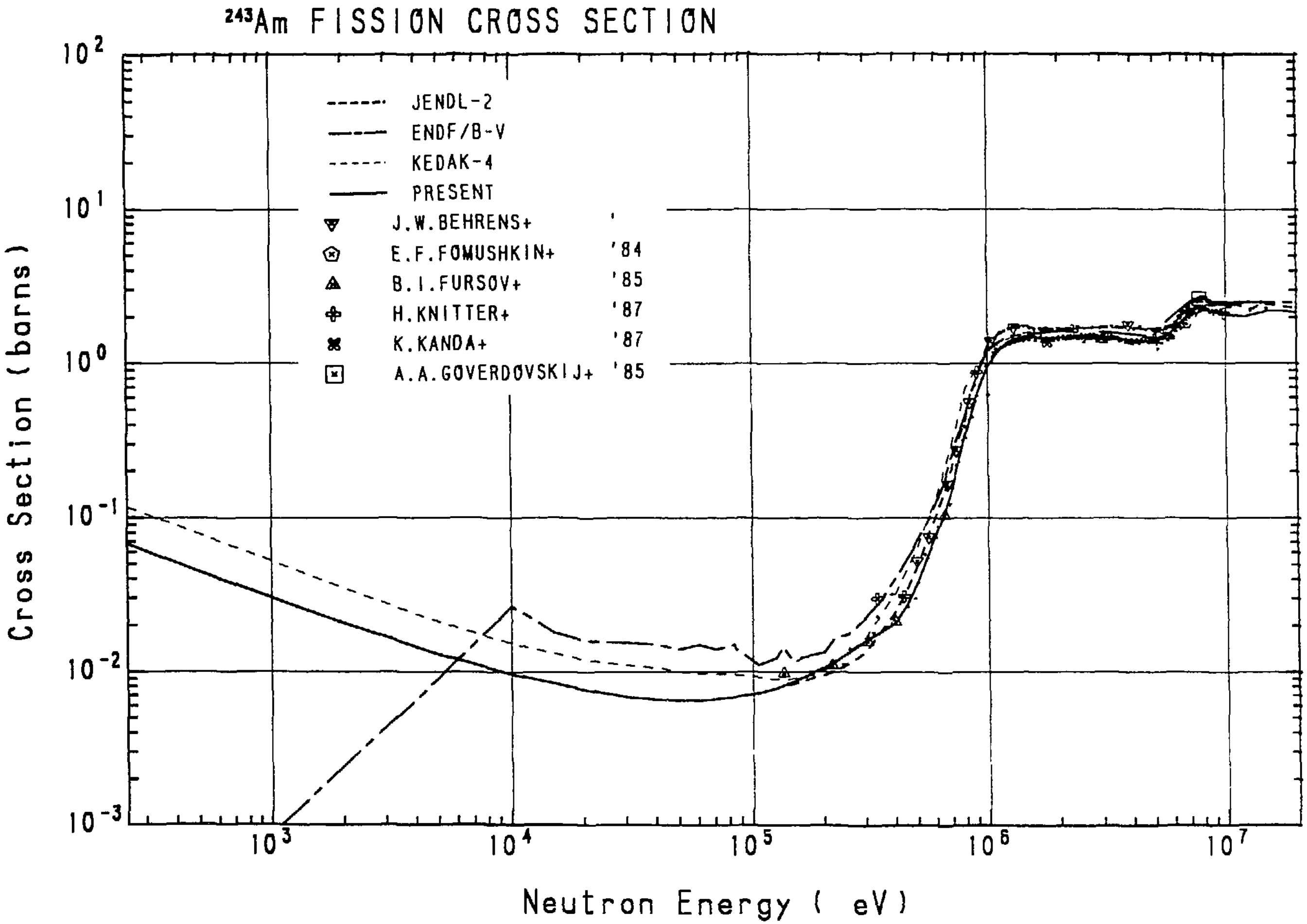

Fig. 29 Fission cross section of ^{243}Am in the energy range above 250 eV.

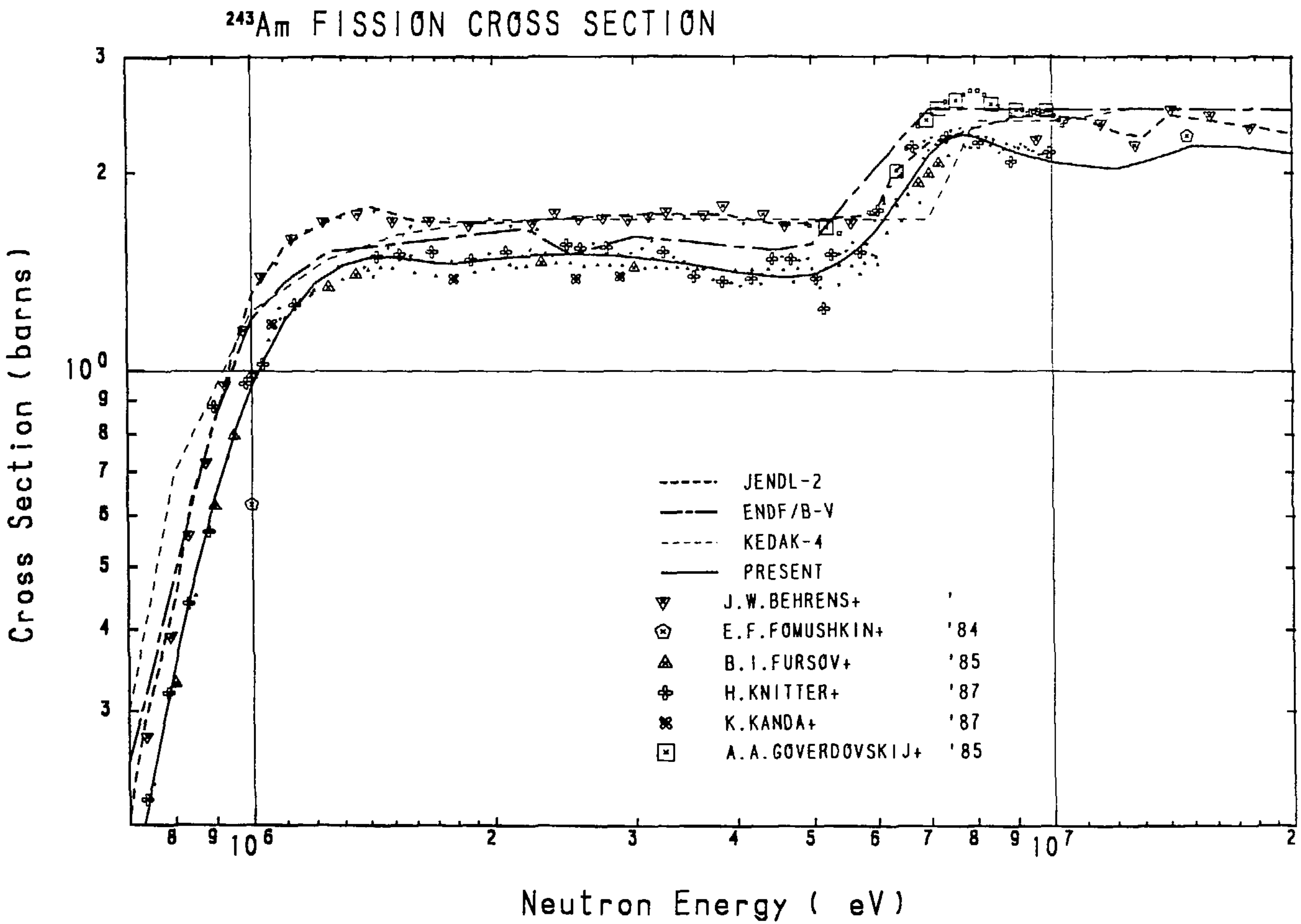

Fig. 30 Fission cross section of ^{243}Am in the energy range above 700 keV.

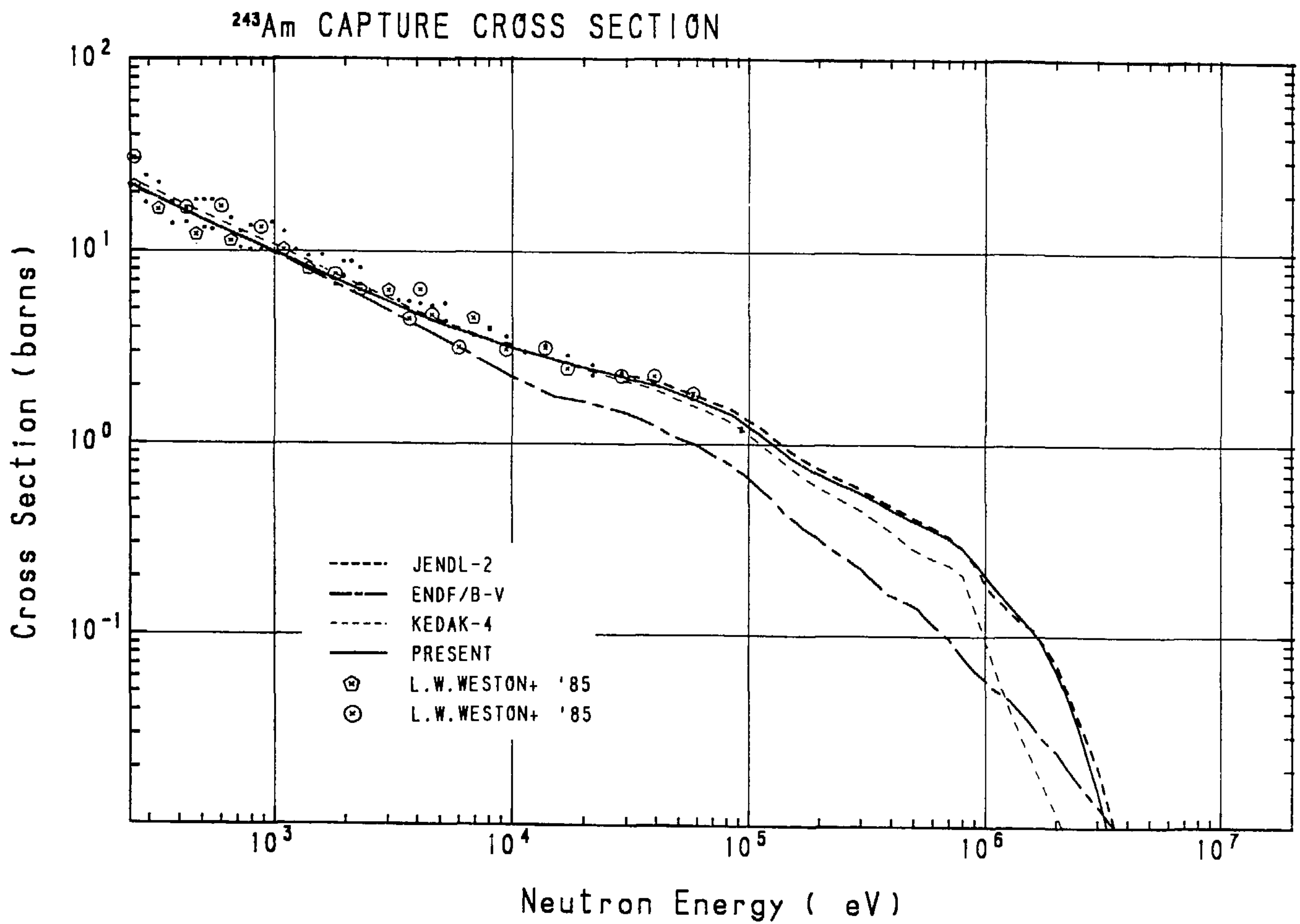

Fig. 31 Capture cross section of ^{243}Am.

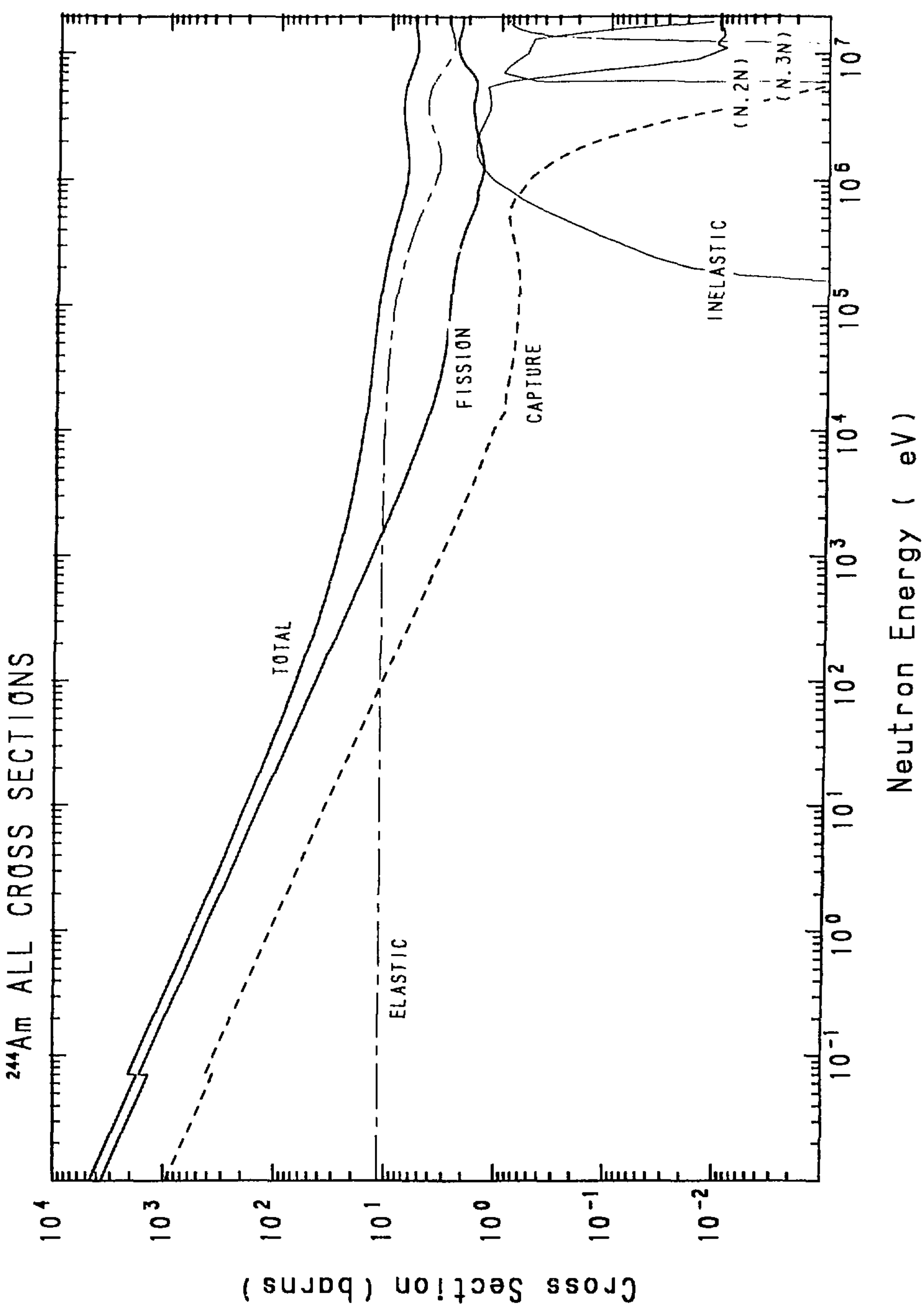

Fig. 32 Cross sections of ^{244g}Am.

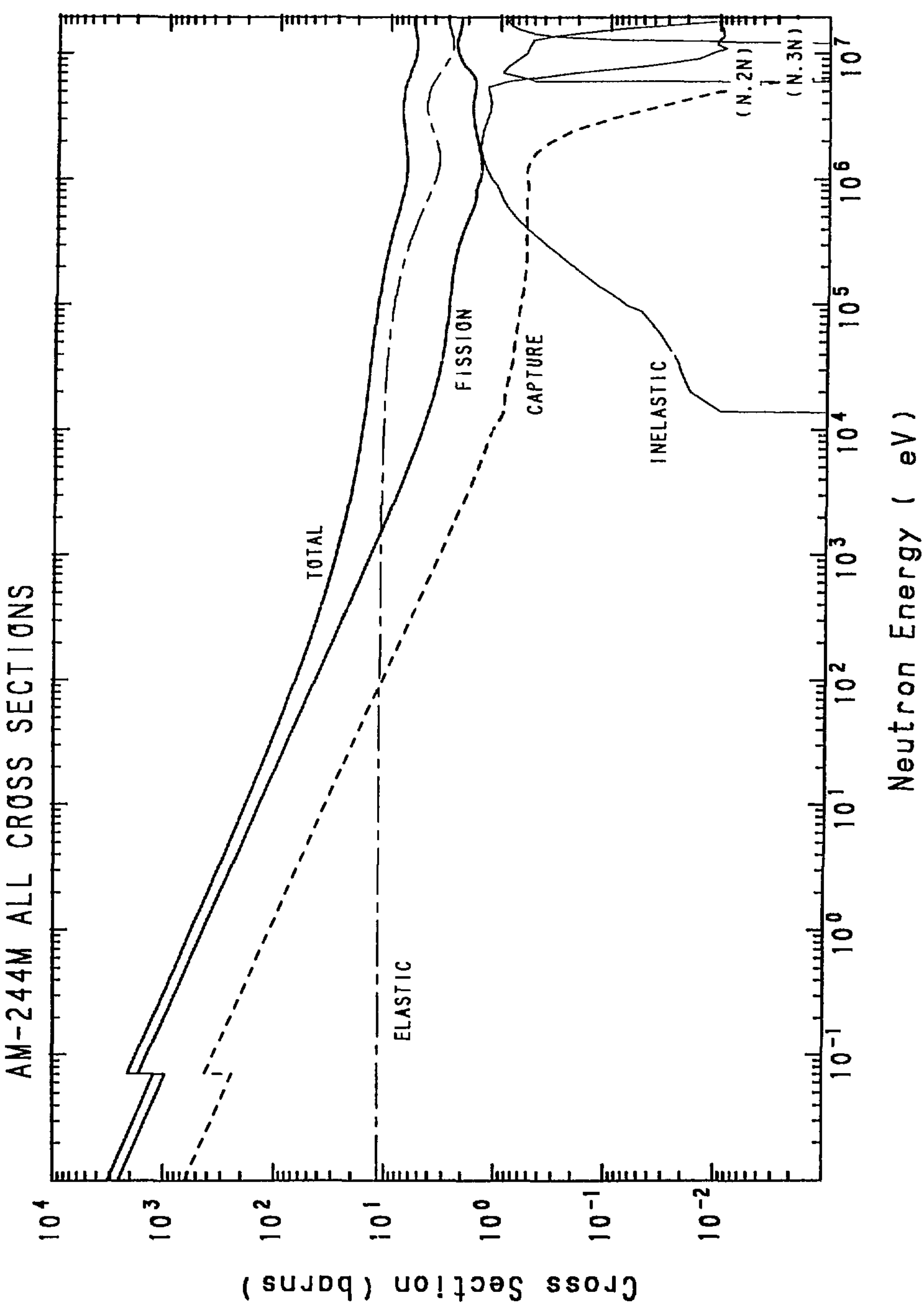

Fig. 33 Cross sections of ^{244m}Am.