IPPJ-AM-56

TOTAL AND PARTIAL CROSS SECTIONS FOR ELECTRON CAPTURE FOR C^{q+}(q=6−2) AND O^{q+}(q=8−2) IONS IN COLLISIONS WITH H, H_2 AND He ATOMS

H.TAWARA

INSTITUTE OF PLASMA PHYSICS
NAGOYA UNIVERSITY

NAGOYA, JAPAN

IPPJ-AM-56

TOTAL AND PARTIAL CROSS SECTIONS FOR ELECTRON CAPTURE FOR C^{q+} (q=6−2) AND O^{q+} (q=8−2) IONS IN COLLISIONS WITH H, H_2 AND He ATOMS

H. Tawara

Institute of Plasma Physics, Nagoya University
Chikusa-ku, Nagoya 464, Japan

October 1987

Abstract

Experimental and theoretical total and partial cross sections for single and double electron capture of C^{q+} and O^{q+} ions in colliding with H, H_2 and He targets are surveyed. Presently available data for these ions are summarized in the following table:

ion / Target		C^{q+}			O^{q+}		
		H	H_2	He	H	H_2	He
Ionic charge q	8				P	T	P
	7				T	T	T
	6	P	T	P	P	P	P
	5	T	T	T	T	T	T
	4	P	T	P	T	T	T
	3	P	P	P	P	T	T
	2	P	T	T	P	T	P
	1	T	T		T	T	T

Note : T and P indicate that the investigations or measurements for total and partial cross sections have been made, respectively.

Introduction

This report is concerned with a survey of total and partial cross sections for electron capture for C^{q+}(q=6-2) and O^{q+}(q=8-2) ions in collisions with H, H_2 and He atoms. These C^{q+} and O^{q+} ions are very typical impurity ions in all fusion plasma apparatus, whereas H, H_2 and He are copious there. These collisions are known to play a key role in plasmas. Therefore, data for these processes are requisite for understanding the behavior of plasmas. In most of such electron capture processes, an electron is captured into excited states of ions, resulting in photon emissions when these ions are relaxed. These photons are one of the important parameters in evaluating the energy balance in plasmas and also one of the most useful techniques to diagnose and investigate plasmas.

These data are urgently needed by plasma community. Here we have made a quick survey for these data, in particular those for partial cross sections involving the impurity ions mentioned above and compiled them in graphical forms. As total cross sections for these processes are already available,[1-4] we plan to make more extended compilations of these data for partial cross sections in the near future. So we strongly hope that anyone who makes new experiments and calculations supply us new and reliable data on these electron capture processes in order to make the revised version of this compilation.

References

1. H. Tawara, T. Kato, and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. K.W. Wu, H.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables (to be published)
3. R. A. Phaneuf, R.K. Janev and M.S. Pindzola (editors), ORNL-6090 (Oak Ridge National Laboratory, 1987)
4. R.K. Janev, B.H. Bransden and J.W. Gallagher, J. Phys. Chem. Ref. Data 12 (1983) 829: J.W. Gallagher, B.H. Bransden and R.K. Janev, ibid 12 (1983) 873: R.K. Janev and J.W. Gallagher, ibid 13 (1984) 1199

In the following are shown some abbreviated notations for theoretical methods:

MO : Molecular orbital expansion calculation

AO : Atomic orbital expansion calculation

AO-MO : Atomic orbital-orbital matching method

LZ : Landau-Zener method

MLZRC : Multichannel Landau-Zener model with rotational coupling

PSS : Perturbed stationary state method

CC : Close coupling calculation

SCA : Semiclassical approximation

OBK : Oppenheimer-Born-Kramer calculation

SPB : Strong potential Born calculation

UDWA : Unitarized distorted-wave approximation

EDWA : Exponential distorted-wave approximation

CDWA : Continuum distoreted-wave approximation

R : R-matrix calculation

CTMC : Classical trajectory Monte Carlo calculation

Acknowledgements

The author would like to thank Dr. T. Kato and M. Suga for making a series of the graphs shown here. He is also grateful to Prof. N. Shimakura and Dr. T. Ohyama-Yamaguchi for providing numerical tables for their calculated results. A lot of typing work of the present manuscript by M. Itonaga, M. Udaka and S. Ito is highly appreciated.

List of electron capture processes

I C^{q+} + H(1s) collisions

I-1 $C^{6+} + H(1s) \rightarrow C^{5+}(n\ell) + H^+$

I-2 $C^{5+}(1s) + H(1s) \rightarrow C^{4+}(1sn\ell) + H^+$

I-3 $C^{4+}(1s^2) + H(1s) \rightarrow C^{3+}(1s^2n\ell) + H^+$

I-4 $C^{3+}(1s^22s) + H(1s) \rightarrow C^{2+}(1s^22\ell n\ell') + H^+$

I-5 $C^{2+}(1s^22s^2) + H(1s) \rightarrow C^+ + H^+$

II C^{q+} + H_2 collisions

II-1 $C^{6+} + H_2 \rightarrow C^{5+}(n\ell) + H_2^+,\ C^{4+}(n\ell n'\ell') + H_2^{2+}$

II-2 $C^{5+}(1s) + H_2 \rightarrow C^{4+}(1sn\ell) + H_2^+,\ C^{3+}(1sn\ell n'\ell') + H_2^{2+}$

II-3 $C^{4+}(1s^2) + H_2 \rightarrow C^{3+}(1s^2n\ell) + H_2^+,\ C^{2+}(1s^2n\ell n'\ell') + H_2^{2+}$

II-4 $C^{3+}(1s^22s) + H_2 \rightarrow C^{2+}(1s^22\ell n\ell') + H_2^+,\ C^+ + H_2^{2+}$

III C^{q+} + He Collisions

III-1 $C^{6+} + He \rightarrow C^{5+}(n\ell) + He^+,\ C^{4+}(n\ell n'\ell') + He^{2+}$

III-2 $C^{5+}(1s) + He \rightarrow C^{4+}(1sn\ell) + He^+,\ C^{3+}(1sn\ell n'\ell') + He^{2+}$

III-3 $C^{4+}(1s^2) + He \rightarrow C^{3+}(1s^2n\ell) + He^+,\ C^{2+}(1s^2n\ell n'\ell') + He^{2+}$

III-4 $C^{3+}(1s^22s) + He \rightarrow C^{2+}(1s^22sn\ell) + He^+,\ C^+ + He^{2+}$

III-5 $C^{2+}(1s^22s^2) + He \rightarrow C^+(1s^22s^22p\ ^2P) + He^+,\ C^0 + He^{2+}$

IV O^{q+} + H collisions

IV-1 $O^{8+} + H(1s) \rightarrow O^{7+}(n\ell) + H^+$

IV-2 $O^{7+}(1s) + H(1s) \rightarrow O^{6+}(1sn\ell) + H^+$

IV-3 $O^{6+}(1s^2) + H(1s) \rightarrow O^{5+}(1s^2n\ell) + H^+$

IV-4 $O^{4+}(1s^22s^2) + H(1s) \rightarrow O^{3+}(1s^22s^2n\ell) + H^+$

IV-5 $O^{3+}(1s^22s^22p) + H(1s) \rightarrow O^{2+}(1s^22s^22pn\ell) + H^+$

IV-6 $O^{2+}(1s^22s^22p^2) + H(1s) \rightarrow O^+ + H^+$

V O^{q+} + H_2 collisions

V-1 $O^{8+} + H_2 \rightarrow O^{7+}(n\ell) + H_2^+,\ O^{6+}(n\ell n'\ell') + H_2^{2+}$

V-2 $O^{7+}(1s) + H_2 \rightarrow O^{6+}(1sn\ell) + H_2^+,\ O^{5+}(1sn\ell n'\ell') + H_2^{2+}$

V-3 $O^{6+}(1s^2) + H_2 \rightarrow O^{5+}(1s^2n\ell) + H_2^+,\ O^{4+}(1s^2n\ell n'\ell') + H_2^{2+}$

V-4 $O^{2+}(1s^22s^22p^2) + H_2 \rightarrow O^+ + H_2^+,\ O^0 + H_2^{2+}$

VI O^{q+} + He collisions

VI-1 $O^{8+} + He \rightarrow O^{7+}(n\ell) + He^{+},\ O^{6+}(n\ell n'\ell') + He^{2+}$

VI-2 $O^{7+}(1s) + He \rightarrow O^{6+}(1sn\ell) + He^{+},\ O^{5+}(1sn\ell n'\ell') + He^{2+}$

VI-3 $O^{6+}(1s^2) + He \rightarrow O^{5+}(1s^2n\ell) + He^{+},\ O^{4+}(1s^2n\ell n'\ell') + He^{2+}$

VI-4 $O^{5+}(1s^22s) + He \rightarrow O^{4+}(1s^22sn\ell) + He^{+},\ O^{3+}(1s^22sn\ell n'\ell') + He^{2+}$

VI-5 $O^{4+}(1s^22s^2) + He \rightarrow O^{3+}(1s^22s^2n\ell) + He^{+},\ O^{2+}(1s^22s^2n\ell n'\ell') + He^{2+}$

VI-6 $O^{3+}(1s^22s^22p) + He \rightarrow O^{2+}(1s^22s^22pn\ell) + He^{+},\ O^{+}(1s^22s^22pn\ell n'\ell') + He^{2+}$

VI-7 $O^{2+}(1s^22s^22p^2) + He \rightarrow O^{+} + He^{+},\ O^{0} + He^{2+}$

I C^{q+} + H(1s) collisions

I-1 $C^{6+} + H(1s) \rightarrow C^{5+}(n\ell) + H^+$

Experimental data for total cross sections are summarized.[1] A number of total cross sections have been calculated using different techniques:

Salop and Olson[2]	(LZ model, 0.04 - 2.9 keV/amu)	1976
Olson and Salop[3]	(CTMC, 20 - 25 keV/amu)	1977
Bottcher[4]	(IP, <225 keV/amu)	1977
Vaaben and Briggs[5]	(MO basis, 1.06 - 6.25 keV/amu)	1977
Greenland[5a]	(S-matrix, 0.06 - 25 keV/amu)	1978
Ryufuku and Watanabe[6]	(UDWA, 0.025 - 2000 keV/amu)	1979
Crothers and Todd[7]	(exponential model, 0.25 - 25 keV/amu)	1980
Ryufuku[8]	(UDWA, 0.025 - 2000 keV/amu)	1982
Green et al.[9]	(LZ, 0.8 - 52 keV/amu)	1982
Green et al.[10]	(MO, 3 - 1300 eV/amu)	1982
Fritsch[11]	(AO, 0.1 - 1.0 keV/amu)	1982
Suzuki et al.[12]	(EDWA, 0.1 - 10 keV/amu)	1984
Toshima and Watanabe[13]	(DWA, 0.2 - 500 keV/amu)	1986
Kimura[14]	(travelling MO, 0.15 - 10 keV/amu)	1986
Kimura and Lane[15]	(travelling MO, 0.15 - 10 keV/amu)	1987.

It should be noted that the electron capture cross sections from hydrogen atoms in the 2s excited states calculated by Salop[16] are far large and nearly constant over the energy range 0.02 - 2.5 keV/amu (~ 3 x 10^{-14} cm^2) and even at the highest energies are larger by one order of magnitude, compared with those for the ground state which increase sharply with increasing the energy:

$$C^{6+} + H(2s) \rightarrow C^{5+}(n\ell) + H^+ . \qquad (1)$$

Janev et al.[17], using MLZRC technique, calculated the n-dependence of the cross sections over 0.05 - 64 keV/amu with n=4 dominance.

At the selected energies the cross sections for ($n\ell$) distributions have been also calculated:

Ryufuku and Watanabe[18](UDWA, 25, 75 keV/amu) 1979
Hardie and Olson[19] (CTMC, 25, 50 keV/amu) 1983
Presnyakow and Uskov[20](Keldysh model, $n\ell=4\ell$, 25 keV/amu)1984
Grozdanov and Belic[21] (LZ, $n\ell=4\ell$, 0.5 - 20 keV/amu) 1984.

More systematic calculations for ($n\ell$) distributions have been reported as follows:

Salop[22](CTMC, 25 - 72 keV/amu) 1979
Green et al.[23] (MO, 0.01 - 27 keV/amu) 1982
Kazanskii and Komarov[24](MO, $n\ell=4\ell$, 5ℓ, 0.25 - 4 keV/amu)1982
Fritsch and Lin[25] (AO, 0.1 - 20 keV/amu) 1984
Salin[26] (MO, 1.0 - 16 keV/amu) 1984
Bedahman et al.[27] (MO, 0.25 - 50 keV/amu) 1985
Kimura and Lin[28] (AO-MO, 0.2 - 4 keV/amu) 1985.

Fritsch[29] extended his calculation for less dominant ($n\ell$) states, namely for n=6, 7, 8 at 4,10 and 25 keV/amu. At higher energies, Crothers and McCann[30] calculated the ($n\ell m$) distributions using CDW and OBK over 5 - 2000 keV/amu. Recently Belkic et al.[31] reported ($n\ell$) distributions (n=1-7) at higher energies (200-3500 keV) calculated by the first Born approximation with correct boundary condition. Similar calculations were made by Dube and Burgdorfer.[31a] Experimental work is quite limited. Kimura et al.[32], using translational energy spectroscopy, observed the dominant channel of the electron capture into n=4 states. Using photon spectroscopy, Dijkkamp et al.[33] determined the emission cross sections for n=4 → n=2(13.5 nm), n=3 → n=2(18.2 nm) and n=4 → n=3 (52.1 nm) transitions. This measurement was extended by Hoekstra et al.[34] who determined the emission cross sections for n=4 → n=2 (13.5 nm), n=4 → n=3 (52.1 nm), n=3 → n=2 (18.2 nm), n=5 → n=3 (35.6 nm), n=7 → n=6 (343.5 nm)and n=8 → n=7 (529.5 nm) transitions over 1 - 9 keV/amu.

References

1. H. Tawara, T. Kato and Y. Nakai, At Data and Nucl. Data Tables 32 (1985)235
2. A. Salop and R.E. Olson, Phys. Rev. A 13 1312

3. R.E. Olson and A. Salop, Phys. Rev. A 16 (1977)531
4. C. Bottcher, J. Phys. B 10 (1977) L213
5. J. Vaaben and J.S. Briggs, J. Phys. B 10 (1977) L521
5a. P.T. Greenland, J. Phys. B 12 (1978) L191
6. H. Ryufuku and T. Watanabe, Phys. Rev. A 19 (1979) 1538
7. D.S.F. Crothers and N.R. Todd, J. Phys. B 13 (1980) 547
8. H. Ryufuku, Phys. Rev. A 25(1982) 720
9. T.A. Green, J.M. Peek, M.E. Riley, E.J. Shipsey and J.C. Browne, Phys. Rev. A 26 (19820 1278
10. T.A. Green, M.E. Riley, E.J. Shipsey and J.C. Browne, Phys. Rev. A 26 (1982) 3668
11. W. Fritsch, J. Phys. B 15 (1982) L389
12. H. Suzuki, Y. Kajikawa, N. Toshima, H. Ryufuku and T.Watanabe, Phys. Rev. A 29(1984) 529
13. N. Toshima and T. Watanabe, Phys. Rev. A 33 (1986) 1382
14. M. Kimura, Phys. Rev. A 33 (1986) 4440
15. M. Kimura and N.F. Lane, Phys. Rev. A 35 (1987) 70
16. A. Salop, Phys. Rev. A 13(1976)1321
17. R.K. Janev, D.S. Belic and B.H. Bransden, Phys. Rev. A 28 (1983) 1293
18. H. Ryufuku and T. Watanabe, Phys. Rev. A 20 (1979) 1828
19. D.J.W. Hardie and R.E. Olson, J. Phys. B 16 (1983)1983
20. L.P. Presnyakov and D.B. Uskov, Sov. Phys.-JETP 59 (1984) 515
21. T.P. Grozdanov and D.S. Belic, Phys. Scripta 30 (1984) 194
22. A. Salop, J.Phys. B 12 (1979) 910
23. T.A. Green, E.J. Shipsey and J.C. Browne, Phys. Rev. A 25(1982) 1364
24. A.K. Kazanskii and I.V. Komarov, Sov. Phys.-Techn. Phys. 27 (1982) 1064
25. W. Fritsch and C.D. Lin, Phys. Rev. A 29 (1984) 3039
26. A. Salin, J. Physique 45 (1984) 671
27. M. Bedahaman, S. Bliman, S. Dousson, D. Hitz, R.Gayet, J. Hanssen, C. Harel and A. Salin, J. Physique 46 (1985) 561
28. M. Kimura and C.D. Lin, Phys. Rev. A 32 (1987) 1357
29. W. Fritsch, Phys. Rev. A 30 (1984) 3324

30. D.S.F. Crothers and J.F. McCann, Phys. Letters 92A (1982) 170
31. D. Belkic, S. Saini and H.S. Taylor, Phys. Rev. A 36 (1987) 1601
31a. L.J. Dube and J. Burgdorfer, Nucl. Instr. Meth. in Phys. Res. B 9 (1985) 392
32. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873
33. D. Dijkkamp, D. Ciric and F.J. de Heer, Phys. Rev. Letters 54 (1985) 1004
34. R. Hoekstra, D. Ciric, A.N. Zinoviev, Yu.S. Gordeev, F.J. de Heer and R. Morgenstern, to be published

Fig.1 $C^{6+} + H \dashrightarrow C^{5+}(\text{total}) + H^{+}$

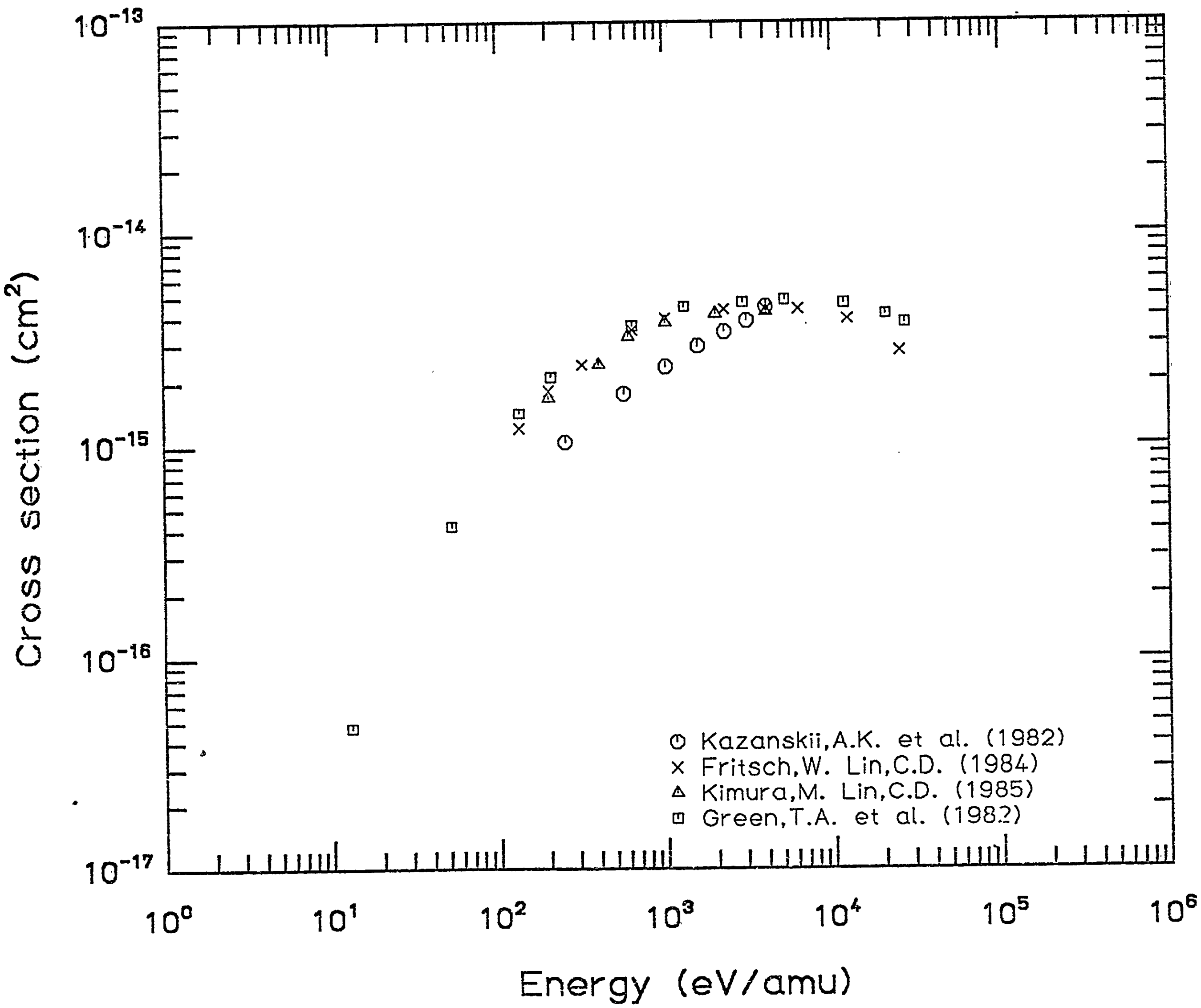


Fig.2 $C^{6+} + H \rightarrow C^{5+}(3s) + H^{+}$

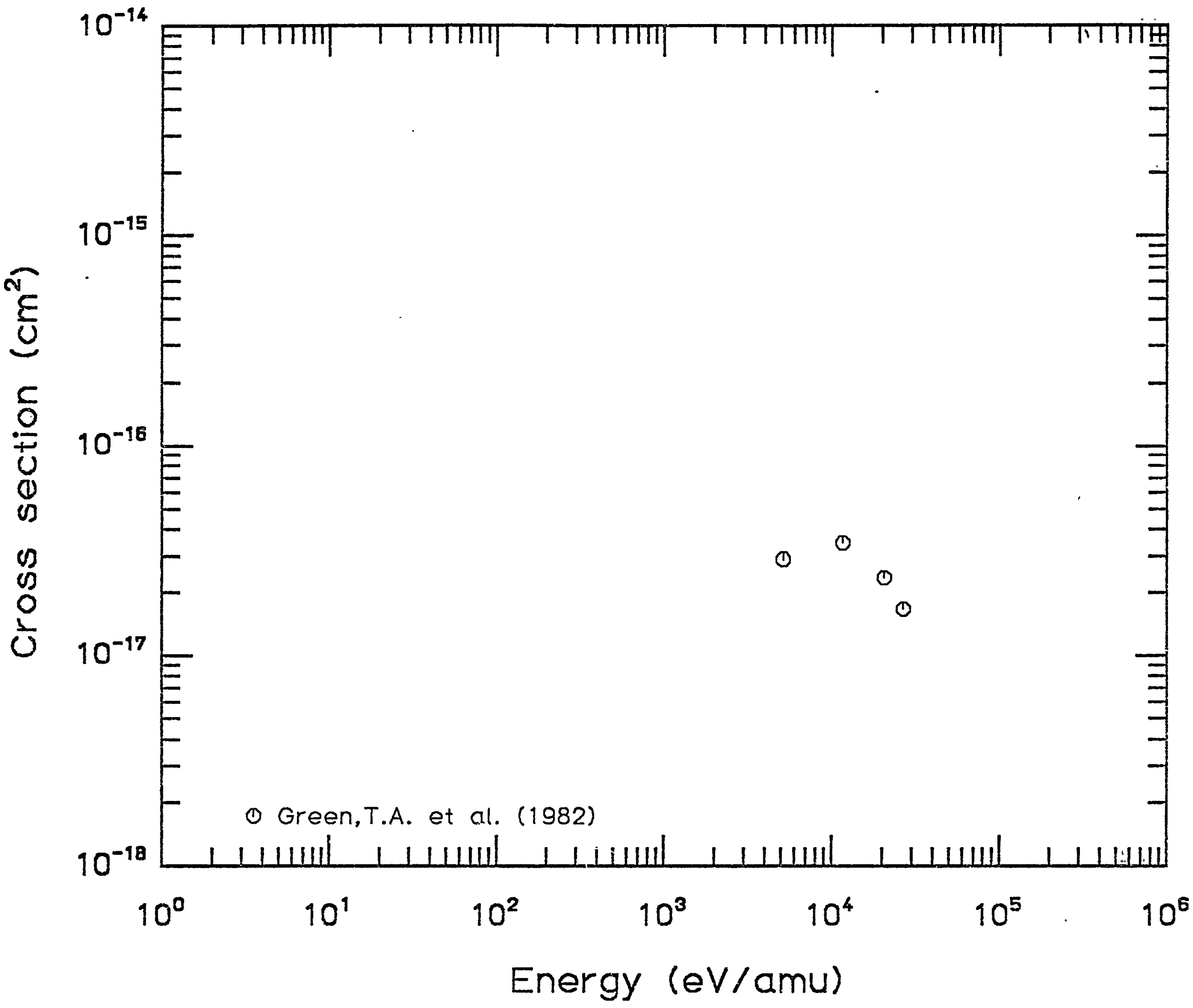


Fig.3 $C^{6+} + H \dashrightarrow C^{5+}(3p) + H^{+}$

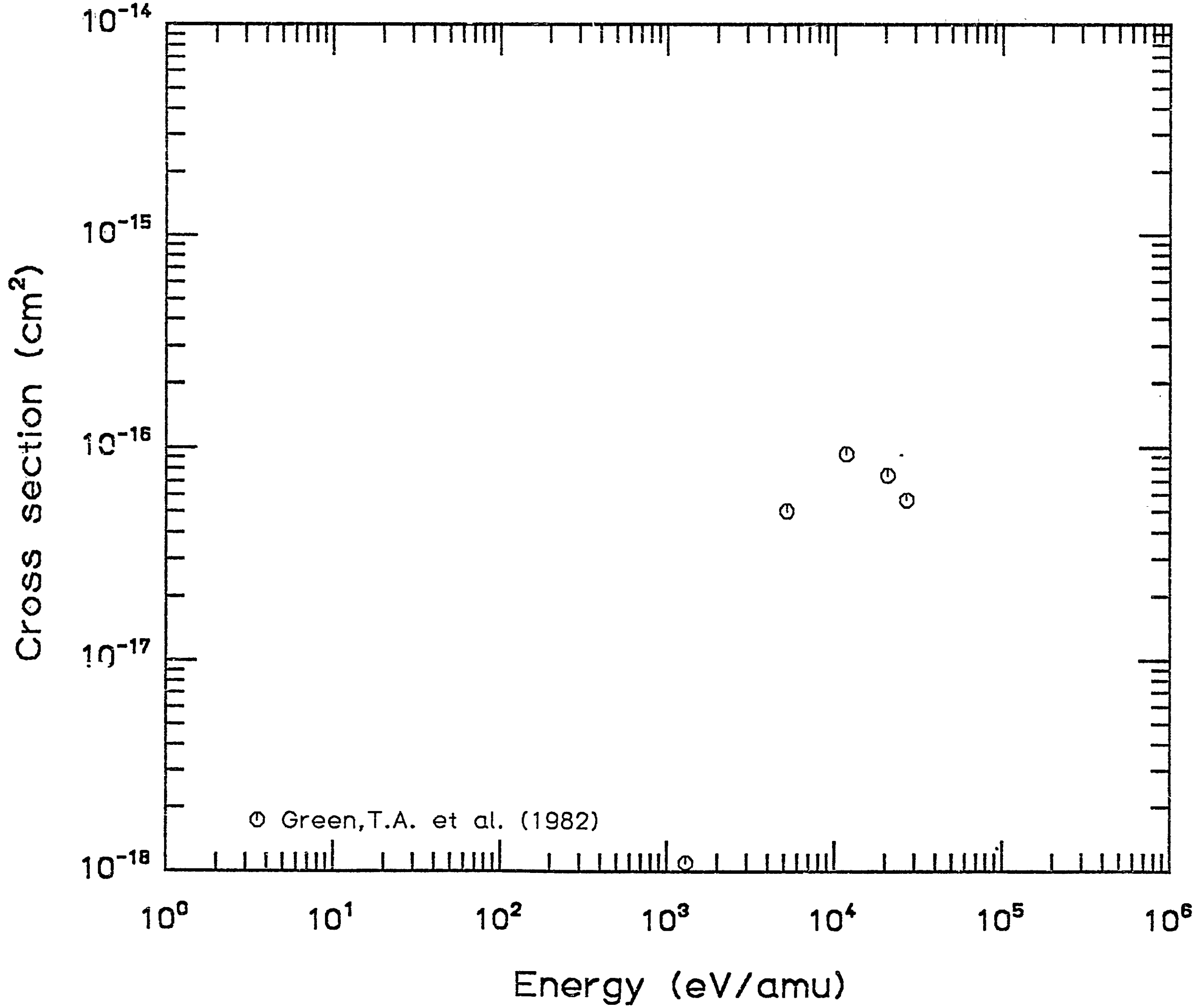


Fig.4 $C^{6+} + H \longrightarrow C^{5+}(3d) + H^{+}$

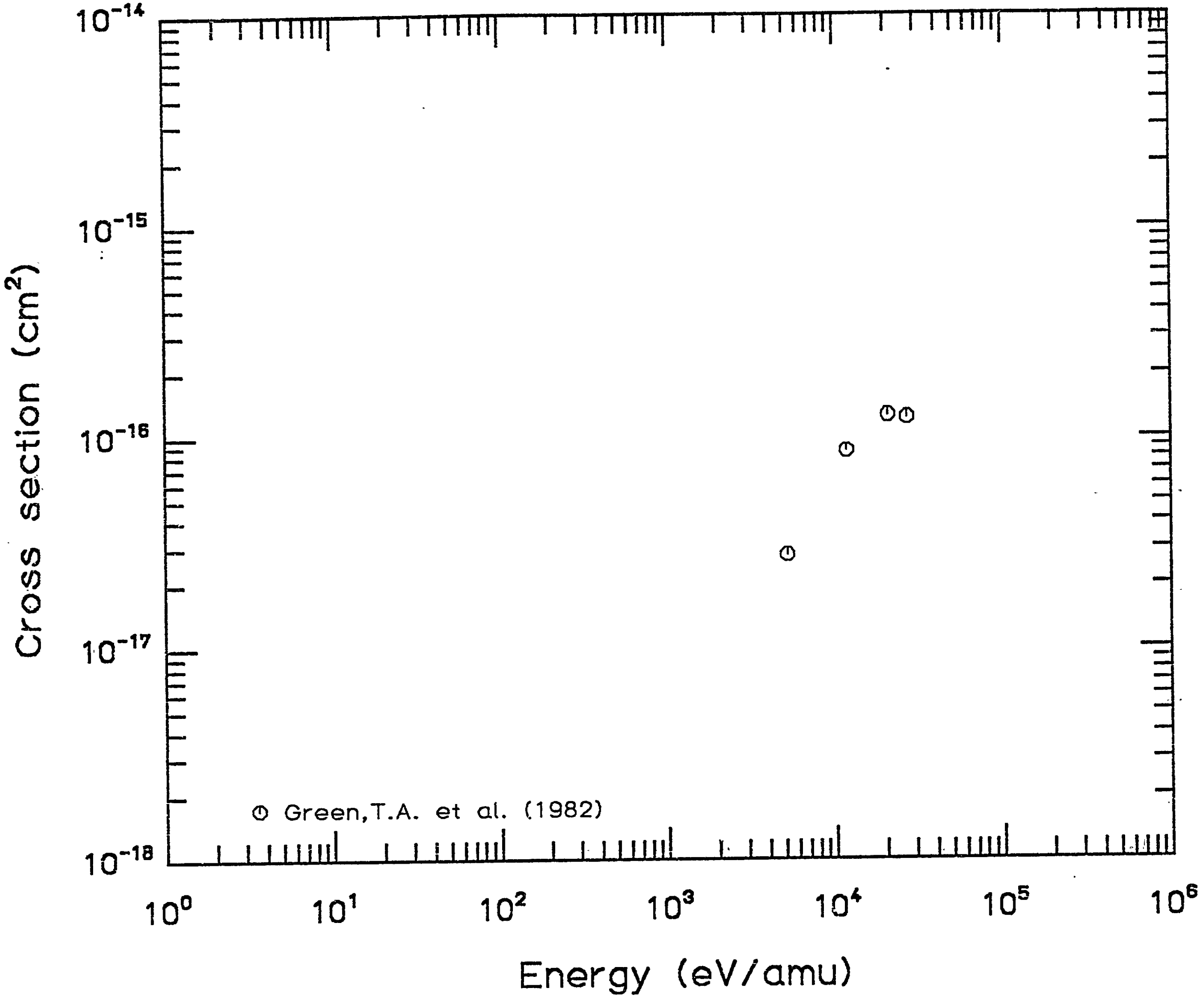


Fig.5 $C^{6+} + H \dashrightarrow C^{5+}(4s) + H^{+}$

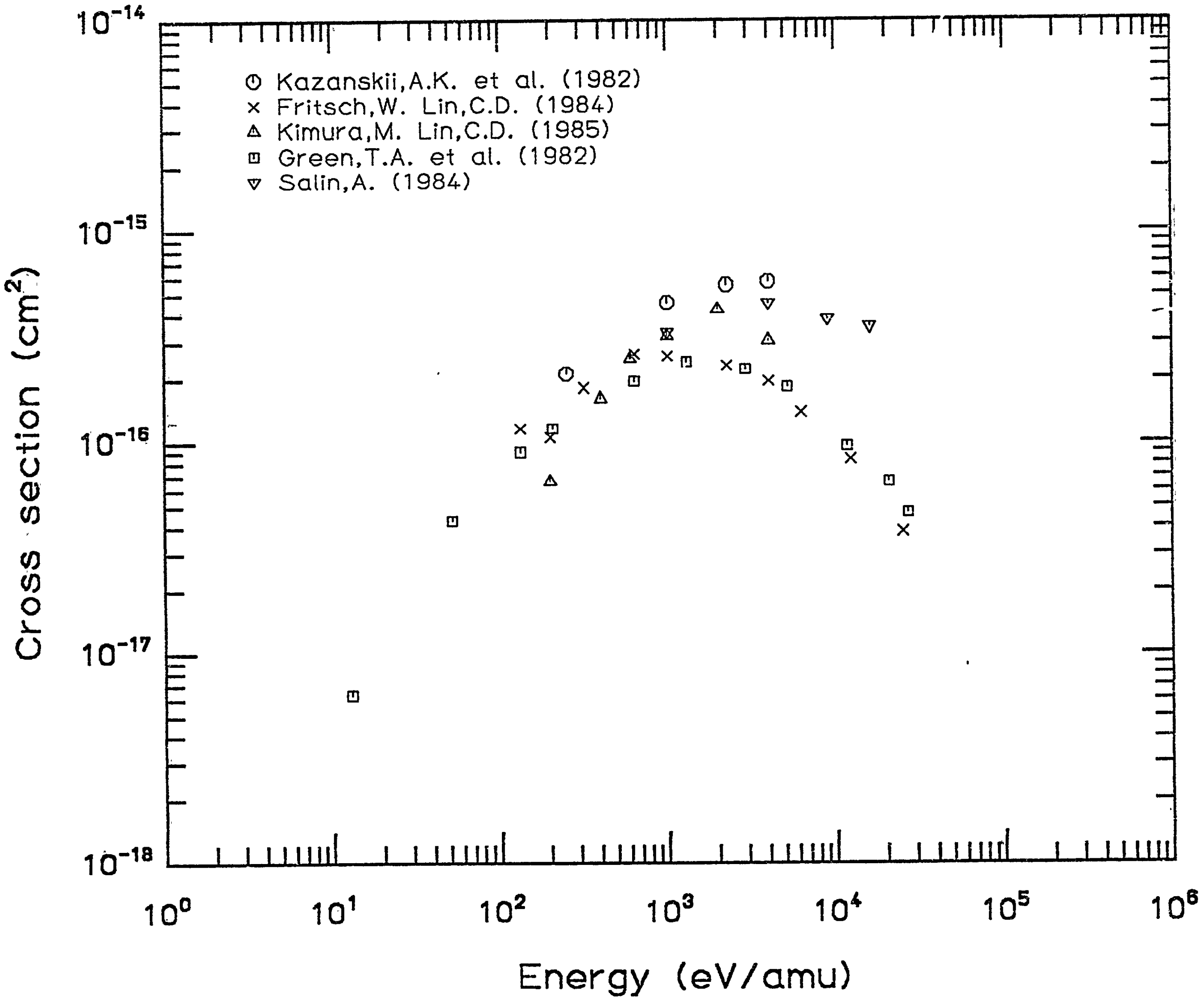


Fig.6 $C^{6+} + H \rightarrow C^{5+}(4p) + H^{+}$

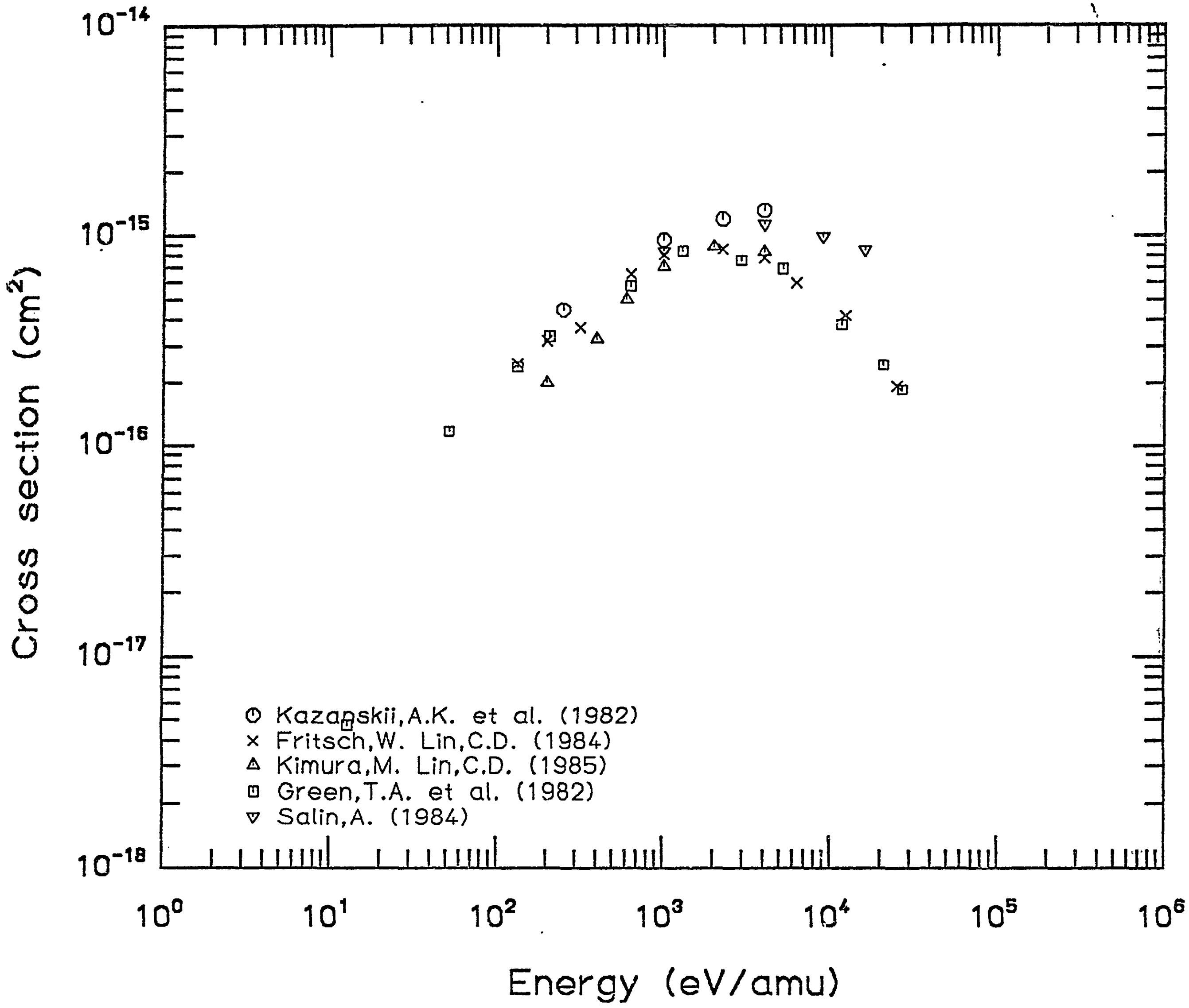


Fig.7 $C^{6+} + H \dashrightarrow C^{5+}(4d) + H^{+}$

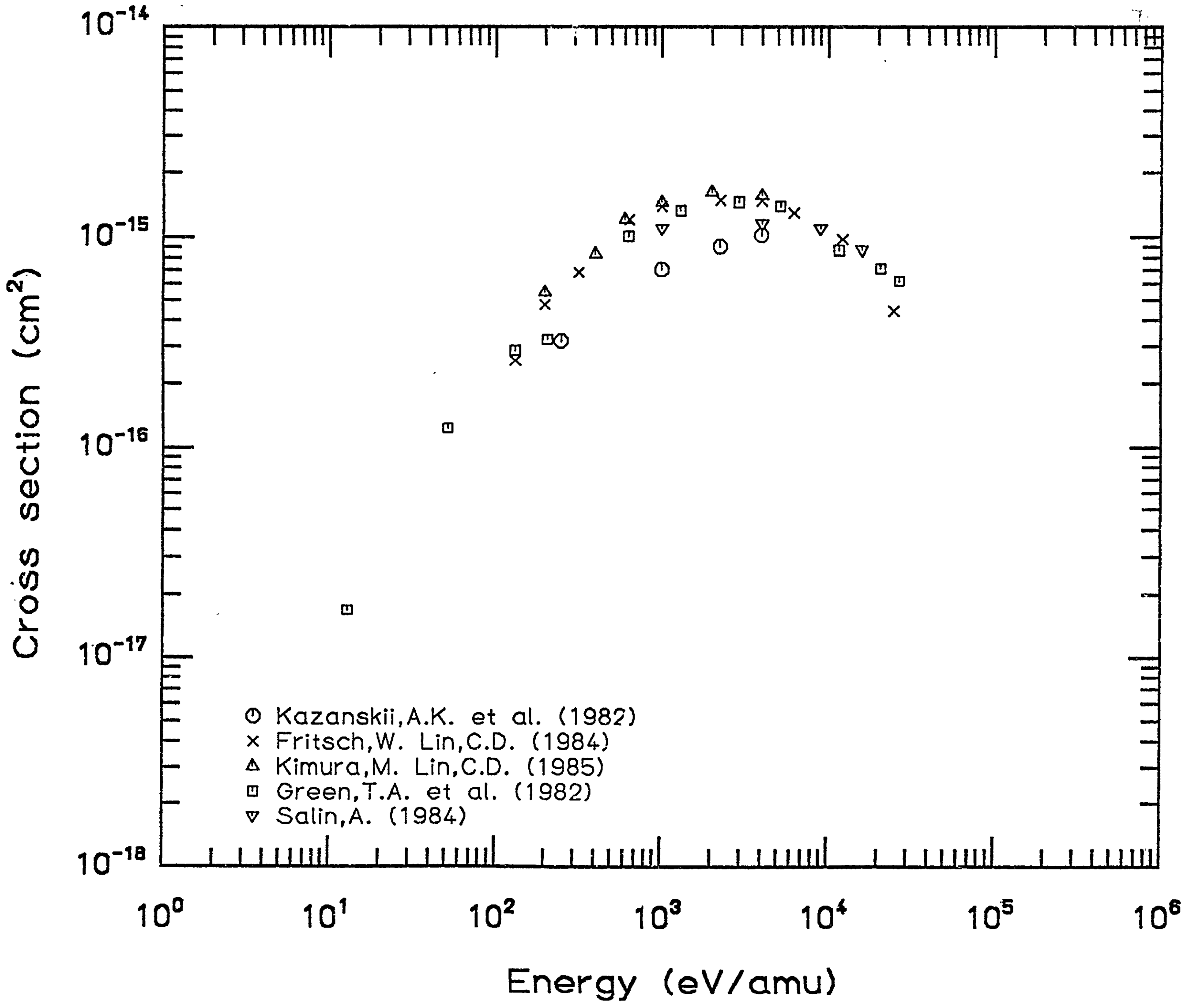


Fig.8 $C^{6+} + H \dashrightarrow C^{5+}(4f) + H^{+}$

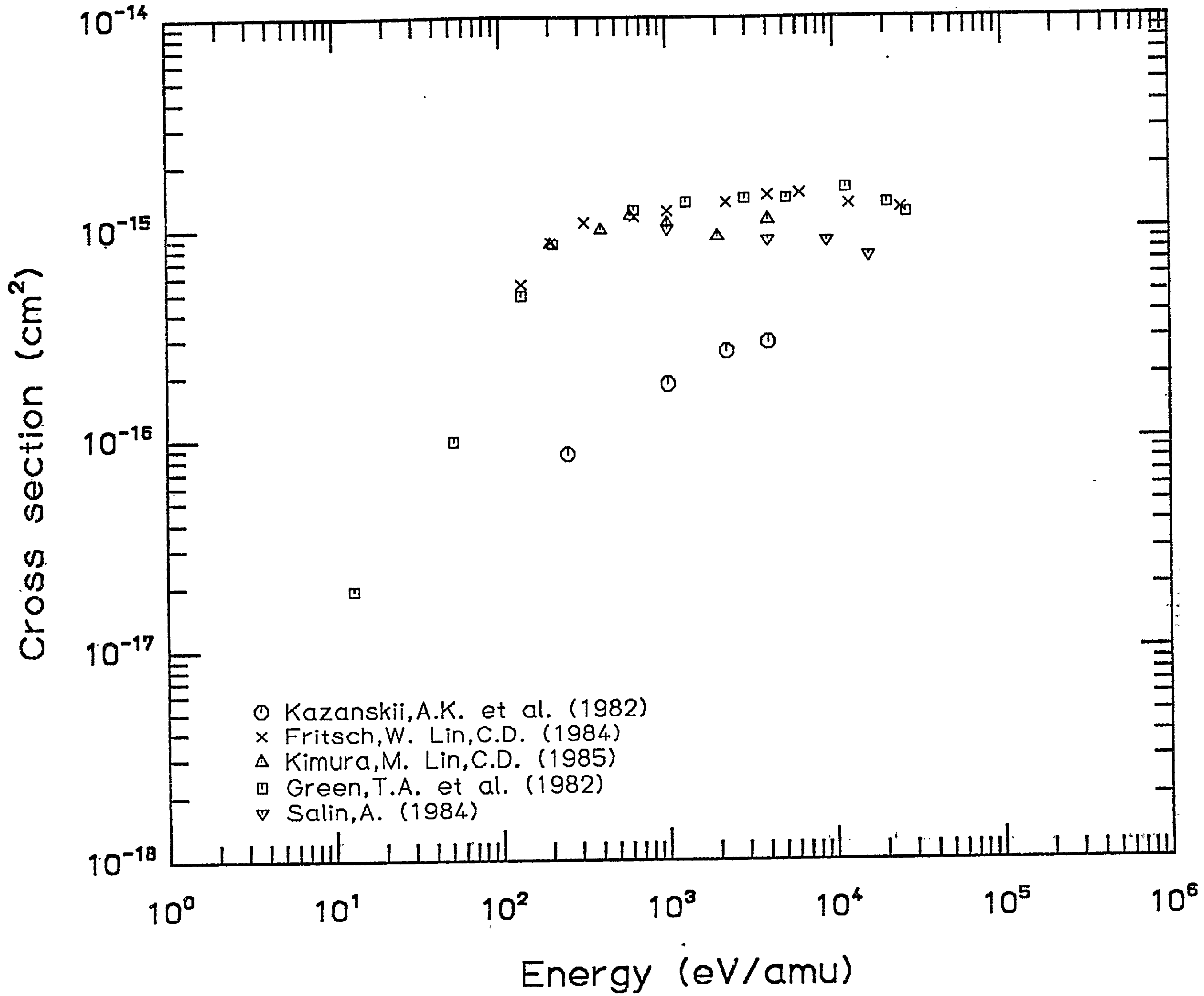


Fig.9 $C^{6+} + H \dashrightarrow C^{5+}(5s) + H^{+}$

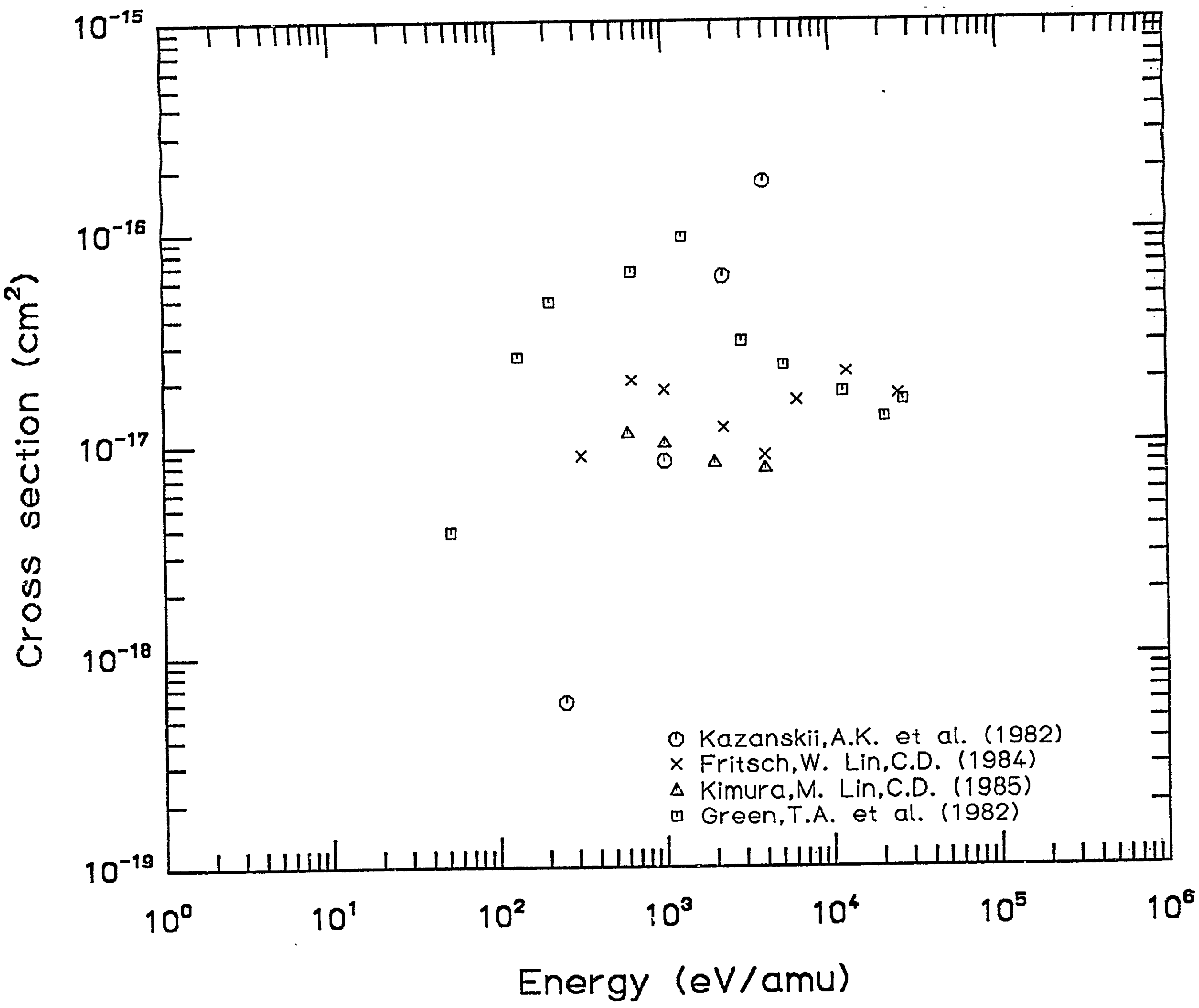


Fig.10 $C^{6+} + H \dashrightarrow C^{5+}(5p) + H^{+}$

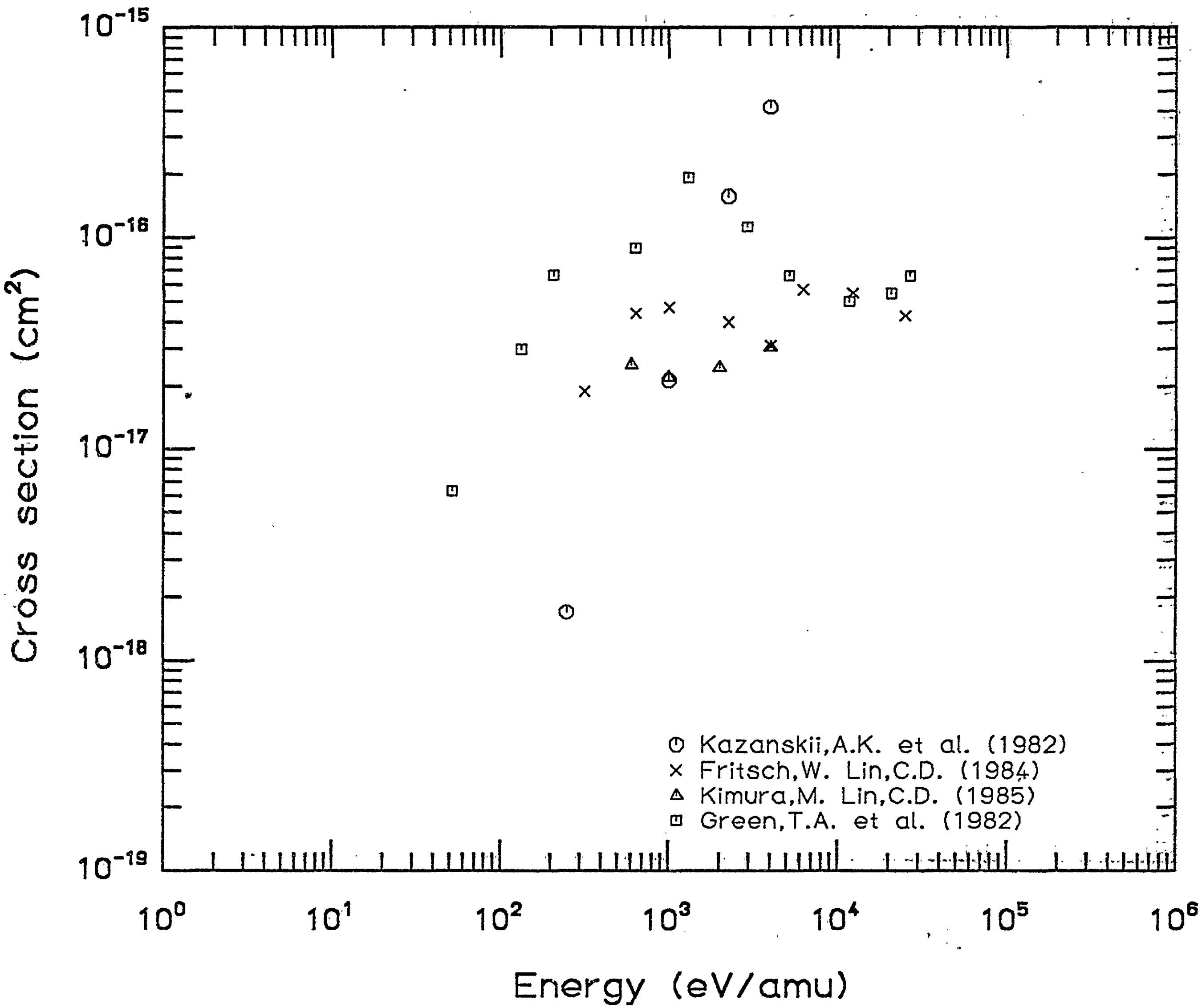


Fig.11 $C^{6+} + H \dashrightarrow C^{5+}(5d) + H^{+}$

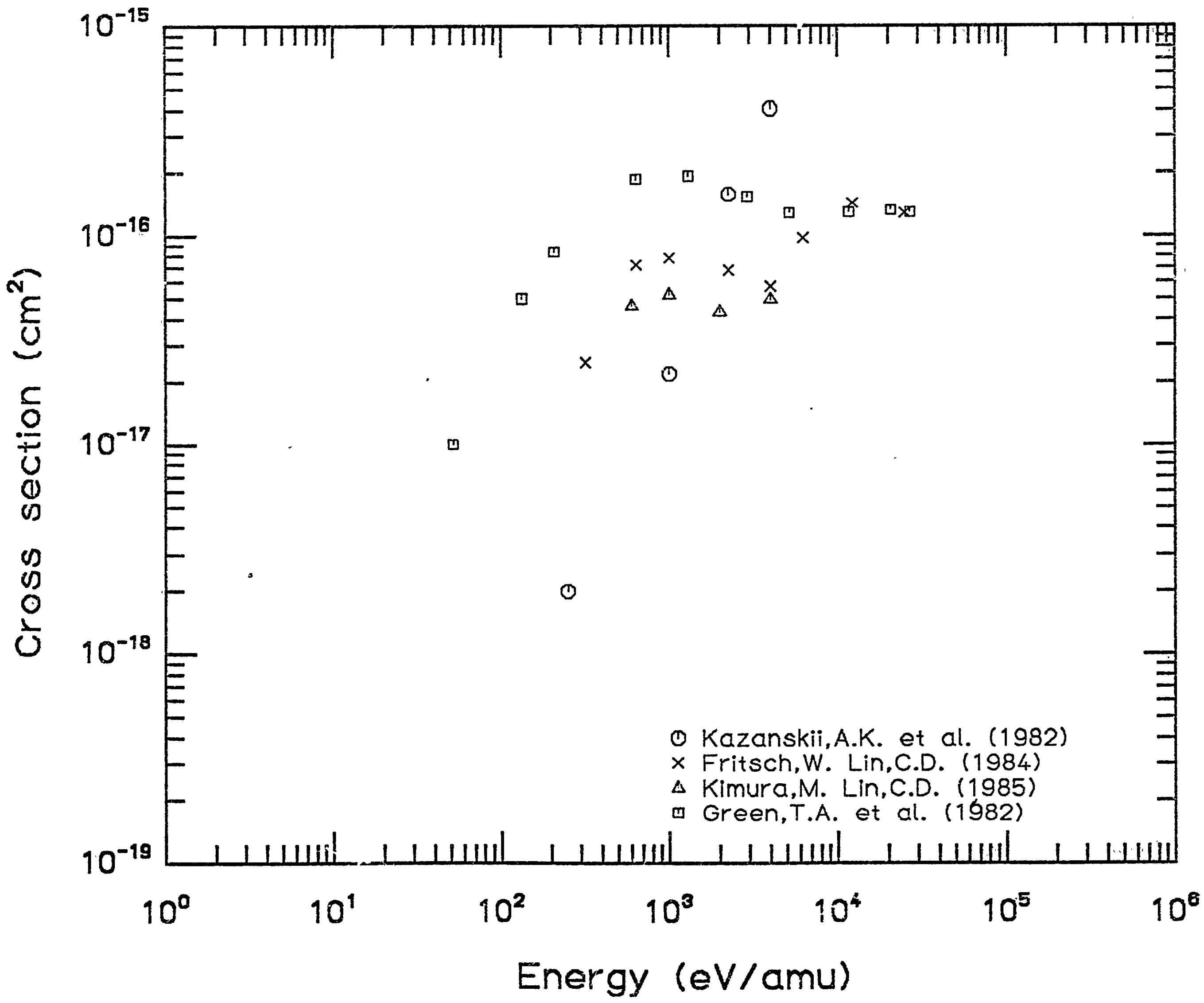


Fig.12 $C^{6+} + H \longrightarrow C^{5+}(5f) + H^{+}$

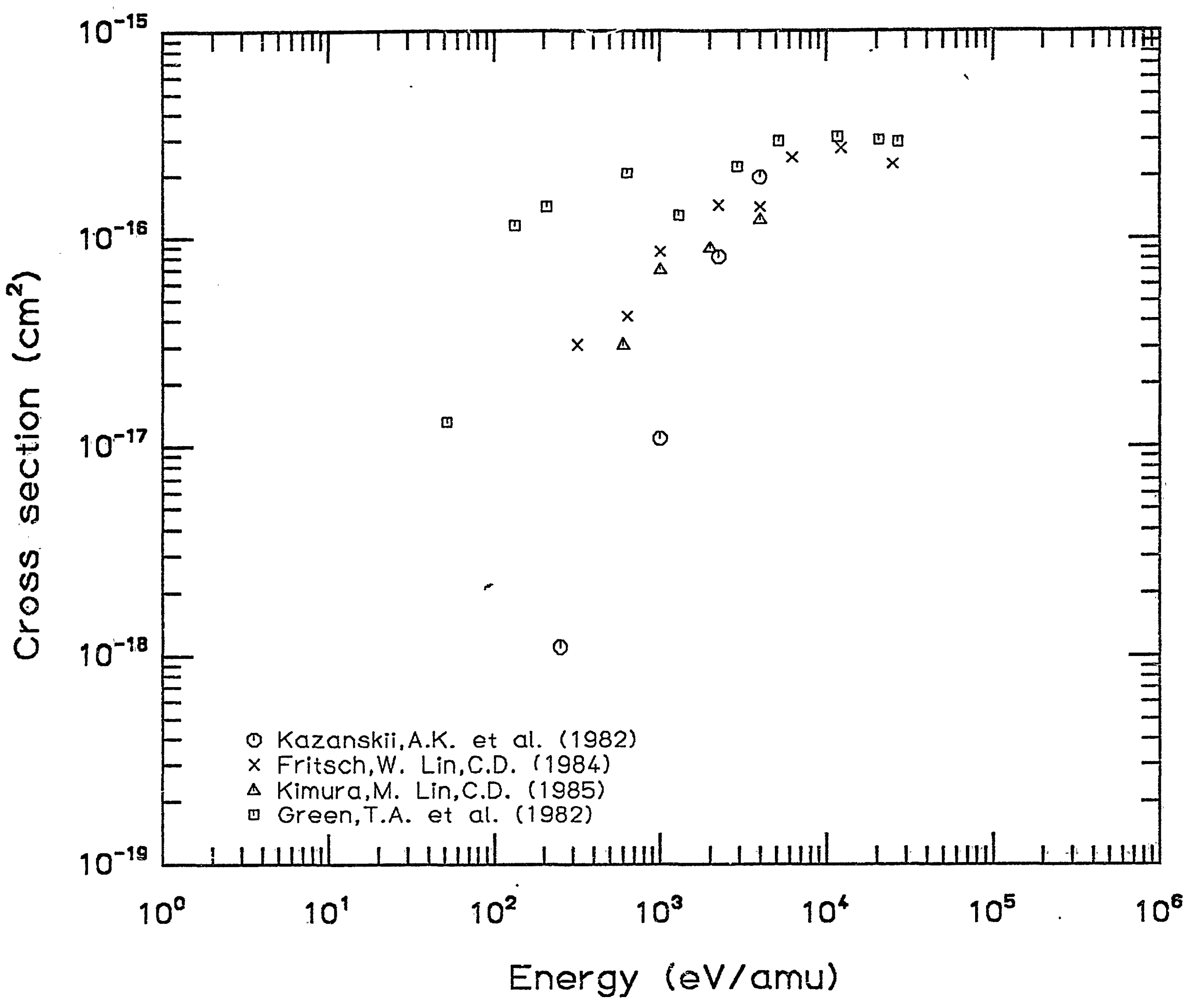
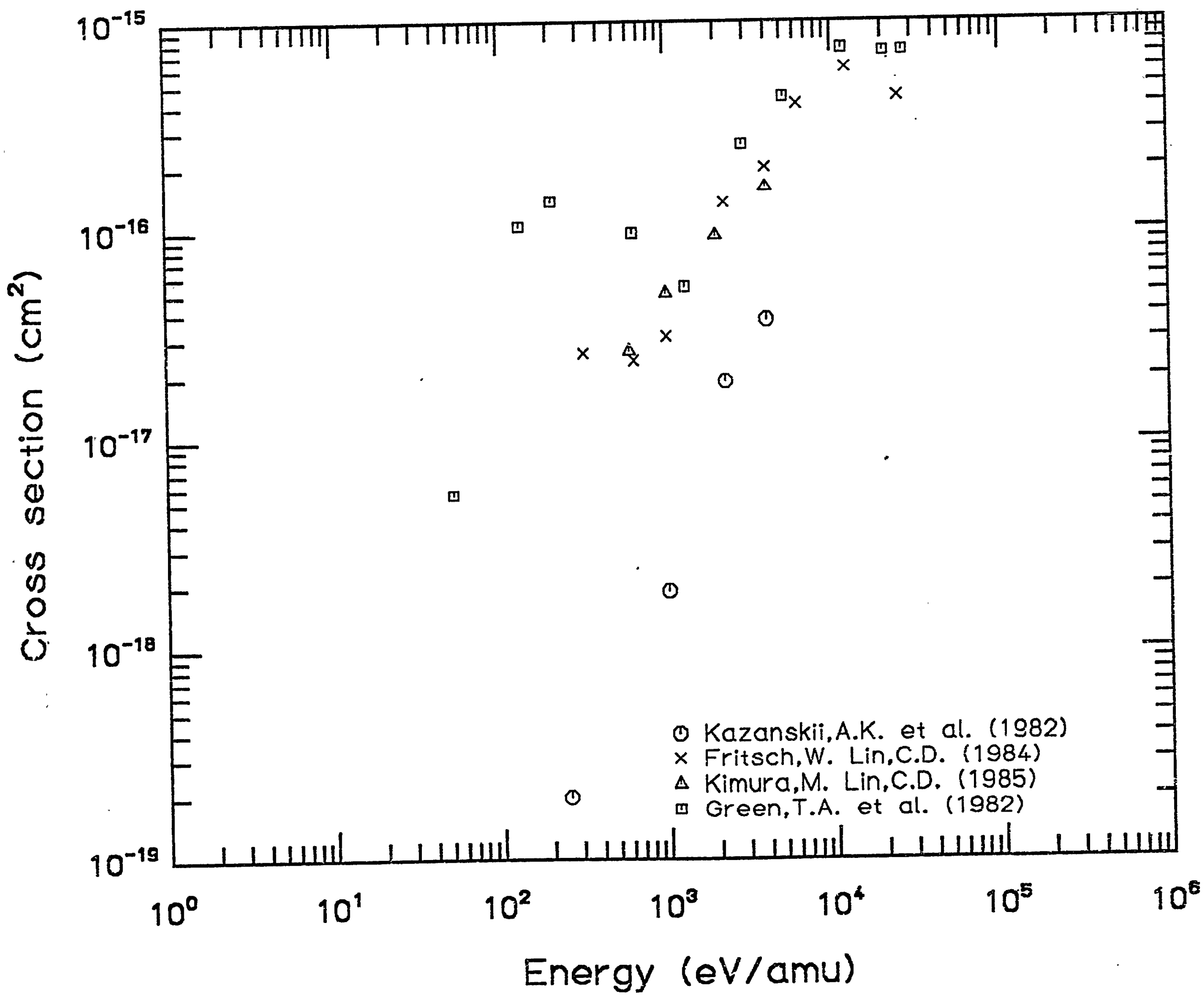


Fig.13 $C^{6+} + H \dashrightarrow C^{5+}(5g) + H^{+}$



I-2 $C^{5+}(1s) + H(1s) \rightarrow C^{4+}(1sn\ell) + H^+$

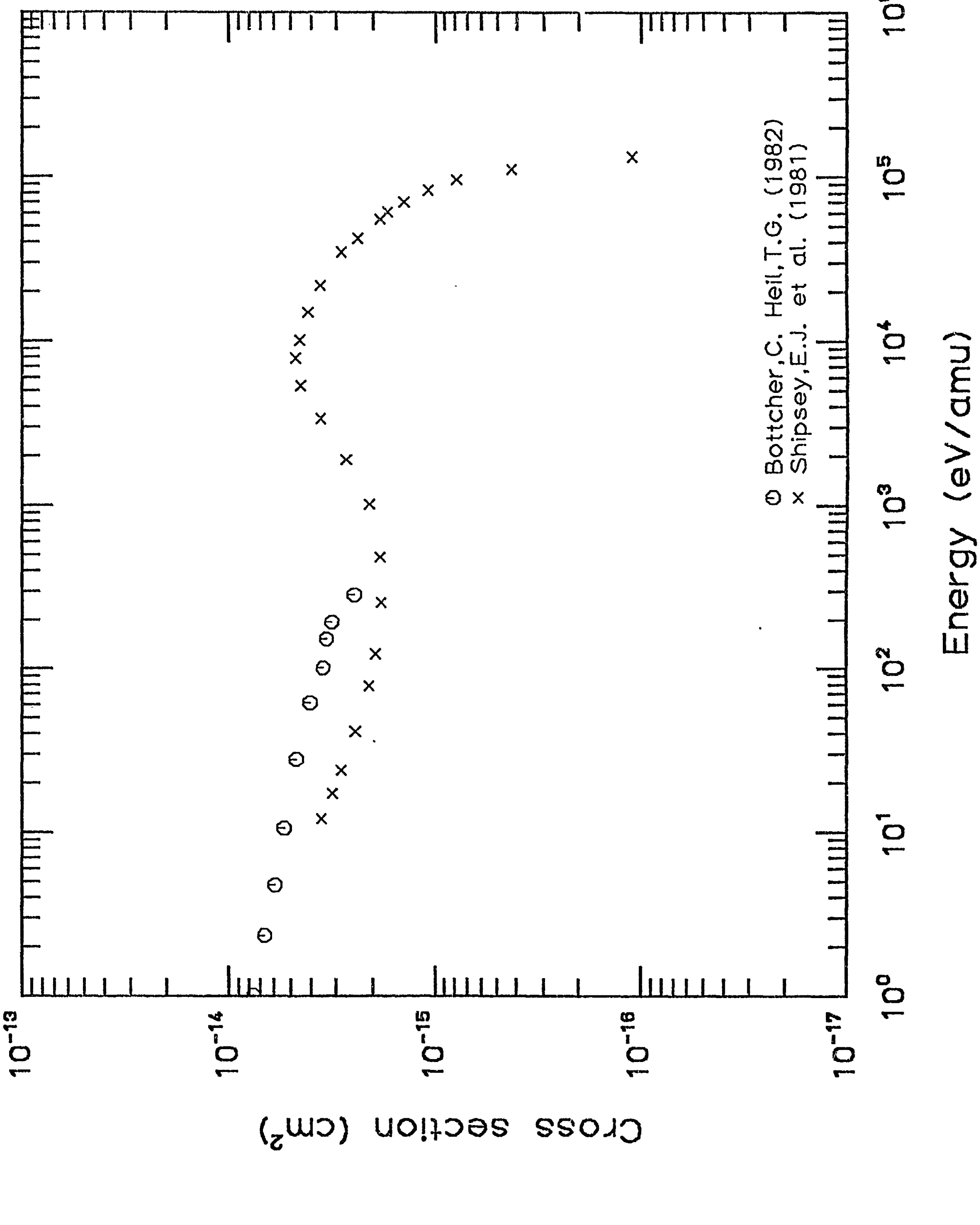
The dominant capture occurs into n=4 states of C^{4+} ions at low energies, as clearly understood from the energy diagram of the system. Total electron capture cross sections have been calculated by Bottcher and Heil[1] using fully quantal PSS method over the energy range 1 - 250 eV/amu and by Shipsey et al.[2] using MO (for low energy) and CTMC (for high energy) over 10^{-2} - 200 keV/amu. Experimental situation of total cross sections is summarized.[3]

Total cross sections show a minimum at intermediate energy : The cross sections increase with decreasing the collision energy, reaching about 10^{-14} cm^2 at the energy less than 1 eV/amu, meanwhile, after passing a minimum (2×10^{-15} cm^2) at 500 eV/amu, the cross sections reach a maximum (5×10^{-15} cm^2) at 7 -8 keV/amu and then decrease rapidly with increasing the collision energy. Unfortunately no experimental and theoretical data for the ($n\ell$) distributions have been reported up to now. Shipsey et al.[2] estimated the contribution from n states other than n=4 is quite small at intermediate energy range: for example, that from n=3 state increases with increasing the collision energy, however, being only about 5% at 5 keV/amu and that from n=5 state is even smaller. This situation is also confirmed experimentally by Kimura et al.[4]

References

1. C. Bottcher and T.G. Heil, Chem. Phys. Letters 86 (1982) 506
2. E.J. Shipsey, J.C. Browne and R.E. Olson, J. Phys. B 14 (1981) 869
3. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
4. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

Fig.14 $C^{5+} + H \dashrightarrow C^{4+}(\text{total}) + H^{+}$



I-3 $C^{4+}(1s^2) + H(1s) \rightarrow C^{3+}(1s^2 n\ell) + H^+$

All the theories predict that the dominant electron capturing level is n=3 and the contribution from other neighbouring levels is small, which are confirmed experimentally[1].

Total electron capture cross sections have been calculated using different methods by Olson et al.[2] (0.05 - 5 keV/amu), Hanssen et al.[3] (0.25 - 25 keV/amu: their numerical numbers are cited by Bendahman et al.[4]) and Bottcher and Heil[5] (0.5 eV - 250 eV), meanwhile experimental data have already been compiled.[6]

On the other hand, the partial cross sections have been calculated by Fritsch and Lin[7] using AO expansion method and by Gargaud et al.[8-10] using MO mode. Only a single experimental measurement of the partial cross sections was made by Dijkkamp et al.[11] using the photon spectroscopy over the energy range 0.25 -6.25 keV/amu. Some preliminary data are given by Dijkkamp et al.[12], Ciric et al.[13] and Dijkkamp et al.[14]

Generally speaking, the agreement among theories and experiments is quite good for dominant capturing levels but the discrepancies are obvious for less intense capture cross sections.

Baptist et al.[15] determined relative intensities among 3s, 3p and 3d subshell cross sections at the energy 0.6 - 40 keV using VUV spectroscopy and compared them with calculations by Fritsch and Lin and Gargaud et al. The agreement is found to be good among them. Some related topics on determining the absolute cross sections from photon measurements were discussed[16-17].

The rate coefficients for this process over the temperature 10^3-$10^{4.5}$ K have been calculated by Butler and Dalgarno using LZ model.[18]

References

1. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

2. R.E. Olson, E.J. Shipsey and J.C. Browne, J. Phys. B 11 (1978) 699
3. J. Hassen, R. Gayet, C. Harel and A. Salin, J. Phys. B 17 (1984) L323
4. M. Bendahman, S. Bliman, S. Dousson, D. Hitz, R. Gayet, J. Hanssen, C. Harel and A. Salin, J. Physique 46 (1985) 561
5. C. Bottcher and T.G. Heil, Chem. Phys. Letters 86 (1982) 506
6. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
7. W. Fritsch and C.D. Lin, J. Phys. B 17 (1984) 3271
8. M. Gargaud, J. Hanssen, R. McCarroll and P. Valion, J. Phys. B 14 (1981) 2259
9. M. Gargaud and R. McCarroll, J. Phys. B 18 (1985) 463
10. M. Gargaud, R. McCarroll and P. Valion, J. Phys. B 20(1987) 1555
11. D. Dijkkamp, D. Ciric, E. Vlieg, A. de Boer and F.J. de Heer, J. Phys. B 18 (1985) 4763
12. D. Dijkkamp, A. Brazuk, A.G. Drentje, F.J. de Heer and H. Winter, J. Phys. B 16 (1983) L343
13. D. Ciric, D. Dijkkamp, E. Vlieg and F.J. de Heer, J. Phys. B 18 (1985) L17
14. D. Dijkkamp, D. Ciric, and F.J. de Heer, Nucl. Instr. Meth. in Phys. Res. B 9 (1985) 403
15. R. Baptist, J.J. Bonnet, M. Bonnefoy, E. Boursey, A. Brenac, M. Chassevent, G. Chauvet, S. Dousson, Y. Le Duff, A. Fleury, M. Gargaud and D. Hitz, Nucl. Instr. Meth. in Phys. Res. B 23 (1987) 123
16. S. Bliman, J.J. Bonnet, G. Chauvet, S. Dousson, D. Hitz, B. Jacquot and E.J. Knystautas, J. Phys. B 16 (1983) L243
17. H. Winter, J. Phys. B 16 (1983) L521
18. S.E. Butler and A. Dalgarno, Astrophys. J. 241 (1980) 838

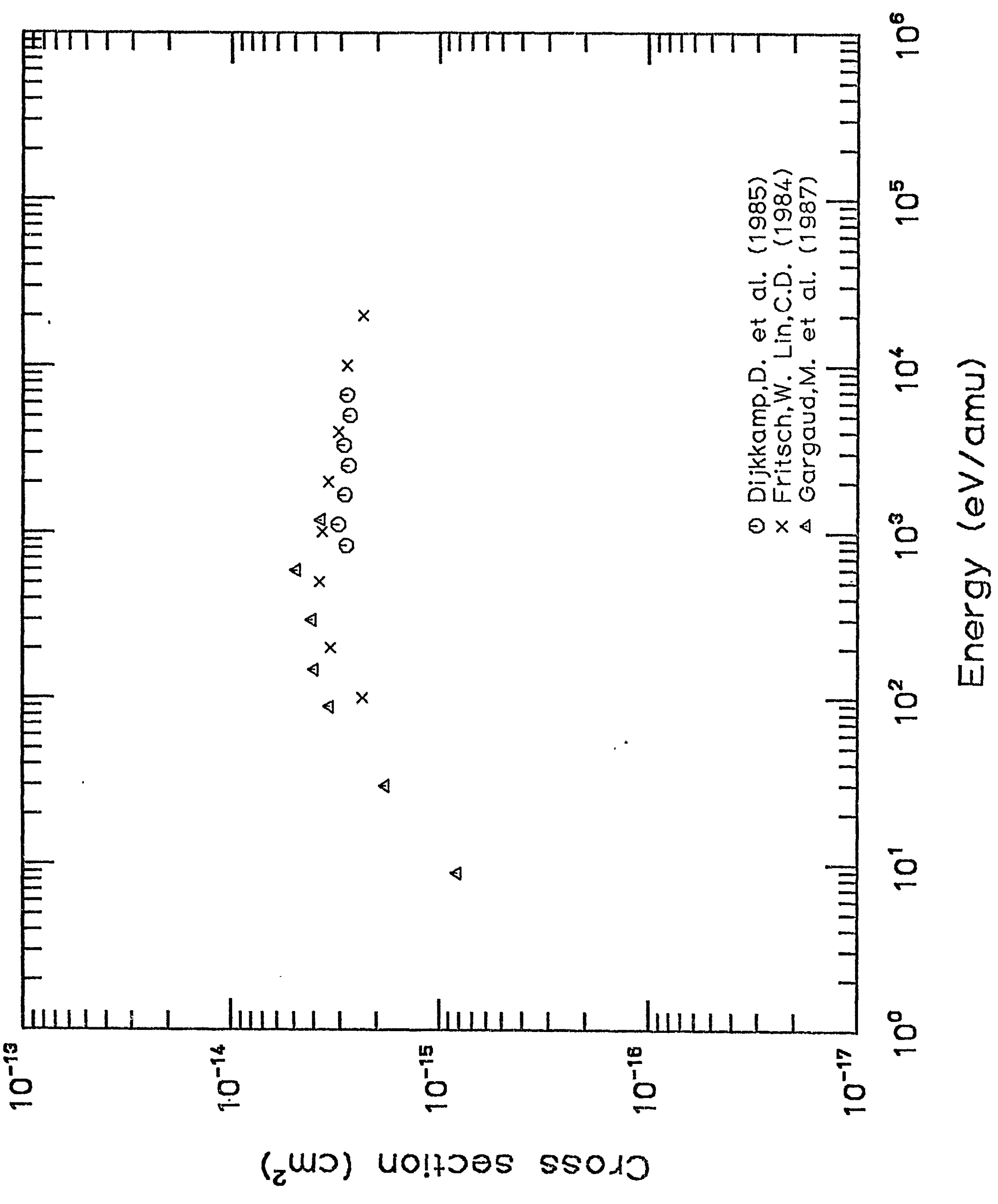


Fig.15 $C^{4+} + H \dashrightarrow C^{3+}(total) + H^+$

Fig.16 $C^{4+} + H \rightarrow C^{3+}(1s^2 2s) + H^+$

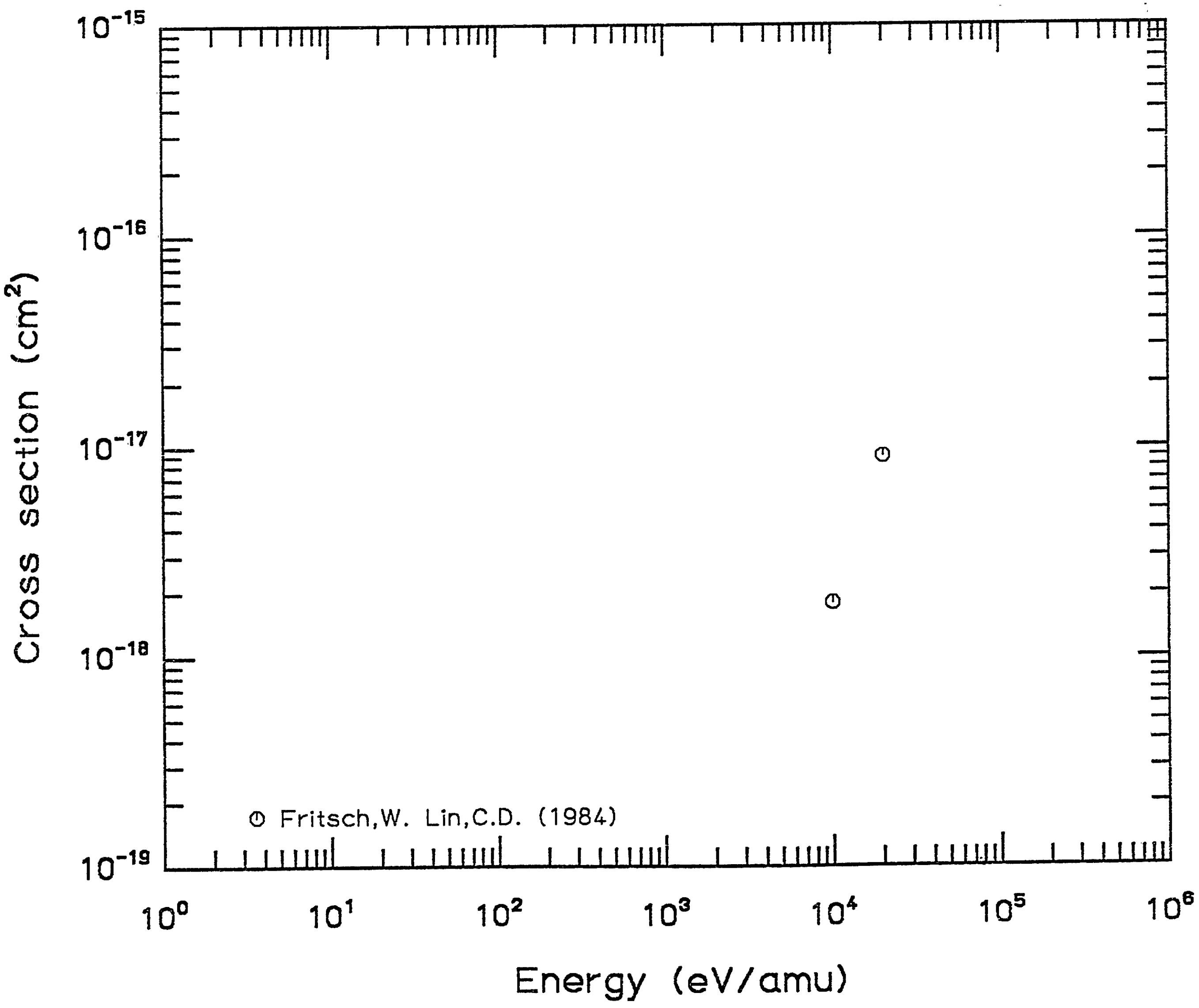


Fig.17 $C^{4+} + H \dashrightarrow C^{3+}(1s^2 2p) + H^+$

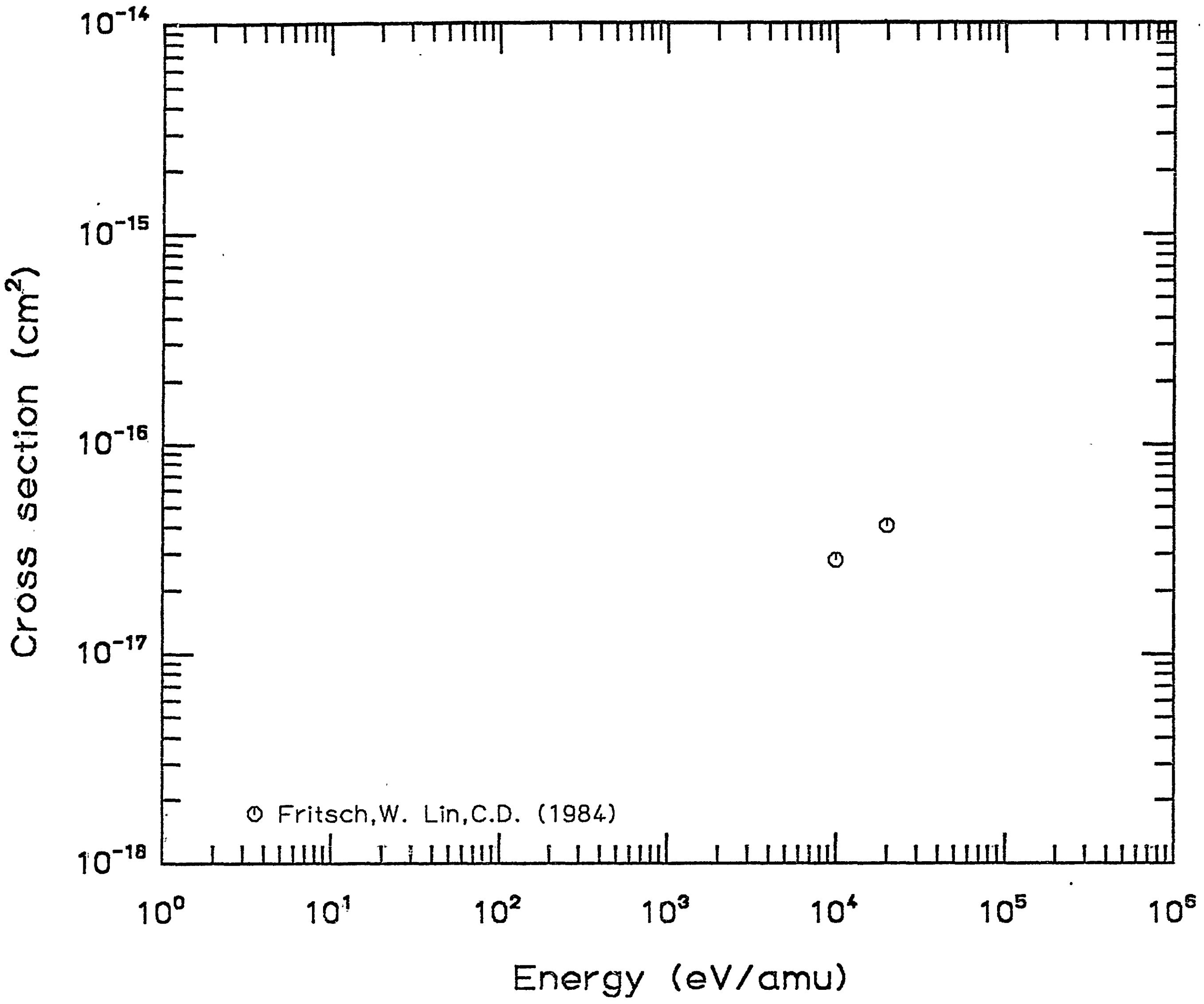


Fig.18 $C^{4+} + H \rightarrow C^{3+}(1s^2 3s) + H^+$

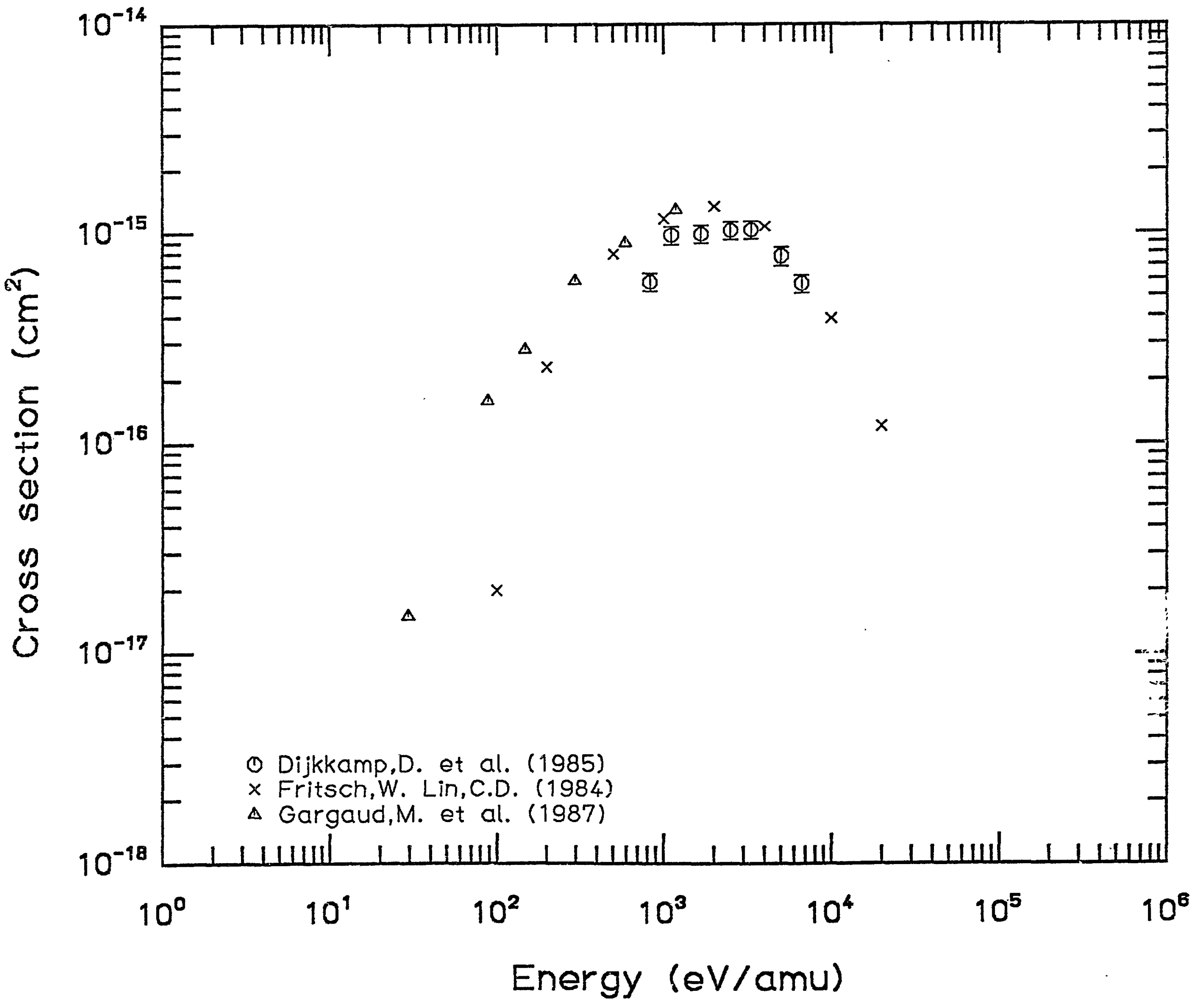


Fig.19 $C^{4+} + H \rightarrow C^{3+}(1s^2 3p) + H^+$

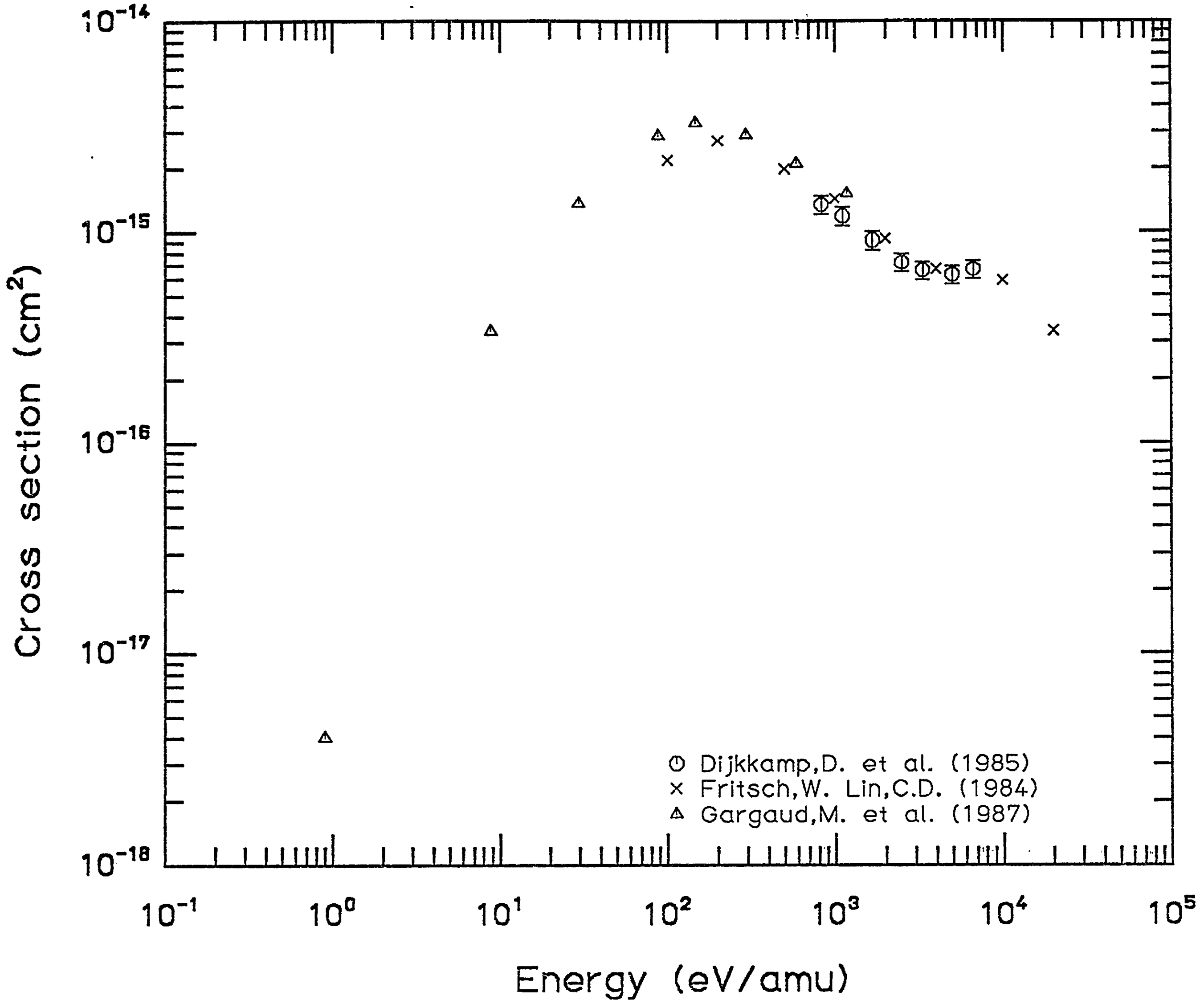


Fig.20 $C^{4+} + H \rightarrow C^{3+}(1s^2 3d) + H^+$

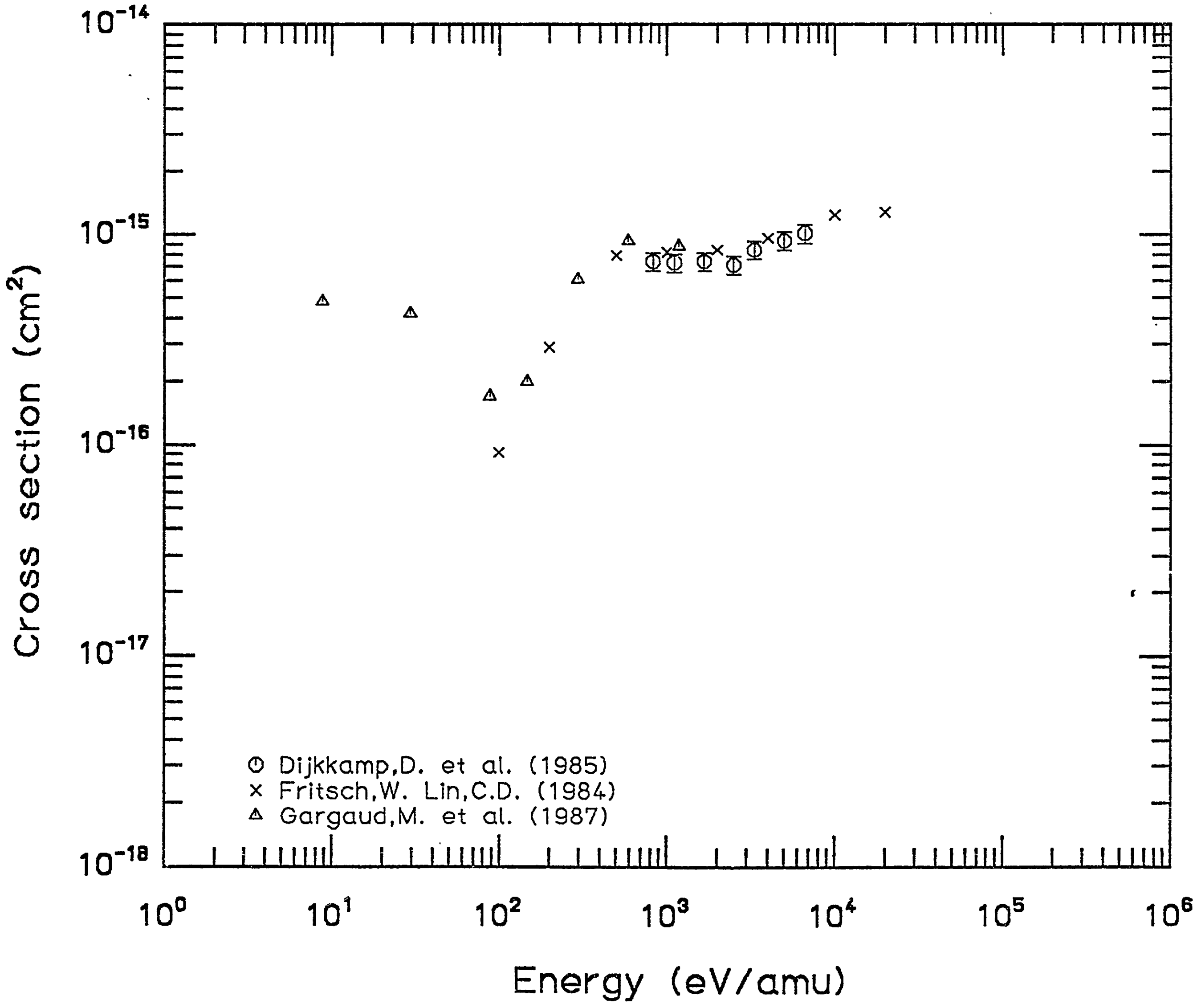


Fig.21 $C^{4+} + H \dashrightarrow C^{3+}(1s^2 4s) + H^+$

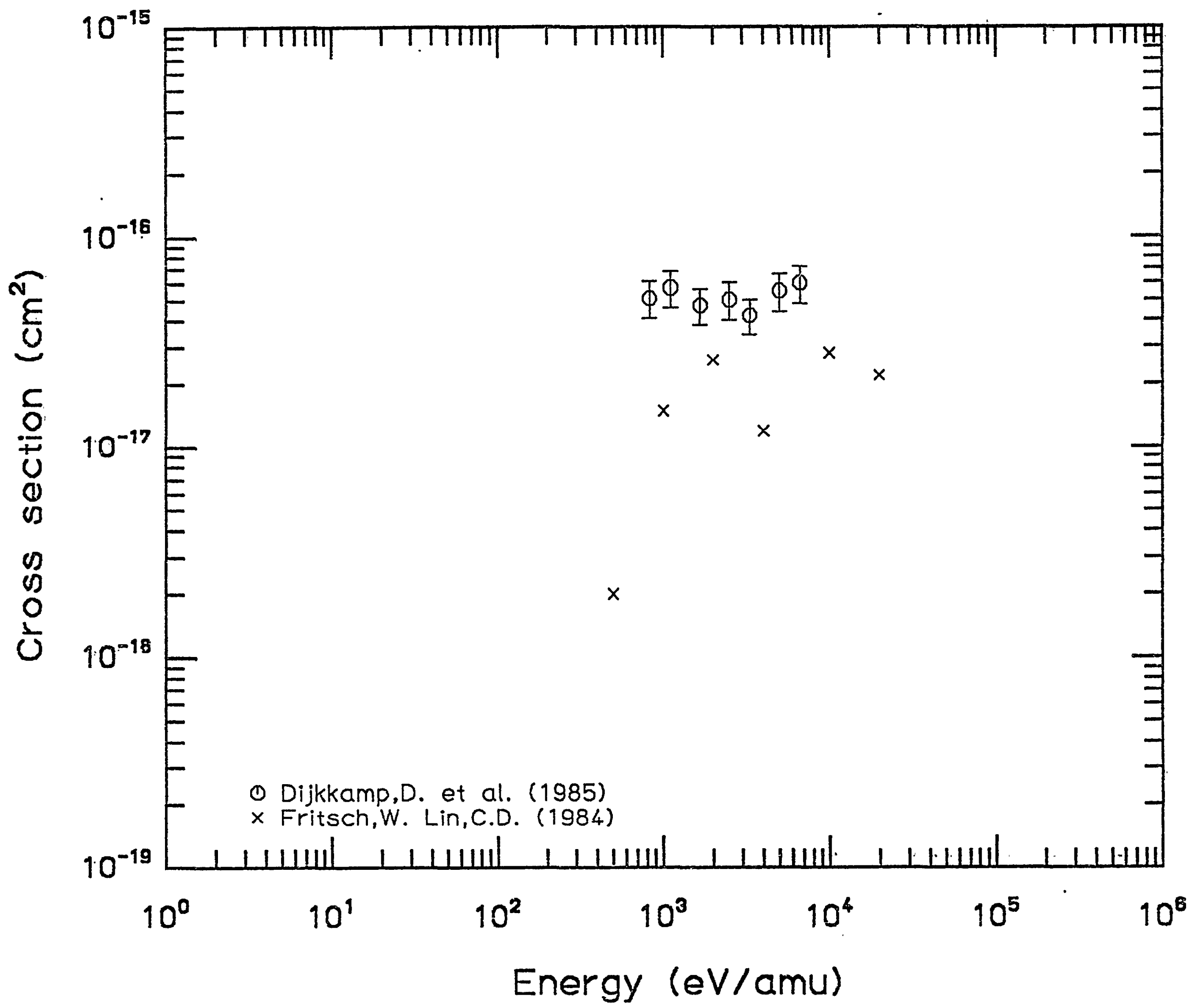


Fig.22 $C^{4+} + H \dashrightarrow C^{3+}(1s^2 4p) + H^+$

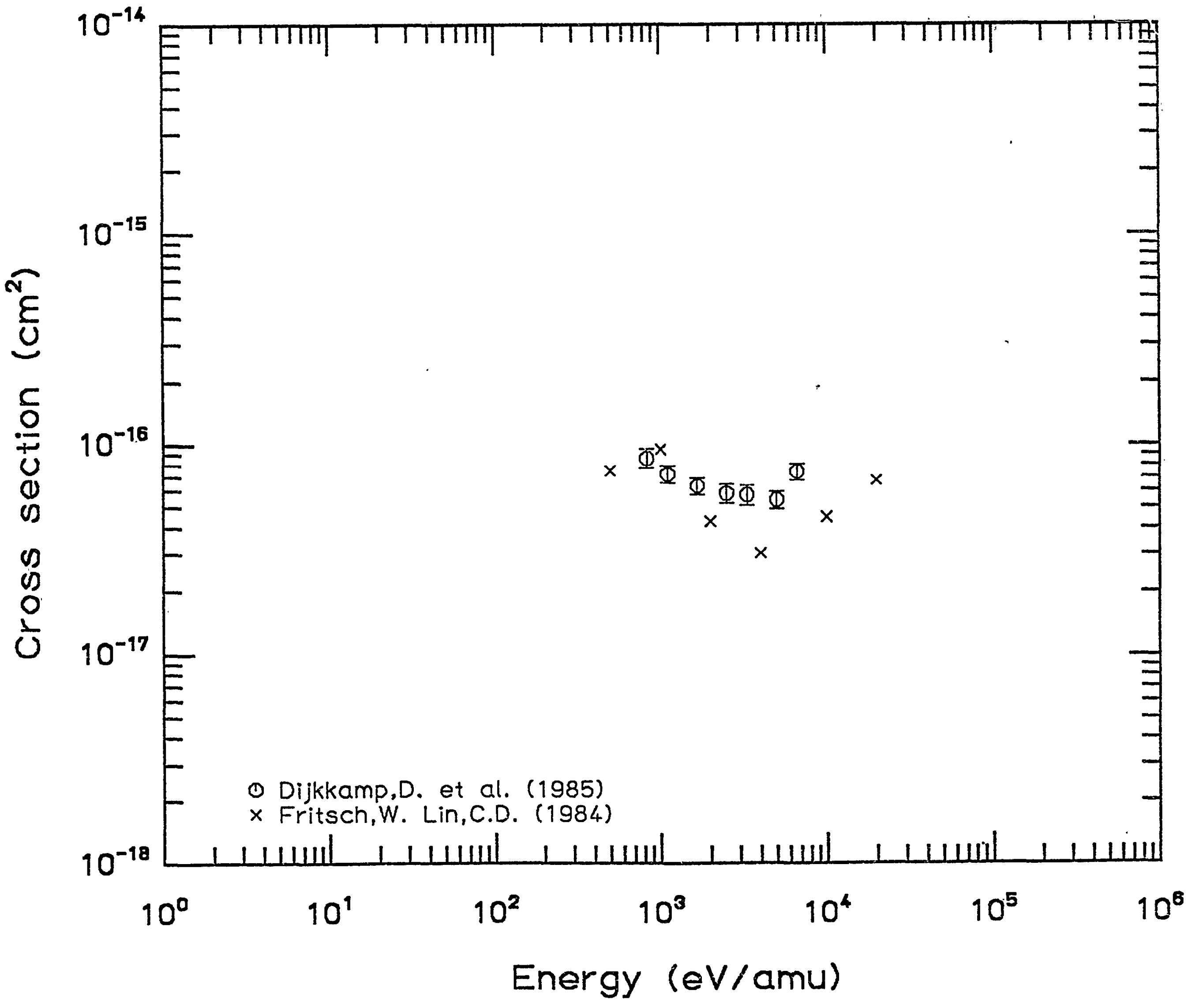


Fig.23 $C^{4+} + H \rightarrow C^{3+}(1s^2 4d) + H^+$

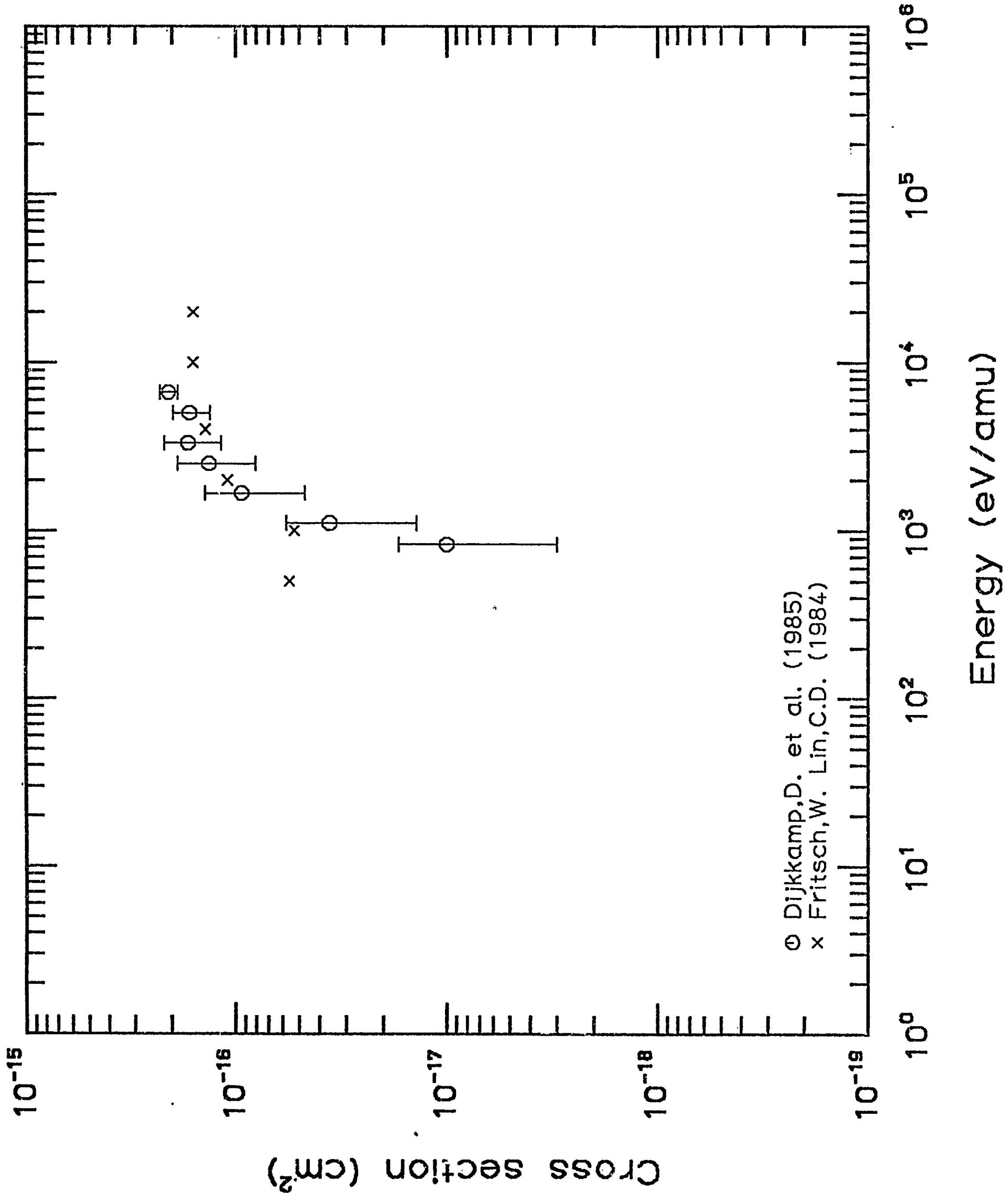
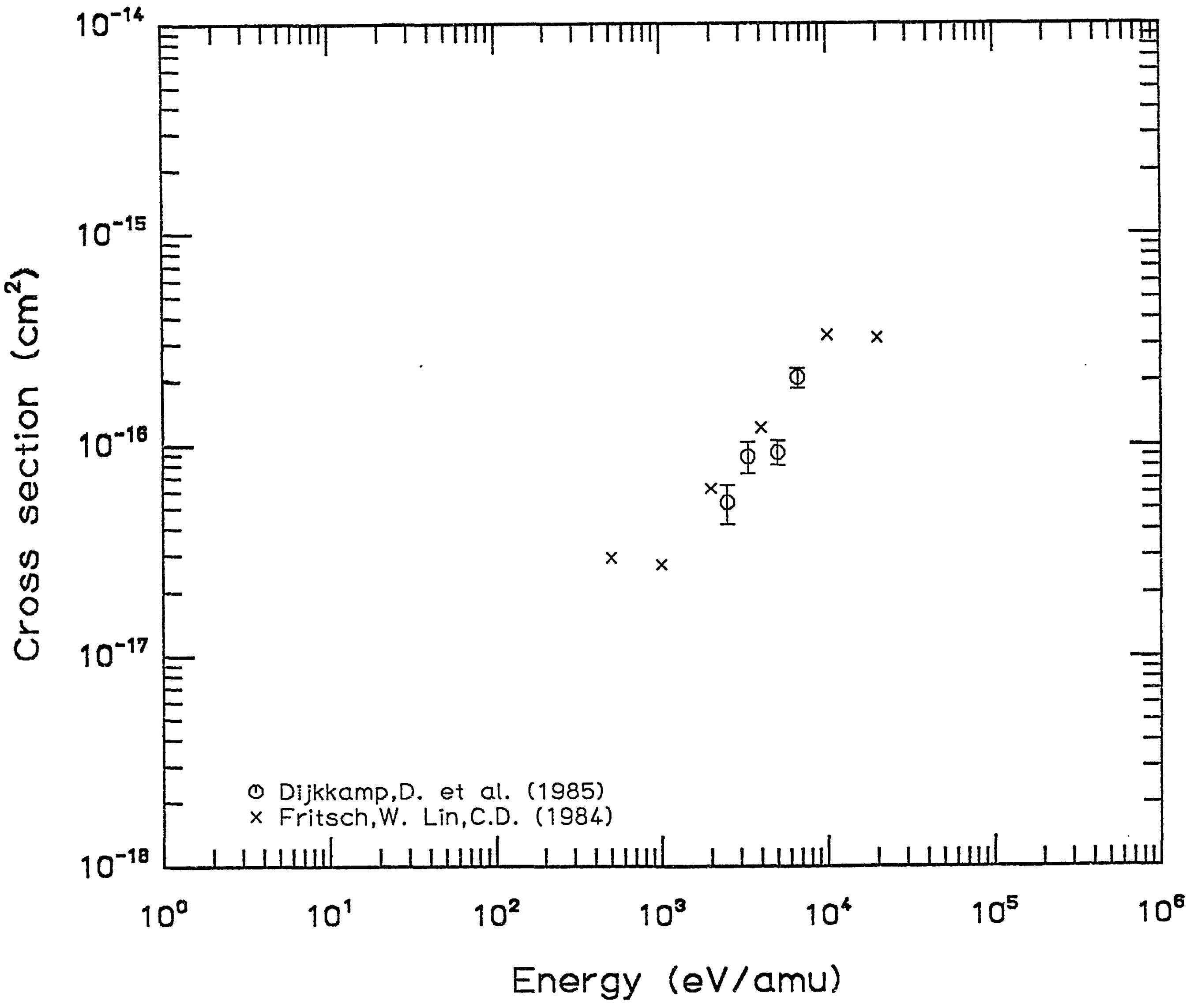


Fig.24 $C^{4+} + H \rightarrow C^{3+}(1s^24f) + H^+$



I-4 $C^{3+}(1s^2 2s\ ^2S) + H(1s) \rightarrow C^{2+}(1s^2 2\ell n\ell') + H^+$

Experimental data of the measured total cross sections are summarized.[1] Blint et al.[2] have calculated the cross sections for the dominant $(1s^2 2s3s\ ^3S)$ states over the energy range 0.1 - 1.75 eV/amu using pertubation theory and also for $(1s^2 2s3s\ ^1S)$ states which are found to be far weak (only 1-2% of those for ^3S states at 1 eV/amu). They also compared their results with Landau-Zener calculation, their agreement being fairly good. Watson et al.[3] also made the full quantal calculation for $1s^2 2s3s\ ^3S$ state over 0.001 - 15 eV/amu. Their results show significant deviation from LZ model at lower energies, in particular below 0.01 eV/amu. The rate coefficients were calculated quantally by Butler et al.[4] over 5×10^3 - 5×10^4 K. Using molecular treatment, Heil et al.[5] calculated the partial cross sections for 2s3s ^3S, 2s3p $^3P^0$, $2p^2\ ^1S$ and $2p^2\ ^1D$ states over 0.27 - 8.1 eV/amu. Furthermore, Bienstock et al.[6] extended their calculations using UDWA over 10 - 5000 eV/amu. Experimental investigations were reported by McCullough et al.[7] using the translational energy spectroscopy over 0.05-1.5 keV/amu, though their results are sometimes mixed from other states because of the limited energy resolution. On the other hand, Ciric et al.[8] determined the absolute partial cross sections for the following processes using photon spectroscopy over 0.7 - 4.6 keV/amu:

$$
\begin{aligned}
C^{3+}(1s^2 2s\ ^2S) + H(1s) \rightarrow C^{2+}&(1s^2 2s3s\ ^3S) + H^+\\
&(1s^2 2s3s\ ^1S)\\
&(1s^2 2s3p\ ^3P^0)\\
&(1s^2 2s3p\ ^1P^0)\\
&(1s^2 2s3d\ ^3D)\\
&(1s^2 2s3d\ ^1D)\\
&(1s^2 2s4d\ ^3D)\\
&(1s^2 2p^2\ ^1S)\\
&(1s^2 2p^2\ ^1D)\\
&(1s^2 2p^2\ ^3P).
\end{aligned}
$$

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985)235
2. R.J. Blint, W.D. Watson and R.B. Christensen, Astrophys. J. 205 (1976) 634
3. W.D. Watson, R.B. Christensen, Astrophys. J. 231 (1979) 627
4. S.E. Butler, T.G. Heil and A. Dalgarno, Astrophys. J. 241 (1980) 442
5. T.G. Heil, S.E. Butler and A. Dalgarno, Phys. Rev. A 23 (1981) 1100
6. S. Bienstock, T.G. Heil, C. Bottcher and A. Dalgarno, Phys. Rev. A 25 (1982) 2850
7. R.W. McCullough, F.G. Wilkie and H.B. Gilbody, J. Phys. B 17 (1984) 1373
8. D. Ciric, A. Brazuk, D. Dijkkamp, F.J. de Heer and H. Winter, J. Phys. B 18 (1985) 3629

Fig.25 $C^{3+} + H \dashrightarrow C^{2+}(\mathrm{total}) + H^+$

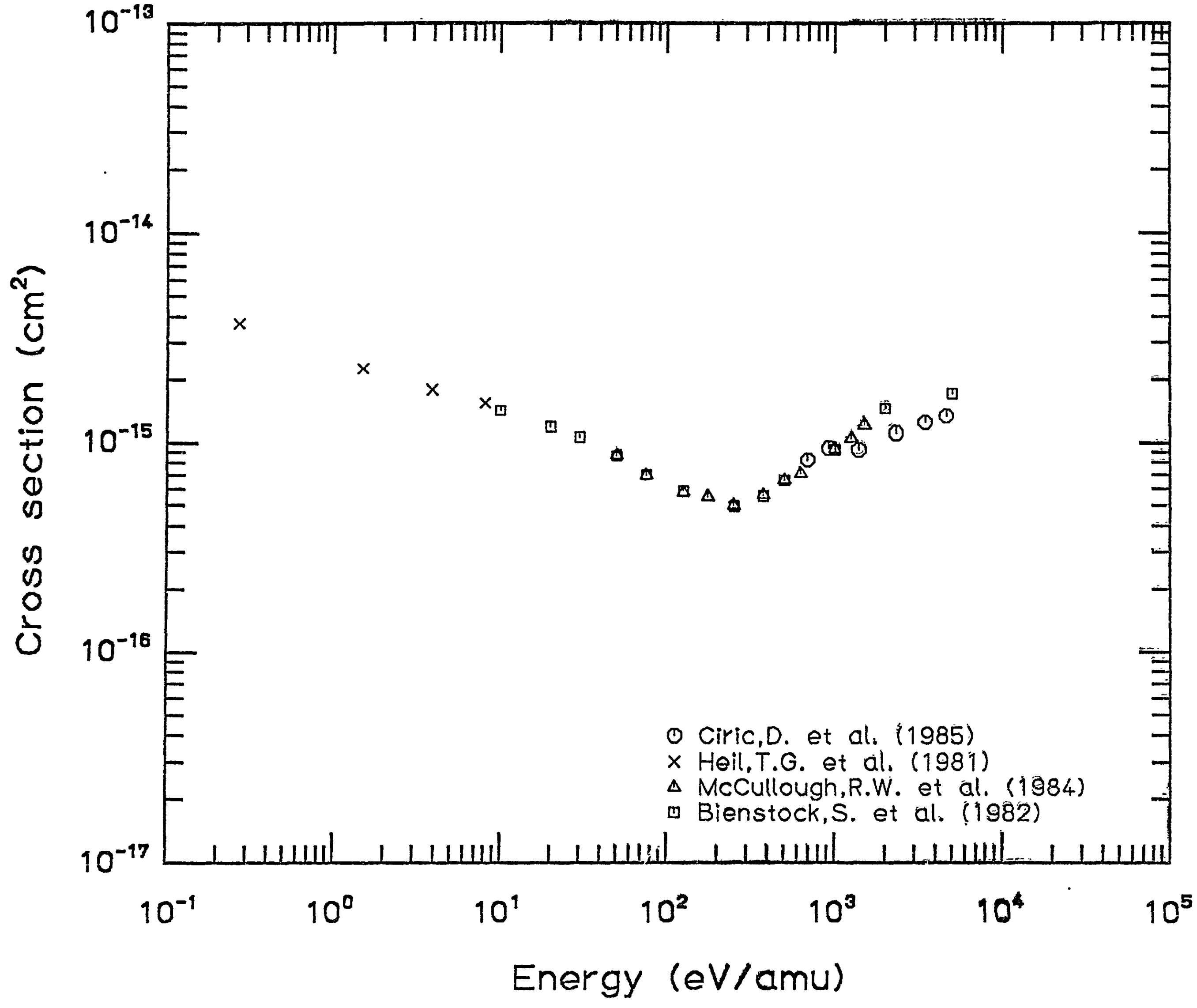


Fig.26(a) $C^{3+} + H \rightarrow C^{2+}(1s^2 2s3s\ ^3S) + H^+$

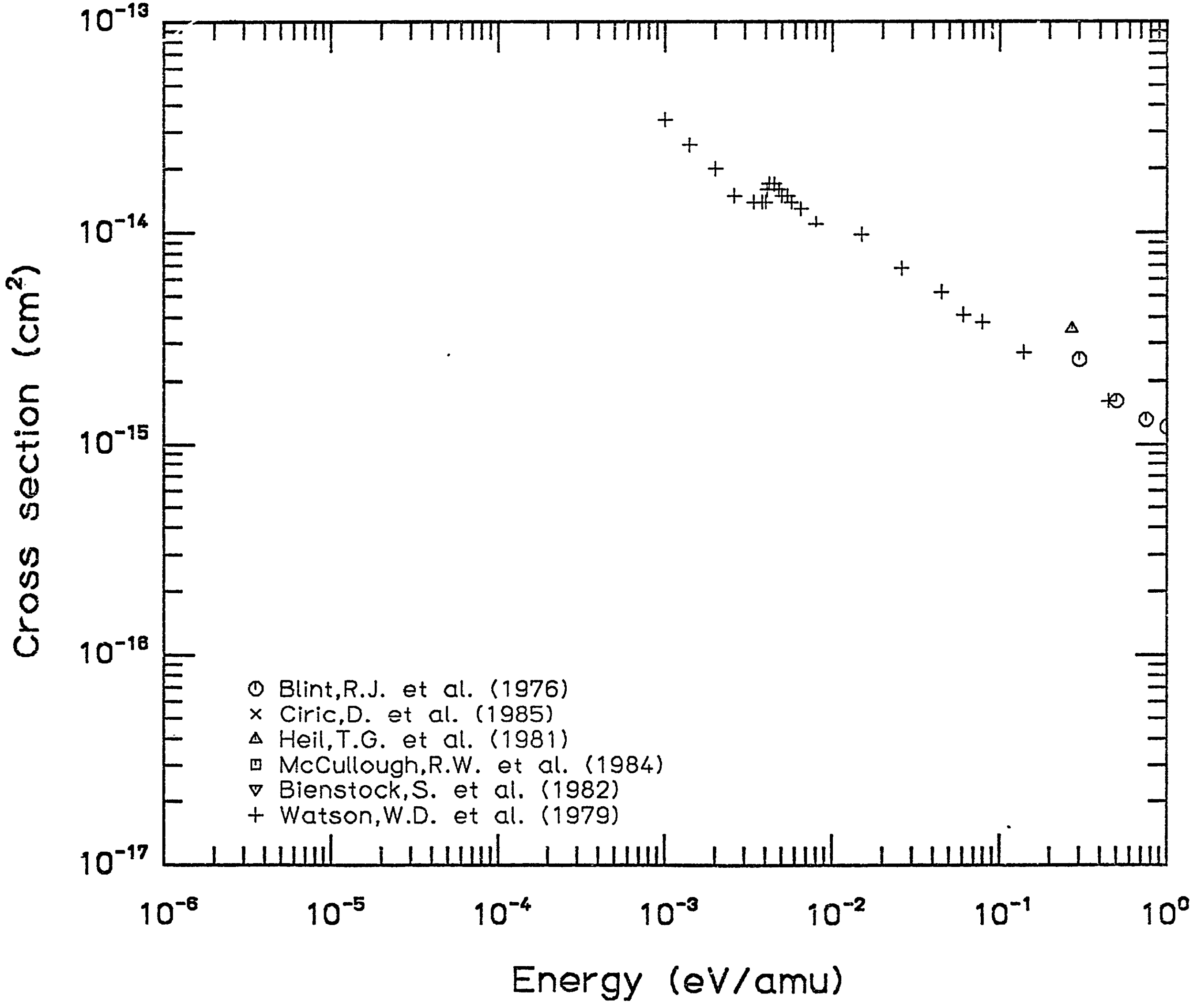


Fig.26(b) $C^{3+} + H \dashrightarrow C^{2+}(1s^2 2s3s\ ^3S) + H^+$

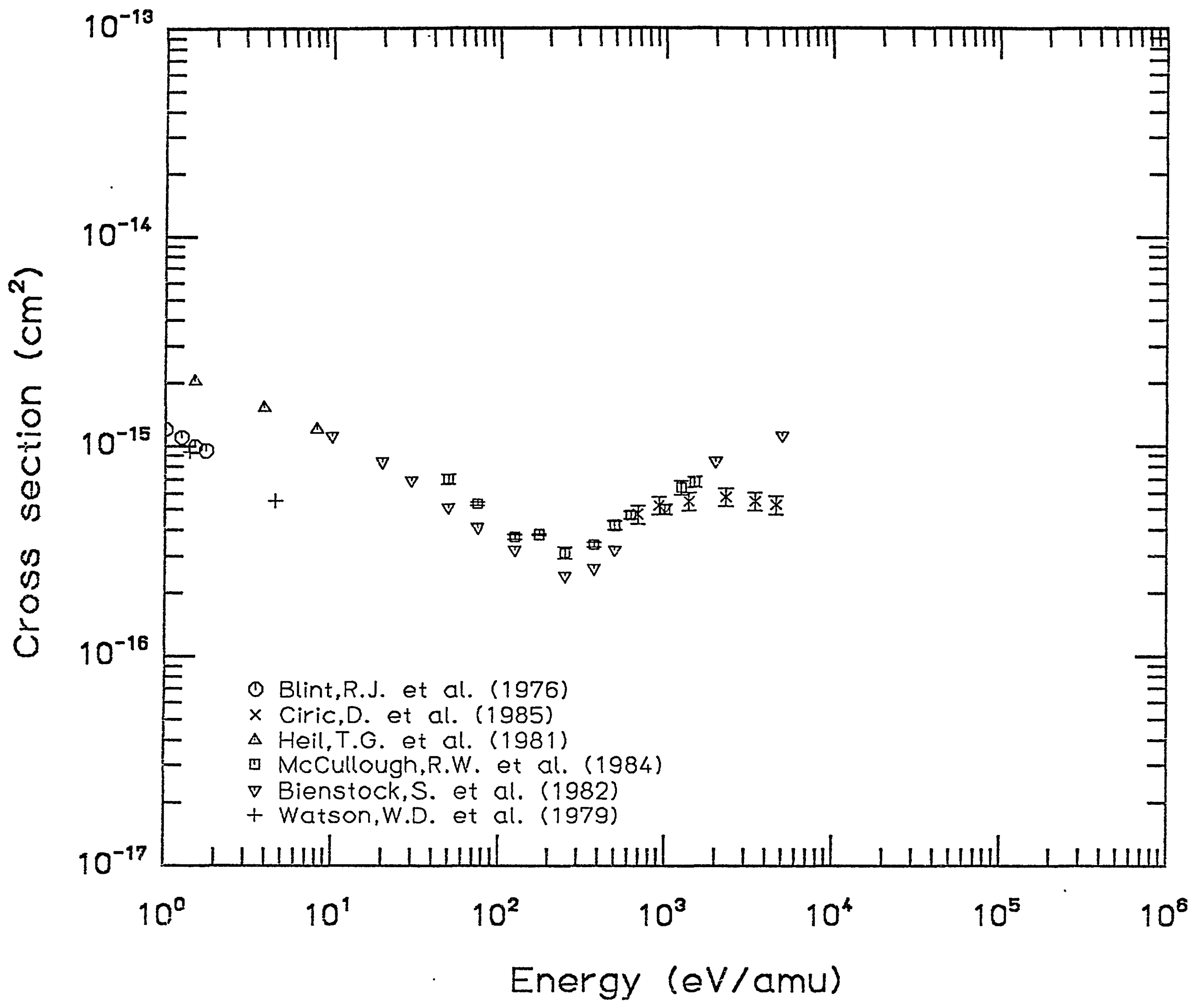


Fig.27 $C^{3+} + H \rightarrow C^{2+}(1s^2 2s3s\ ^1S) + H^+$

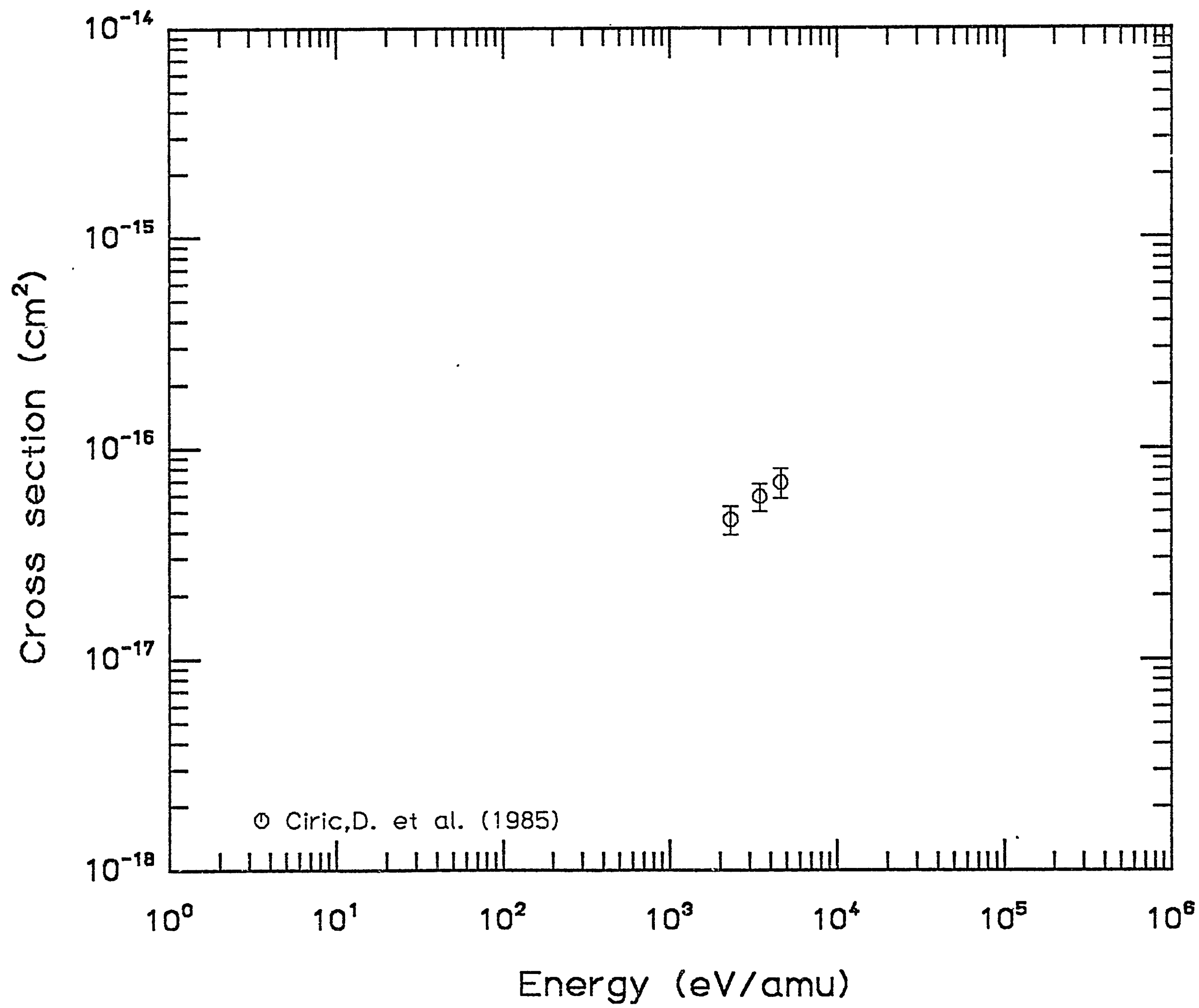


Fig.28 $C^{3+} + H \dashrightarrow C^{2+}(1s^2 2s3p\ ^3P^0) + H^+$

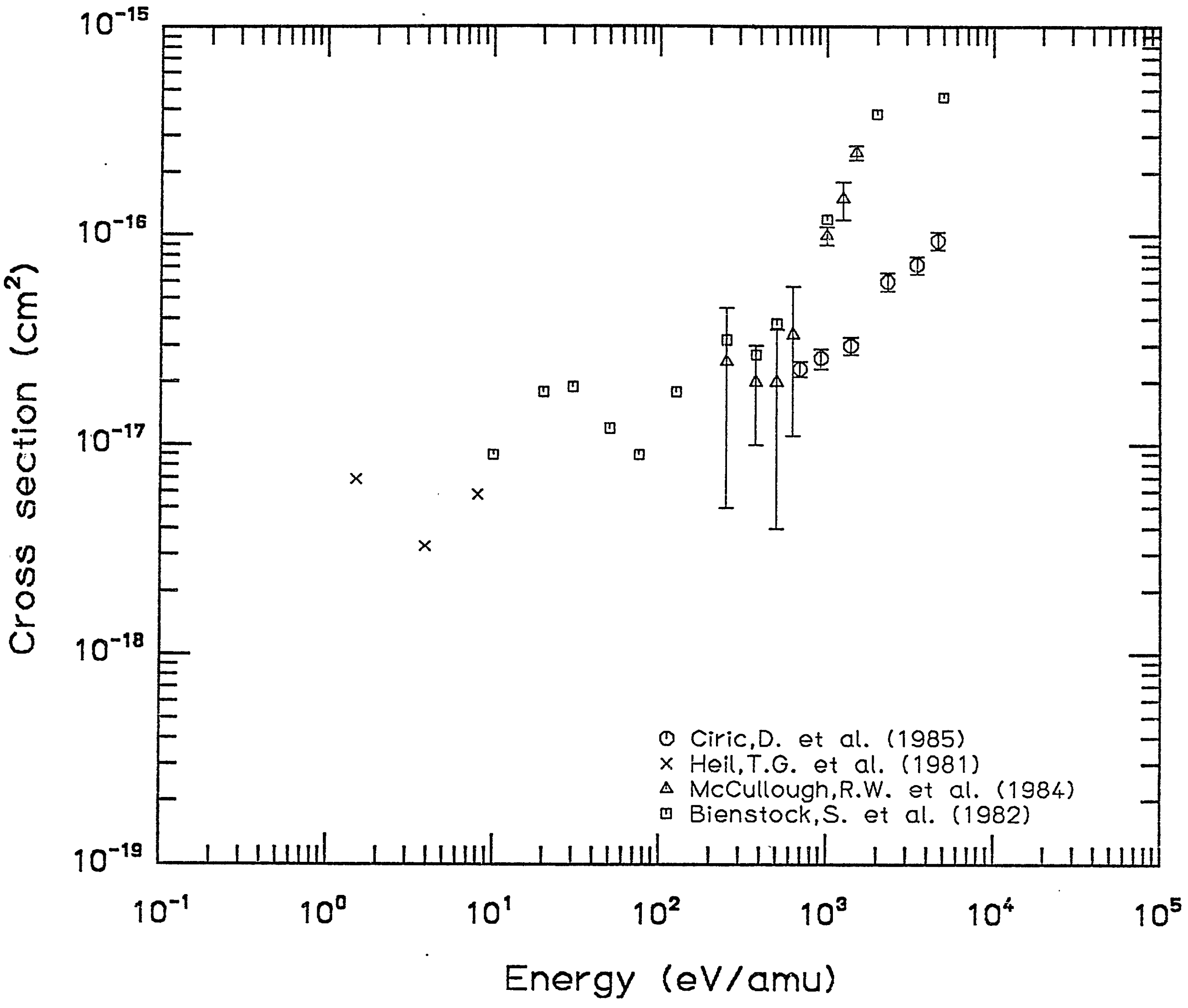


Fig.29 $C^{3+} + H \rightarrow C^{2+}(1s^2 2s3p\ ^1P^0) + H^+$

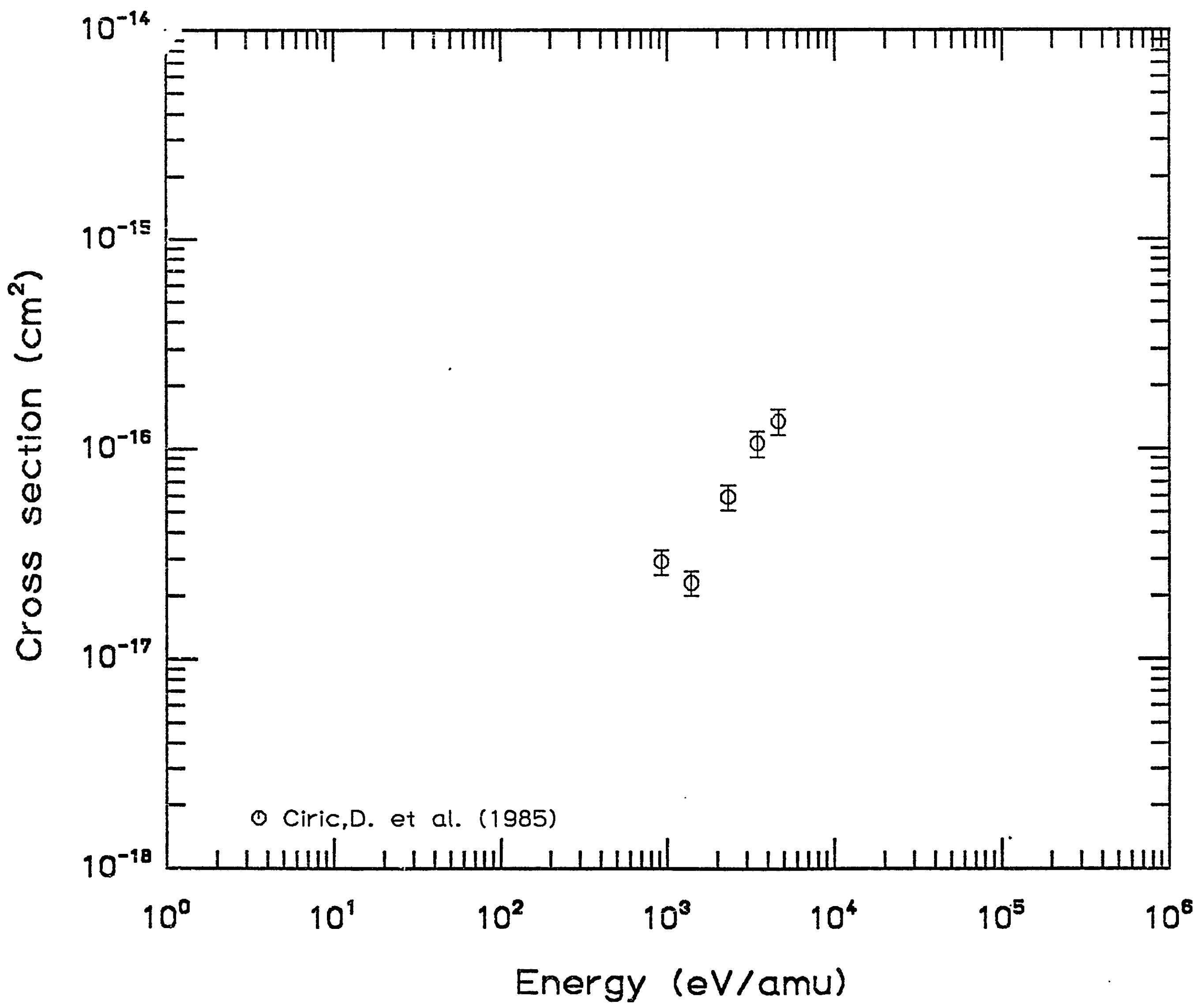


Fig.30 C^{3+} + H --> $C^{2+}(1s^2 2s3d\ ^3D)$ + H^+

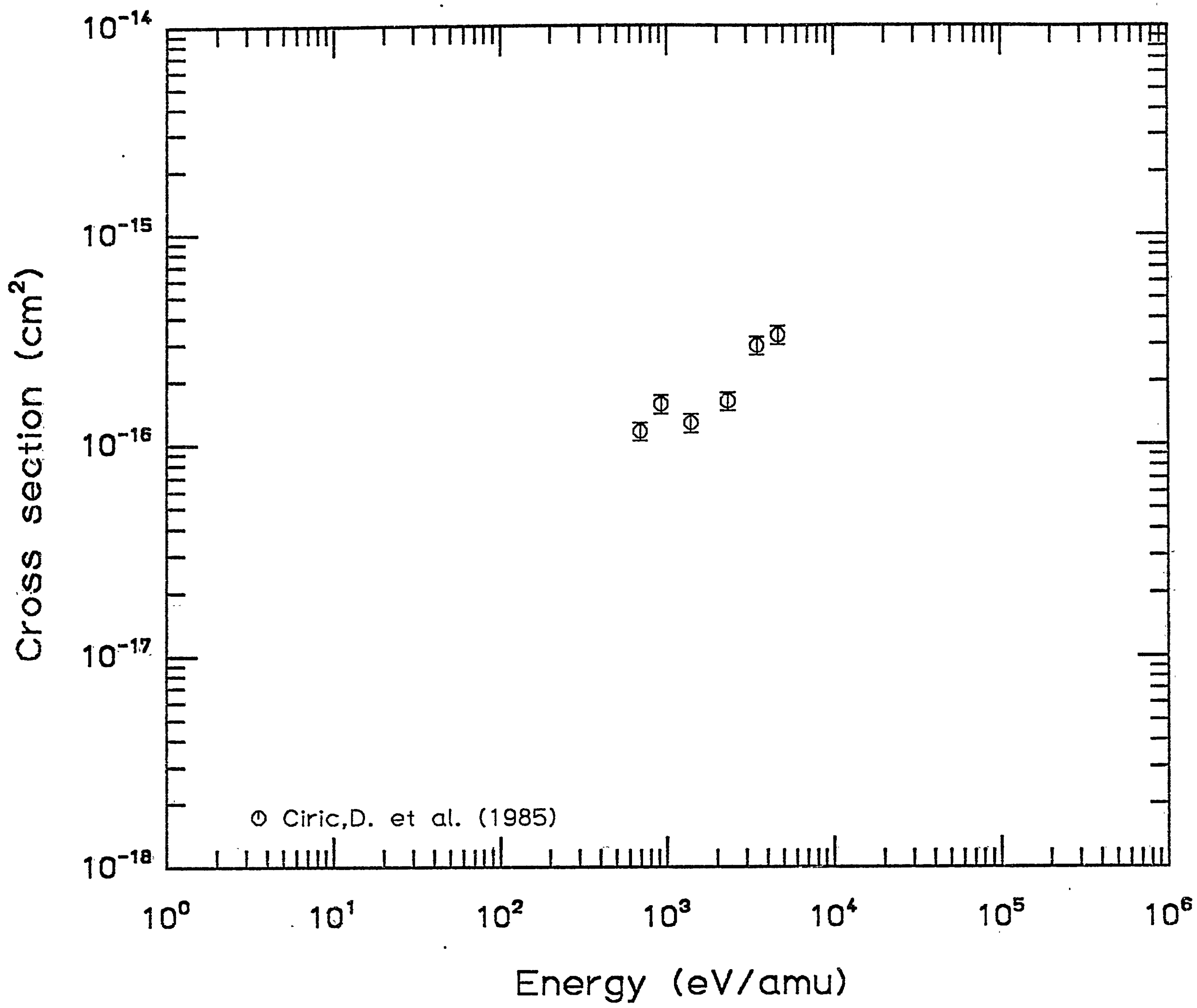


Fig.31 $C^{3+} + H \rightarrow C^{2+}(1s^2 2s3d\ ^1D) + H^+$

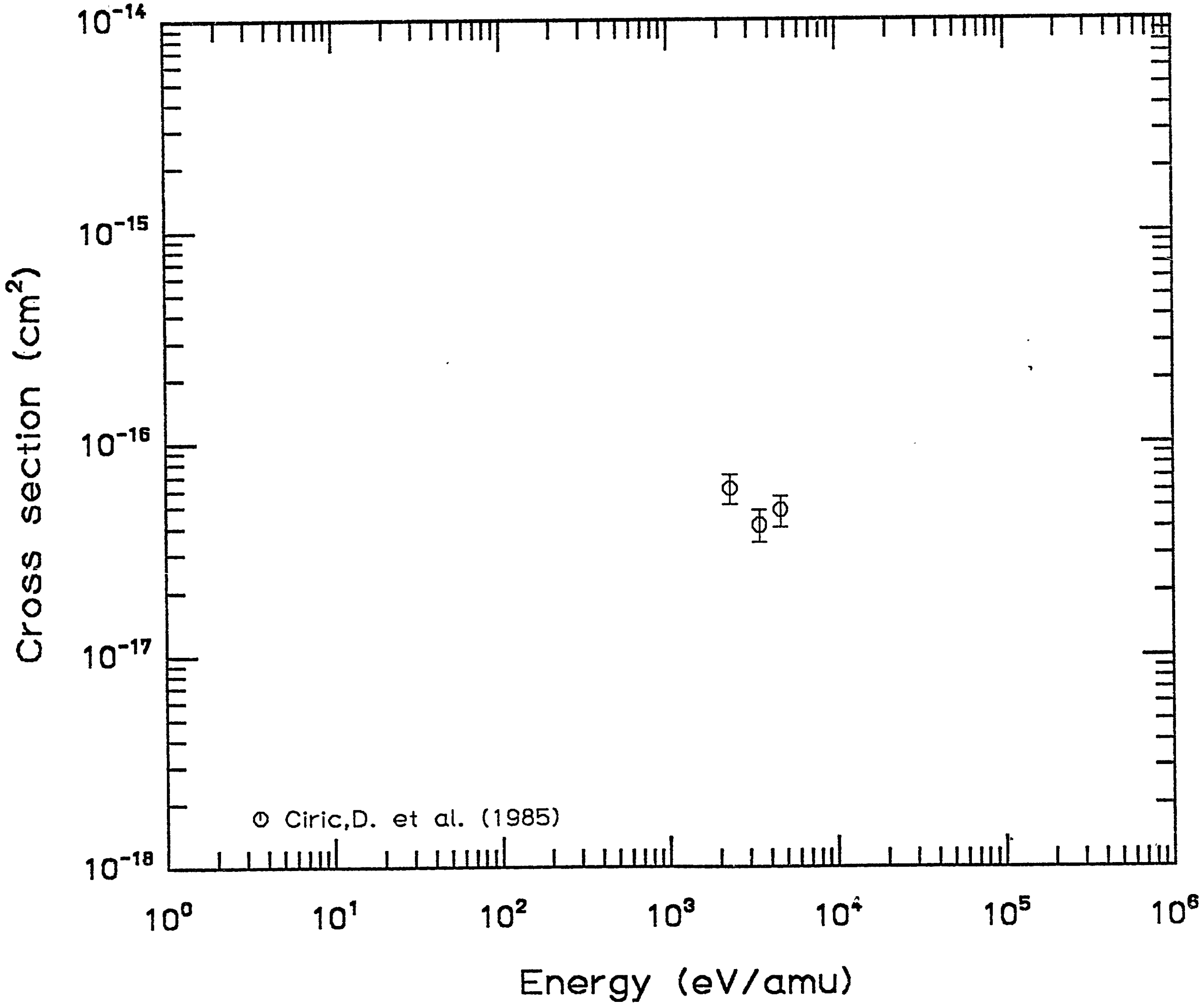


Fig.32 $C^{3+} + H \rightarrow C^{2+}(1s^2 2s4d\ ^3D) + H^+$

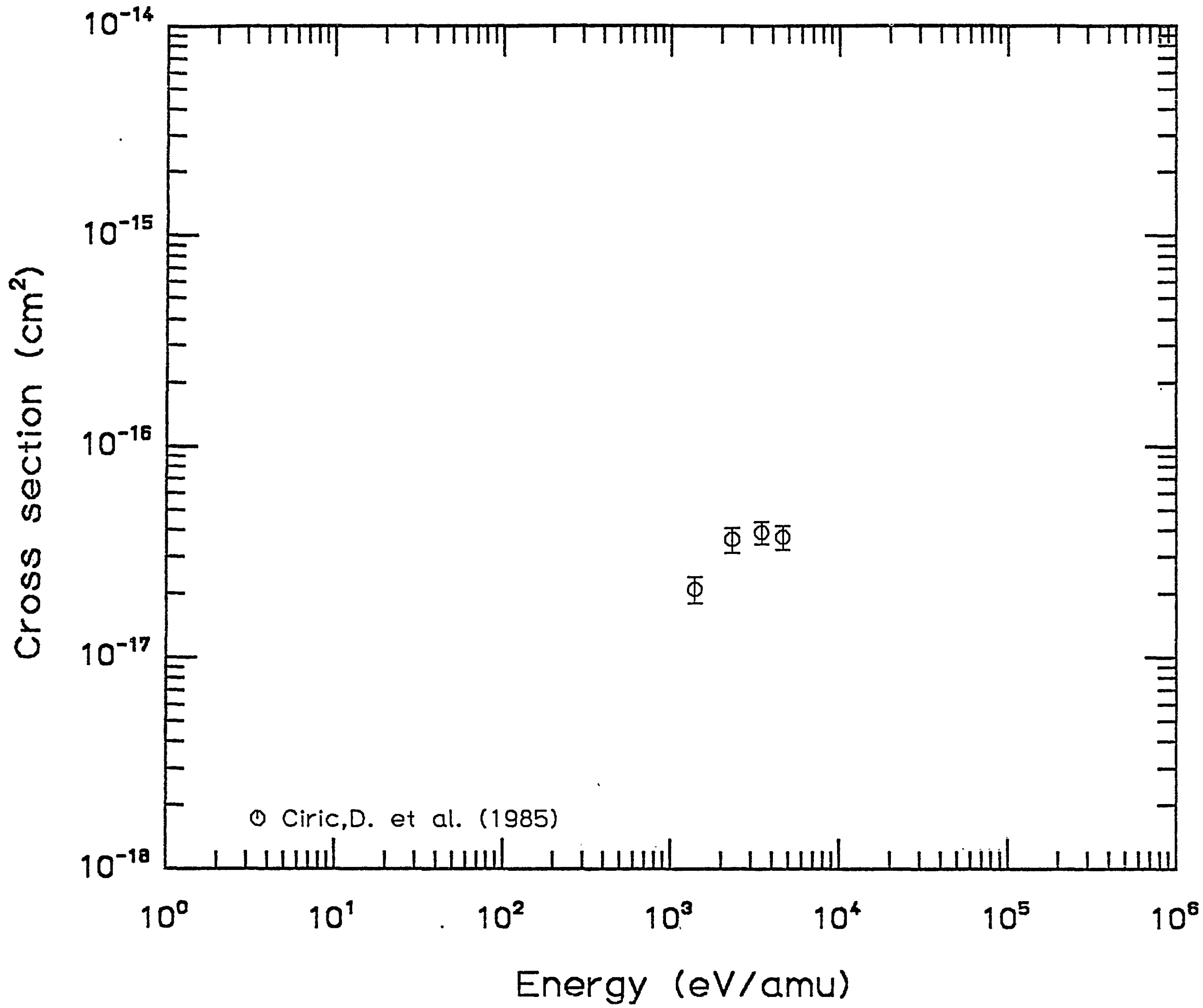


Fig.33 $C^{3+} + H \rightarrow C^{2+}(1s^2 2p^2\ ^1S) + H^+$

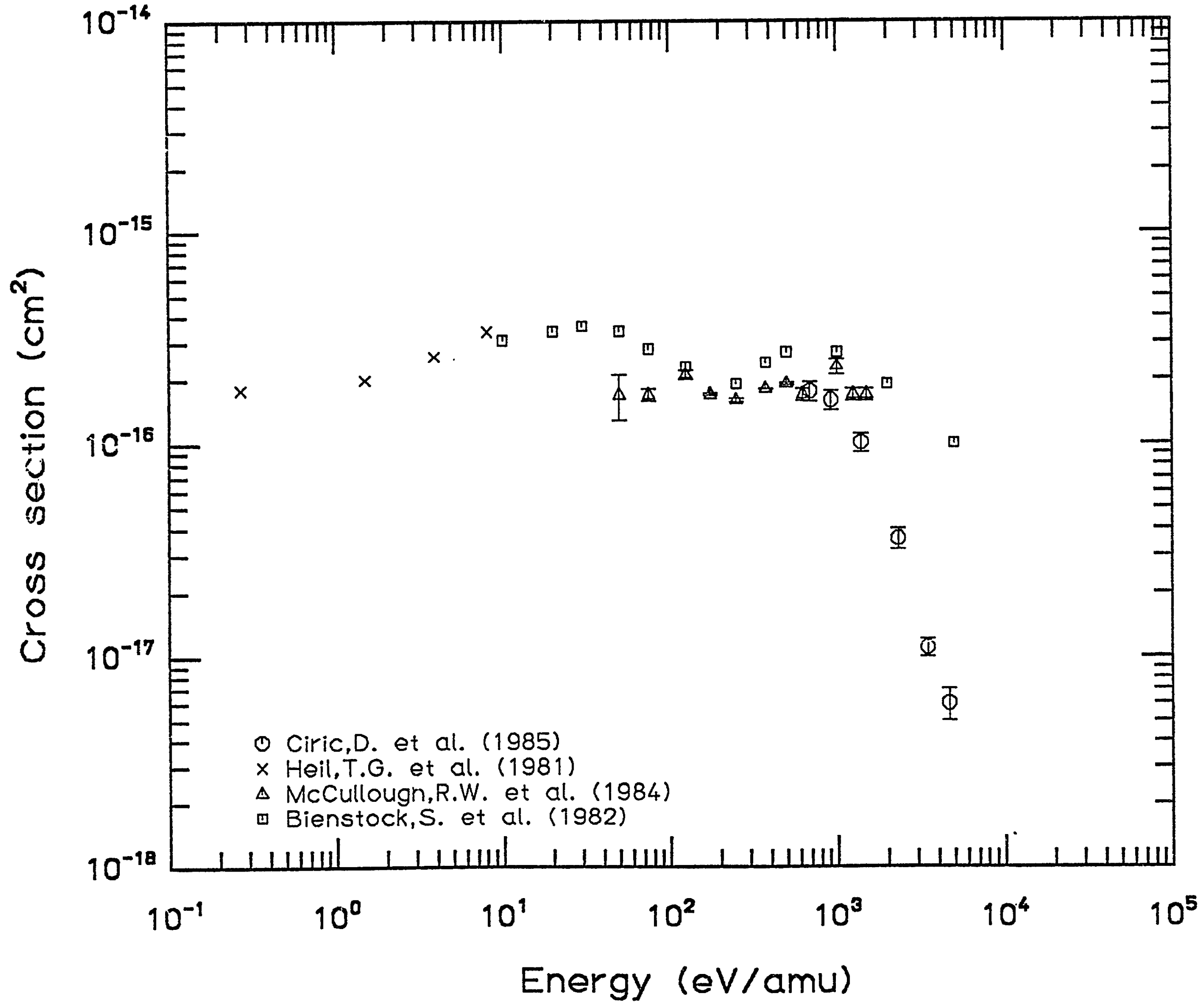


Fig.34 $C^{3+} + H \rightarrow C^{2+}(1s^2 2p^2\ ^3P) + H^+$

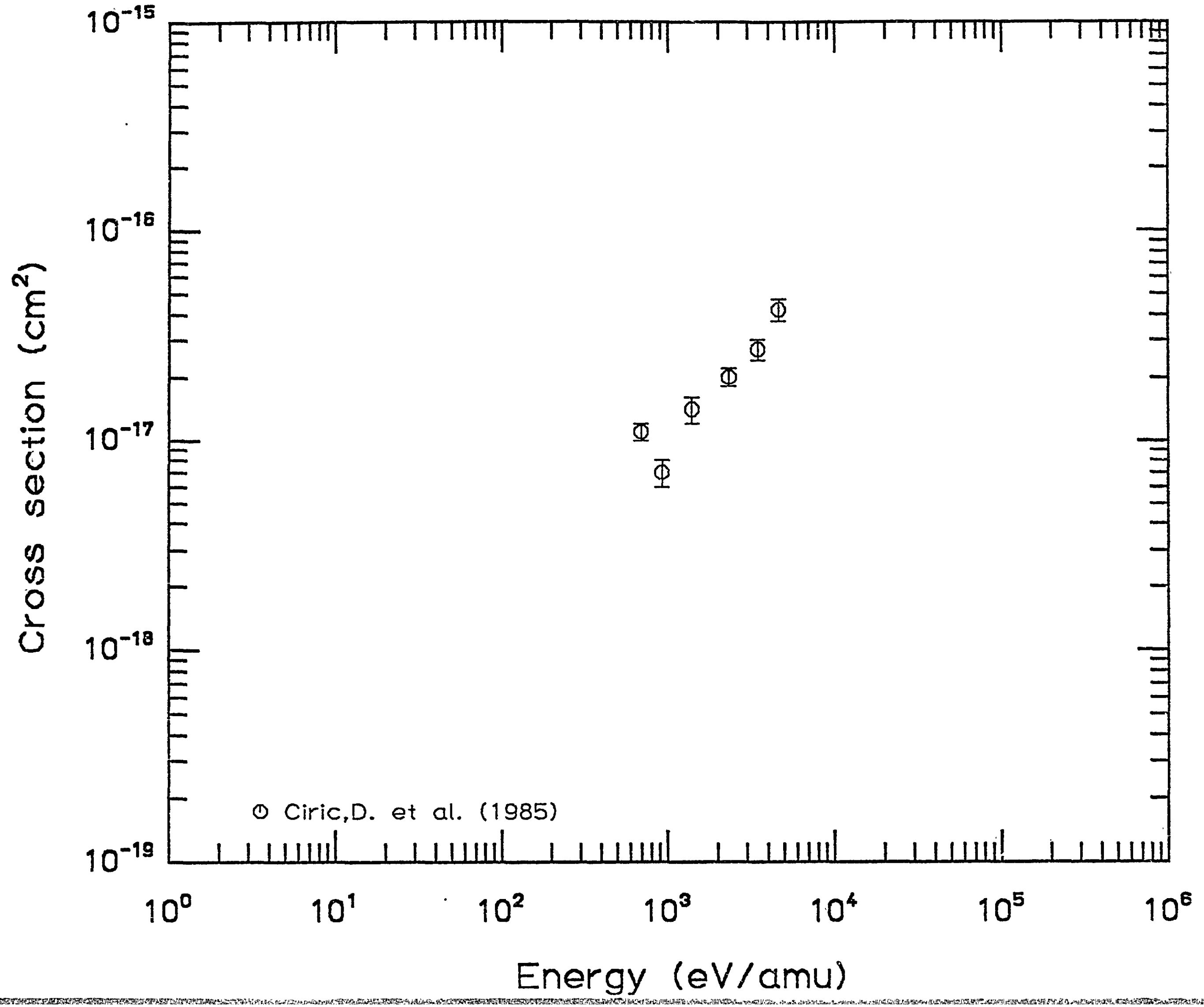
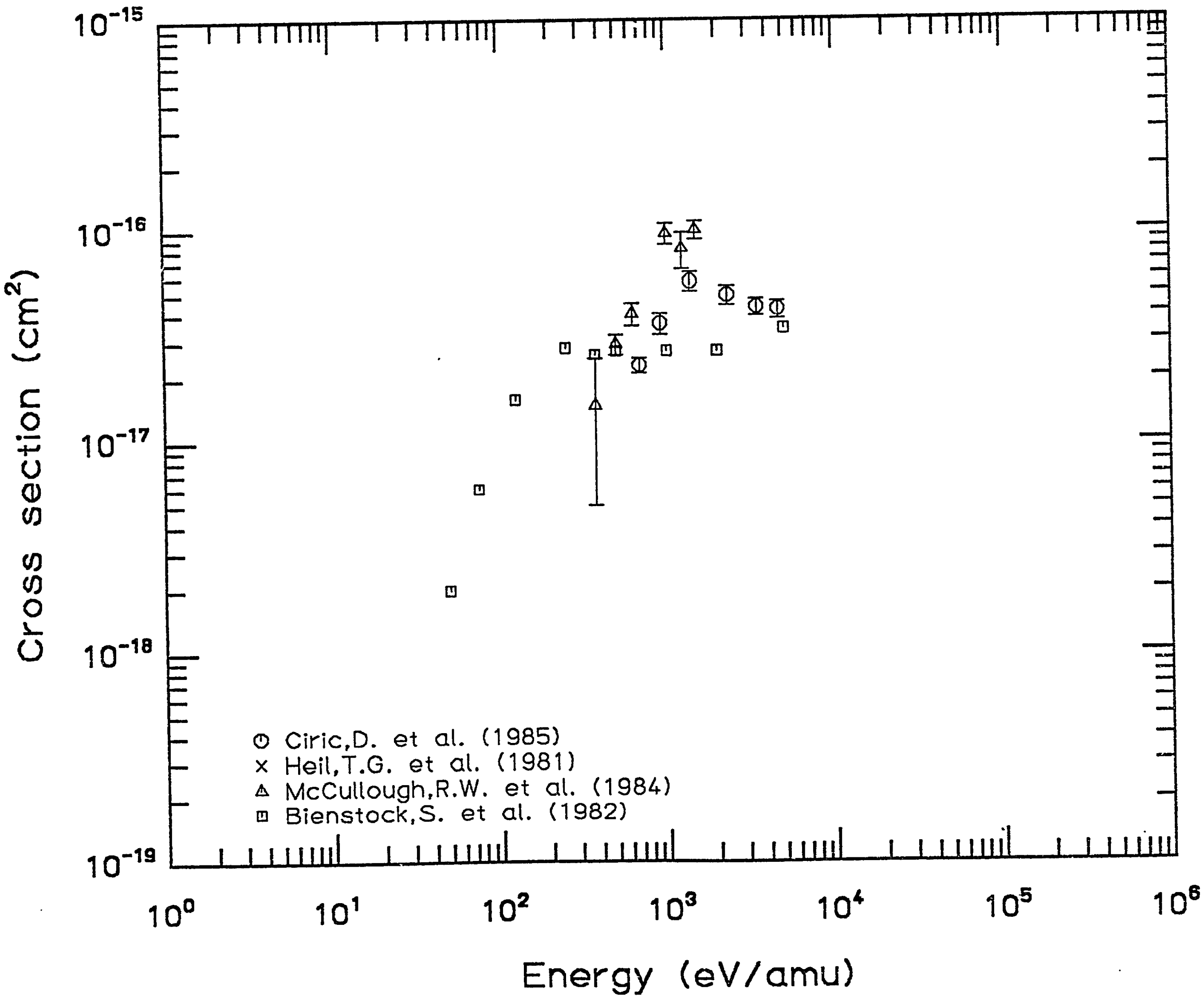


Fig.35 $C^{3+} + H \rightarrow C^{2+}(1s^2 2p^2\ {}^1D) + H^+$



I-5 $C^{2+}(1s^22s^2\ {}^1S) + H(1s) \rightarrow C^+ + H^+$

Total electron capture cross sections for this process are summarized, showing a broad maximum of 8×10^{-16} cm^2 at around 200 keV and decrease with decreasing the energy. However, no ($n\ell$) distributions have been determined experimentally. Only a single experiment on ($n\ell$) distributions was reported by McCullough et al.[2] over the energy range 2-8 keV. Unfortunately they could not provide the cross sections for ($n\ell$) distribution because their C^{2+} ion beams contain not only ions in the ground state, $1s^22s^2\ {}^1S$, but also an unknown but significant fraction of ions in the metastable $1s^22s2p\ {}^3P^o$ state.

On the other hand, some theoretical investigations have been made at low energies from the astrophysical interest[3-6]. Generally the cross sections are small at thermal to eV energy region and the rate coefficients of the electron capture process are 10^{-11} - 10^{-12} cm^3/s, which are two - three orders of magnitude smaller than those for C^{3+} + H collisions.

In these investigations, the following processes can be expected to occur :

$$C^{2+}(1s^22s^2\ {}^1S) + H(1s) \rightarrow C^+(1s^22s^22p\ {}^2P^0) + H^+ \qquad (1)$$
$$\rightarrow (1s^22s2p^2\ {}^2D) \qquad (2)$$
$$\rightarrow (1s^22s2p^2\ {}^2S) \qquad (3)$$
$$\rightarrow (1s^22s3p^2\ {}^2D). \qquad (4)$$

Process (1), electron capture into the ground state, is only important at low energies though the cross sections themselves are small (10^{-18} cm^2 at 1 eV[5]) and decrease with increasing the energy. With increasing the energy, the capture into the excited state accompanying simultaneous excitation, in particular process(2), becomes dominant with the cross section of 10^{-18} cm^2 at 100 eV. The dominance of process(2) at higher energies has been observed experimentally, though only qualitatively, by McCullough et al.[2] There the electron capture into $1s^22s2p^2\ {}^2S$ states begins to play a role (10 - 20% of ^2D state at 2-8 keV).

As already mentioned above, the measured total electron capture might be affected by the presence of the metastable $1s^22s2p\ ^3P^0$ state ions. McCullough et al. have shown that at 1 keV energy region the following processes involving the metastable ion beams are observed:

$$C^{2+}(1s^22s2p\ ^3P^0) + H(1s) \rightarrow C^+(1s^22s2p^2\ ^2D) + H^+ \qquad (5)$$
$$\rightarrow (1s^22s2p^2\ ^2S) \qquad (6)$$
$$\rightarrow (1s^22s^23p\ ^2P^0) \qquad (7)$$
$$\rightarrow (1s^22s^23d\ ^2D) \qquad (8)$$

and process (7) where one electron is captured into 2s state, accompanying 2p state electron excitation into 3p state, is found to be dominant (~50% of total).

The radiative electron transfer process

$$C^{2+}(1s^22s^2\ ^1S) + H(1s) \rightarrow C^+(1s^22s^22p\ ^2P^0) + H^+ + h\nu \qquad (9)$$

has the rate coefficients which are five orders of magnitude smaller than those for non-radiative electron cpture mentioned above in the energy range of 10 - 10^6 K.[6]

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. R.W. McCullough, F.W. Wilkie and H.B. Gilbody, J. Phys. B 17 (1982) 1373
3. R. McCarroll and P. Valiron, Astron. Astrophys. 44 (1975) 465
4. S.E. Butler, T.G. Heil and A. Dalgarno, Astrophys. J. 241 (1980) 442
5. T.G. Heil, S.E. Butler and A. Dalgarno, Phys. Rev. A 27 (1983) 2363
6. S.E. Butler, S.L. Guberman and A. Dalgarno, Phys. Rev. A 16 (1977) 500

Fig.36 $C^{2+} + H \dashrightarrow C^{1+}(1s^2 2s^2 2p\ ^2P^0) + H^+$

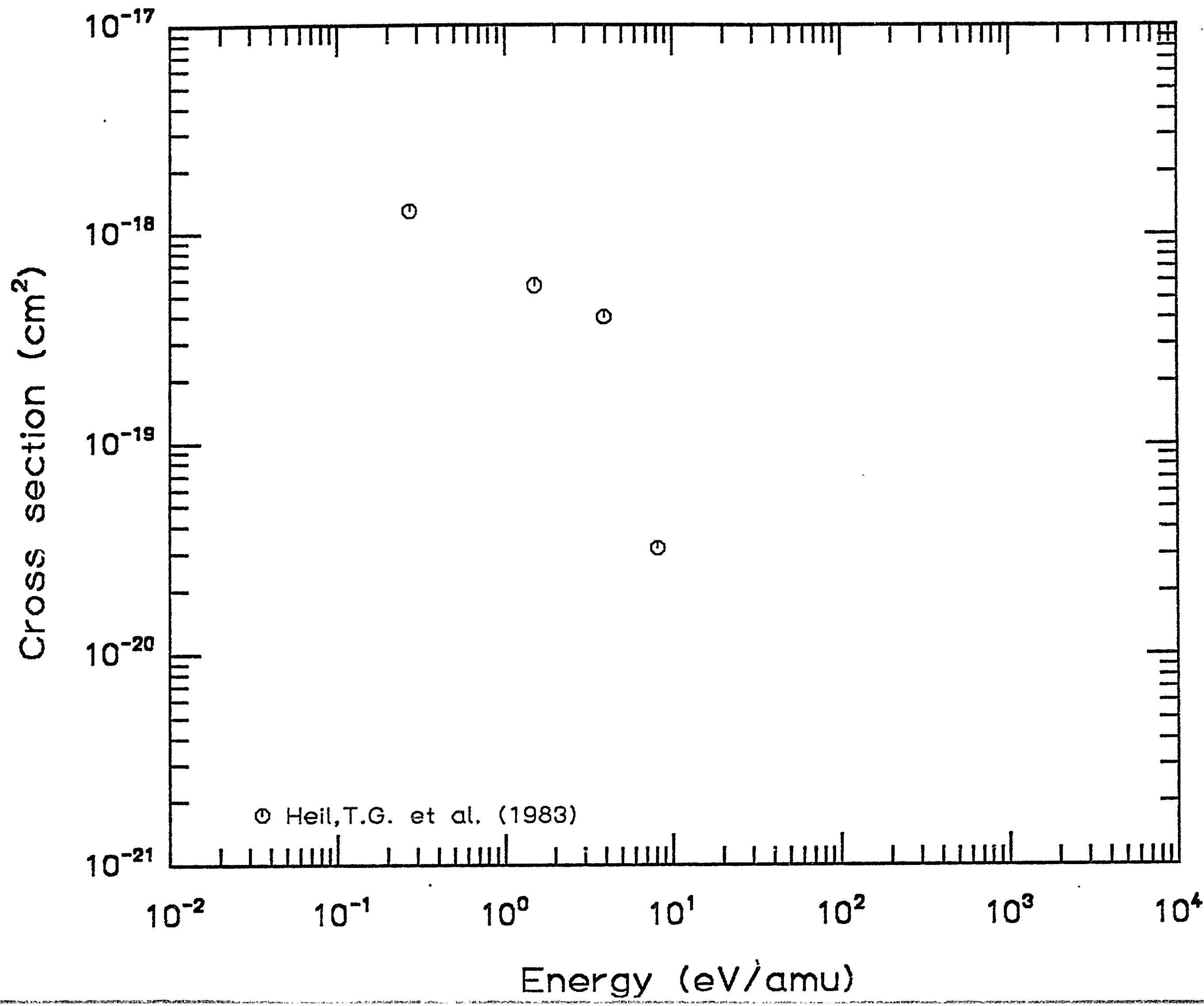
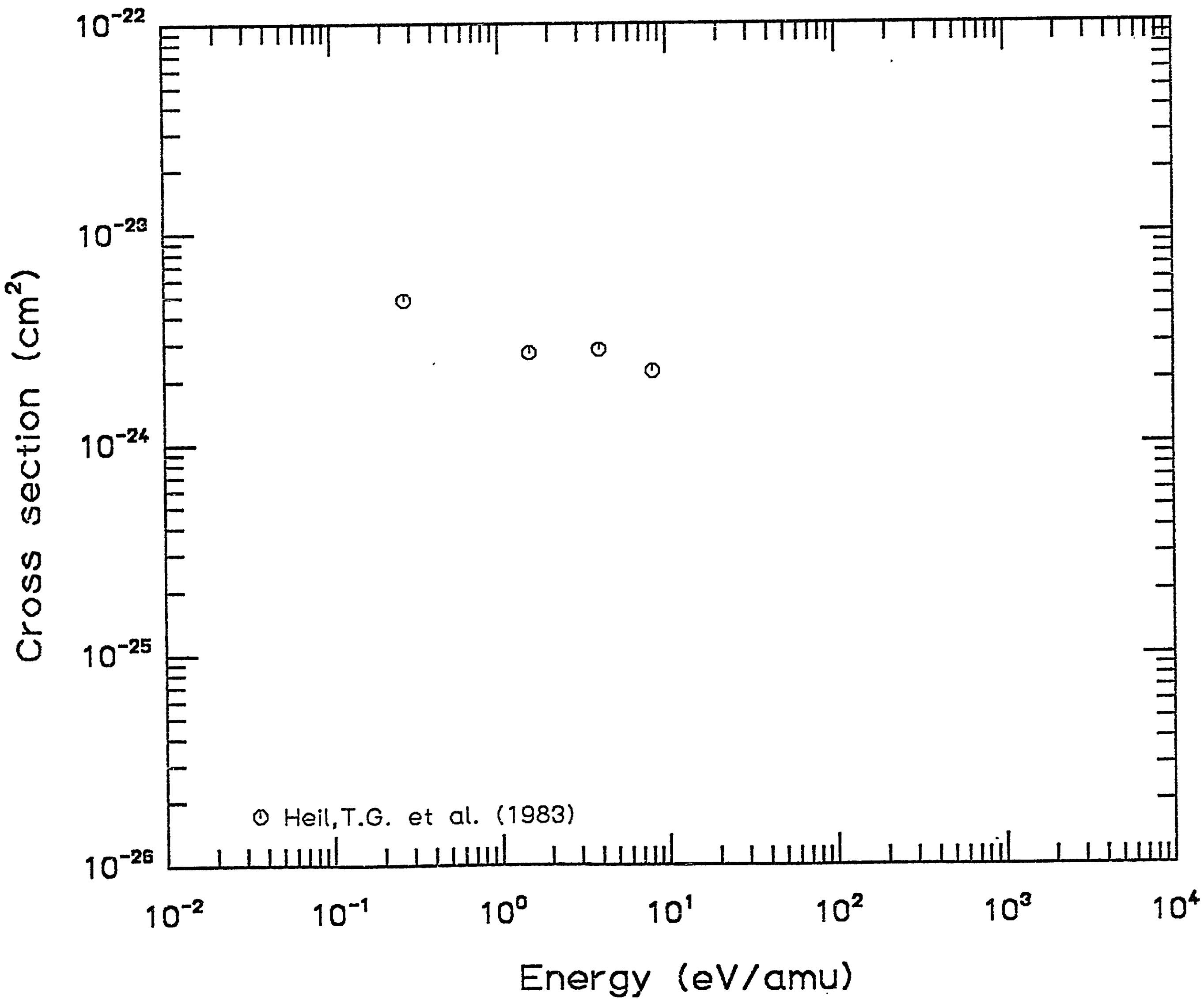


Fig.37 $C^{2+} + H \dashrightarrow C^{1+}(1s^2 2s2p^2\ ^2D) + H^+$



II $C^{q+} + H_2$ collisions

II-1 $C^{6+} + H_2 \rightarrow C^{5+}(n\ell) + H_2^{+}$

$$\rightarrow C^{4}(n\ell n'\ell') + H_2^{2+}$$

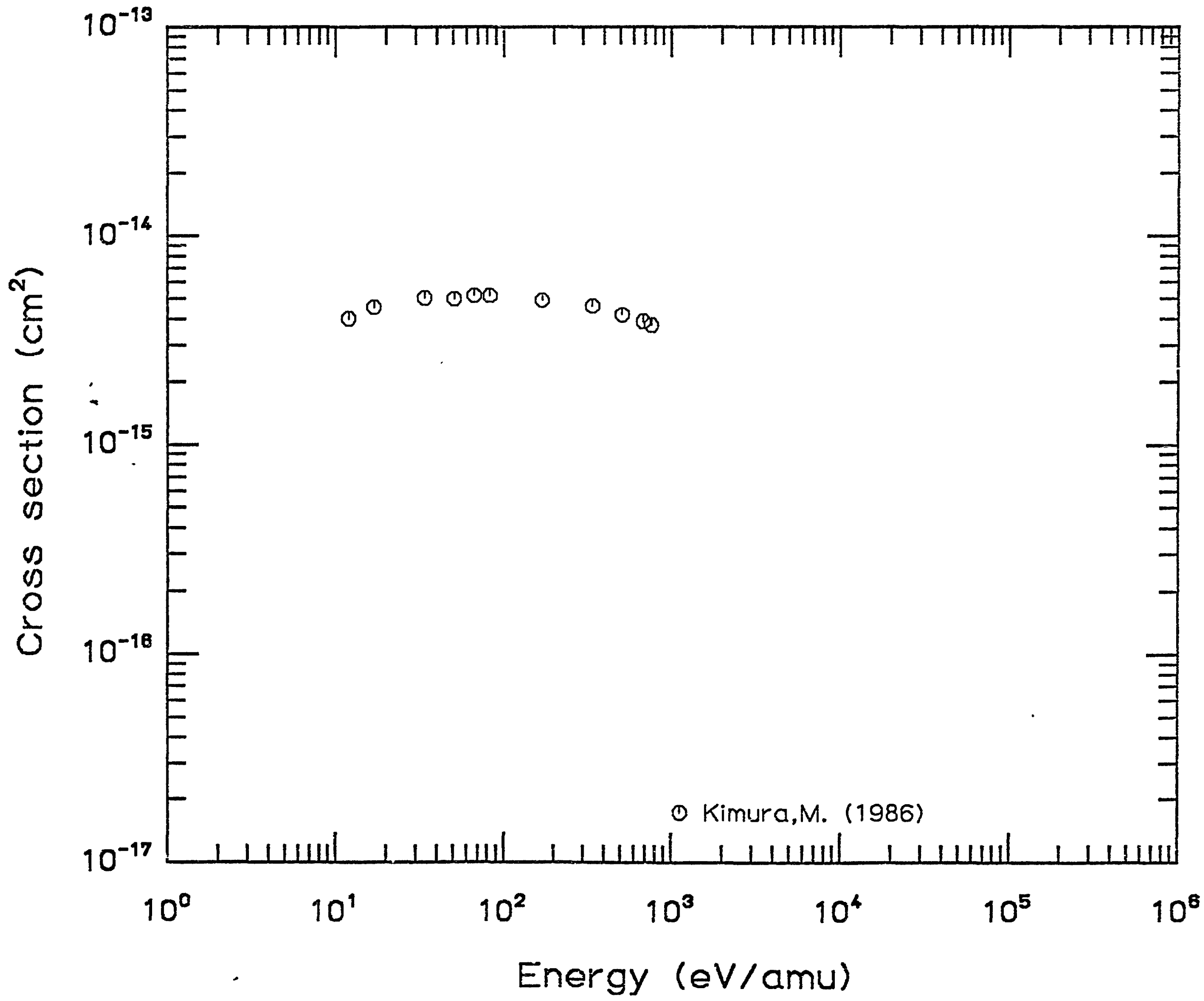
Experimental data for total cross sections for single electron capture are summarized[1]. Using the tunneling model, total electron capture cross sections have been also calculated by Grozdanov and Janev[2] at the energies 0.12 and 2.76 keV/amu. Only a single experiment has been reported for the VUV photon emission measurement by Dijkkamp et al.[3] over the energy range 1.7 - 9.2 keV/amu who determined the absolute emission cross sections for n=3 → n=2(13.5 nm), n=4 → n=2(18.2 nm), and n=4 → n=3(52.0 nm) transitions of C^{5+} ions. Their results show that the dominant electron capture occurs into n=4 state. Though no theoretical calculation of ($n\ell$) distributions has been reported, Kimura and Lane[4] have described the adiabatic potential energy curves for this system and found that there is clear difference between C^{6+} + H and $C^{6+} + H_2$ collision systems in the positions of the avoided crossings and the widths of the energy difference there, resulting in different behaviour of total cross sections between two systems. Their calculation also indicates the dominance of electron capture into n=4 states, agreeing with the experimental observation by Dijkkamp et al.[3] and by Kimura et al.[5]

No total cross section for double electron capture was reported yet.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985)235
2. T.P. Grozdanov and R.K. Janev, J. Phys. B 13 (1980) L69
3. D. Dijkkamp, Yu. S. Gordeev, A. Brazuk, A.G. Drentje and F.J. de Heer, J. Phys. B 18 (1985) 737
4. M. Kimura and N.F. Lane, Phys. Rev. A 35 (1987) 70
   M. Kimura, Phys. Rev. A 33 (1986) 4440
5. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

Fig.38 $C^{6+} + H_2 \rightarrow C^{5+}(\mathrm{total}) + H_2^+$



II-2 $C^{5+}(1s) + H_2 \rightarrow C^{4+}(1sn\ell) + H_2^{+}$
$\rightarrow C^{3+}(1sn\ell n'\ell') + H_2^{2+}$

Although total cross sections for single electron capture are summarized[1], no measurement of the partial cross sections has been reported except for the determination of the dominant electron capturing levels, that is, n=3 with a slight contribution of n=4 states.[2]

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

II-3 $C^{4+}(1s^2) + H_2 \rightarrow C^{3+}(1s^2n\ell) + H_2^+$
$\rightarrow C^{2+}(1s^2n\ell n'\ell') + H_2^{2+}$

Experimental data of total cross sections for single and double electron capture have been compiled[1]. Only a single set of data for the partial ($n\ell$) distributions have been reported by Dijkkamp et al.[2] over the energy range of 0.8 - 6.7 keV/amu, meanwhile a calculation of the partial cross sections has been made by Gargaud and McCarroll[3] using MO treatment over the energy range of 0.5 - 250 eV/amu. Both experiment and theory give the dominant capture into n=3 state which agrees with experimental results obtained through translational energy spectroscopy[4]. The ℓ-distribution among the n=3 states is strongly dependent upon the collision energy, with 3p state being dominant over 1 - 100 eV/amu.

Relative variation of ($n\ell m$) distributions has been determined by Baptist et al.[5] and found to be in agreement with the calculation by Gargaud and McCarroll[3]. Also Baptist et al.[6] measured the polarization of VUV photons emitted from ($3\ell m$) states of C^{3+} ions over 4 - 40 keV/amu with the result of significant polarization for 3s→2p transition and of m=0 and m=±1 being dominant at low and high energies investigated, respectively.

The behaviour of ($n\ell$) distribution of this system at much high energies (2 - 5 MeV) has been investigated also theoretically and experimentally.[7] It is found that the observed ($n\ell$) distributions can well be described by the continuum distorted wave calculation.

The electron capture of C^{4+} ions involving the metastable state (1s2s ^3S) has also been investigated at 3.33 keV/amu energy by Druetta et al.[8]:

$$C^{4+}(1s2s\ ^3S) + H_2 \rightarrow C^{3+}(1s2s3\ell\ ^4L) + H_2^+.$$

The dominant transition observed is 1s2s2p $^4P^0$ ← 1s2s3s ^4S, with the cross section of 1.5×10^{-15} cm^2.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. D. Dijkkamp, D. Ciric, E. Vlieg, A. de Boer and F.J. de Heer, J. Phys. B 18 (1985) 463
3. M. Gargaud and R. McCarroll, J. Phys. B 18 (1985) 463
4. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873
5. R. Baptist, J.J. Bonnet, M. Bonnefoy, E. Bousey, A. Brenac, M. Chassevent, G. Chauvet, S. Dousson, Y. Le Duff, A. Fleury, M. Gargaud and D. Hitz, Nucl. Instr. Meth. in Phys. Res. B 23 (1987) 123
6. R. Baptist, J.J. Bonnet, G. Chauvet, J.P. Desclaux, S. Dousson and D. Hitz, J. Phys. B 17 (1984) L417
7. L.J. Dube, U. Will, R. Bruch, E. Trabert and P.H. Heckmann, Nucl. Instr. Meth. in Phys. Res. B 9 (1985) 408
8. M. Druetta, S. Martin and J. Desesquelles, Nucl. Instr. Meth. in Phys. Res. B 23 (1987) 268

Fig.39 $C^{4+} + H_2 \dashrightarrow C^{3+}(\text{total}) + H_2^+$

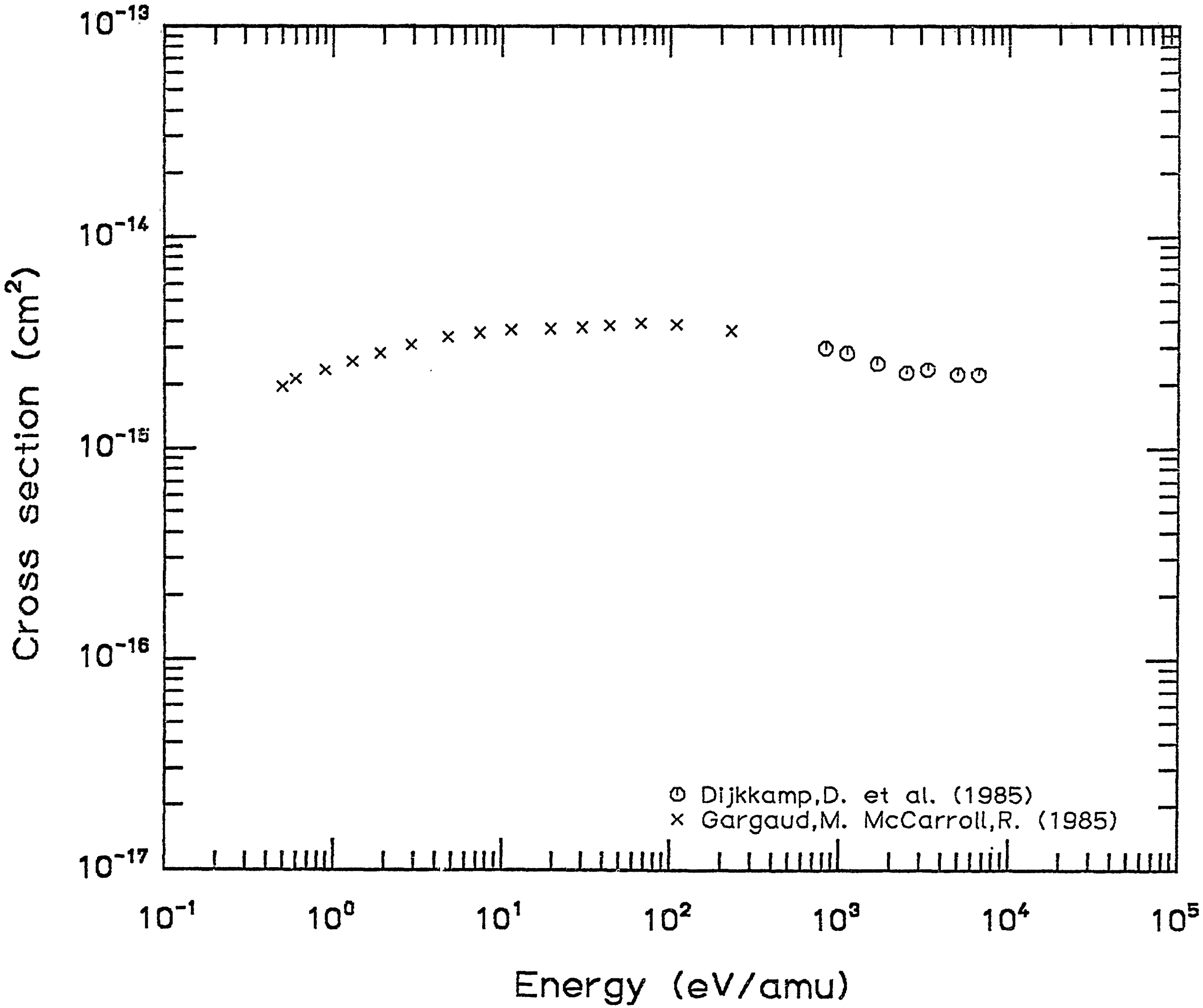


Fig.40 $C^{4+} + H_2 \rightarrow C^{3+}(1s^2 3s) + H_2^+$

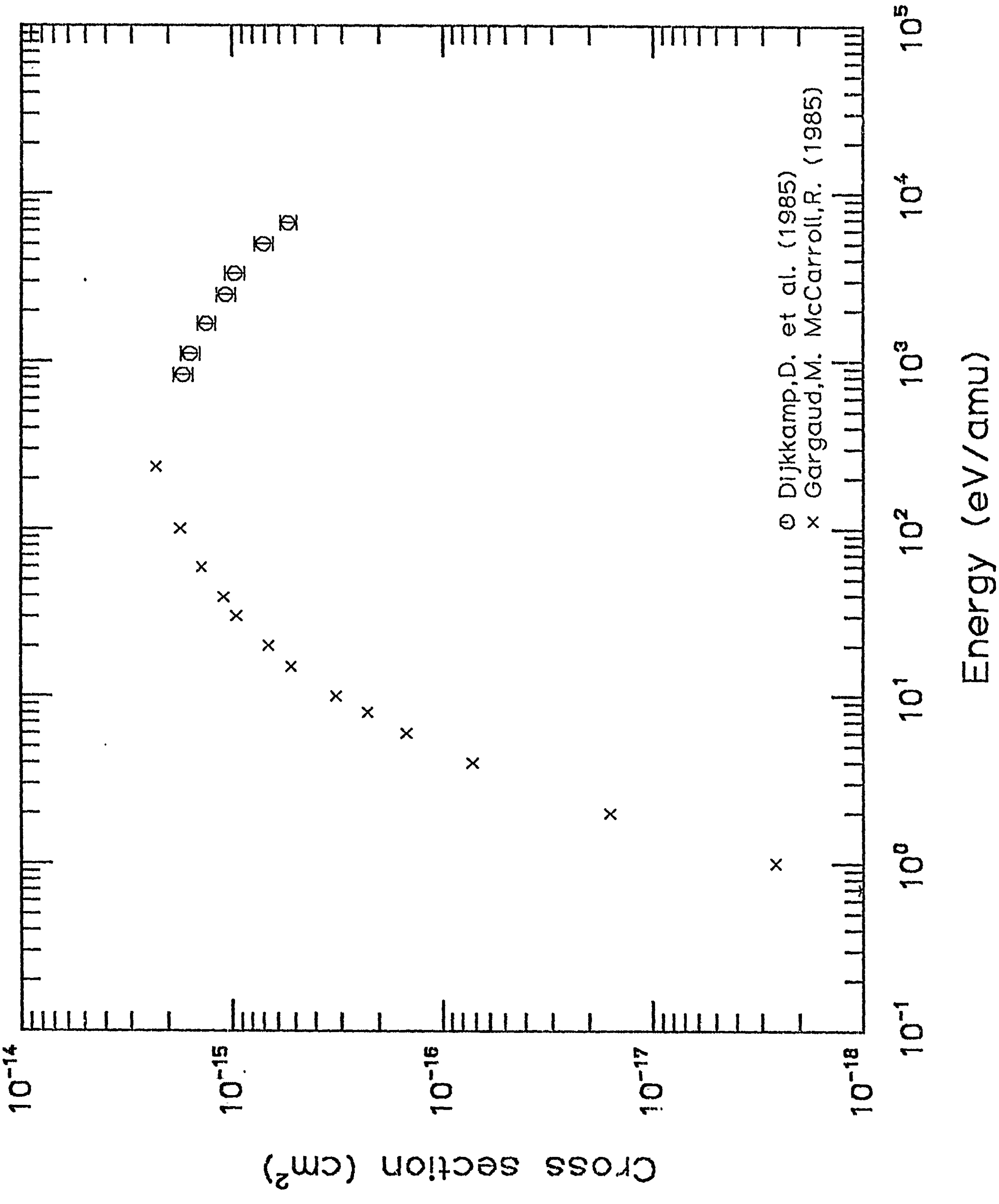


Fig.41 $C^{4+} + H_2 \dashrightarrow C^{3+}(1s^23p) + H_2^+$

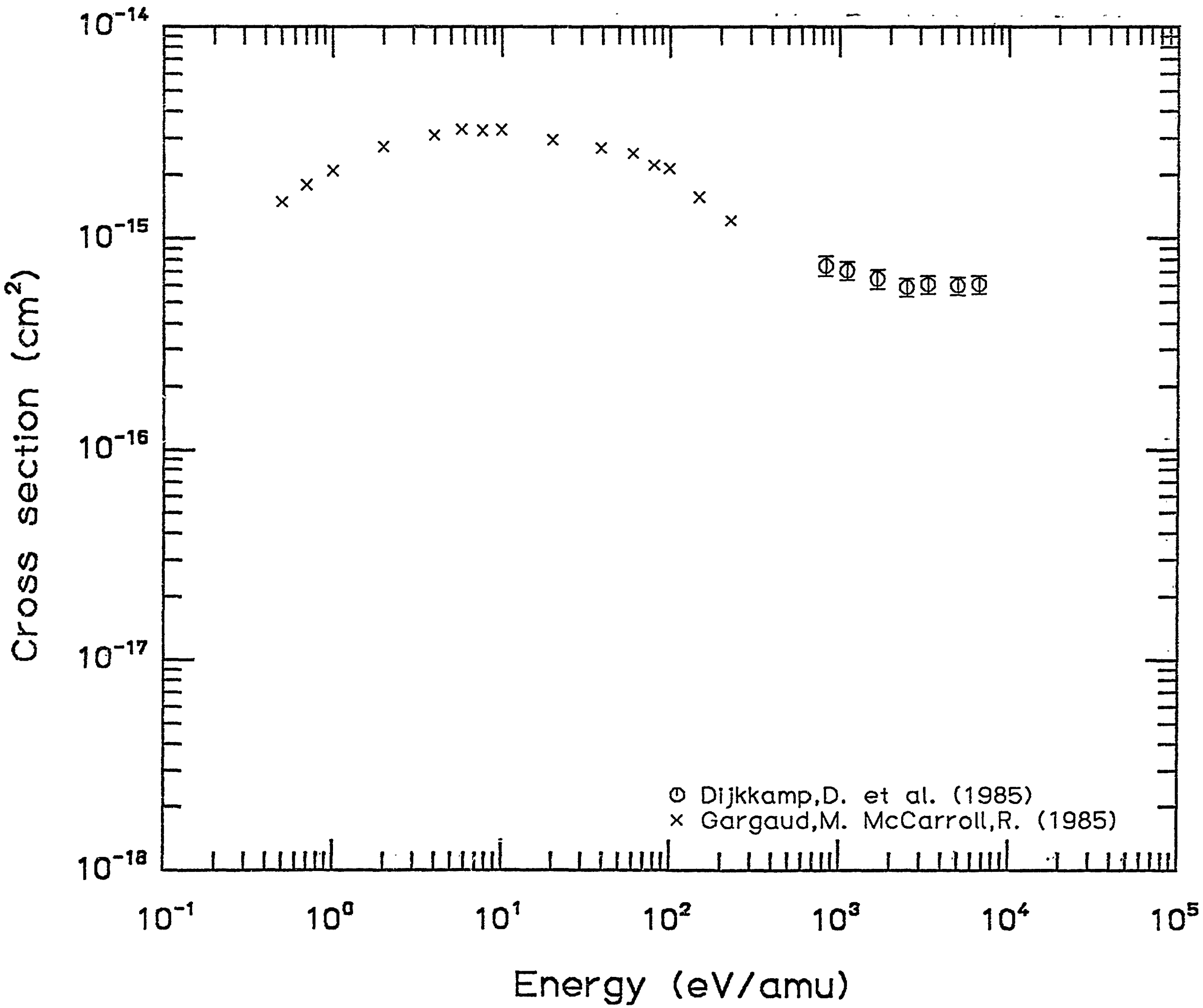


Fig.42 $C^{4+} + H_2 \rightarrow C^{3+}(1s^2 3d) + H_2^+$

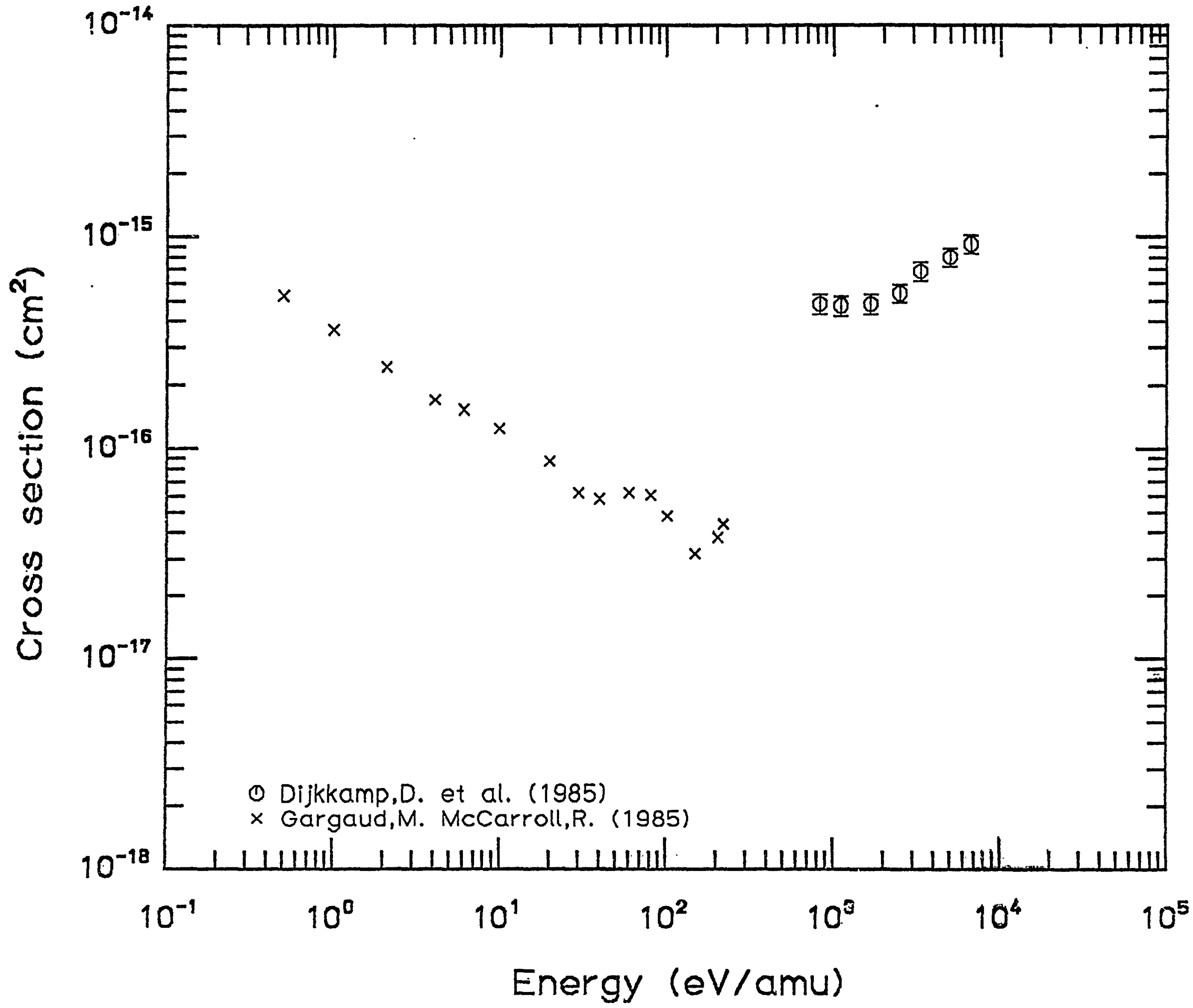


Fig.43 $C^{4+} + H_2 \dashrightarrow C^{3+}(1s^2 4s) + H_2^+$

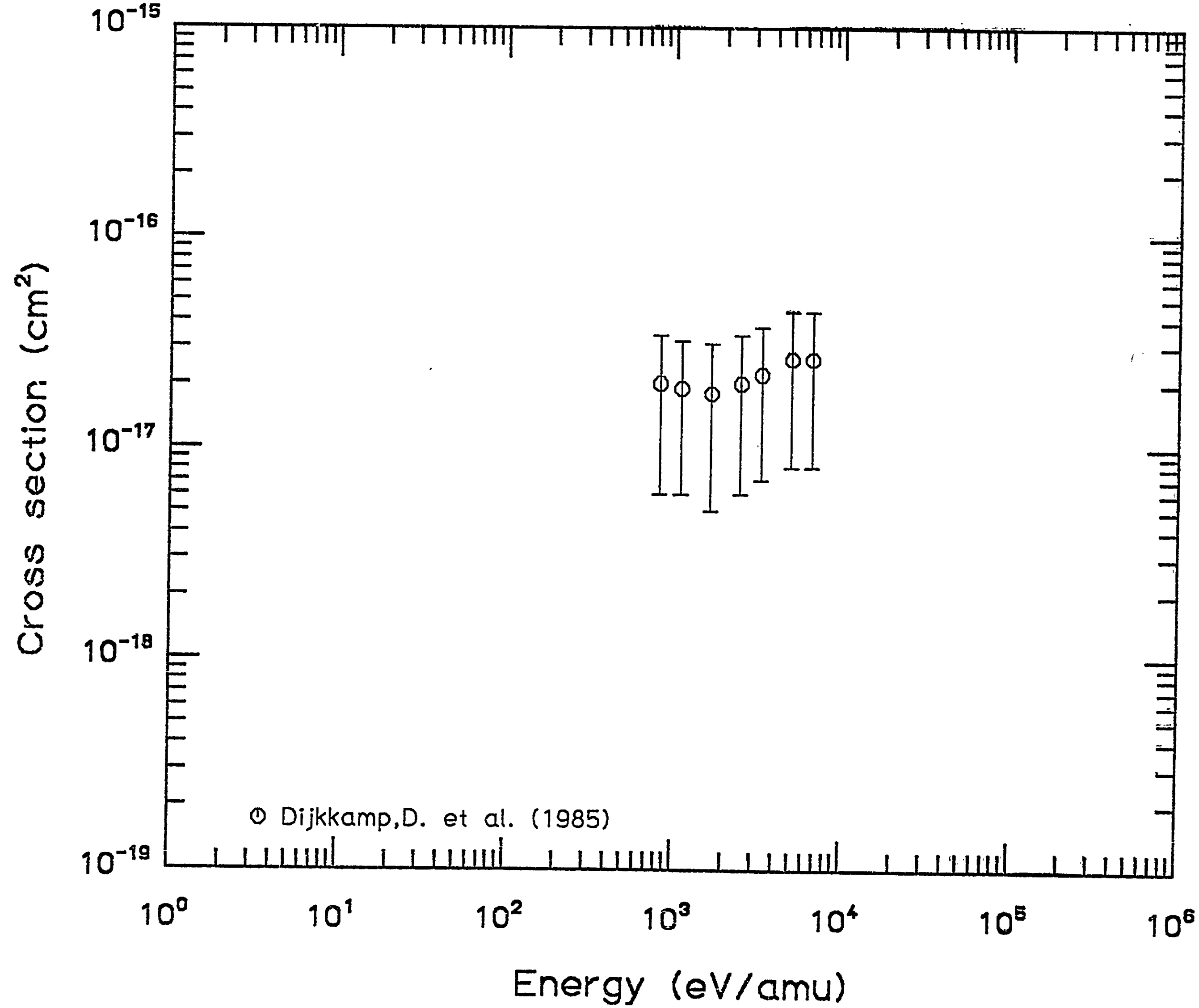


Fig.44 $C^{4+} + H_2 \dashrightarrow C^{3+}(1s^2 4p) + H_2^+$

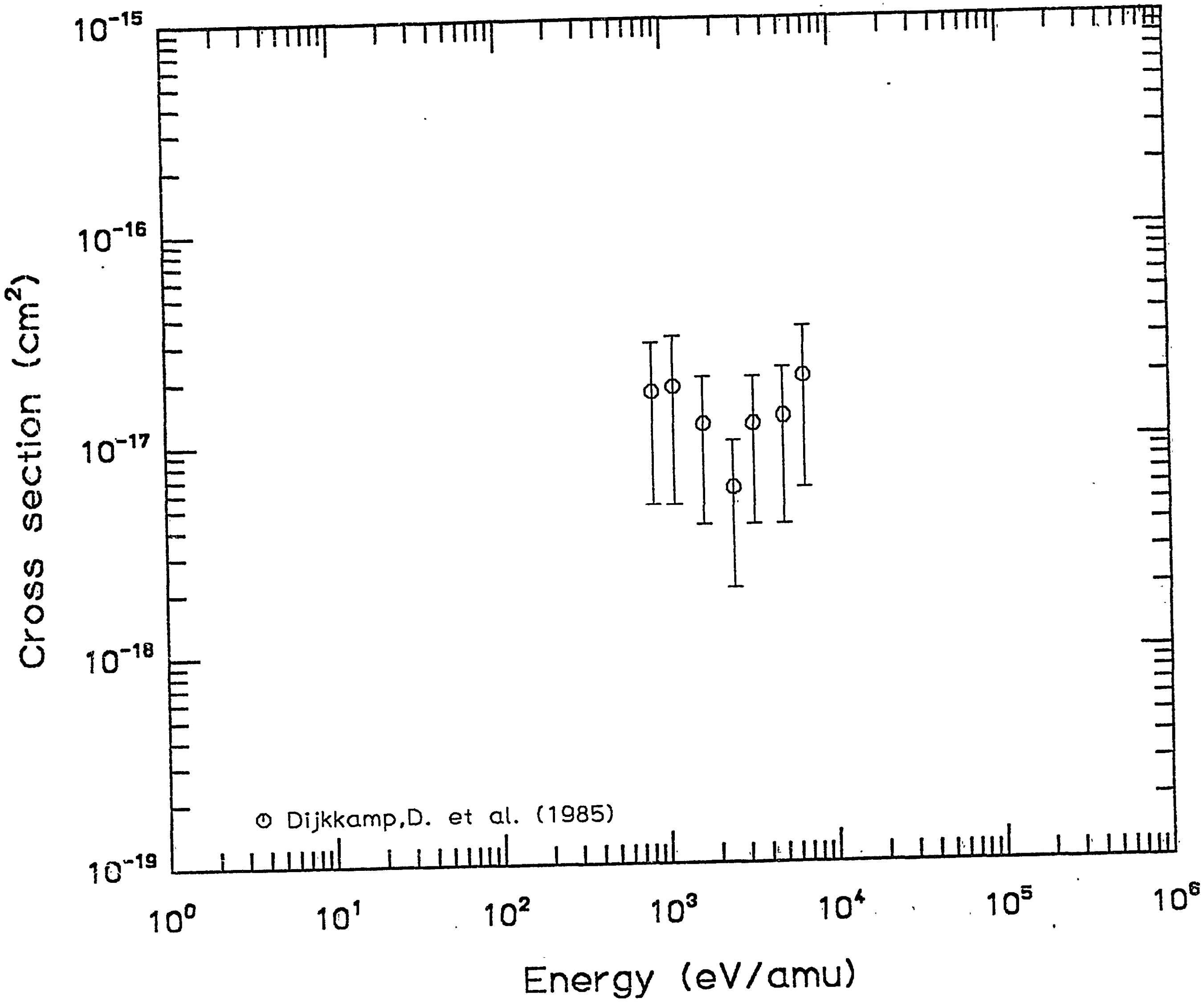


Fig.45 $C^{4+} + H_2 \dashrightarrow C^{3+}(1s^24d) + H_2^+$

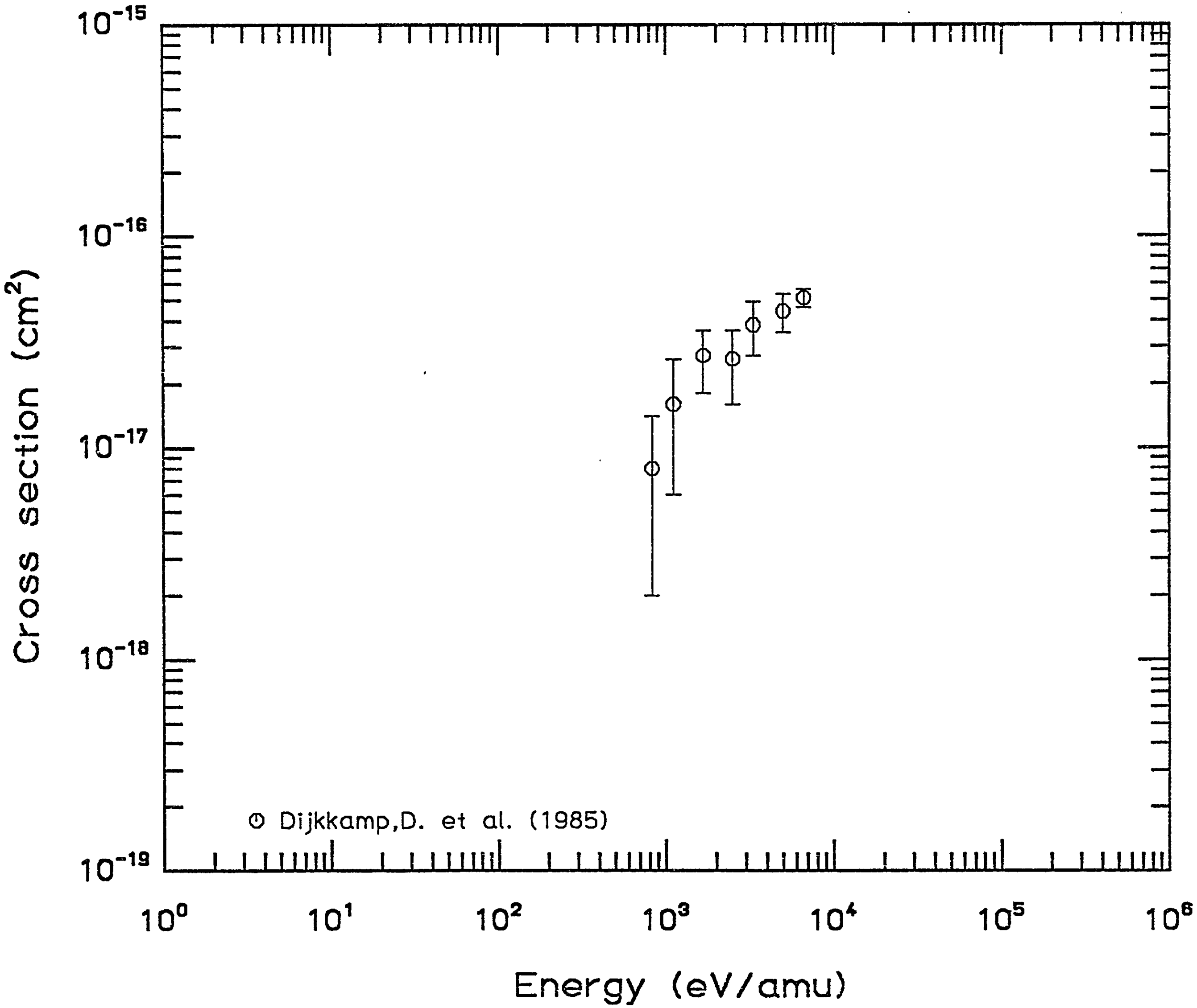
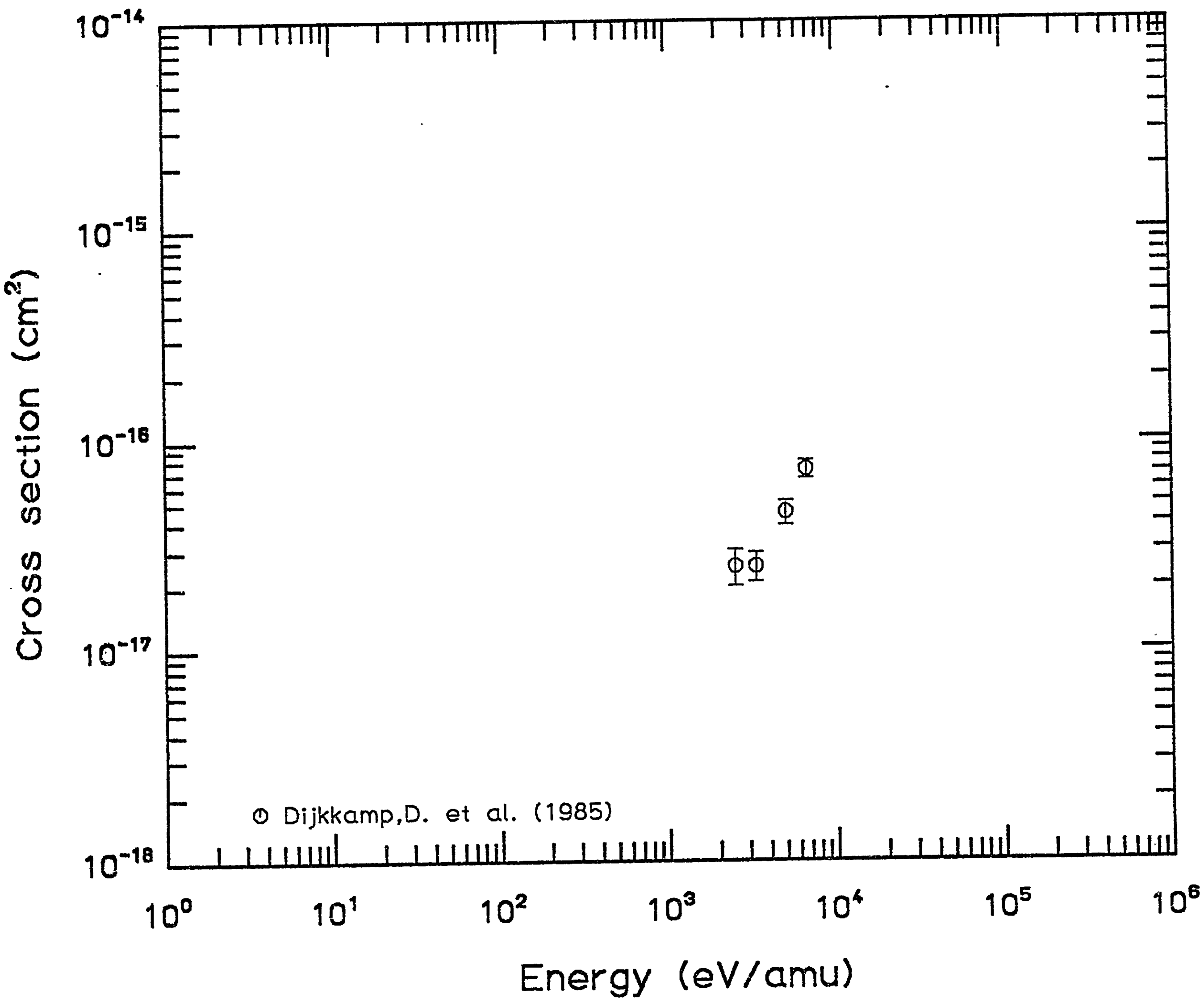


Fig.46 $C^{4+} + H_2 \rightarrow C^{3+}(1s^2 4f) + H_2^+$



II-4 $C^{3+}(1s^2 2s\ ^2S) + H_2 \rightarrow C^{2+}(1s^2 2\ell n\ell') + H_2^+$
$\rightarrow C^+ + H_2^{2+}$

Total cross sections for single electron capture process have been summarized.[1] In collisions with molecular targets, not only the simple electron capture but also target excitation or transfer ionization can occur and, therefore, the collision processes are much more complicated, compared with those of atomic target. In fact, Wilkie et al.[2] observed a number of peaks corresponding to the following processes in their energy spectra:

$$
\begin{aligned}
C^{3+}(1s^2 2s\ ^2S) + H_2 \rightarrow\ & C^{2+}(1s^2 2s3s\ ^3S) + H_2^+ && (1)\\
& (1s^2 2p^2\ ^1S) && (2)\\
& (1s^2 2p^2\ ^1D) && (3)\\
& (1s^2 2p^2\ ^3P) && (4)\\
& (1s^2 2s2p\ ^1P^0) && (5)\\
& (1s^2 2s2p\ ^3P^0) && (6)\\
& (1s^2 2p^2\ ^3P) + H^+ + H(1s) && (7)\\
& (1s^2 2s2p\ ^1P^0) && (8)\\
& (1s^2 2s2p\ ^3P^0) && (9)\\
& (1s^2 2s^2\ ^1S). && (10)
\end{aligned}
$$

The first six processes correspond to the electron capture into projectile ions resulting in simple ionization of H_2, whereas the last four do to the dissociative ionization of target molecules. Even though the limited energy resolution of their system prohibited the complete separation of all these processes, their spectrum clearly shows the dominance of process (3), electron capture plus electron excitation, at their energy range (1.5 - 18 keV). However, they could not determine the cross sections for these processes.

On the other hand, Ciric et al.[3], through photon spectroscopy, determined the cross sections for the same processes as those in atomic hydrogen target (see the above), regardless of the target molecular states after collision. Their result indicates the cross sections for $2p^2\ ^1D$ state are dominant at lower energy (8.28 keV), agreeing qualitatively with those of Wilkie et al., and decrease with increasing the energy, whereas at higher energies (55.4 keV) those for 3s ^3S state become dominant with significant contribution of 3d ^3D state as well as $2p^2$ ^1D state, similar to the trend of atomic hydrogen targets. It should be noted that as their absolute values of the total cross sections obtained by summing up those for all the processes investigated and by their independent direct measurements of total cross sections seem to be inconsistent with each other and also in disagreement with other experiments, their data shown here are renormalized to the known cross sections[1] by multiplying their original data by 1.74, assuming their relative values are correct. No total cross section for double electron capture was reported yet.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. F.G. Wilkie, R.W. McCullough and H.B. Gilbody, J. Phys. B 19 (1986) 239
3. D. Ciric, A. Brazuk, D. Dijkkamp, F.J. de Heer and H. Winter, J. Phys. B 18 (1985) 3629

Fig.47 $C^{3+} + H_2 \text{ --> } C^{2+}(\text{total}) + H_2^+$

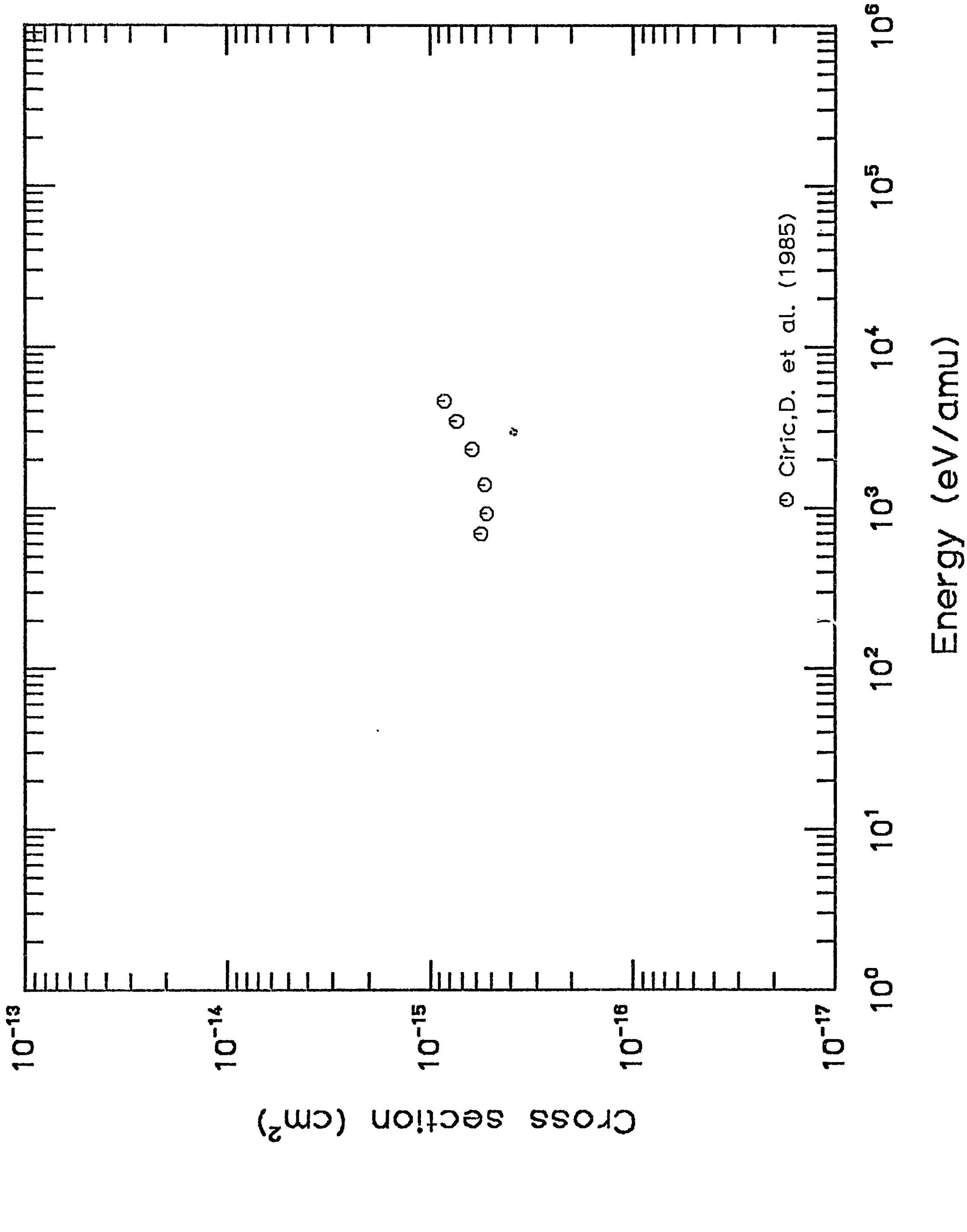


Fig.48 $C^{3+} + H_2 \rightarrow C^{2+}(1s^2 2s3s\ ^3S) + H_2^+$

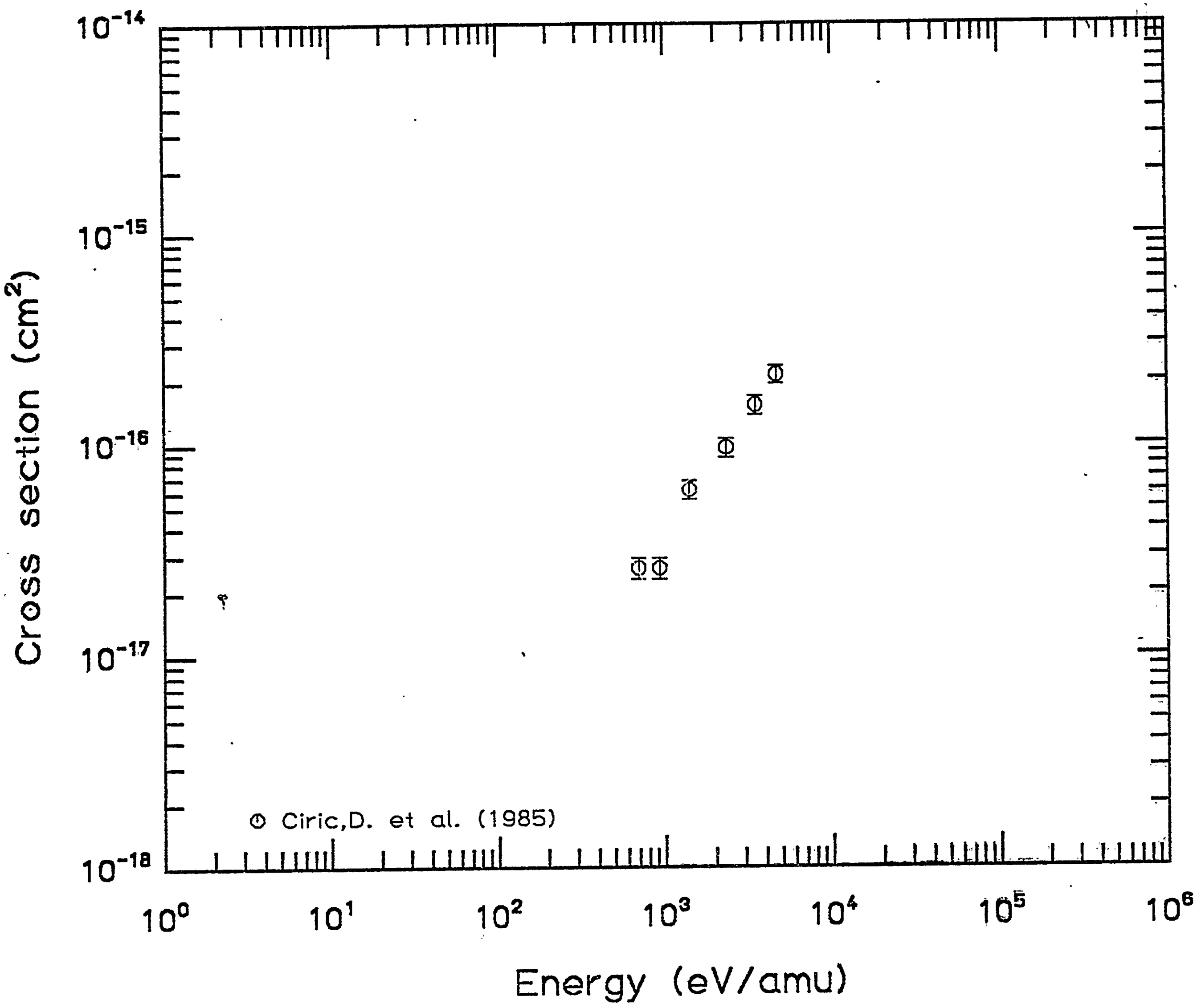


Fig.49 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2s3s\ ^1S) + H_2^+$

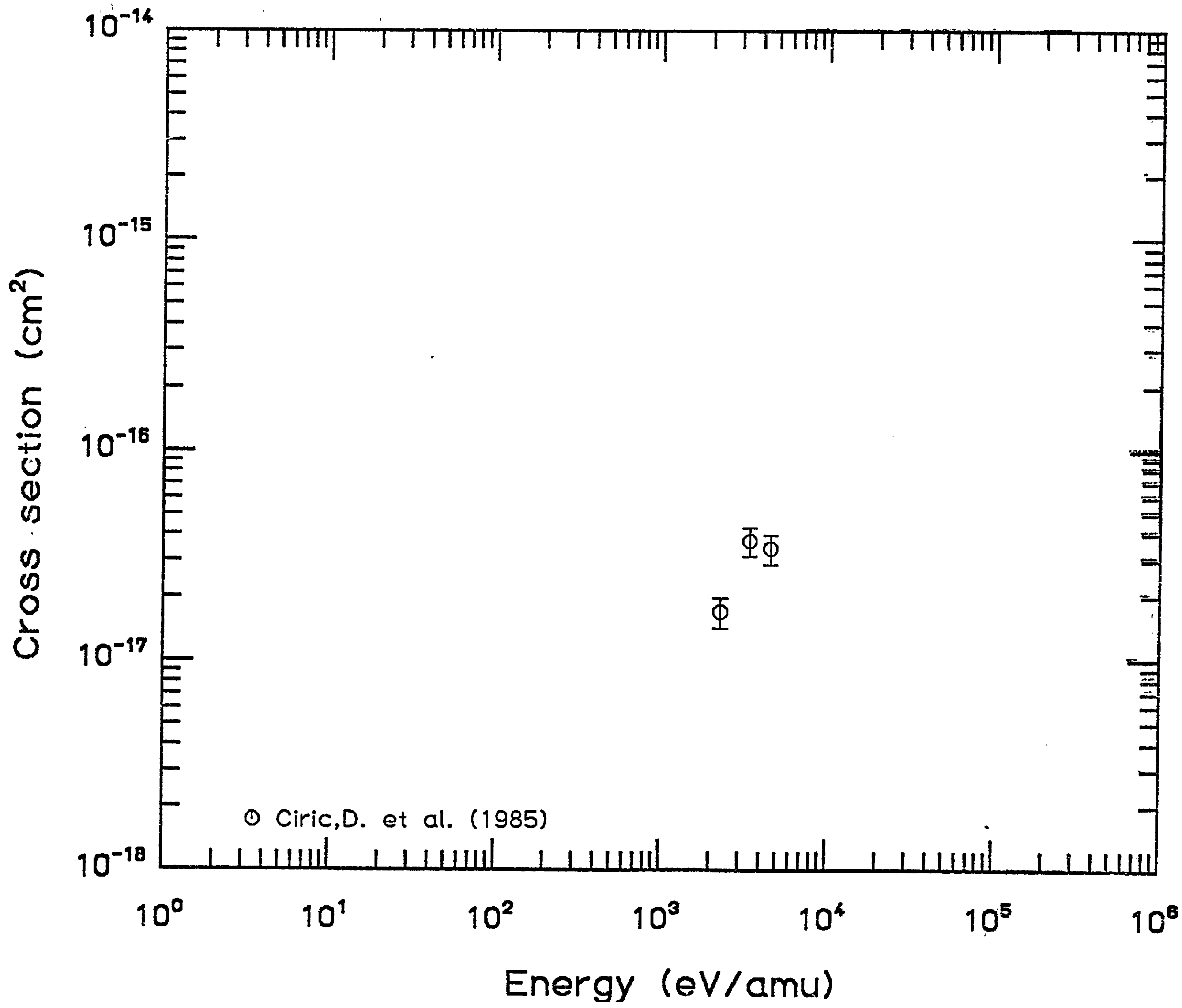


Fig.50 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2s3p\ ^3P^0) + H_2^+$

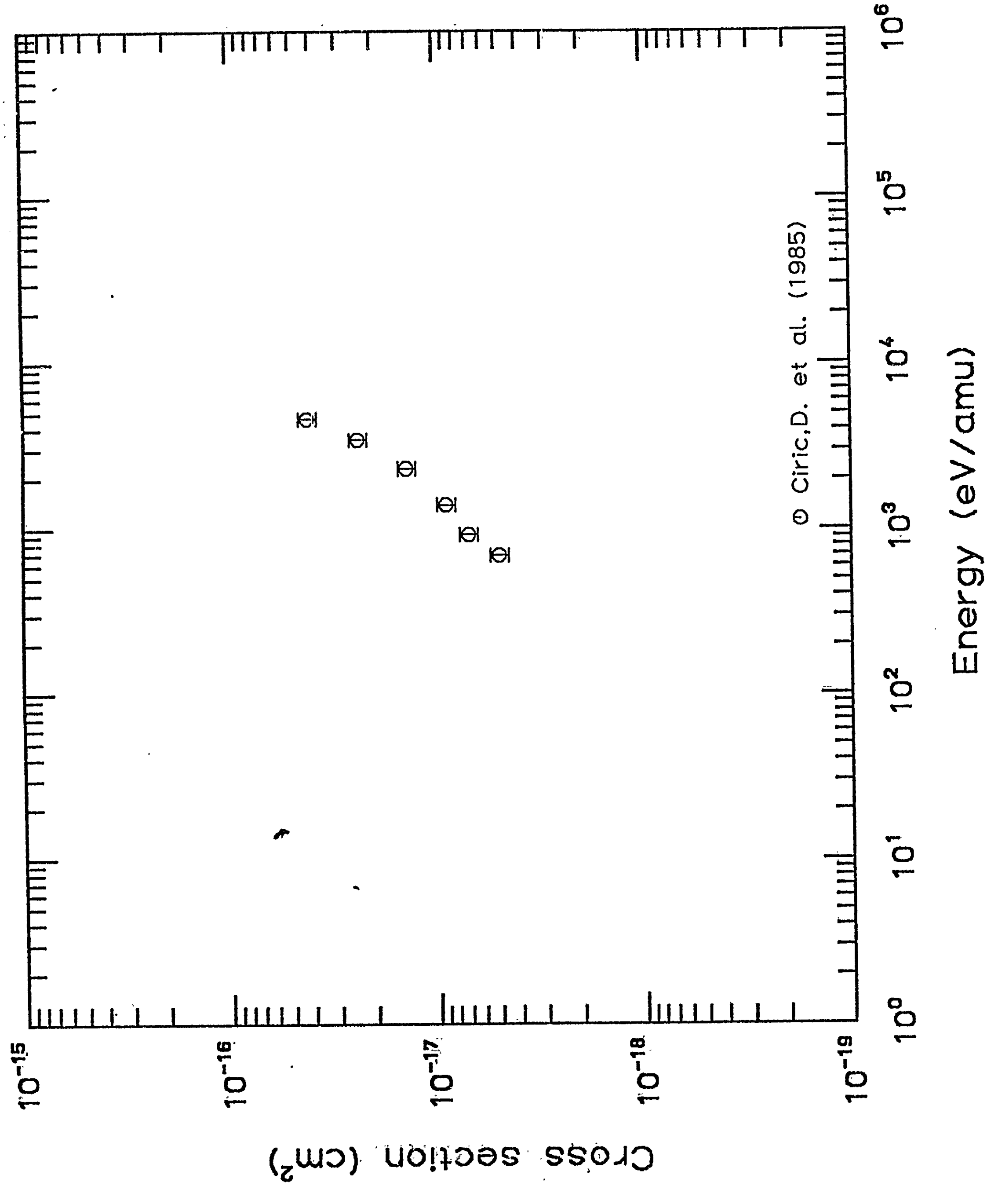


Fig.51 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2s3p\ ^1P^0) + H_2^+$

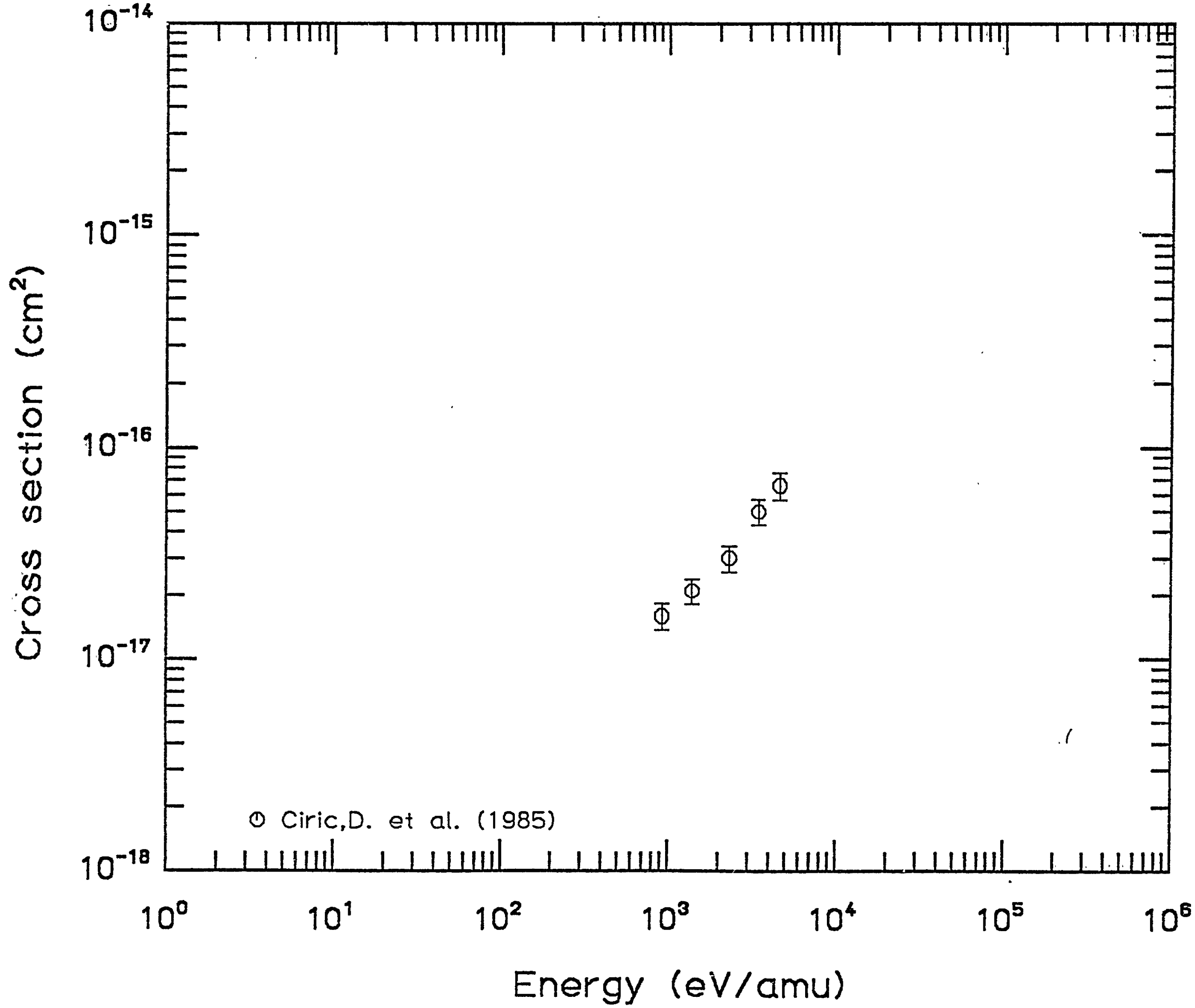


Fig.52 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2s3d\ ^3D) + H_2^+$

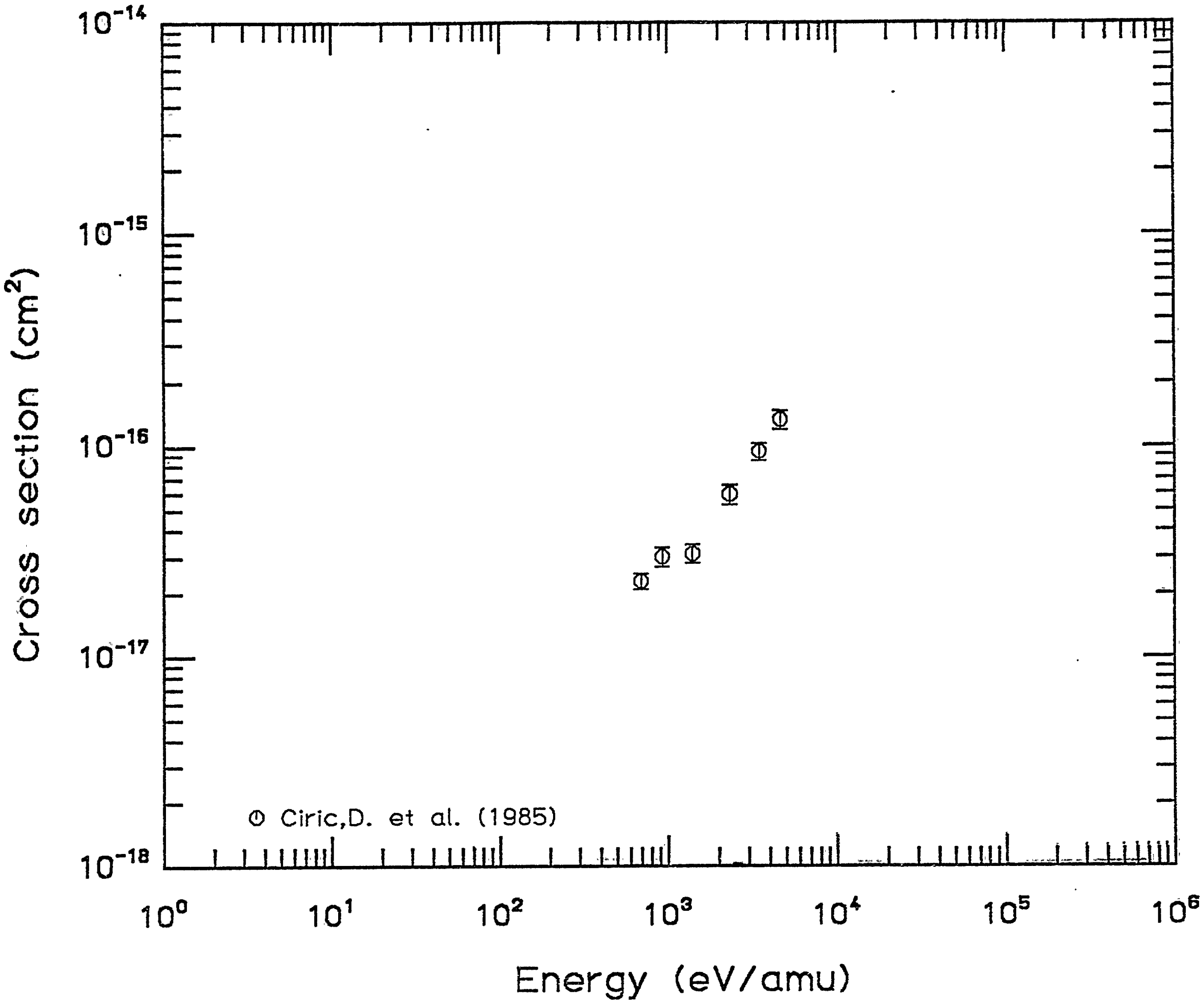


Fig.53 $C^{3+} + H_2$ --> $C^{2+}(1s^2 2s3d\ ^1D) + H_2^+$

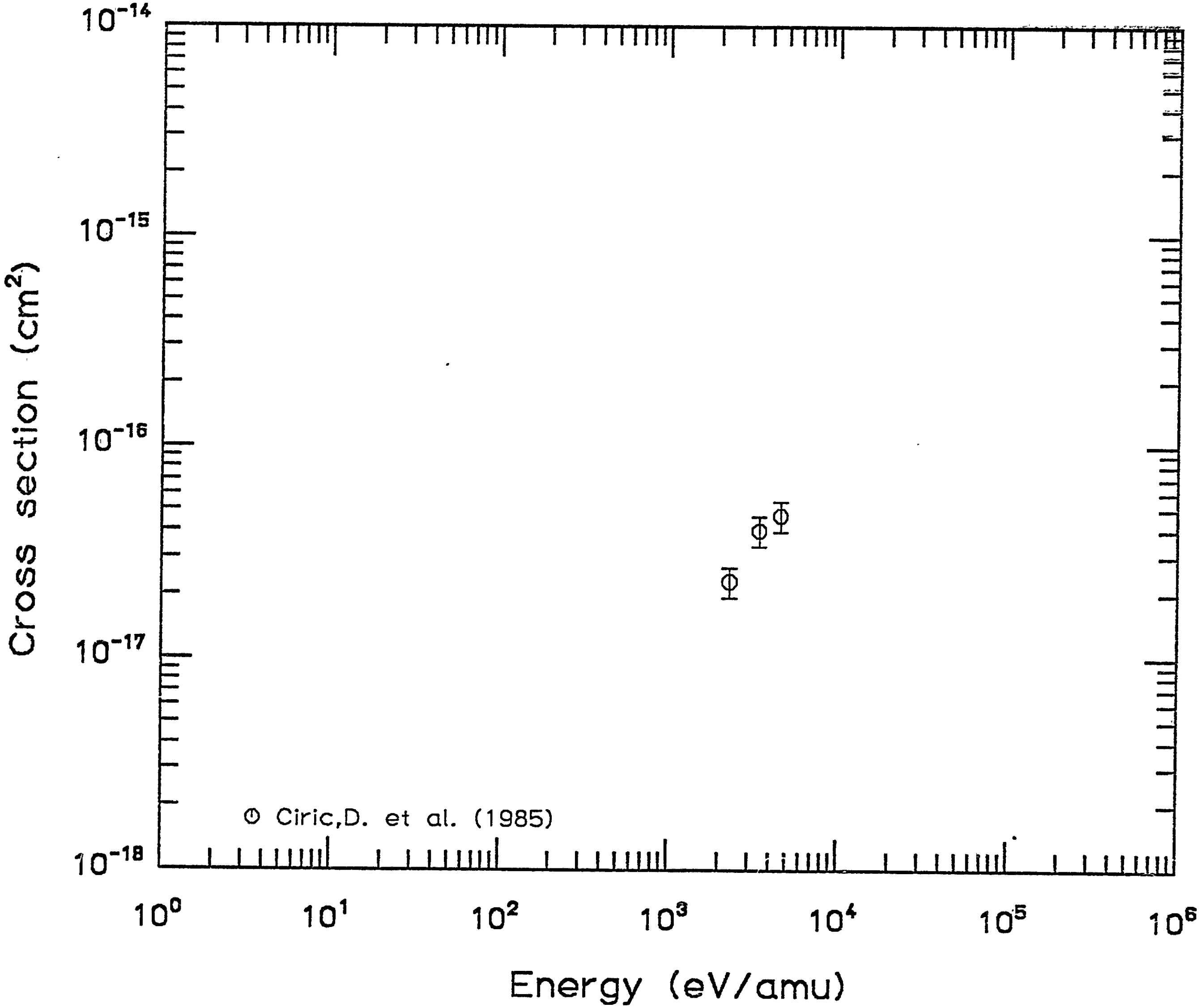


Fig.54 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^22s4d\ ^3D) + H_2^+$

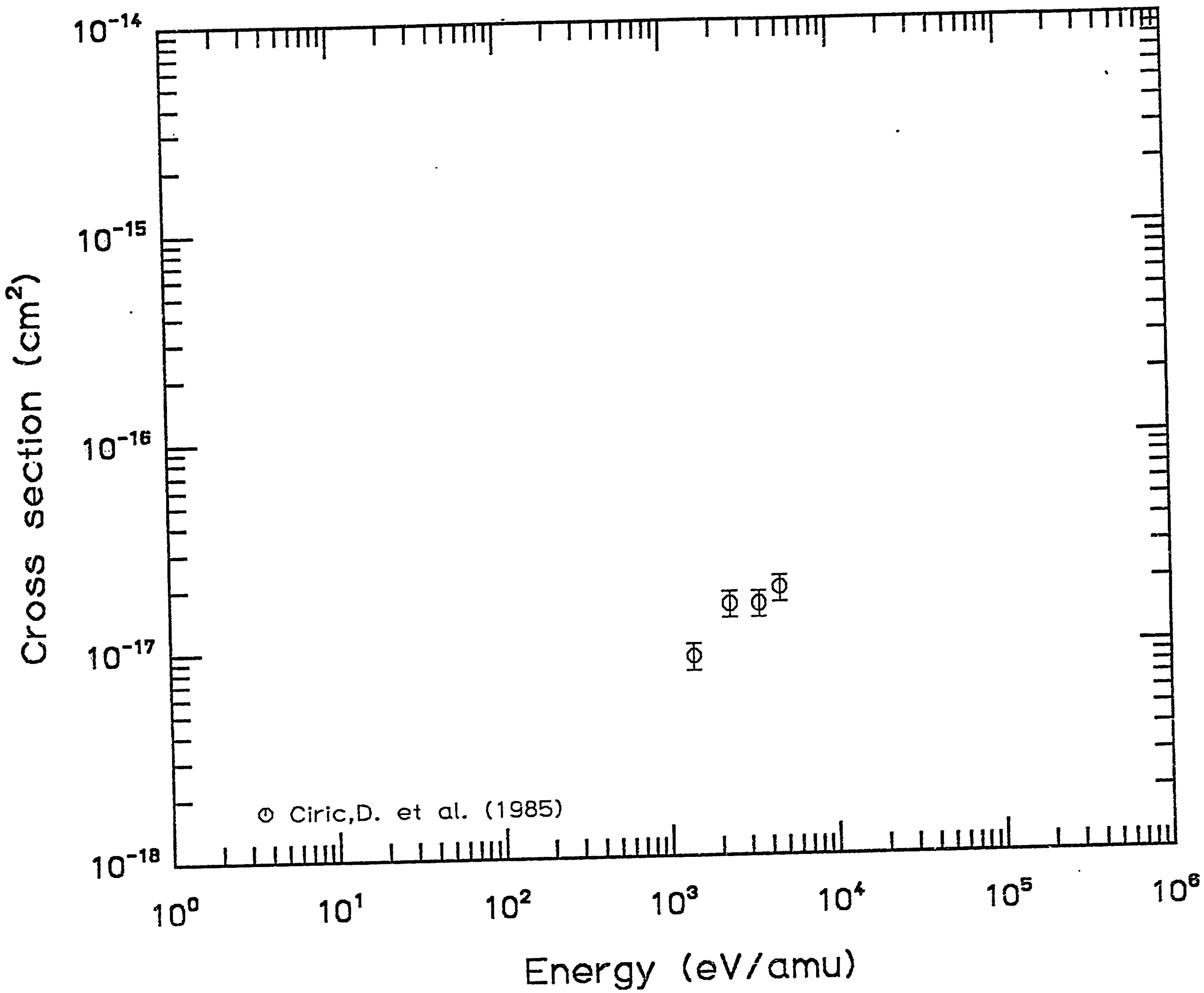


Fig.55 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2p^2\ {}^1S) + H_2^+$

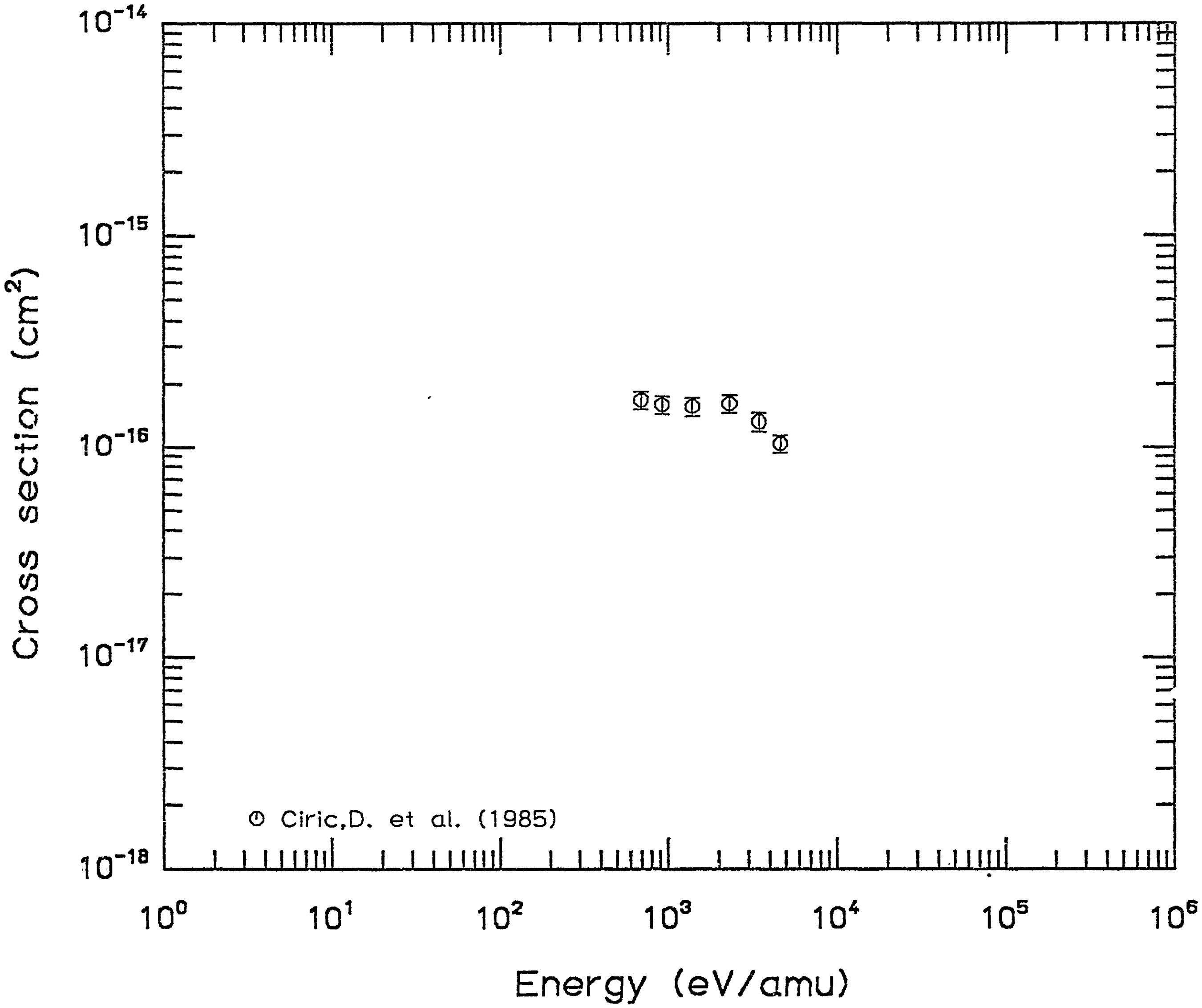


Fig.56 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^2 2p^2\ ^3P) + H_2^+$

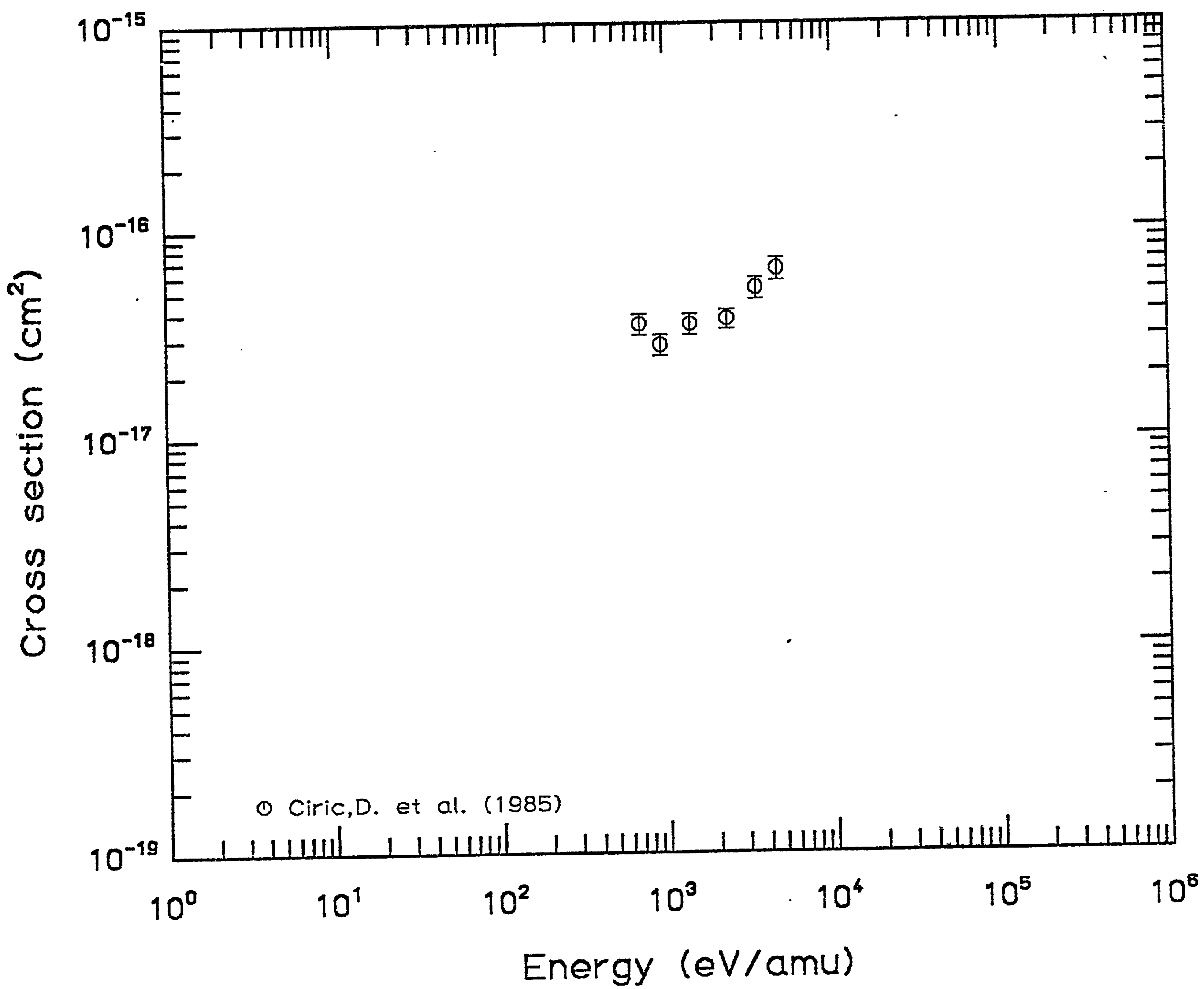
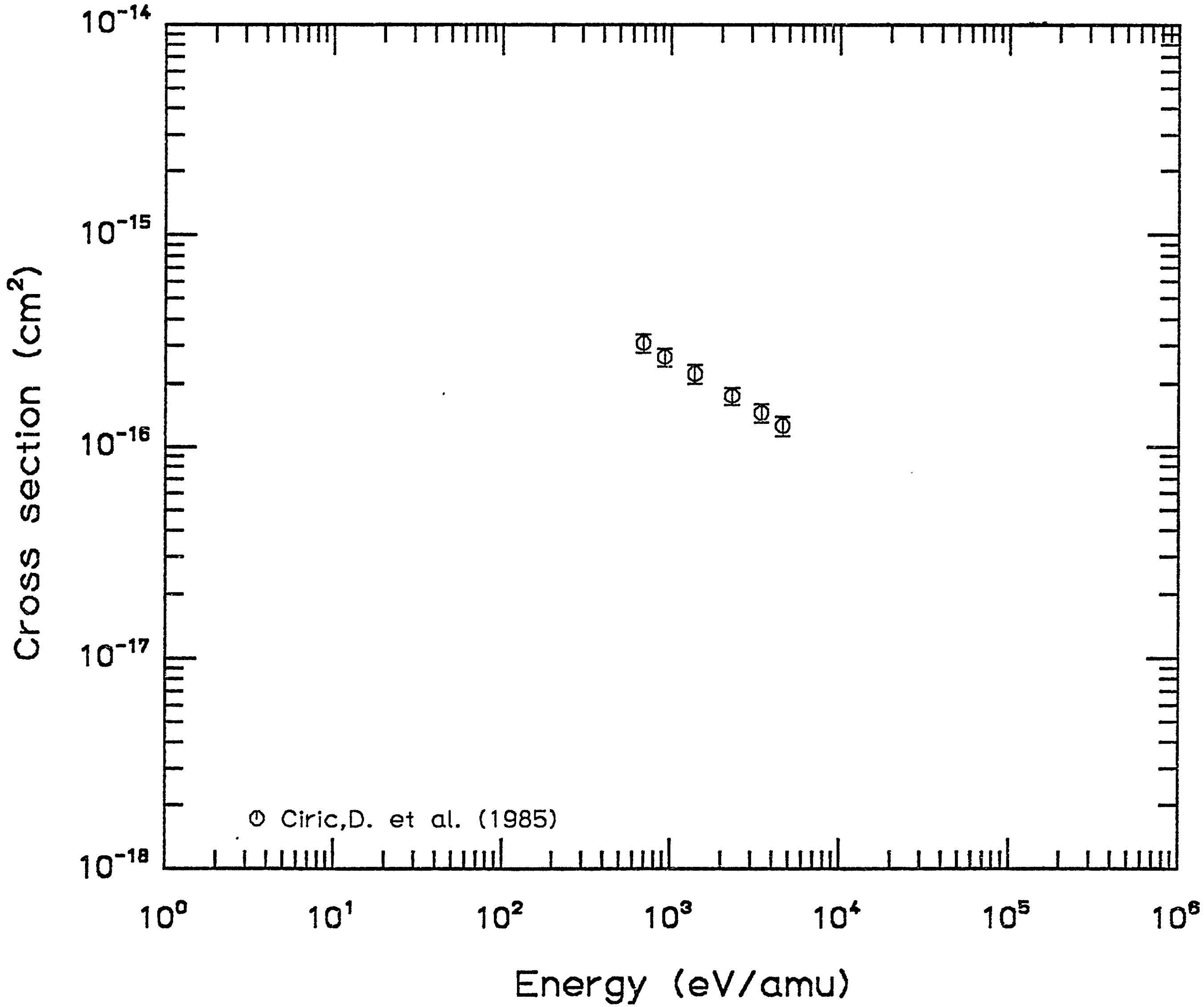


Fig.57 $C^{3+} + H_2 \dashrightarrow C^{2+}(1s^22p^2\ ^1D) + H_2^+$



III C^{q+} + He collisions

III-I $C^{6+} + He(1s^2) \rightarrow C^{5+}(n\ell) + He^{+}(1s)$

$\rightarrow C^{4+}(n\ell n'\ell') + He^{2+}$

Experimental data for total cross sections of single and double electron capture are summarized[1]. Dijkkamp et al.[2] have determined the emission cross sections corresponding to the n=3 → n=2 (13.5 nm) and n=4 → n=3 (52.0 nm) transitions. On the other hand, Kimura and Olson[3], using MO approach, calculated the partial cross sections for 3s, 3p and 3d states over the energy range 1 -200 keV, indicating that the capture into 3d state is dominant at low energies (<10 keV), meanwhile around 20 -200 keV these three cross sections are nearly equal. Using AO method, Fritsch and Lin[4] calculated the partial cross sections for (3ℓ) and (4ℓ) states over 0.5 - 40 keV/amu, with the result slightly different from those of Kimura and Olson in particular at lower energies.
Jain et al.[5] extended, using two-center AO method, the calculation by Fritsch and Lin to get ($n\ell m$) distributions over 10 keV/amu - 2 MeV/amu with the emphasis of those at higher energies. Their results are in general agreement with those of Fritsch and Lin, except for those of 3d subshell.
At around 500 keV/amu, the capture into $^2P_0$ state is dominant, meanwhile that into 1s state becomes dominant at the energy higher than 1.5 MeV/amu.
Total cross sections over 1 -10^3 keV/amu are also given by Suzuki et al.[6] who used UDWA method.
Also total double electron capture as well as total single electron capture have been treated by Ohyama-Yamaguchi[7] recently over the energy range 0.1 - 10 keV/amu using CC method.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. D. Dijkkamp, Yu.S. Gordeev, A. Brazuk, A.G. Drentje and

F.J. de Heer, J. Phys. B 18 (1985) 737
3. M. Kimura and R.E. Olson, J. Phys. B 17 (1984)L713
4. W. Fritsch and C.D. Lin, J. Phys. B 19 (1986) 2683
5. A. Jain, C.D. Lin and W. Fritsch, Phys. Rev. A 34 (1986) 3676
6. H. Suzuki, Y. Kajikawa, N. Toshima, H. Ryufuku and T. Watanabe, Phys. Rev. A 29 (1984) 525
7. T. Ohyama-Yamaguchi, J. Phys. Soc. Japan 56 (1987) 1693

Fig.58 $C^{6+} + He \rightarrow C^{5+}(\text{total}) + He^{+}$

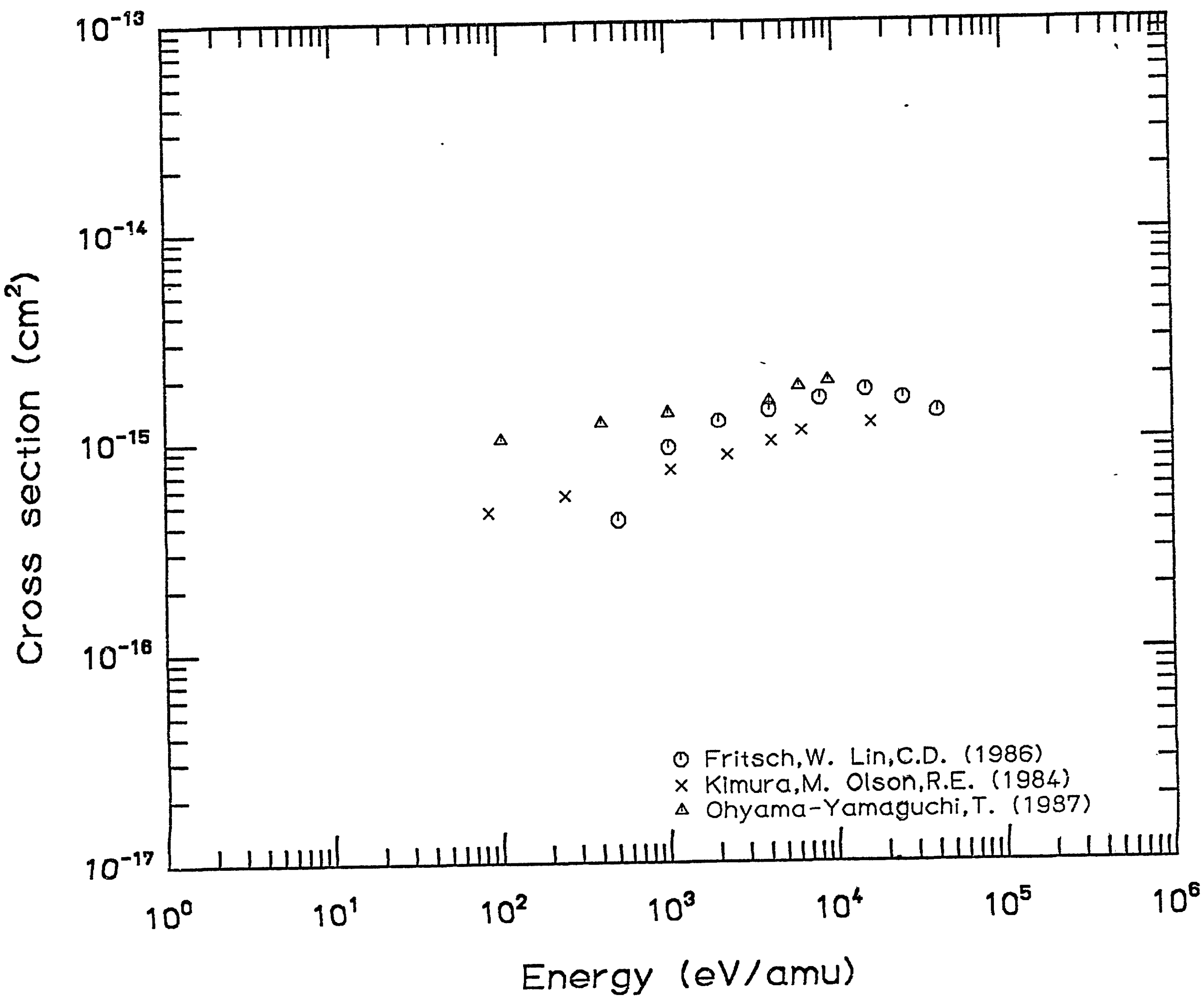


Fig.59 $C^{6+} + He \rightarrow C^{5+}(3s) + He^{+}$

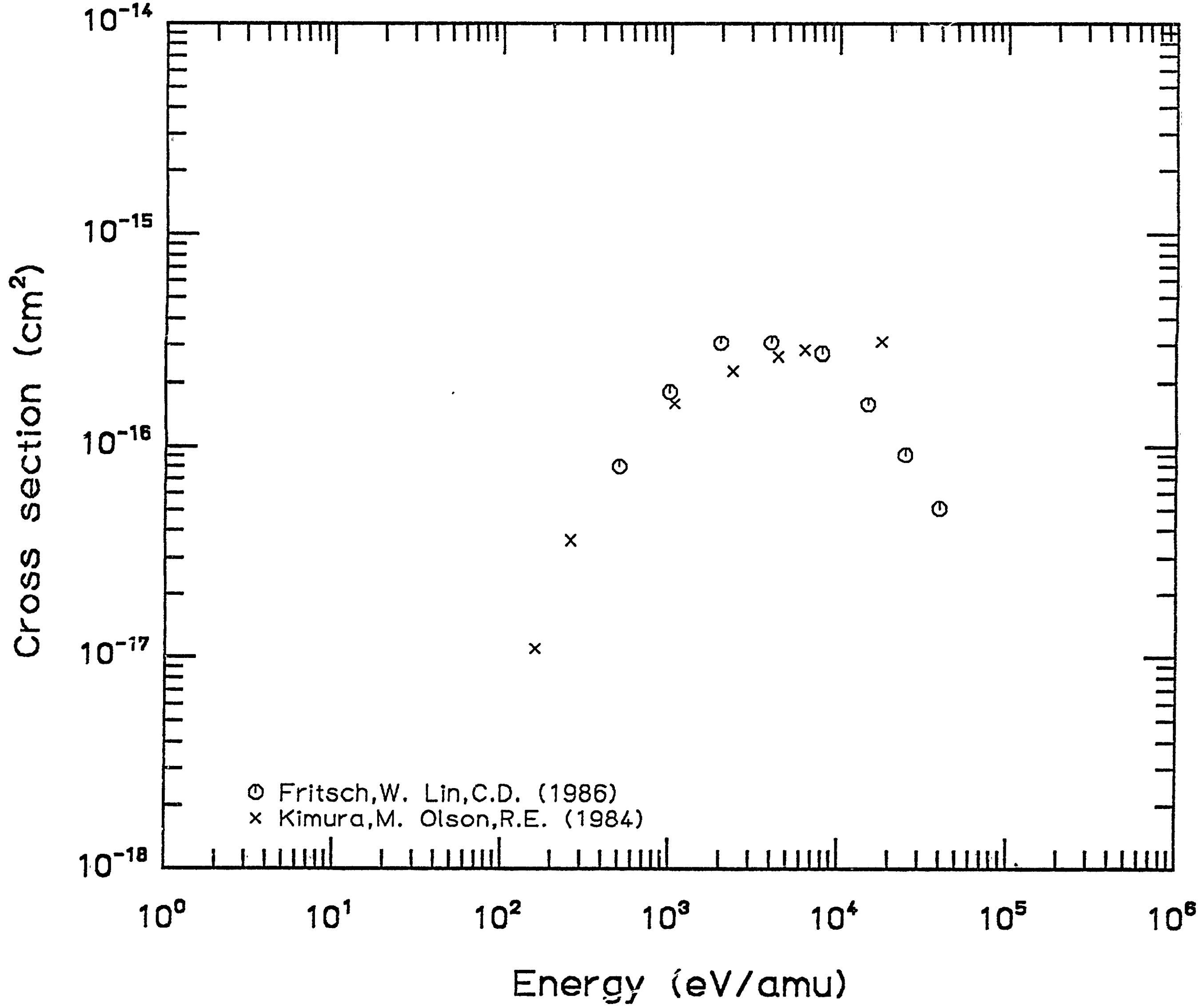
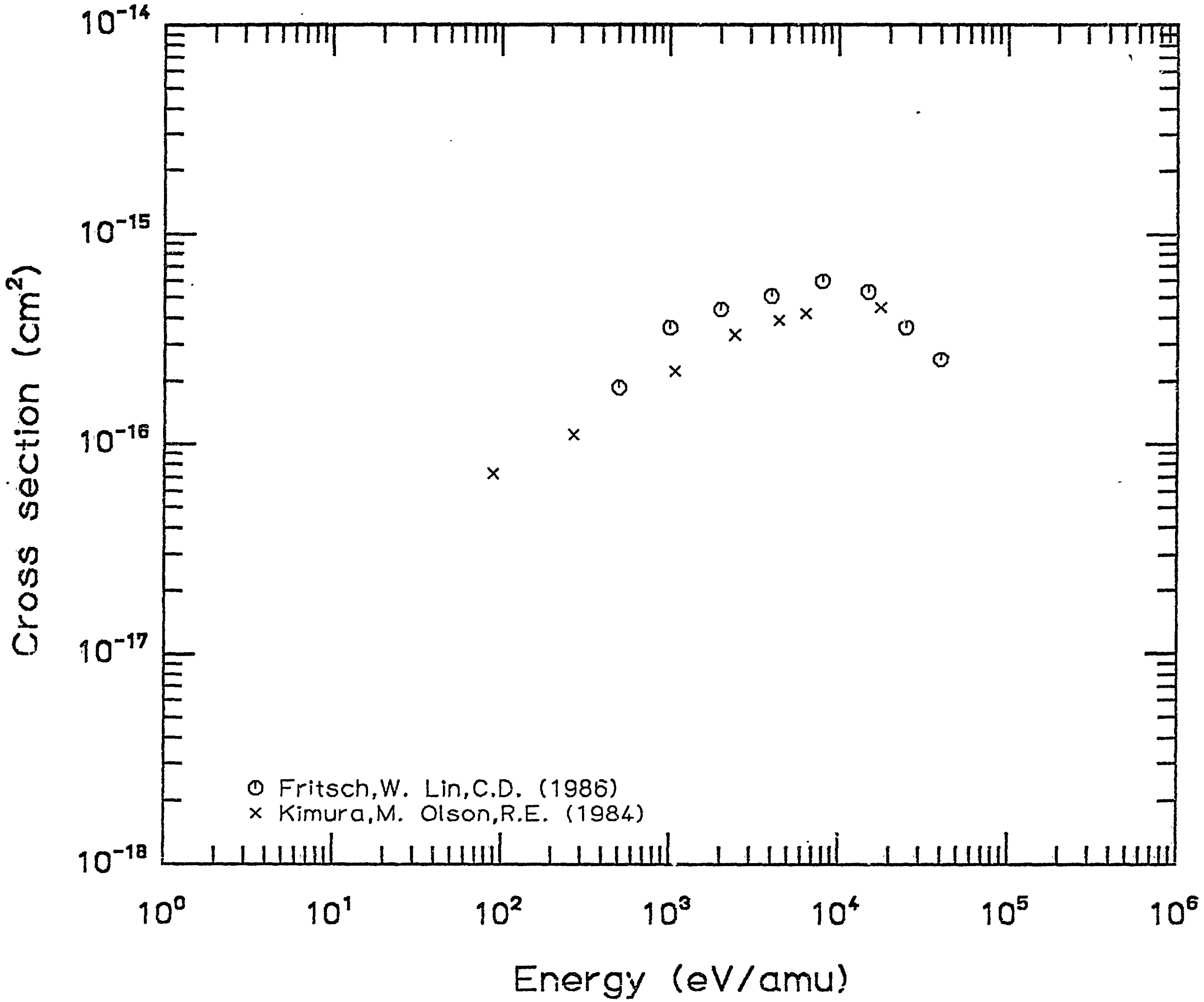


Fig.60 $C^{6+} + He \rightarrow C^{5+}(3p) + He^{+}$



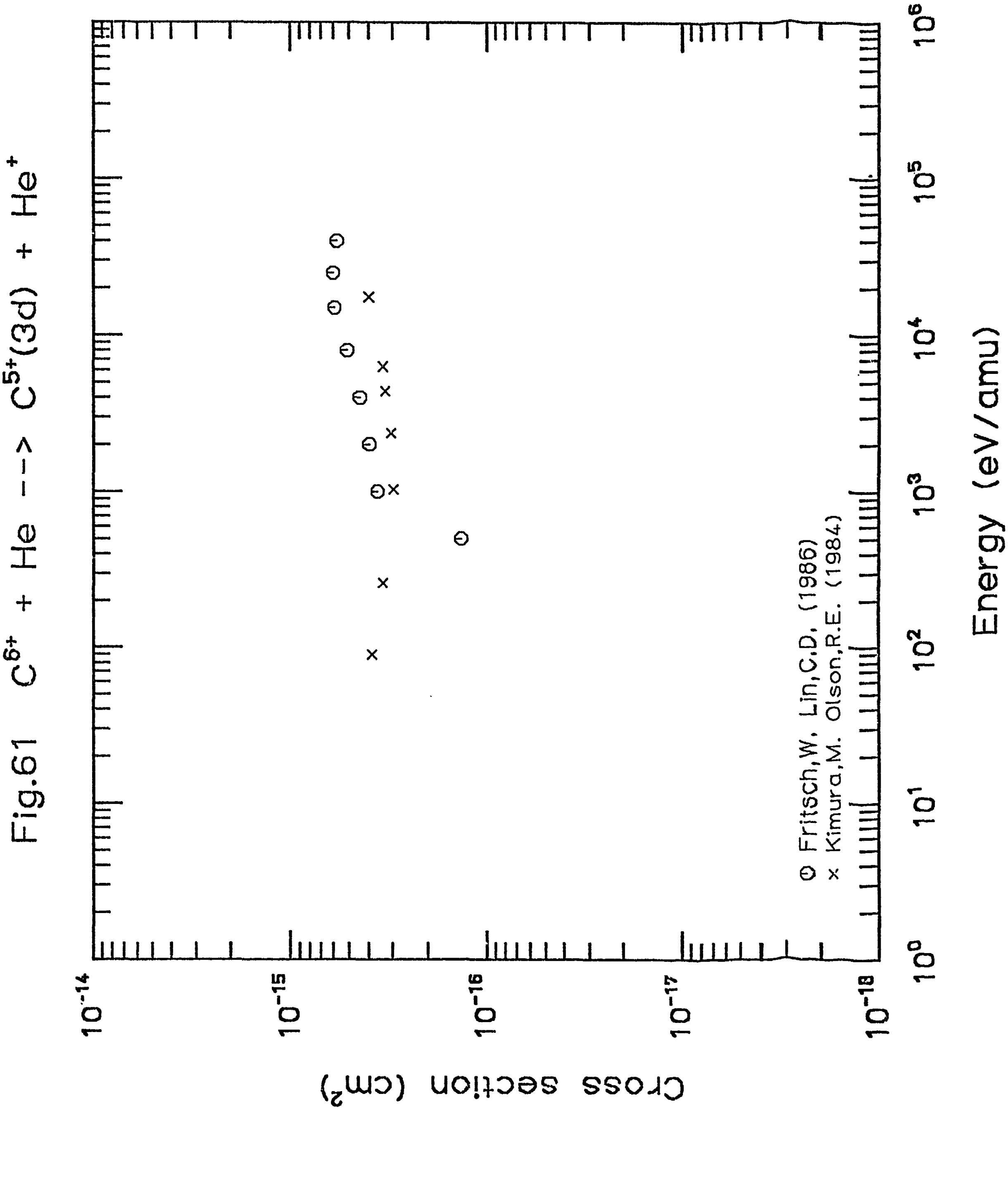


Fig.61 C^{6+} + He --> $C^{5+}(3d)$ + He^{+}
Cross section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Energy (eV/amu)
Fritsch,W. Lin,C.D. (1986)
Kimura,M. Olson,R.E. (1984)

Fig.62 $C^{6+} + He \rightarrow C^{5+}(4s) + He^{+}$

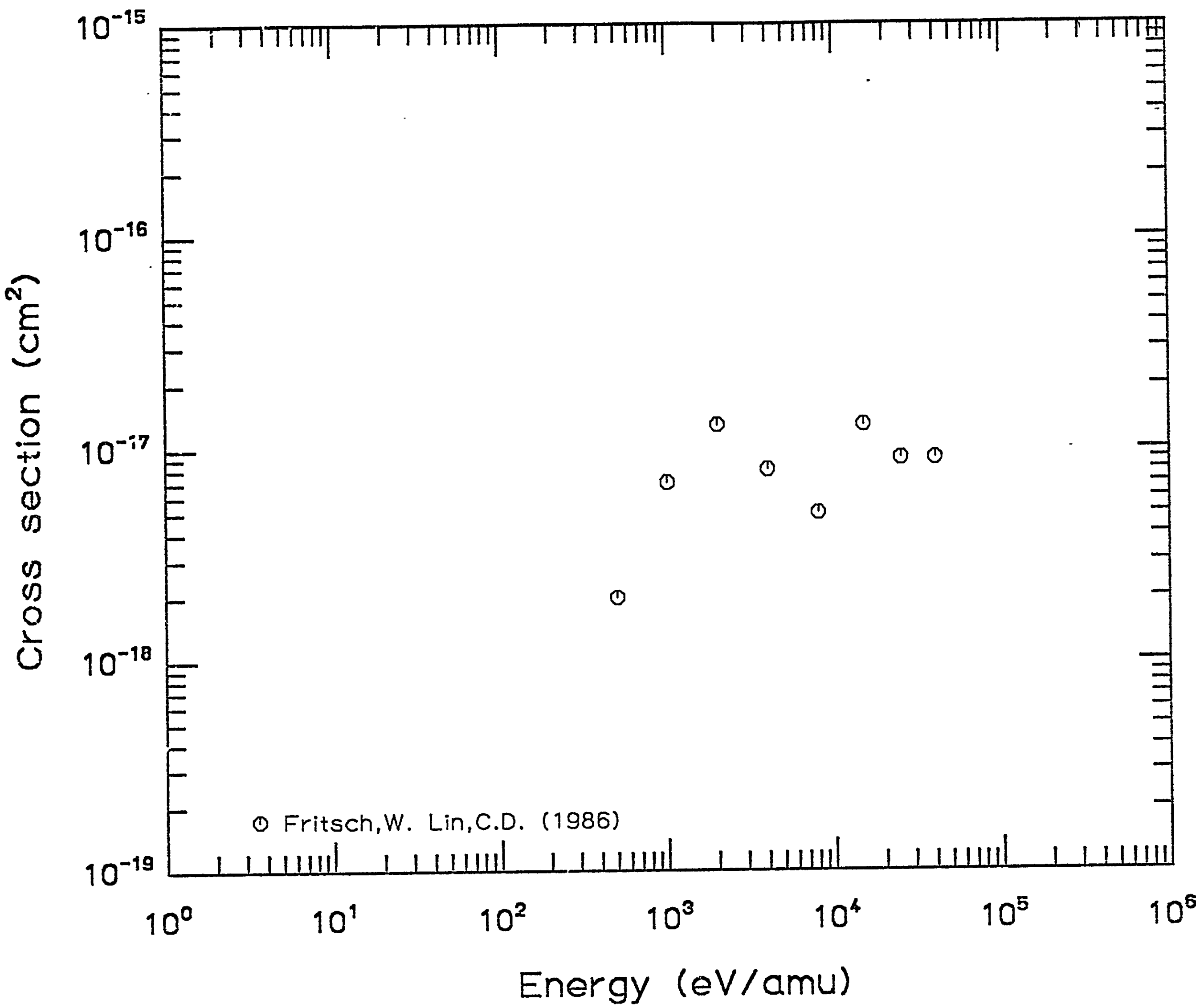


Fig.63 $C^{6+} + He \to C^{5+}(4p) + He^{+}$

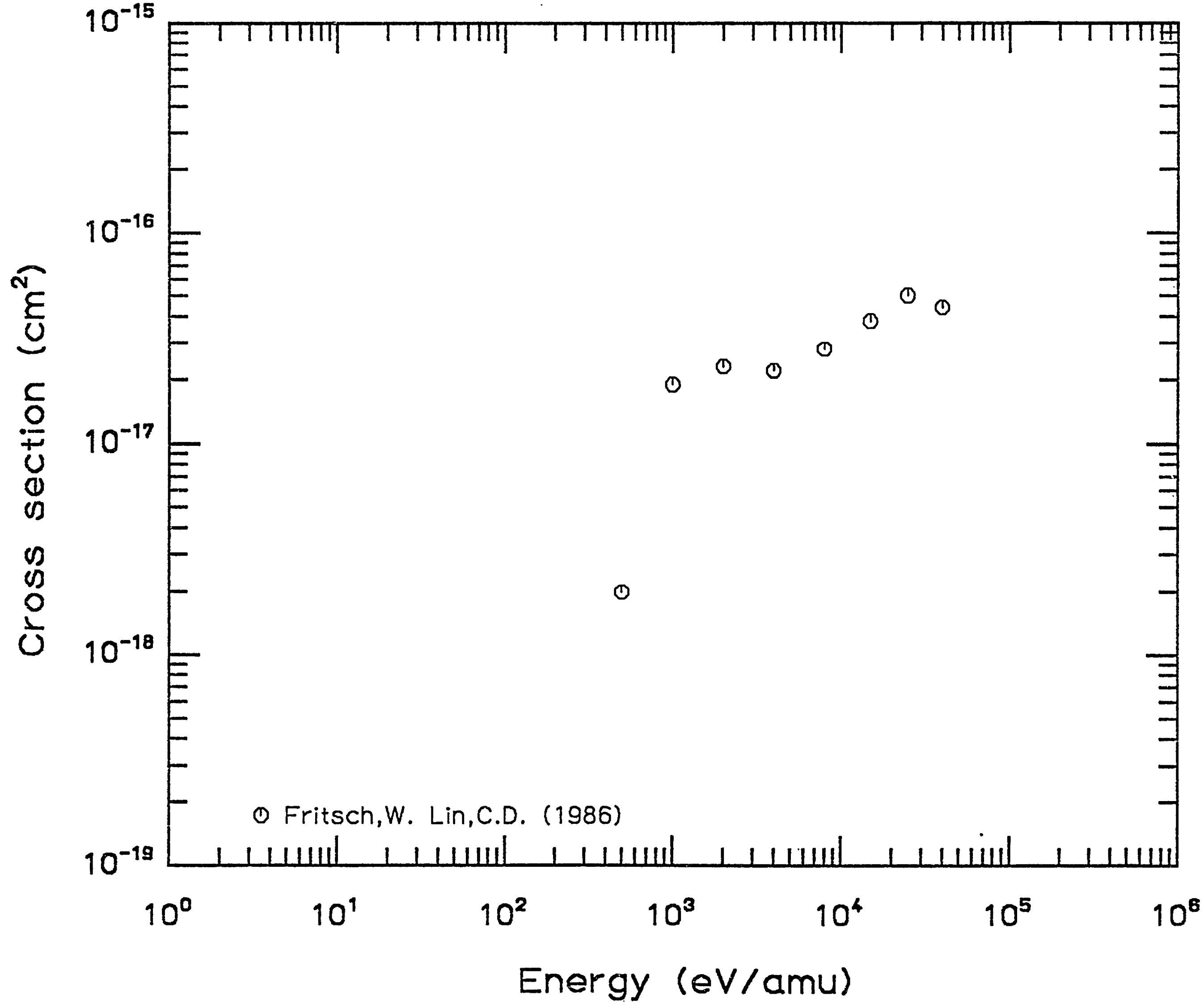


Fig.64 $C^{6+} + He \dashrightarrow C^{5+}(4d) + He^{+}$

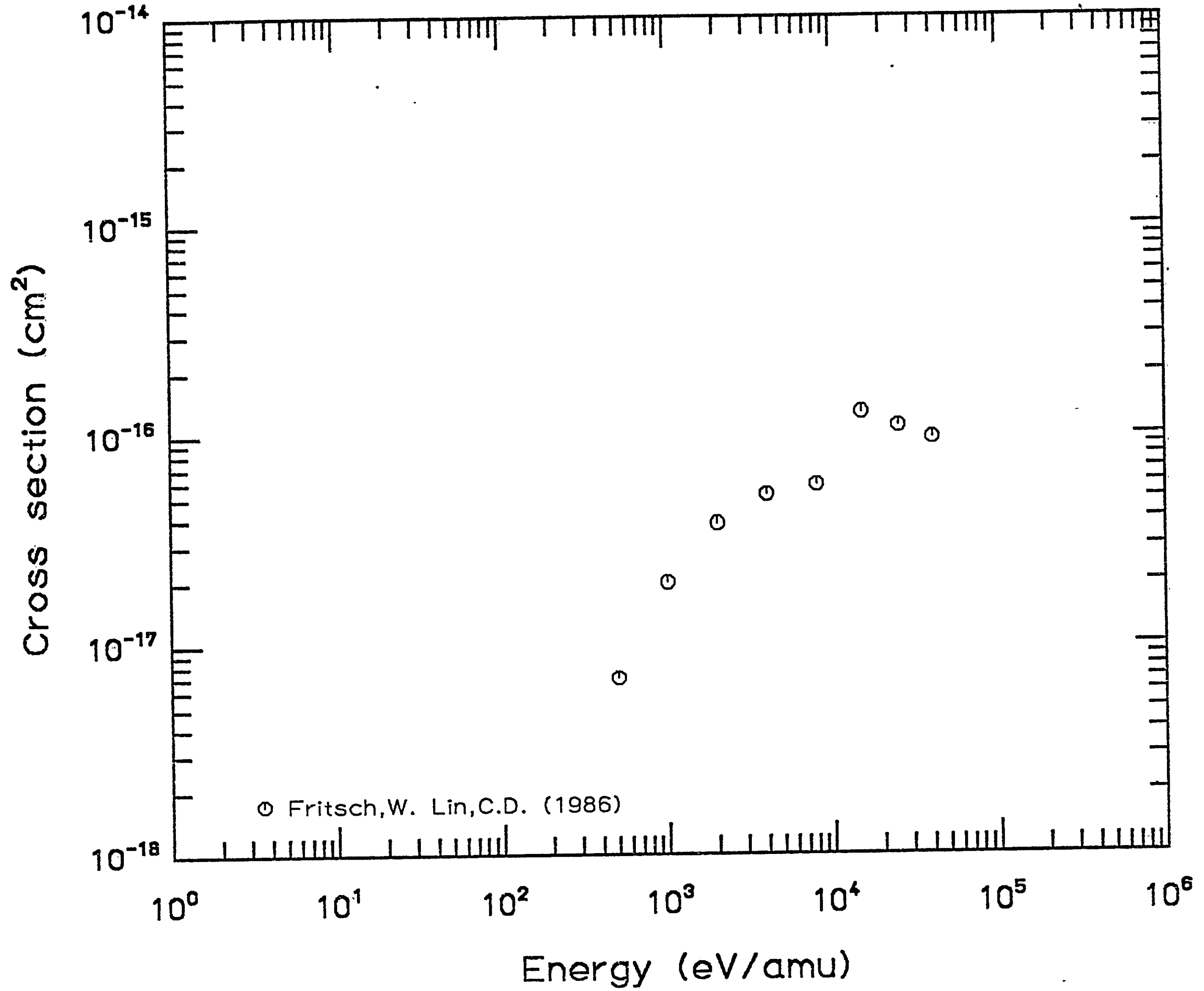


Fig.65 $C^{6+} + He \dashrightarrow C^{5+}(4f) + He^{+}$

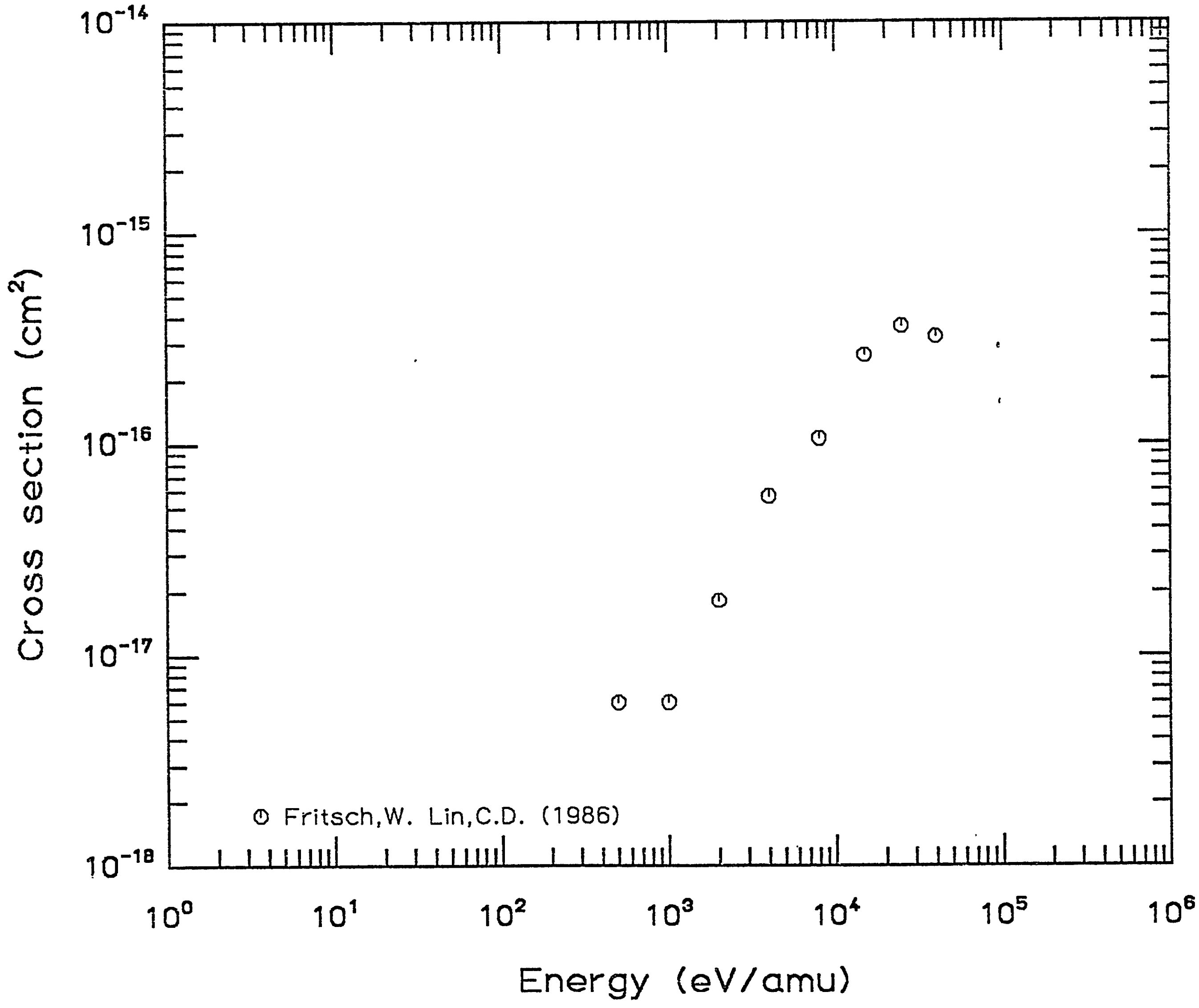
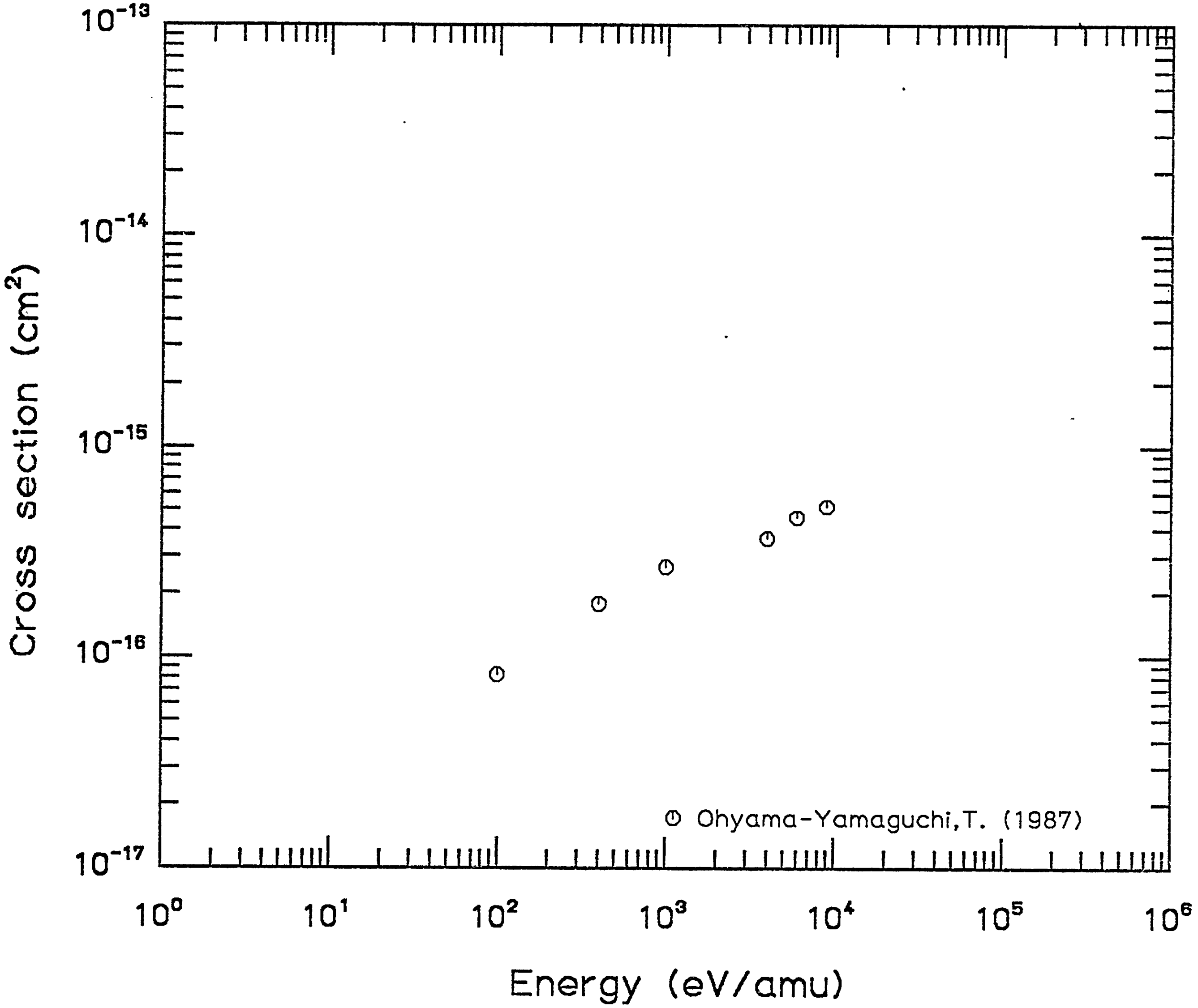


Fig.66 $C^{6+} + He \dashrightarrow C^{4+}(total) + He^{2+}$



III-2 C^{5+} (1s) + He → C^{4+}(1snℓ) + He^{+}
→ C^{3+}(1snℓn'ℓ') + He^{2+}

Total cross sections for single electron capture are summarized[1].

Although there is an indication that the dominant capture occurs into the 3ℓ states, the most likely states being 3p and 3d states,[2] no partial cross section has been reported yet. No total cross sections for double electron copture are reported, either.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. K. Okuno, H. Tawara, T. Iwai, Y. Kaneko, M. Kimura, N. Kobayashi, A. Matsumoto, S. Ohtani, S. Takagi and S. Tsurubuchi, Phys. Rev. A 28 (1983) 127

III-3 $C^{4+}(1s^2) + He \rightarrow C^{3+}(1s^2n\ell) + He^+$
$\rightarrow C^{2+}(1s^2n\ell n'\ell') + He^{2+}$

Experimental data for single and double electron capture cross sections are summarized[1].

It is known that the double electron capture is more probable at lower energies than the single electron capture[2]. In fact Crandall determined total cross sections for single and double electron capture and showed the double capture is dominant at the energies lower than 20 keV over the single electron capture. This feature is explained theoretically through the energy potential curves. The double electron capture proceeds to the following dominant channel :

$$C^{4+}(1s^2) + He \rightarrow C^{2+}(1s^22s^2) + He^{2+},$$

meanwhile the single electron capture does through the 2p state[3,4] and becomes dominant at higher energies. Recently this was confirmed experimentally[5], indicating that the double electron capture into $C^{2+}(1s^22s^2\ {}^1S)$ is dominant at 0.3 keV/amu. Also total double electron capture cross sections have been calculated by Grozdanov and Janev over the energy range 0.01 - 7.5 keV/amu[6].

It should be noted that in order to understand the features in both processes the angular distribution of the product ions must be known correctly [7-9].

The partial cross sections for single electron capture have been determened by Dijkkamp et al[10]. over the energy range 0.8 - 6.7 keV/amu. The observed results indicate the dominance of the capture into 2p state in the energy range investigated, as predicted by theories.

Some features of the $(n\ell)$ disttributions in this system at higher energies (2-5 MeV) have been investigated theoretically and experimentally[11].

The rate coefficients for single electron capture over the temperature $10^3 - 10^{4.5}$ K were calculated by Butler and Dalgarno[12] using LZ model.

References

1. K.W. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. D. Crandall, Phys. Rev. A 16 (1977) 958
3. E.J. Shipsey, J.C. Browne and R.E. Olson, Phys. Rev. A 15 (1977) 2166
4. M. Kimura and R.E. Olson, Phys. B 17 (1977) L713
5. K. Okuno, H. Tawara, T. Iwai, Y. Kaneko, M. Kimura, N. Kobayashi, A. Matsumoto, S. Ohtani, S. Takagi and S. Tsurubuchi, Phys. Rev. A 28 (1928) 127; H. Cederquist, L.H. Andersen, A. Barany, P. Hvelplund, H. Knudsen, E.H. Nielsen, J.O.K. Pedersen and J. Sorensen, J. Phys. B 18 (1985) 3951
6. T.P. Grozdanov and R.K. Janev, J. Phys. B 13 (1980) 3431
7. A. Barany, H. Danared, H. Cederquist, P. Hvelplund, H. Knudsen, J.O.K. Pedersen, C.L. Cocke, L.N. Tunnel, W. Waggoner and J.P. Giese, J. Phys. B 19 (1986) L427
8. H. Danared and A. Barany, J. Phys. B 19 (1980) 3109
10. D. Dijkkamp, D. Ciric, E. Vlieg, A.de Boer and F.J.de Heer, J. Phys. B 18 (1985) 4763
11. L.J. Dube, U. Will, R. Bruch, E. Trabert and P.H. Heckmann, Nucl. Instr. Meth. in Phys. Res. B 9 (1985) 408
12. S.E. Butler and A. Dalgarno, Astrophys. J. 241 (1980) 838

Fig.67 $C^{4+} + He \dashrightarrow C^{3+}(total) + He^{+}$

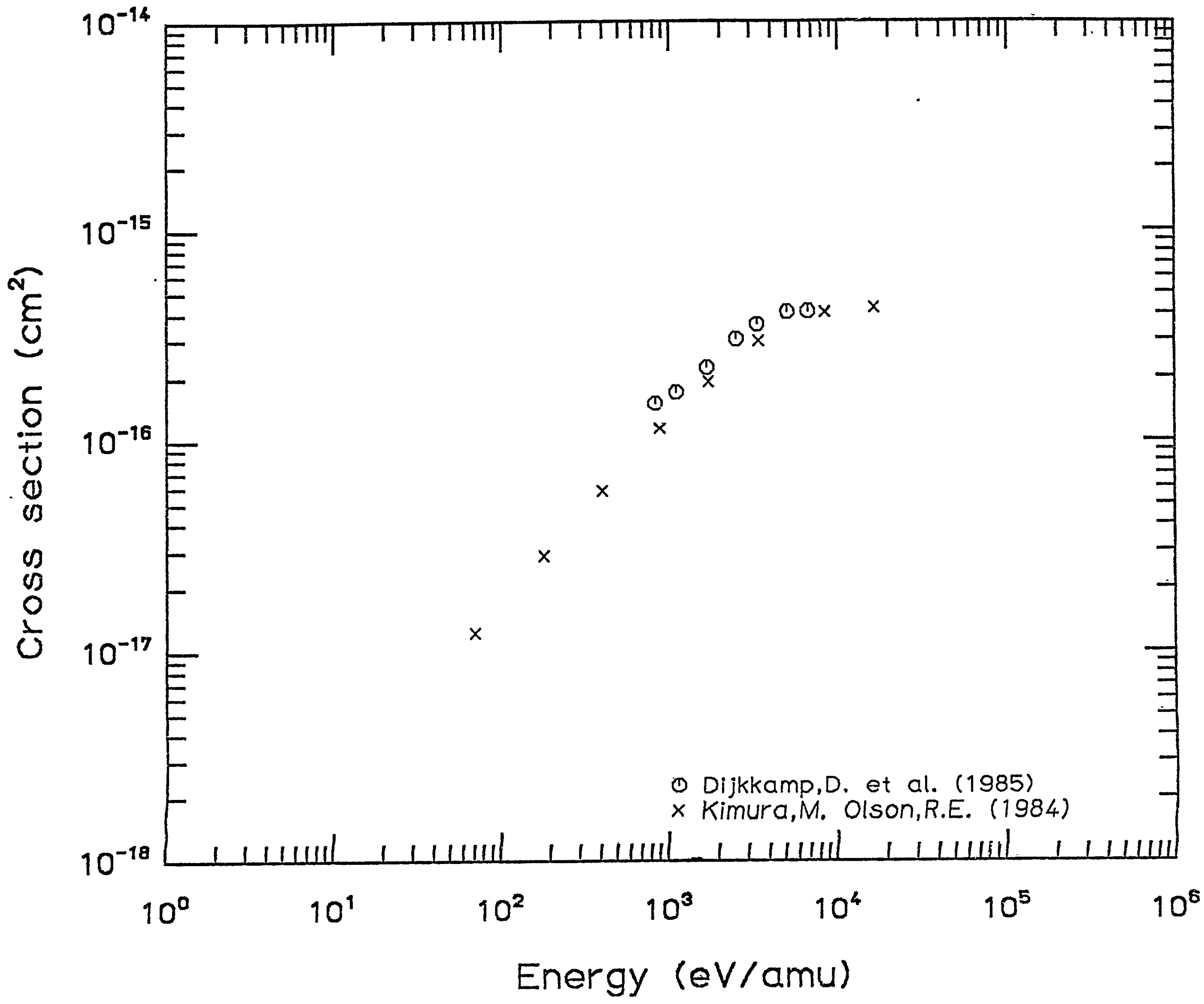


Fig.68 C^{4+} + He --> $C^{3+}(1s^22p)$ + He^+

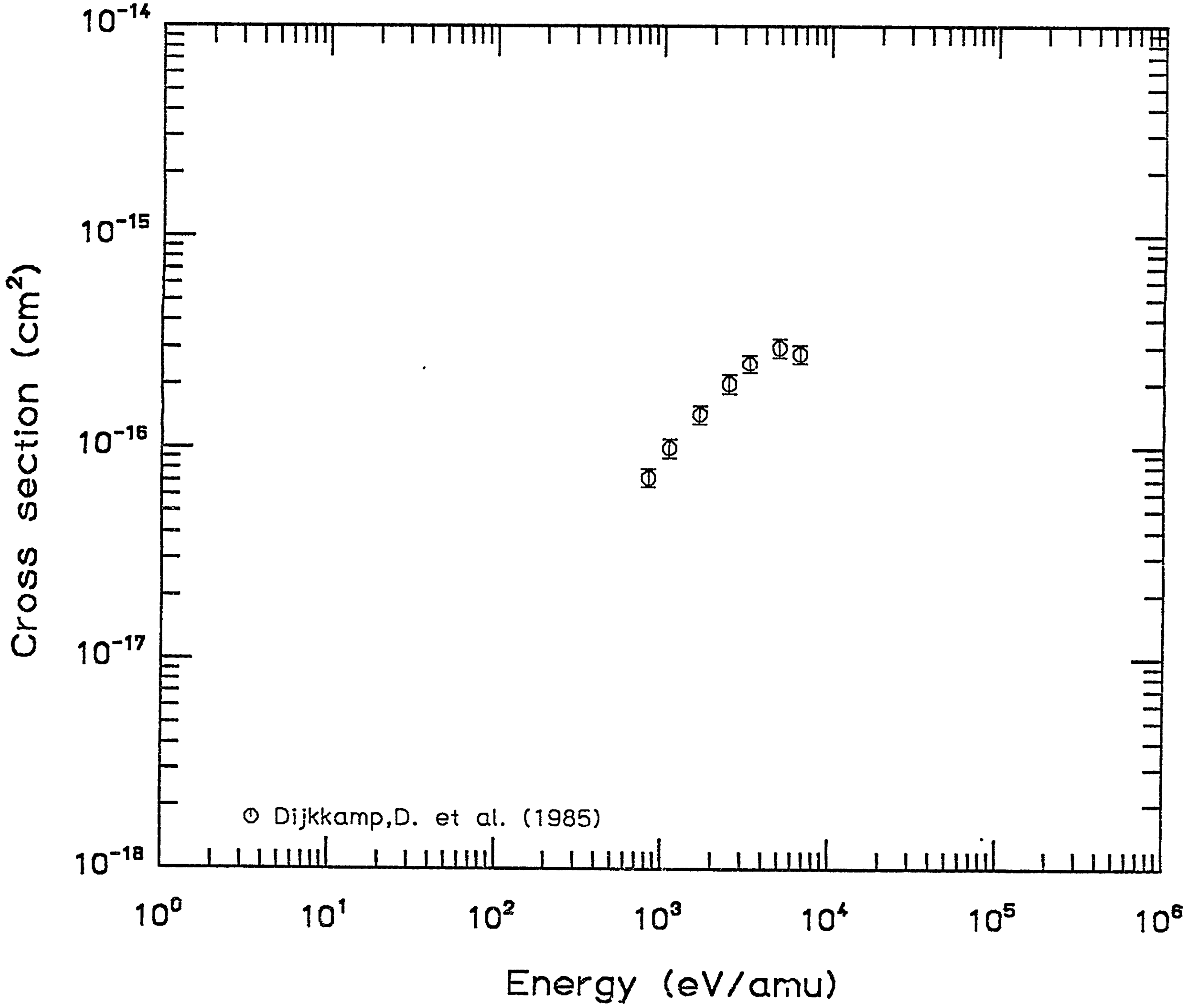


Fig.69 $C^{4+} + He \rightarrow C^{3+}(1s^2 3s) + He^+$

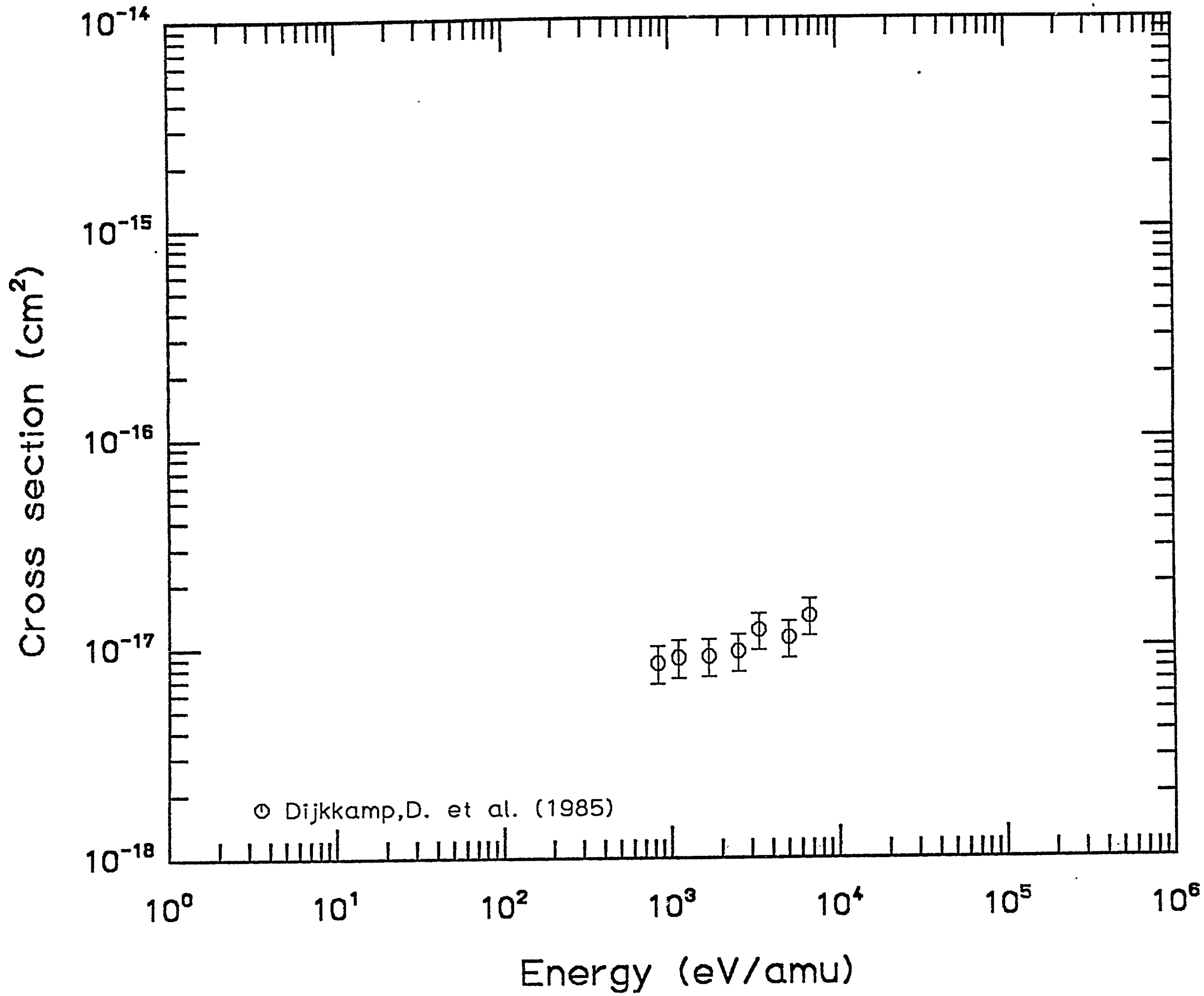


Fig.70 $C^{4+} + He \rightarrow C^{3+}(1s^2 3p) + He^+$

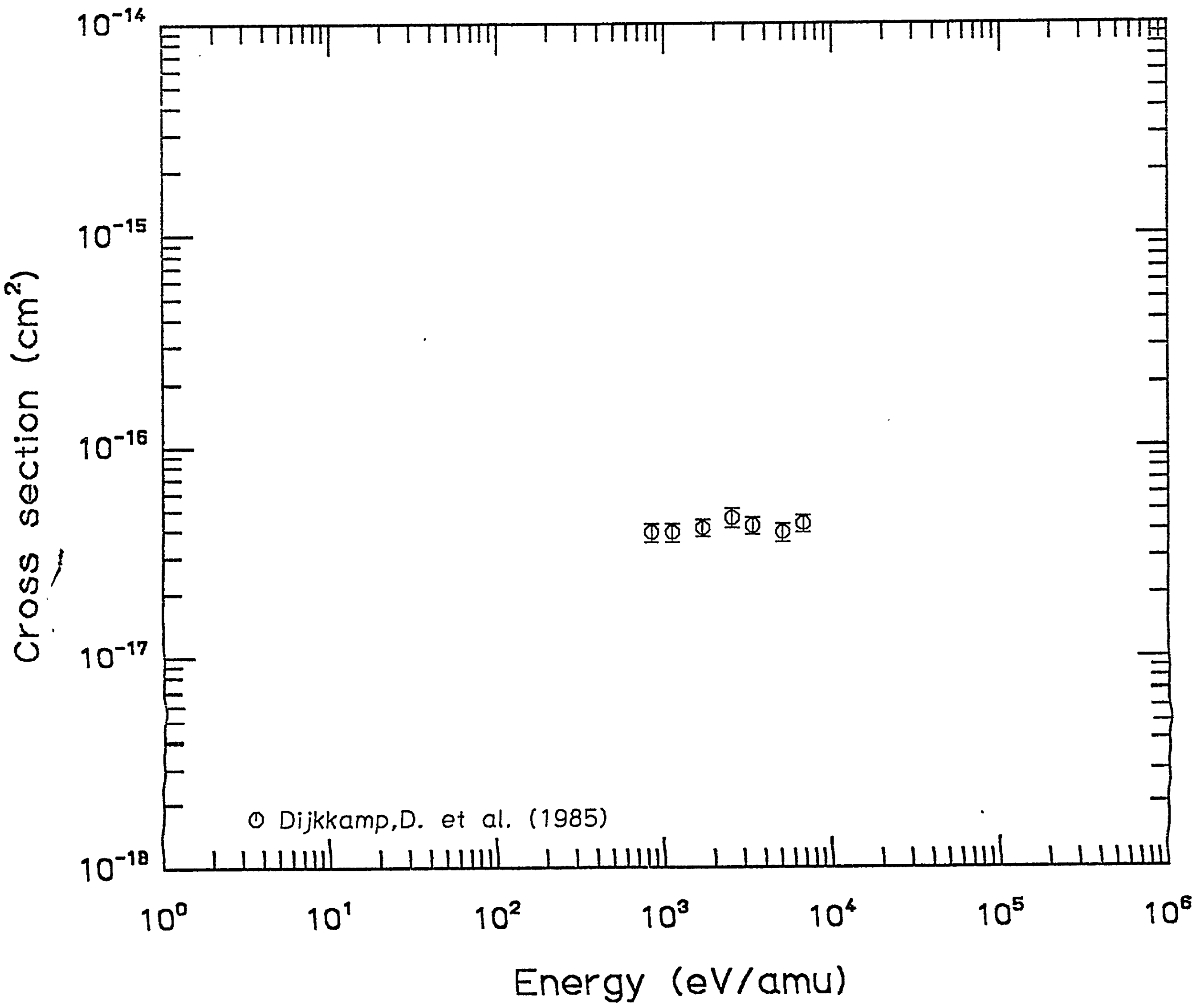


Fig.71 $C^{4+} + He \longrightarrow C^{3+}(1s^2 3d) + He^+$

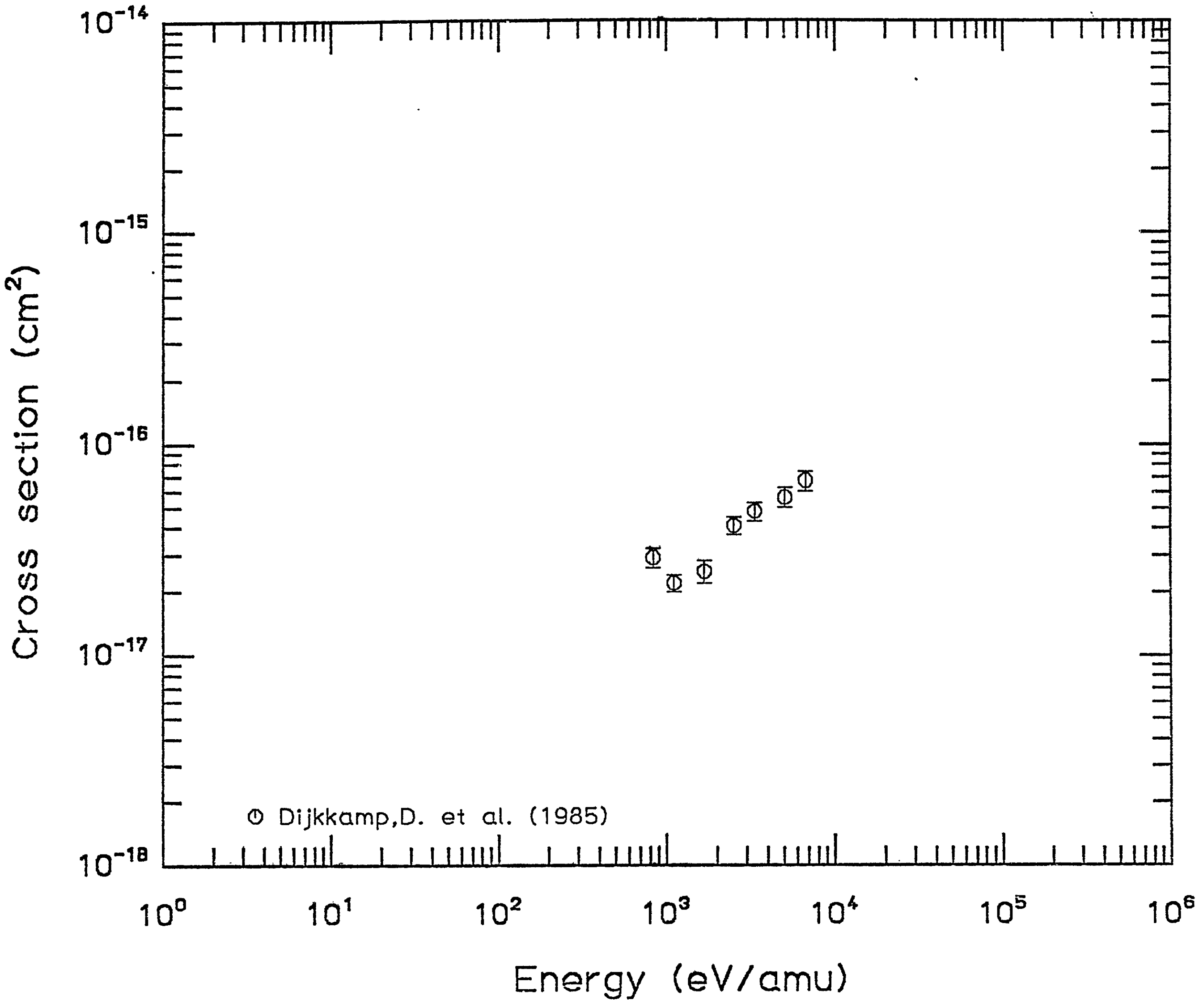
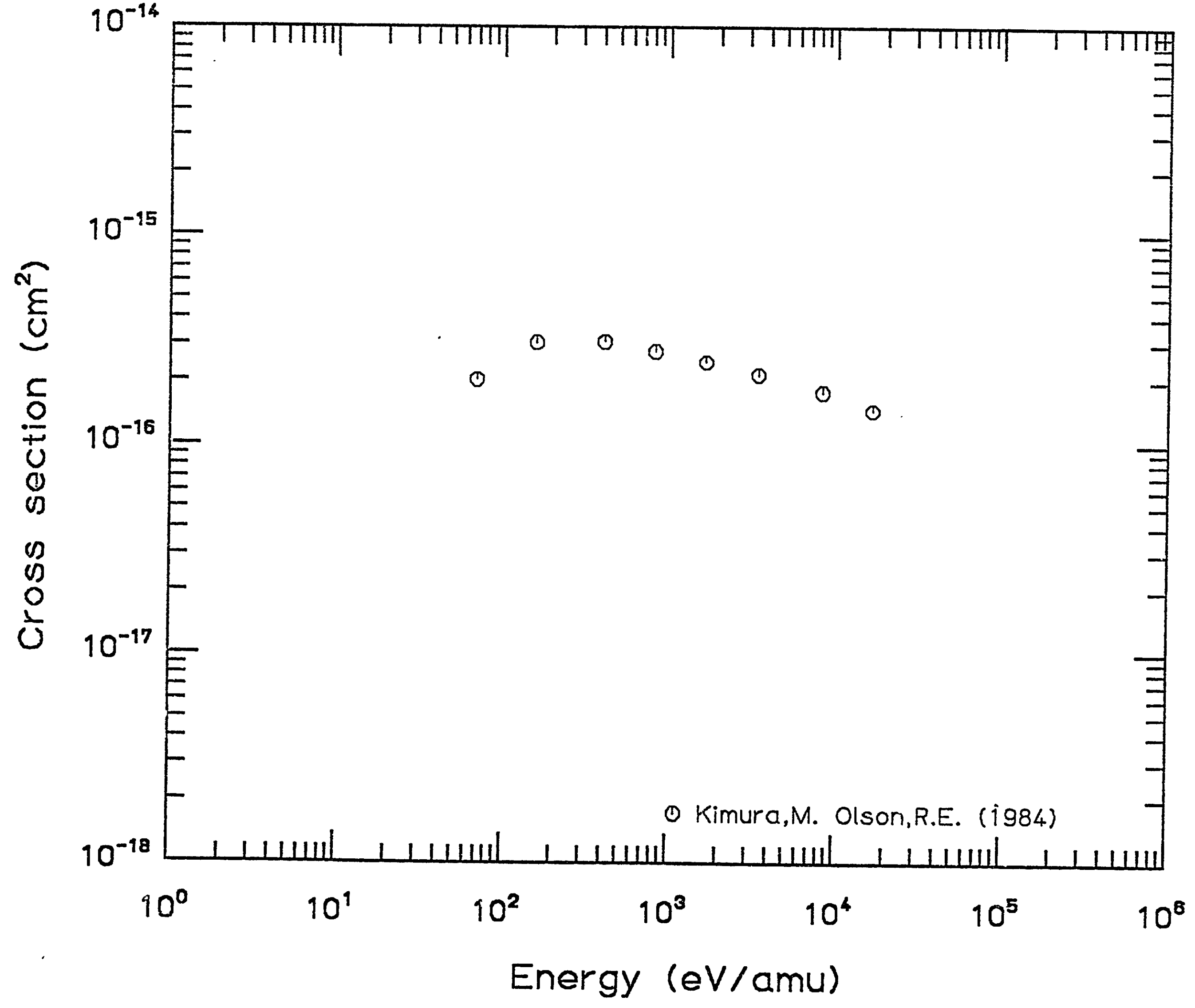


Fig.72 $C^{4+} + He \dashrightarrow C^{2+}(total) + He^{2+}$



III-4 $C^{3+}(1s^22s\ ^2S) + He \rightarrow C^{2+}(1s^22s^2\ ^1S) + He^+$ (1)

$(1s^22s2p\ ^3P^0)$ (2)

$(1s^22s2p\ ^1P^0)$ (3)

$(1s^22p^2\ ^3P)$ (4)

$(1s^22p^2\ ^1D)$ (5)

Total cross sections for single electron capture are summarized[1].

In single electron capture, the above processes have been investigated using the translational energy spectroscopy technique. Kimura et al. [2] have shown that the most dominant capture goes into 2s2p ^1P states at 500 eV/amu, with a small contribution of 2s2p ^3P and far less contribution from $2s^2$ and $2p^2$ states. Lennon et al.[3] determined the partial cross sections for the above processes over the energy range 3-18 keV. Their results show that at the lowest energy 2s2p ^1P states are far dominant over other channels but with increasing the collision energy 2s2p ^3P and $2p^2$ ^3P ,^1D channels become significant. The rate coefficients over the temperature 10^3-$10^{4.5}$ K were calculated by Butler and Dalgarno[4] using LZ mode. No cross section for double electron capture was reported yet.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. K. Kimura, T. Iwai, Y. Kaneko, N. Kobayashi, A. Matsumoto, S. Ohtani, S. Takagi, H. Tawara and S. Tsurubuchi, J. Phys. B 15 (1982) L851
3. M. Lennon, R.W. McCullough and H.B. Gilbody, J. Phys. B 16 (1983) 2191
4. S.E. Butler and A. Dalgarno, Astrophys. J. 241 (198) 838

Fig.73 $C^{3+} + He \rightarrow C^{2+}(total) + He^{+}$

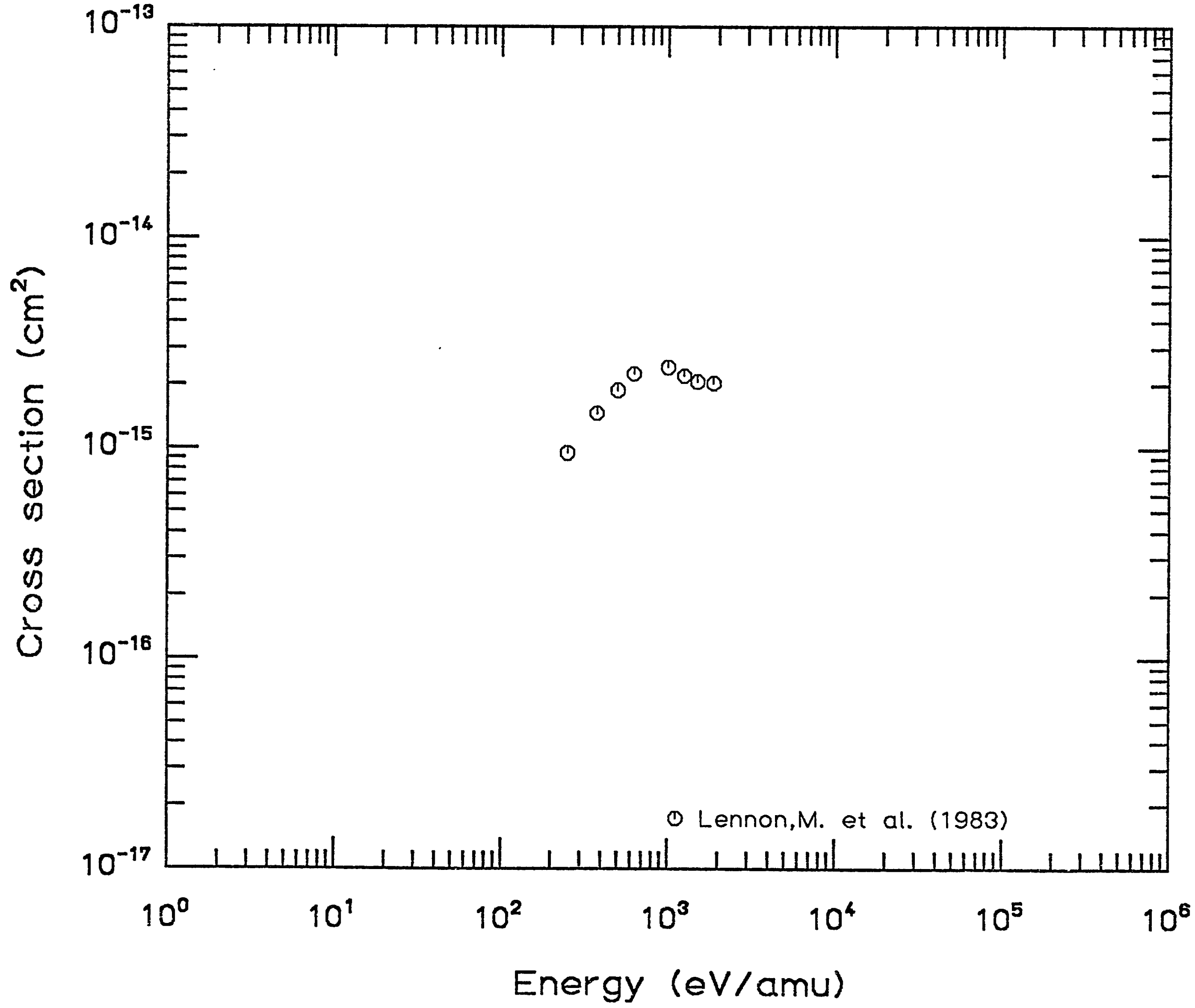


Fig.74 $C^{3+} + He \rightarrow C^{2+}(1s^2 2s^2\ ^1S) + He^+$

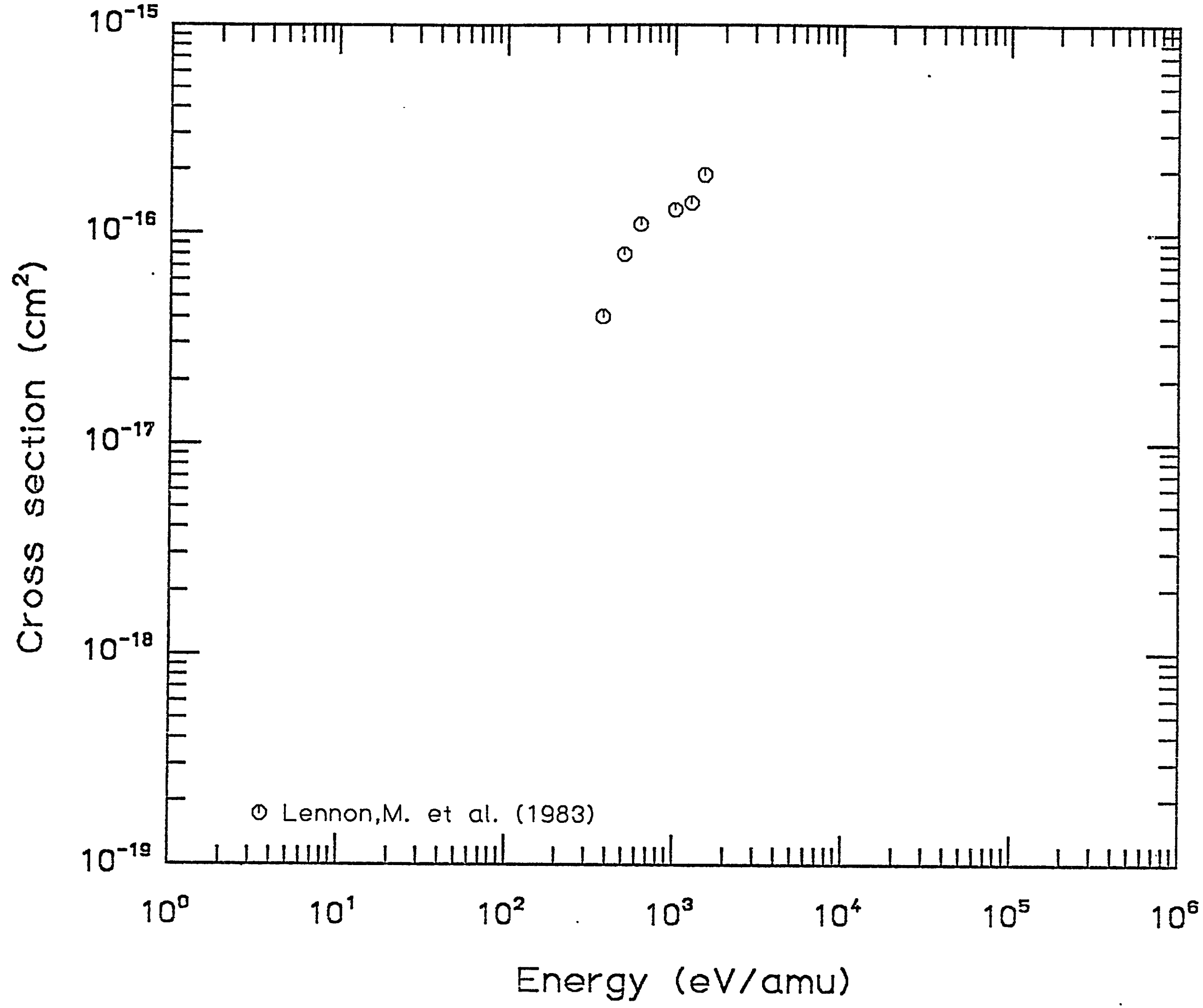


Fig.75 $C^{3+} + He \dashrightarrow C^{2+}(1s^2 2s2p\ ^3P^0) + He^+$

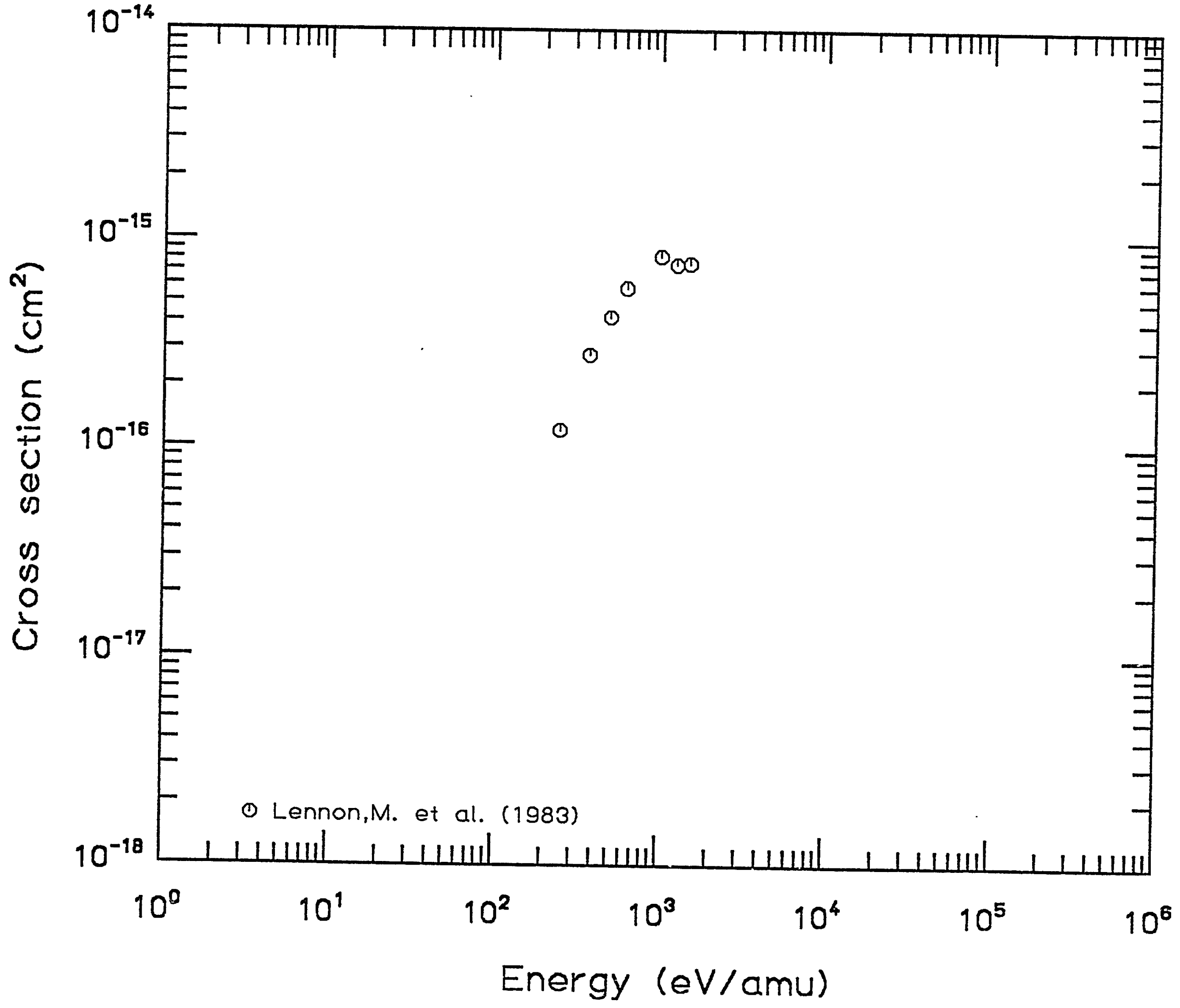


Fig.76 $C^{3+} + He \rightarrow C^{2+}(1s^22s2p\ ^1P^0) + He^+$

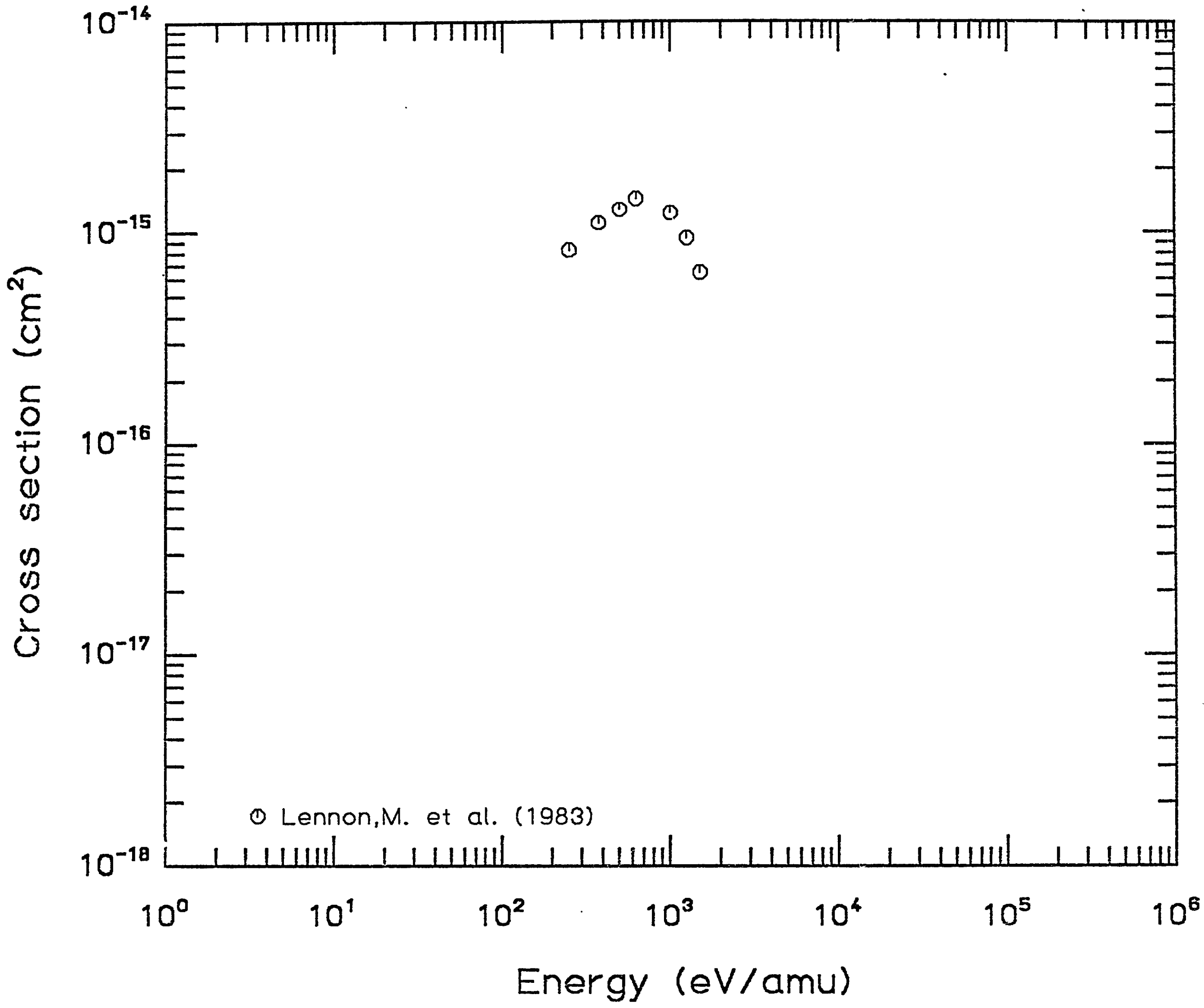
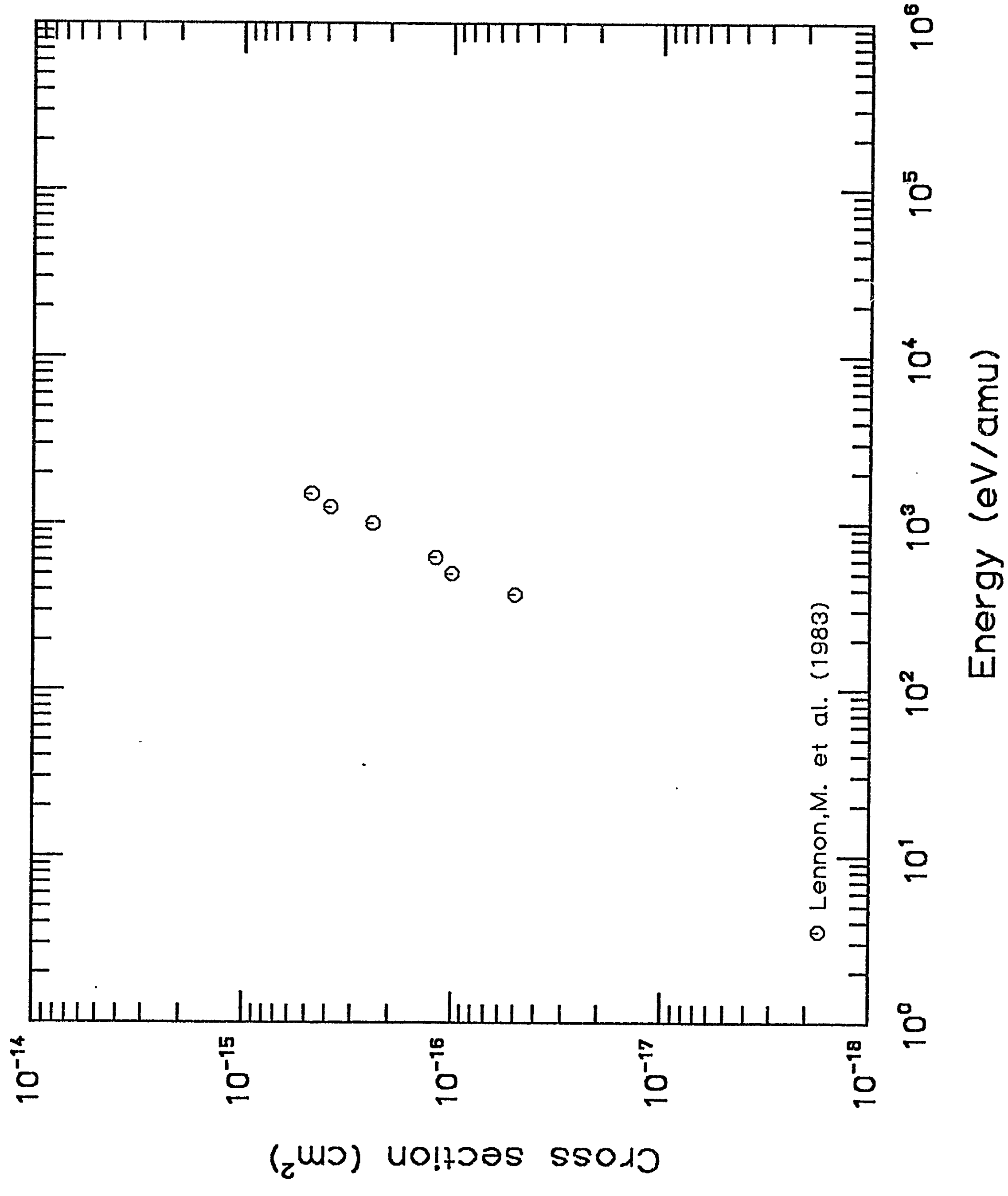


Fig.77 $C^{3+} + He \rightarrow C^{2+}(1s^2 2p^2\ ^3P + ^1D) + He^+$



$$\text{III-5}\quad C^{2+}(1s^2 2s^2\ {}^1S) + He \rightarrow C^{+}(1s^2 2s^2 2p\ {}^2P) + He^{+} \qquad (1)$$

Total cross sections for single electron capture are summarized.[1] On the other hand, Lennon et al.[2], using C^{2+} ion beams containing an unknown, but significant fraction of the metastable state, observed the translational energy spectrum over the energy range 1 - 6 keV and found that the peak corresponding to the process (1) is very small at low energies. This can be understood because the process is endothermic. Instead, the peak corresponding to the metastable beams due to the following process

$$C^{2+}(1s^2 2s2p\ {}^3P) + He \rightarrow C^{+}(1s^2 2s^2 2p\ {}^2P) + He^{+} \qquad (2)$$

is found to be significant, because the process(2) is exothermic. However, as the fraction of the metastable beam is not known, they could obtain no cross sections. Thus it shoud be noted that the observed total cross sectioons[1] are also affected by the presence of the metastable beams.

No cross sections for double electron capture was reported yet.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. M. Lennon, R.W. McCullough and H.B. Gilbody, J. Phys. B <u>16</u> (1983) 2191

IV $O^{q+} + H(1s)$ collisions

IV-1. $O^{8+} + H(1s) \rightarrow O^{7+}(n\ell) + H^+$

Experimental data for total electron capture cross sections are summarized.[1] Using MO description, Harel and Salin[2] calculated total cross sections with the indication of the predominance of electron capture into n = 5 state at intermediate energies. Similar results have been given by Salop and Olson[3] (MO + CTMC, 0.5 - 500 keV/amu) with the dominant contribtion from n = 5 states. Some calculation of total cross sections was also reported by Grozdanov[5] over 2.5 - 100 keV/amu using his classical model. Kazanskii and Komarov[6], using molecular calculation, have given the ($n\ell$) distributions (n = 4,5) over the energy range 0.25 - 4 keV/amu, with the dominance of n=5 states and relatively weak contribution from n=4 and n=6 states. Janev et al.[7] calculated the n-distributions using MLZRC method with the result of the dominant n=5 states over 0.5 - 25 keV/amu. Shipsey et al.[8], combining MO and LZ models, calculated the partial cross sections for $n\ell$ =4ℓ,5ℓ and 6ℓ and for n=7 states over 13 eV/amu - 34 keV/amu. The ($n\ell$) distributions at 25 and 50 keV/amu have been also calculated by Hardie and Olson[9] using CTMC, with an additional result of total cross sections over 25 - 200 keV/amu. Fritsch and Lin[10] have reported the calculated ($n\ell$) distributions at 0.1 - 30 keV/amu using AO method. Furthermore, Fritsch[11] calculated, using the same technique, similar cross sections for non-dominant capture processes, namely 7ℓ, 8ℓ and 9ℓ states. Presnyakov and Uskov[12] calculated total and n=5 states partial cross sections at 6.25 - 56 keV/amu. The partial cross sections for ($5\ell m$) states have been calculated by Salin[13] using MO model over 1 - 16 keV/amu. Using the same method, Bendahman et al.[14] gave the cross sections for different n states over 0.25 - 50 keV/amu, indicating that those for n=5 states are dominant at low energies and those for n=6 become significant at higher energies. Recently

Kimura and Lane[15], using the travelling MO method, reported a similar trend over 0.2 - 5 keV/amu.

Experimentally, Kimura et al.[16] confirmed the predominance of n=5 states, with the contribution of 20% from n=6 states using the translational energy spectroscopy. Most recently, Hoekstra et al.[17] determined the emission cross sections for n=3 → n=4 (63.3 nm), n=5 → n=3 (20.0 nm) and n=6 → n=3 (17.0 nm) transitions with the agreement with calculations for the dominant processes but with significant discrepancies for less dominant processes.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. C. Harel and A. Salin, J. Phys. B 10 (1977) 351
3. A. Salop and R.E. Olson , Phys. Rev. A 19 (1979) 1921
4. A. Salop, J. Phys. B 12 (1979) 919
5. T.P. Grozdanov, J. Phys. B 13 (1980) 3835
6. A.K. Kazanskii and I.V. Komarov, Sov. Phys.-Techn. Phys. 27 (1982) 1064
7. R.K. Janev, D.S. Belic and B.H. Bransden, Phys. Rev. A 28 (1983) 1293
8. E.J. Shipsey, T.A. Green and J.C. Browne, Phys. Rev. A 27 (1983) 821
9. D.J.W. Hardie and R.E. Olson, J. Phys. B 16 (1983) 1983
10. W. Fritsch and C.D. Lin, Phys. Rev. A 29 (1984) 3039
11. W. Fritsch, Phys. Rev. A 30 (1984) 3324
12. L.P. Presnyakov and D.B. Uskov, Sov. Phys.-JETP 59 (1984) 515
13. A. Salin, J. Physique 45 (1984) 671
14. M. Bendahman, S. Bliman, S. Dousson, D. Hitz, R. Gayet, J. Hanssen, C. Harel and A. Salin, J. Physique 46 (1985) 561
15. M. Kimura and N.F. Lane, Phys. Rev. A 35 (1987) 70
16. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873
17. R. Hoekstra, D. Ciric, F.J. de Heer and R. Morgenstern, Phys. Letters A 124 (1987) 73

Fig.78 $O^{8+} + H \dashrightarrow O^{7+}(\text{total}) + H^{+}$

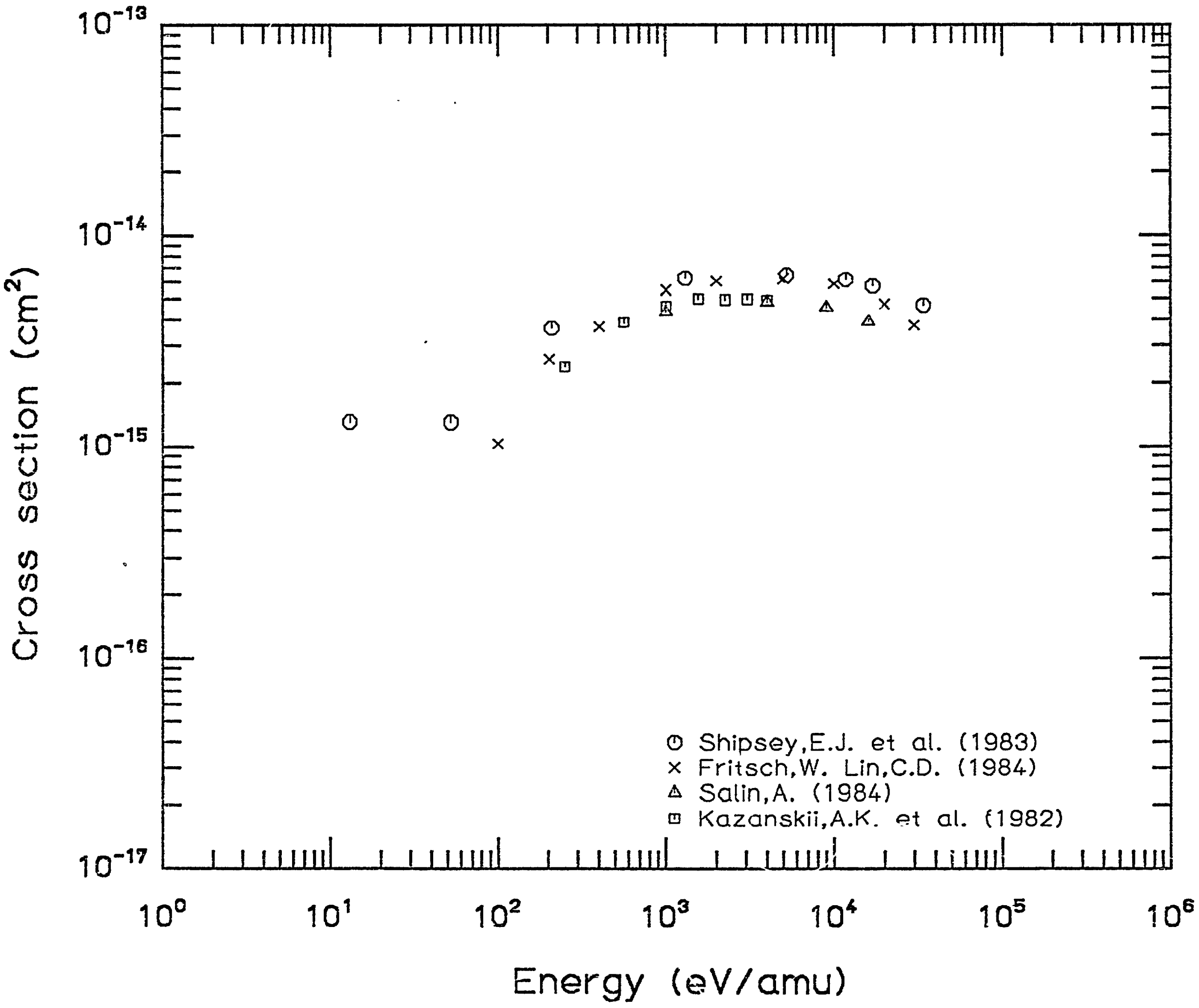


Fig.79 $O^{8+} + H \dashrightarrow O^{7+}(4s) + H^{+}$

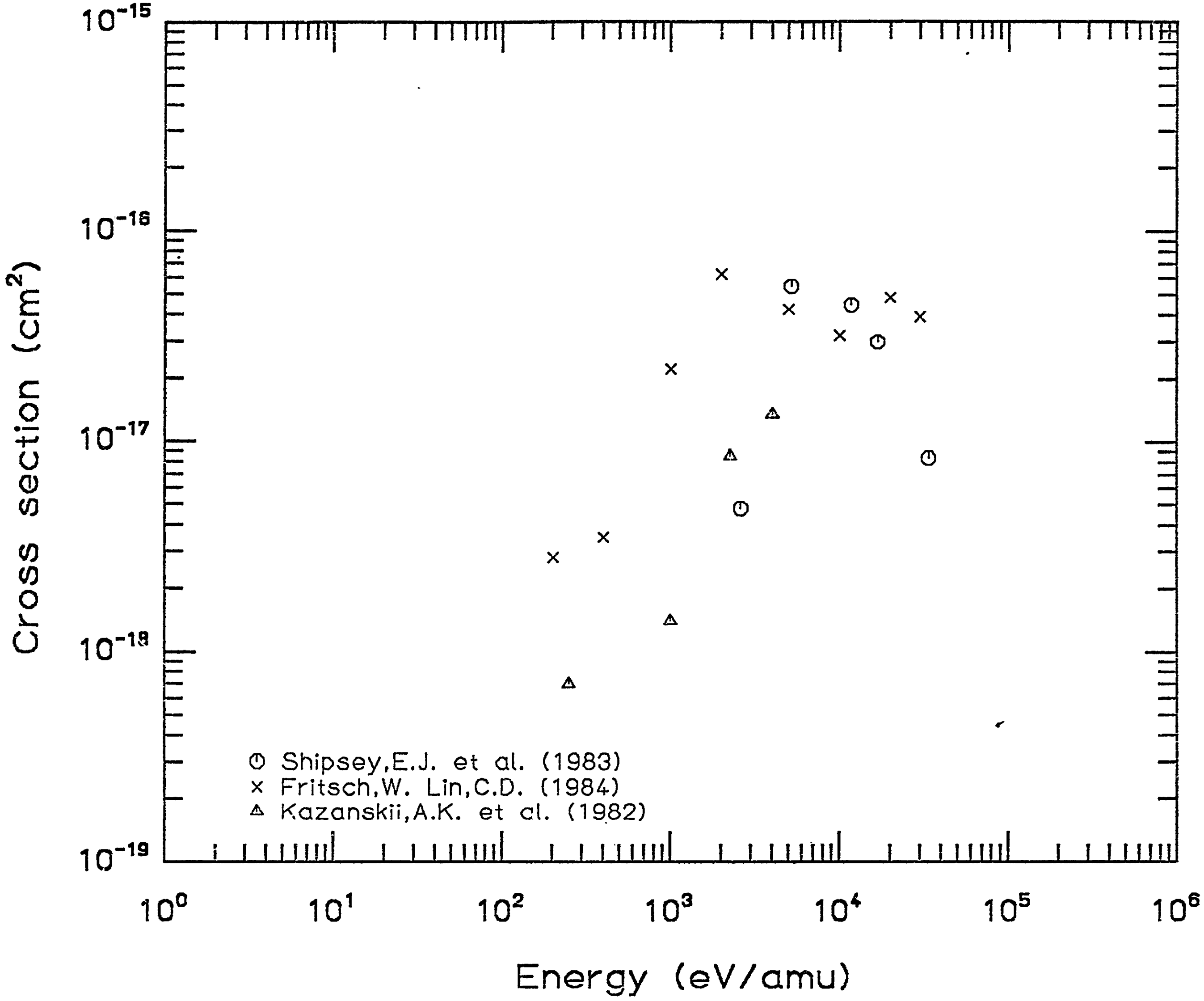


Fig.80 $O^{8+} + H \rightarrow O^{7+}(4p) + H^{+}$

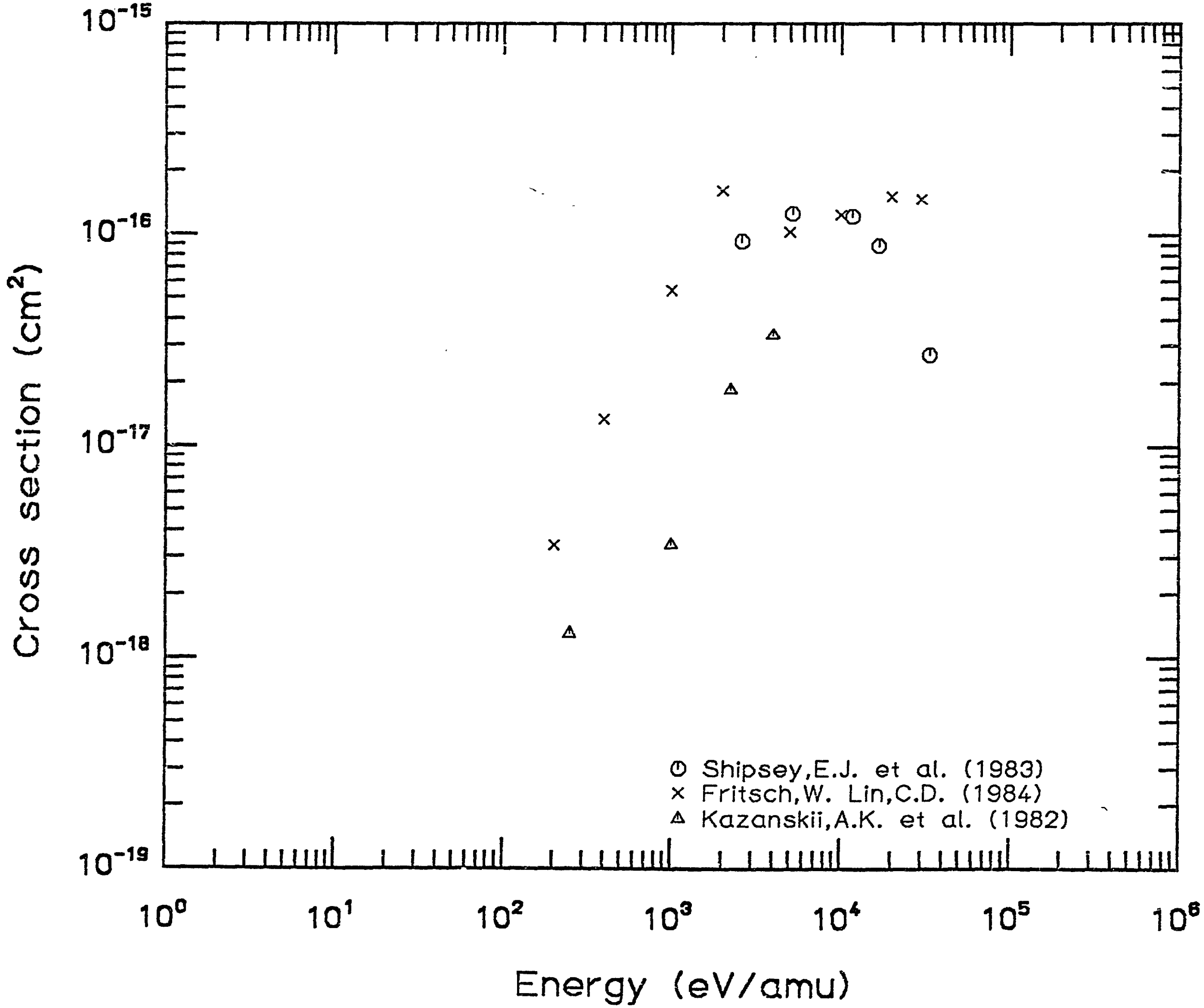


Fig.81 $O^{8+} + H \dashrightarrow O^{7+}(4d) + H^{+}$

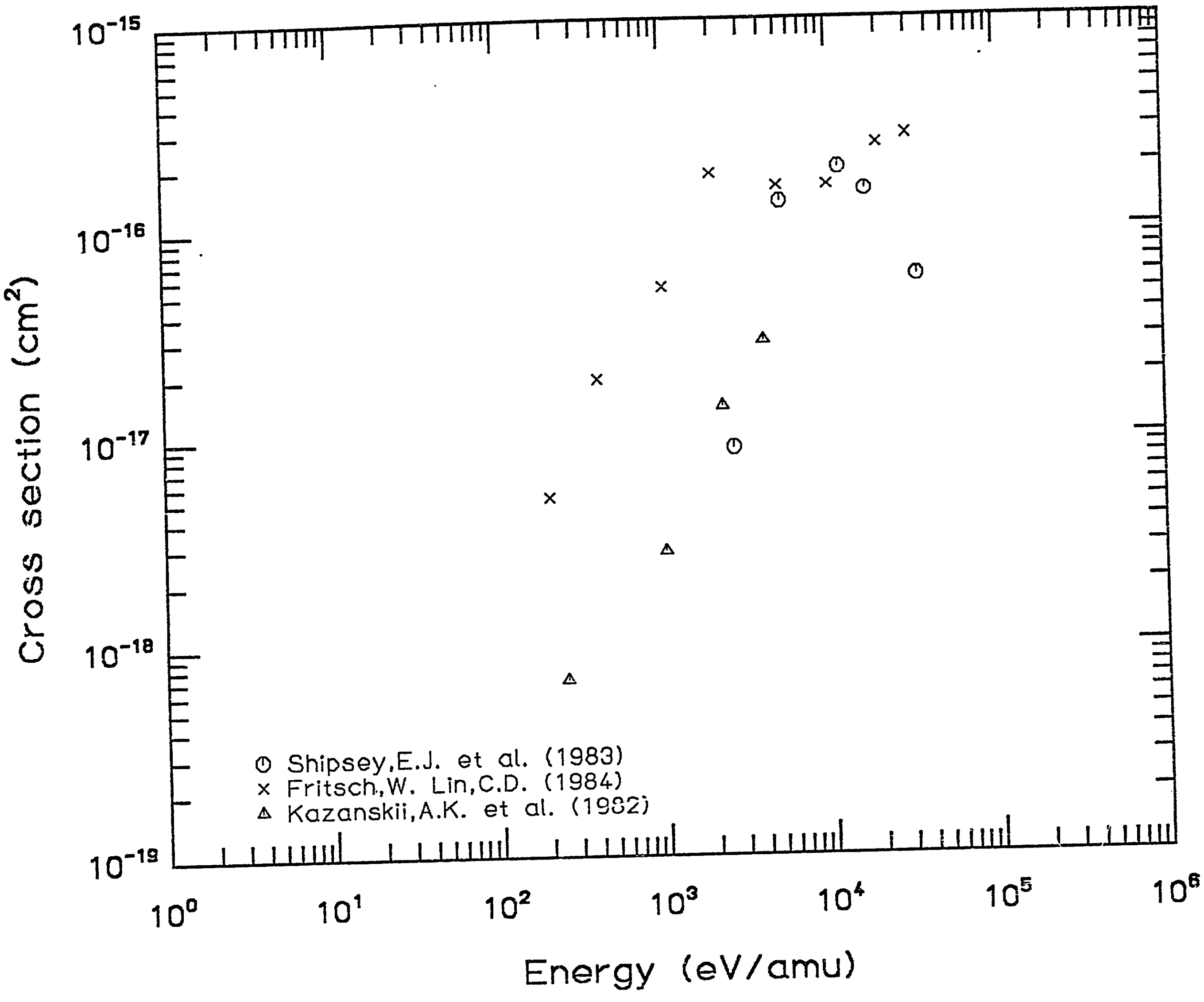


Fig.82 $O^{8+} + H \dashrightarrow O^{7+}(4f) + H^{+}$

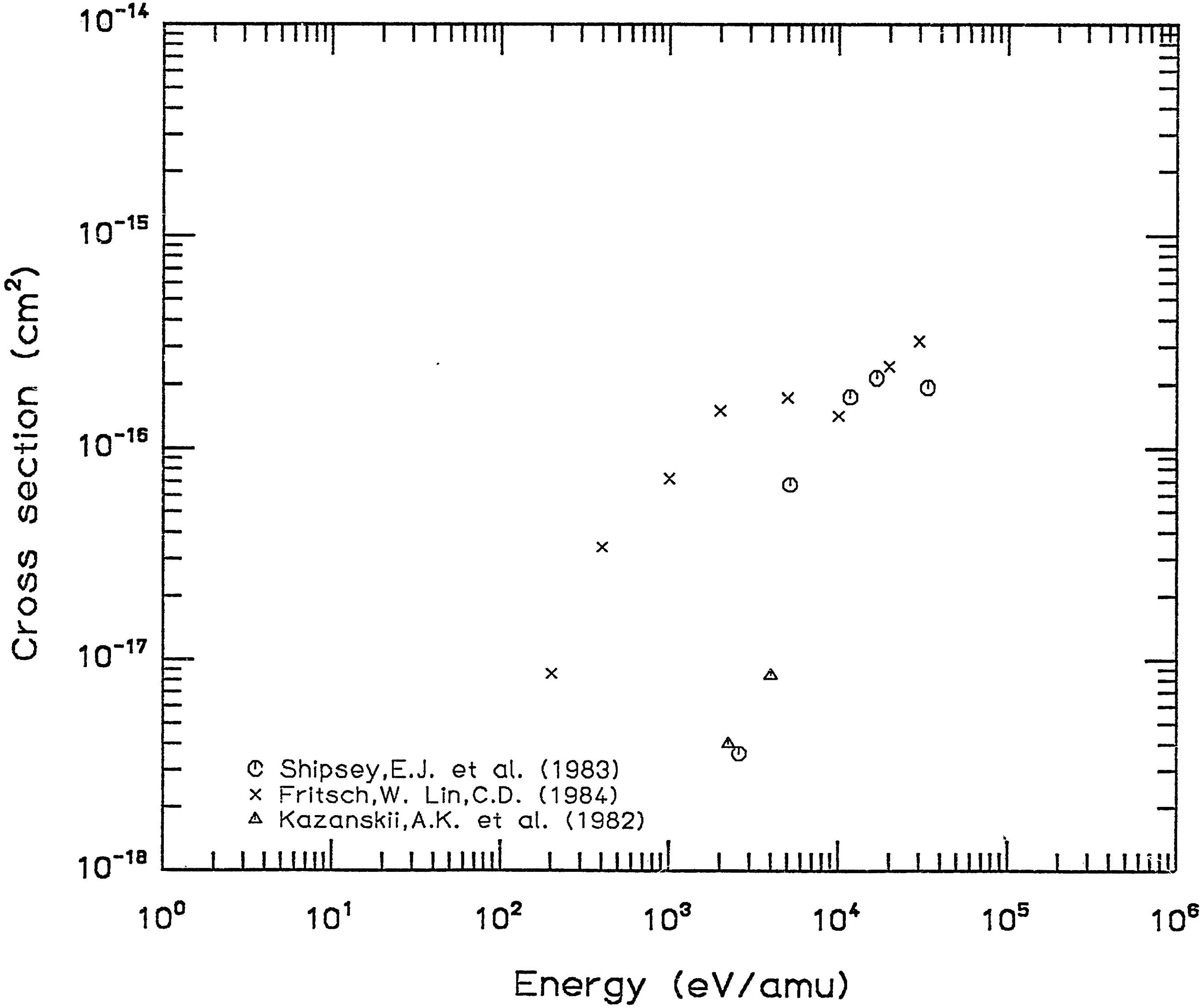


Fig.83 $O^{8+} + H \dashrightarrow O^{7+}(5s) + H^{+}$

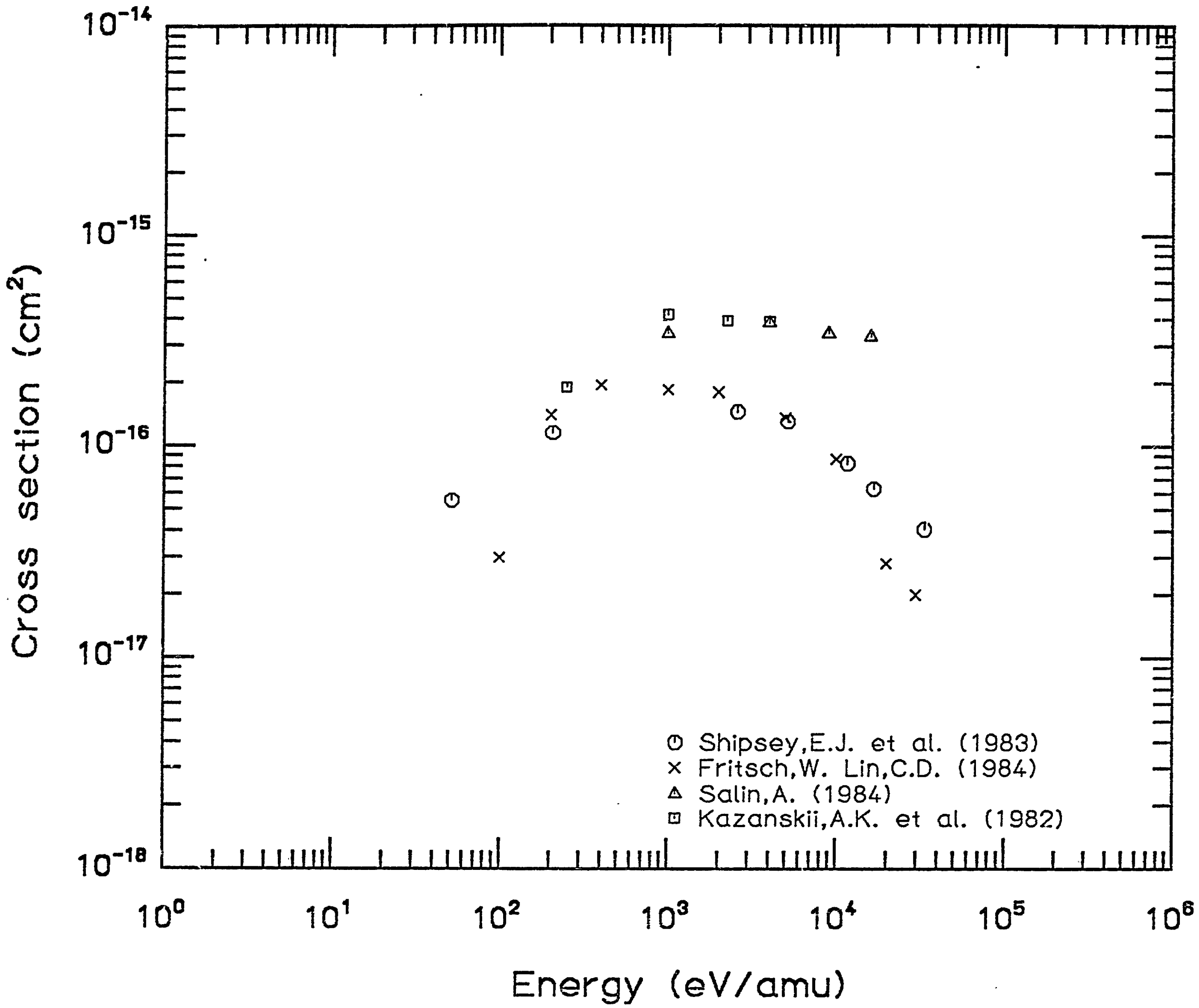


Fig.84 $O^{8+} + H \rightarrow O^{7+}(5p) + H^{+}$

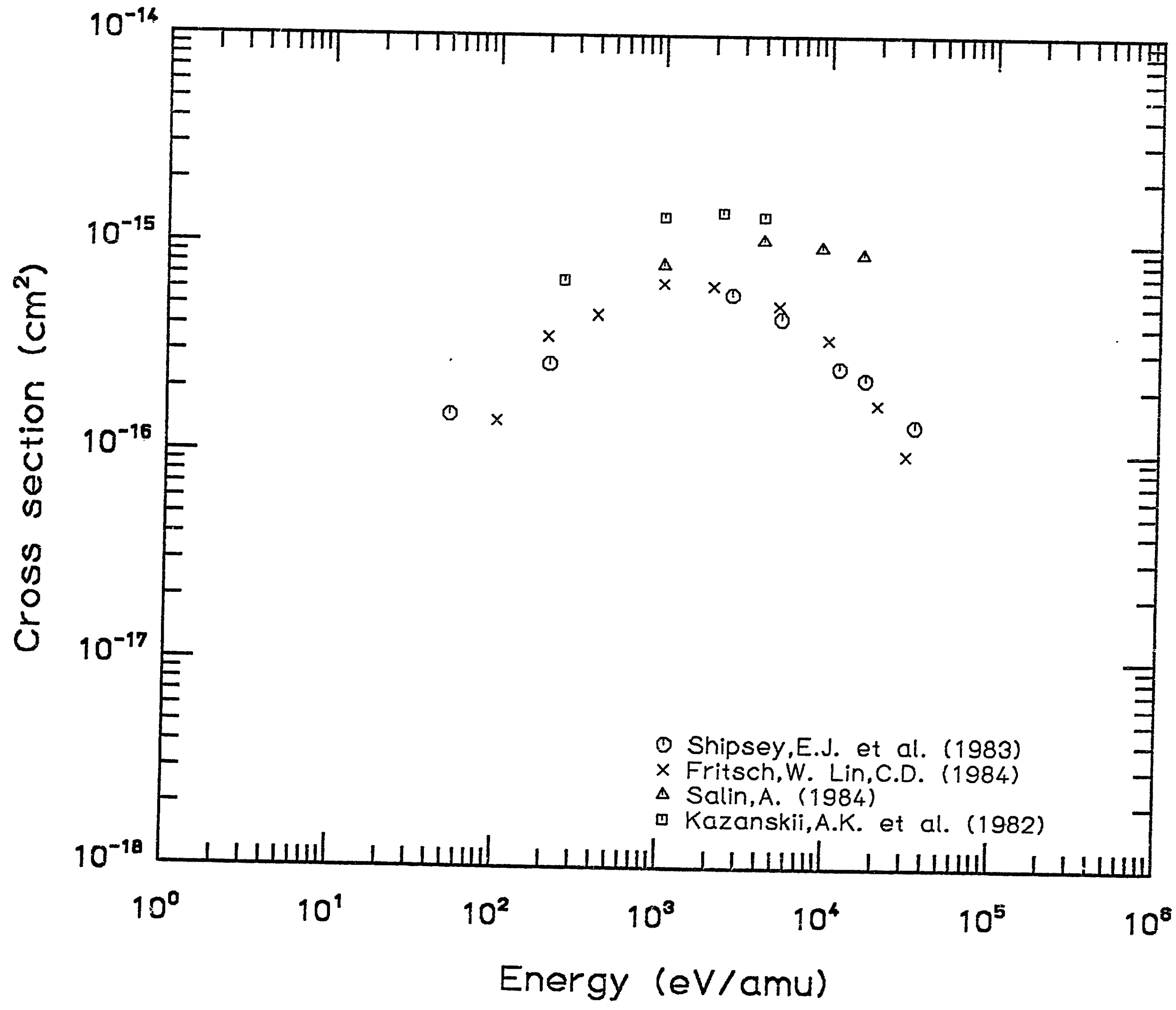


Fig.85 $O^{8+} + H \rightarrow O^{7+}(5d) + H^{+}$

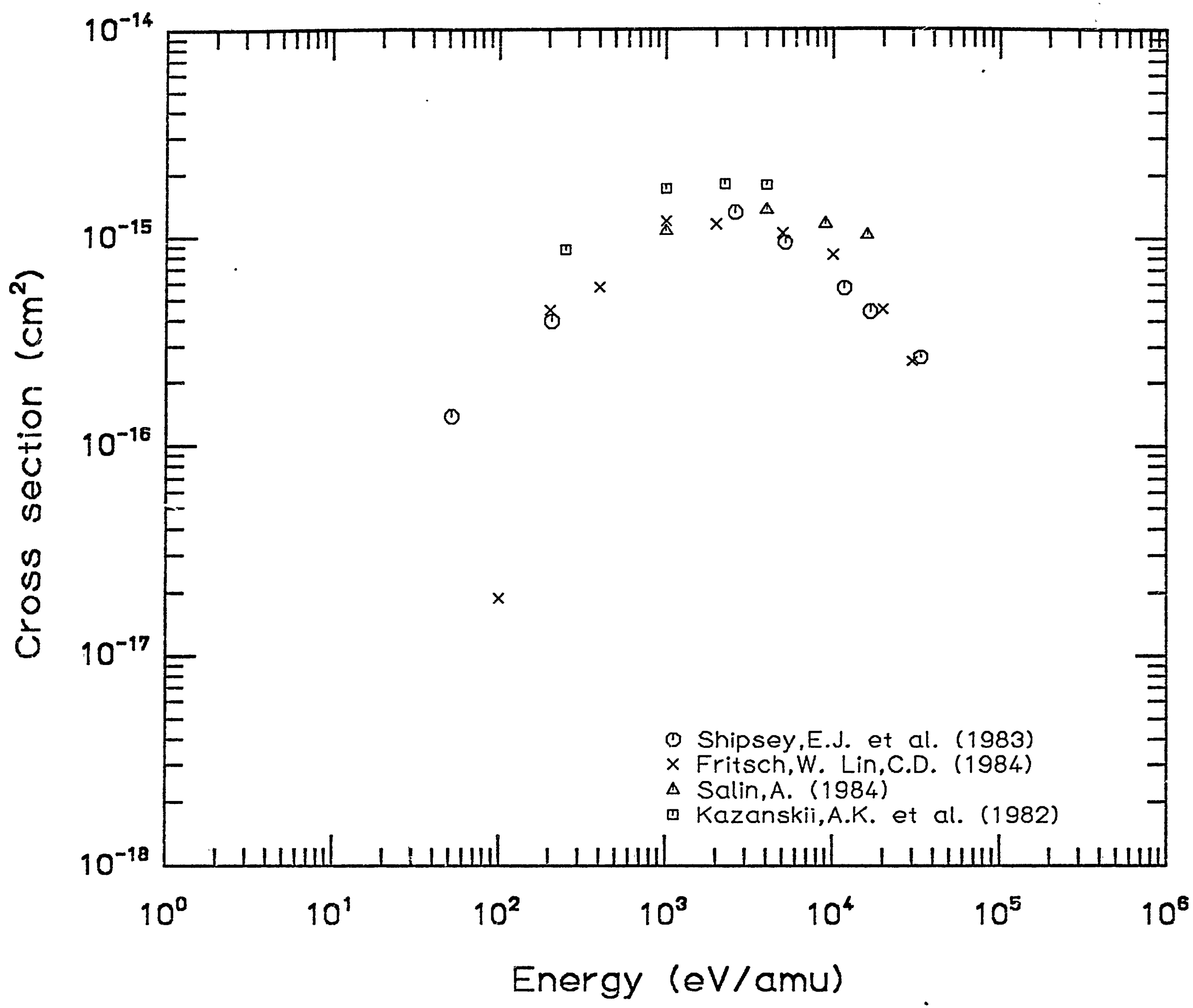


Fig.86 $O^{8+} + H \rightarrow O^{7+}(5f) + H^+$

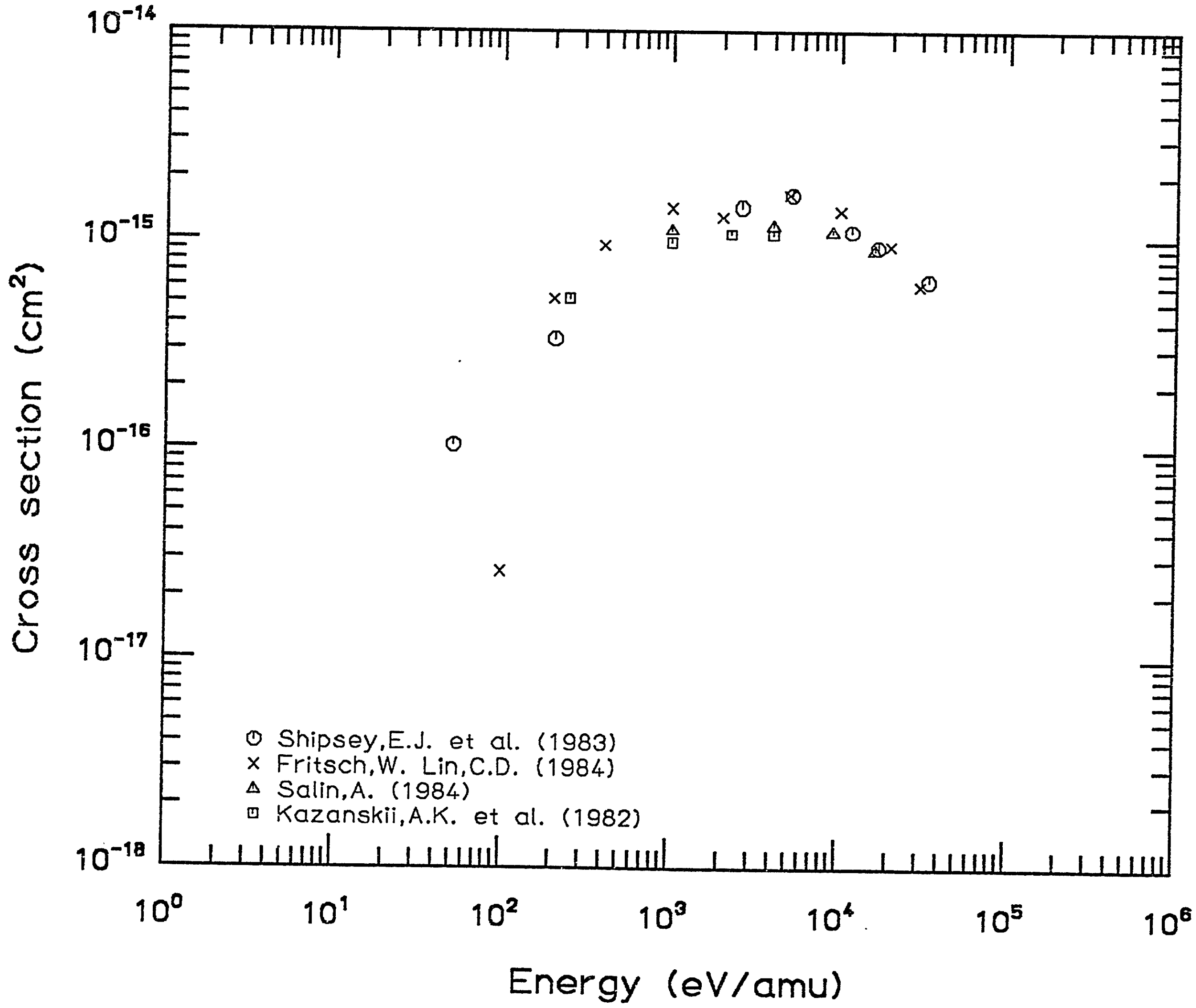


Fig.87 $O^{8+} + H \rightarrow O^{7+}(5g) + H^{+}$

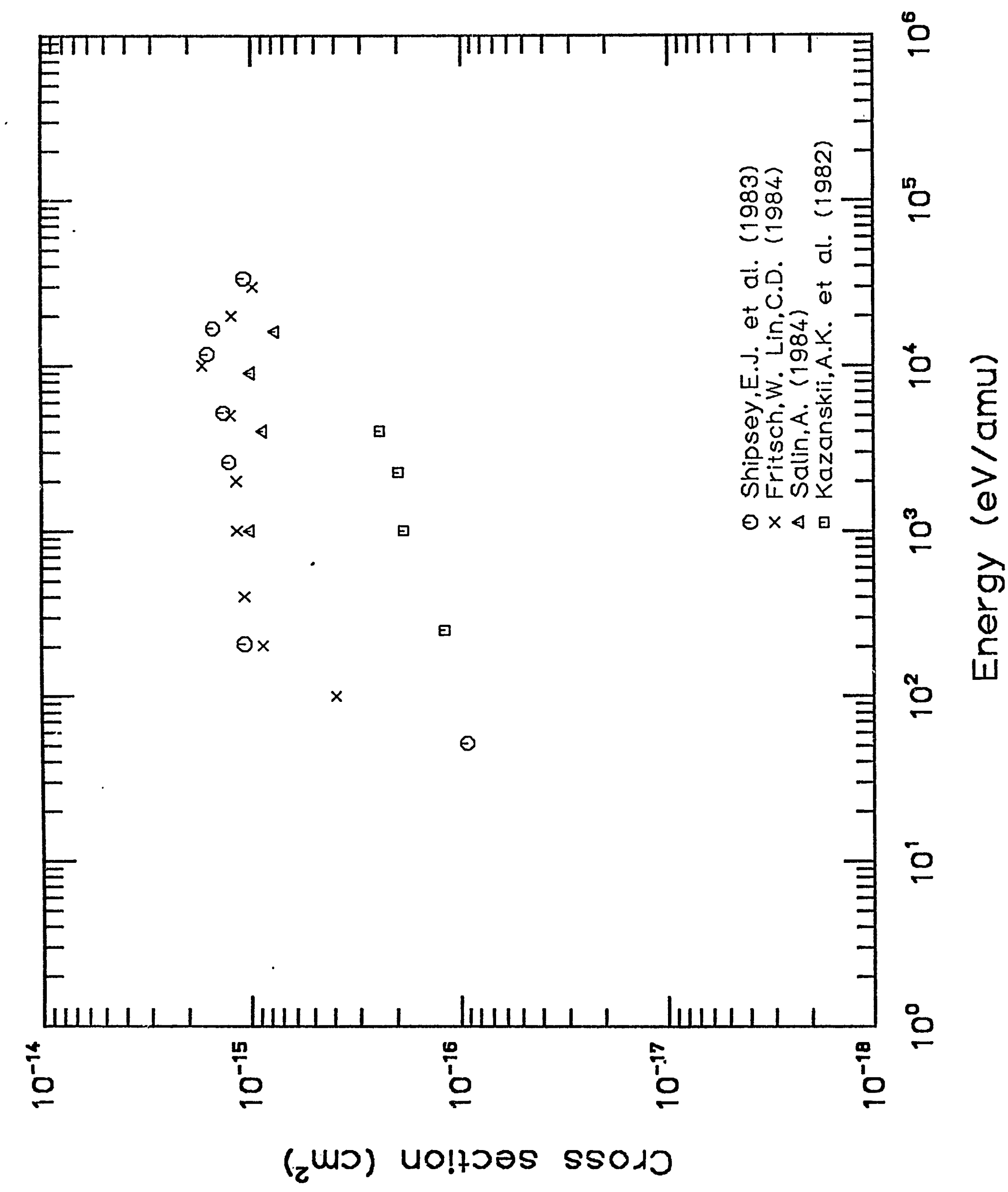


Fig.88 $O^{8+} + H \dashrightarrow O^{7+}(6s) + H^{+}$

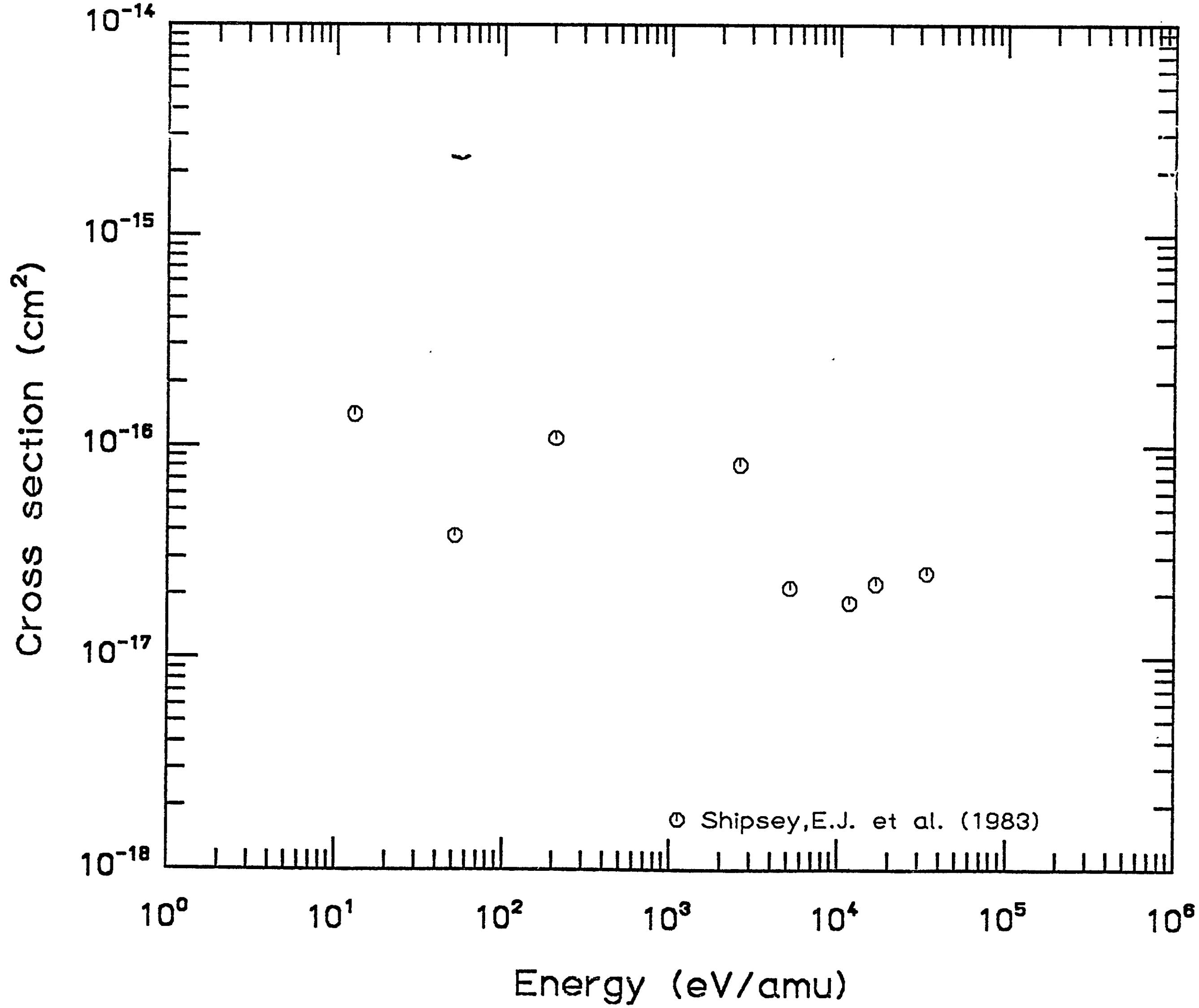


Fig.89 $O^{8+} + H \rightarrow O^{7+}(6p) + H^{+}$

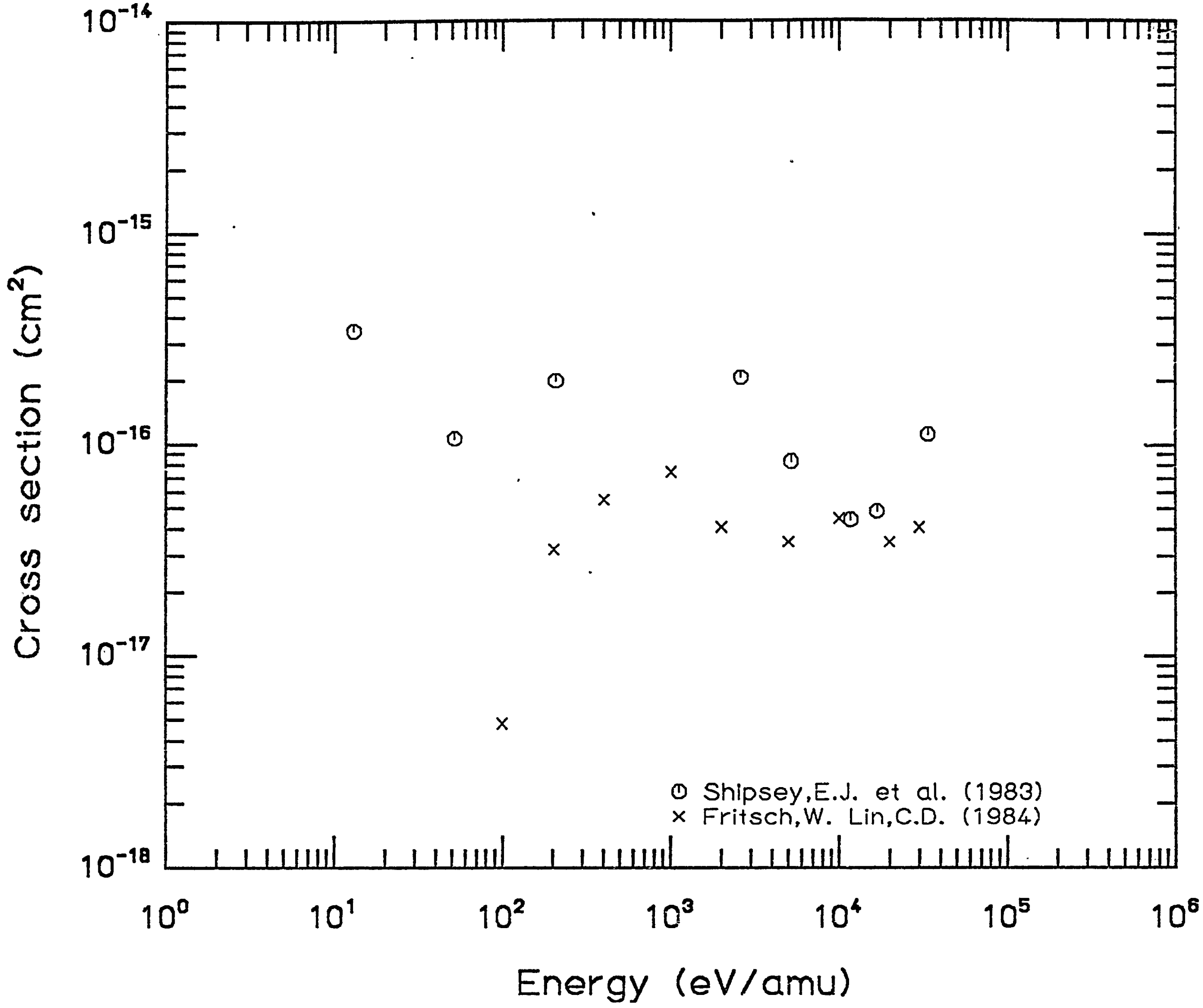


Fig.90 $O^{8+} + H \dashrightarrow O^{7+}(6d) + H^{+}$

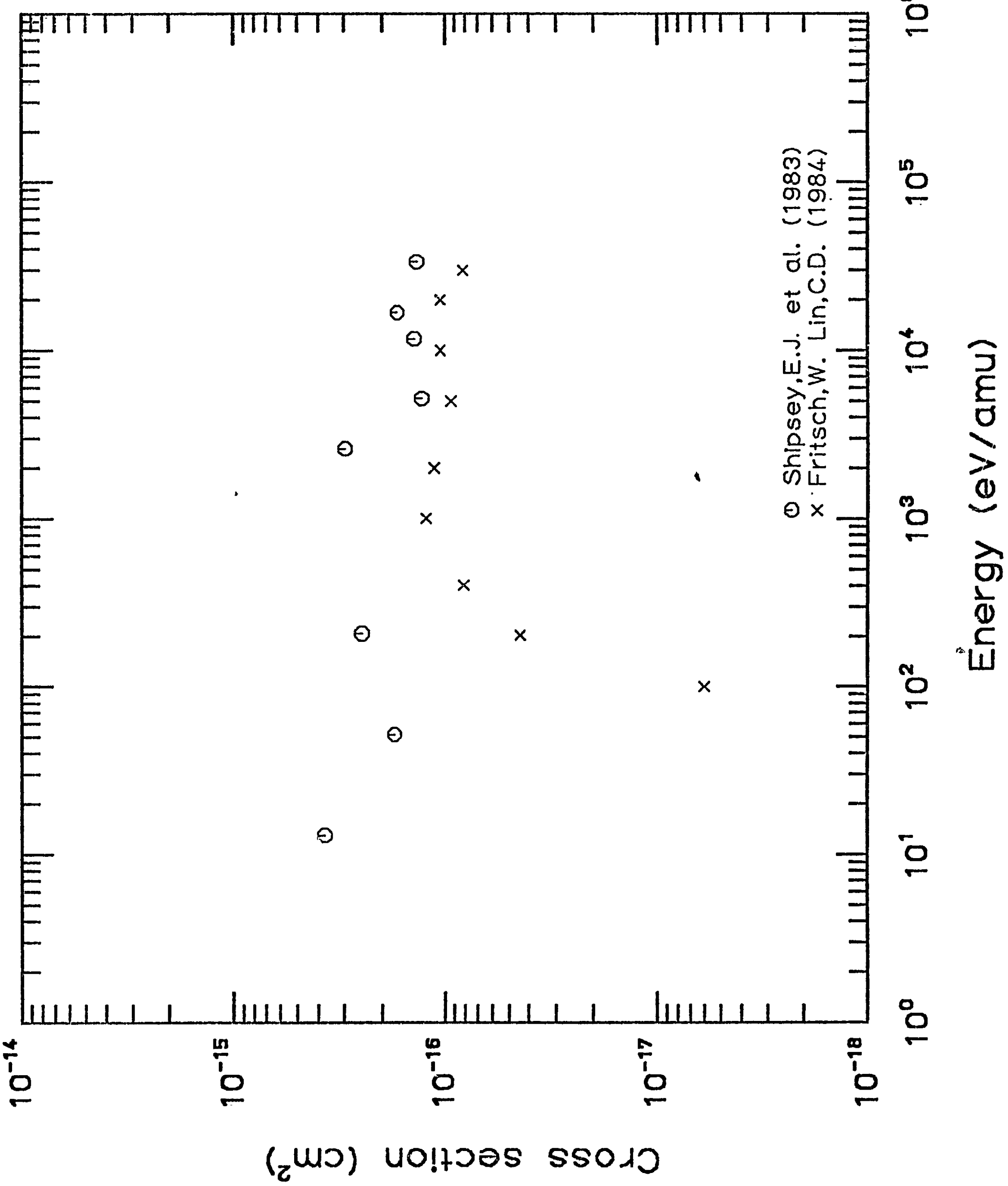
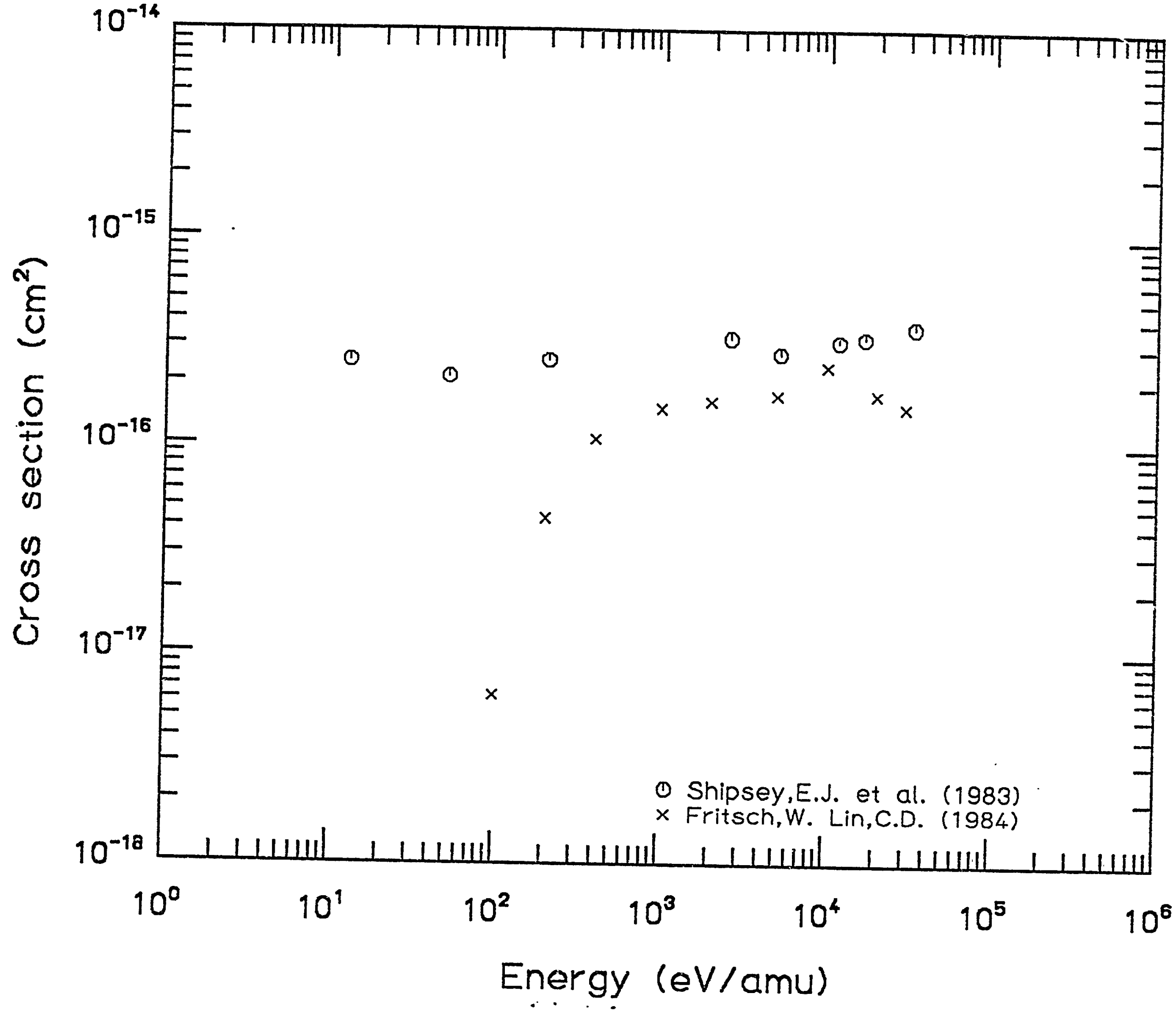


Fig.91 $O^{8+} + H \rightarrow O^{7+}(6f) + H^{+}$



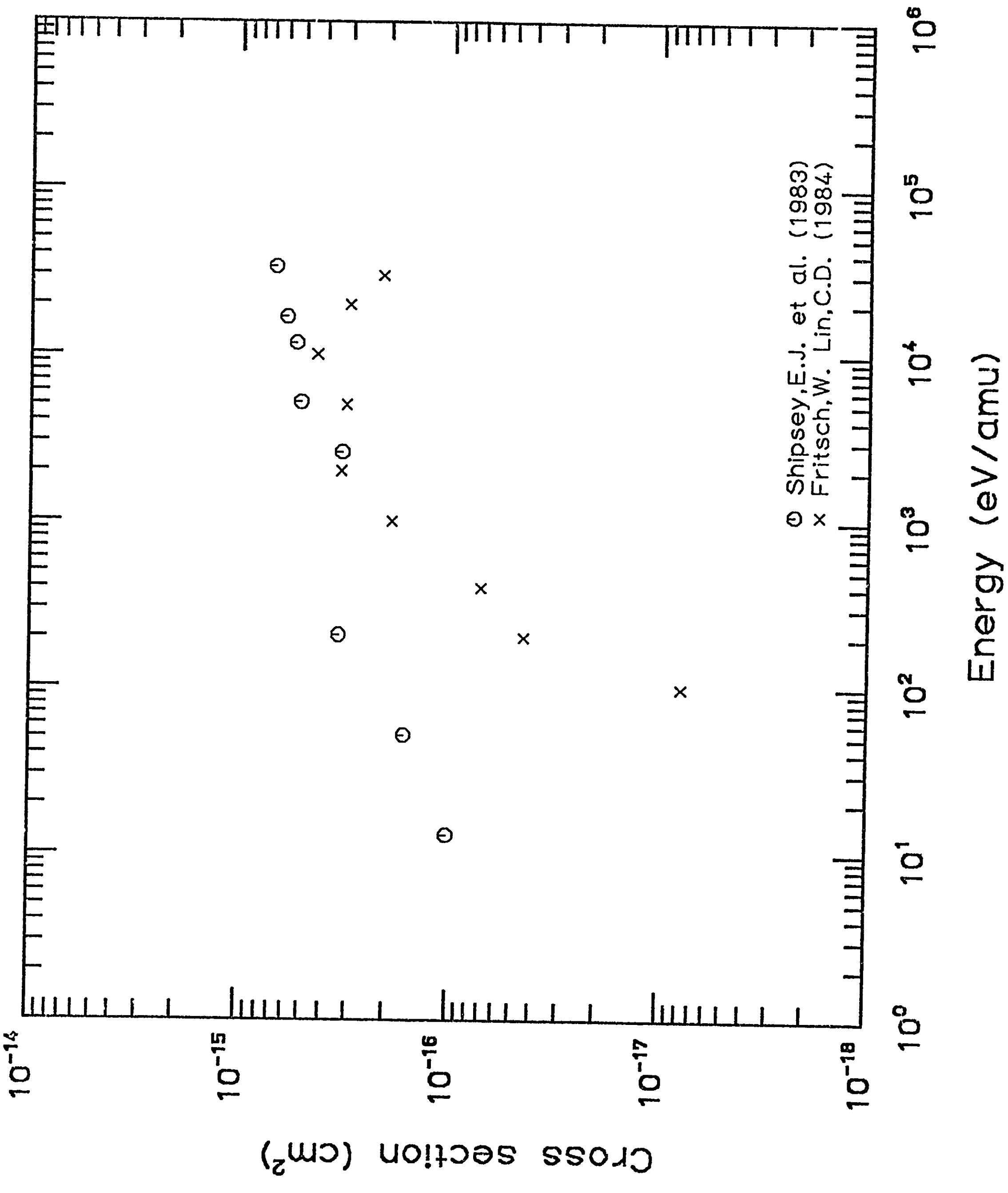
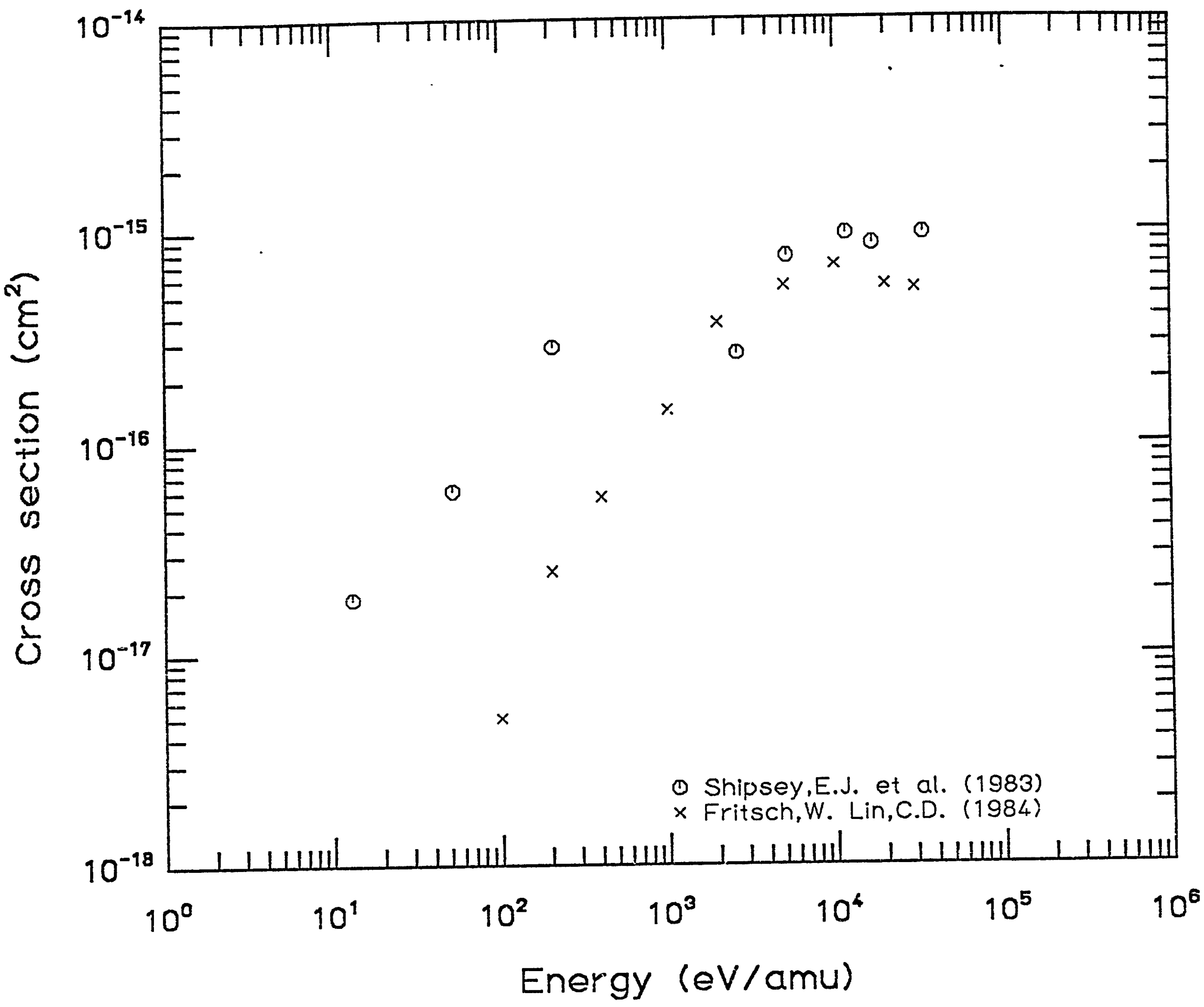


Fig.92 $O^{8+} + H \to O^{7+}(6g) + H^+$

Fig.93 $O^{8+} + H \rightarrow O^{7+}(6h) + H^{+}$



IV-2 $O^{7+}(1s) + H(1s) \rightarrow O^{6+}(1sn\ell) + H^{+}$

Total electron capture cross sections are summarized.[1] However, no work was reported on the final state distribution except for a single experimental work by Kimura et al.[2] who observed that the dominant electron capture goes into n=5 states at around 500 eV/amu energy range using translational energy spectroscopy.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

IV-3 $O^{6+}(1s^2) + H(1s) \rightarrow O^{5+}(1s^2 n\ell) + H^+$

Total electron capture cross sections are summarized.[1] Theoretical calculations of the cross sections have been reported by Shipsey et al.[2] who give total cross sections over the energy range 10^{-2} - 200 keV/amu using molecular treatment and CTMC, with the indication of the predominance of electron capture into n=4 states at low energies. Similar results have been given by Hanssen et al.[3] using MO model over 0.25 - 25 keV/amu who also show the dominant capture into n=4 states with a slight contribution from n=3 states. Bendahman et al.[4] gave the cross sections for n=4 and 5, showing that the capture into n=4 states is dominant at low energies, whereas at higher energies the capture into n=4 and n=5 becomes comparable.

Experimental confirmation of the dominance of the capture into n=4 states is given by Dijkkamp et al.[5] and Kimura et al.[6] In particular, Dijkkamp et al. determined the absolute cross sections for $(n\ell)$ states over 0.94 - 7.5 keV/amu using photon spectroscopy. Their observed average ℓ-distributions $<\ell>$ are found to be well reproduced theoretically based upon the extended classical over-barrier model.[7]

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. E.J. Shipsey, J.C. Browne and R.E. Olson, J. Phys. B 14 (1981) 869
3. J. Hanssen, R. Gayet, C. Harel and A. Salin, J. Phys. B 17 (1984) L323
4. M. Bendahman, S. Bliman, S. Dousson, D. Hitz, R. Gayet, J. Hanssen, C. Harel and A. Salin, J. Physique 46 (1985) 561
5. D. Dijkkamp, D. Ciric, E. Vlieg, A. de Boer and F.J. de Heer, J. Phys. B 18 (1985) 4763
6. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873
7. J. Burgdorfer, R. Morgenstern and A. Niehaus, J. Phys. B 19 (1986) L507

Fig.94 $O^{6+} + H \dashrightarrow O^{5+}(total) + H^{+}$

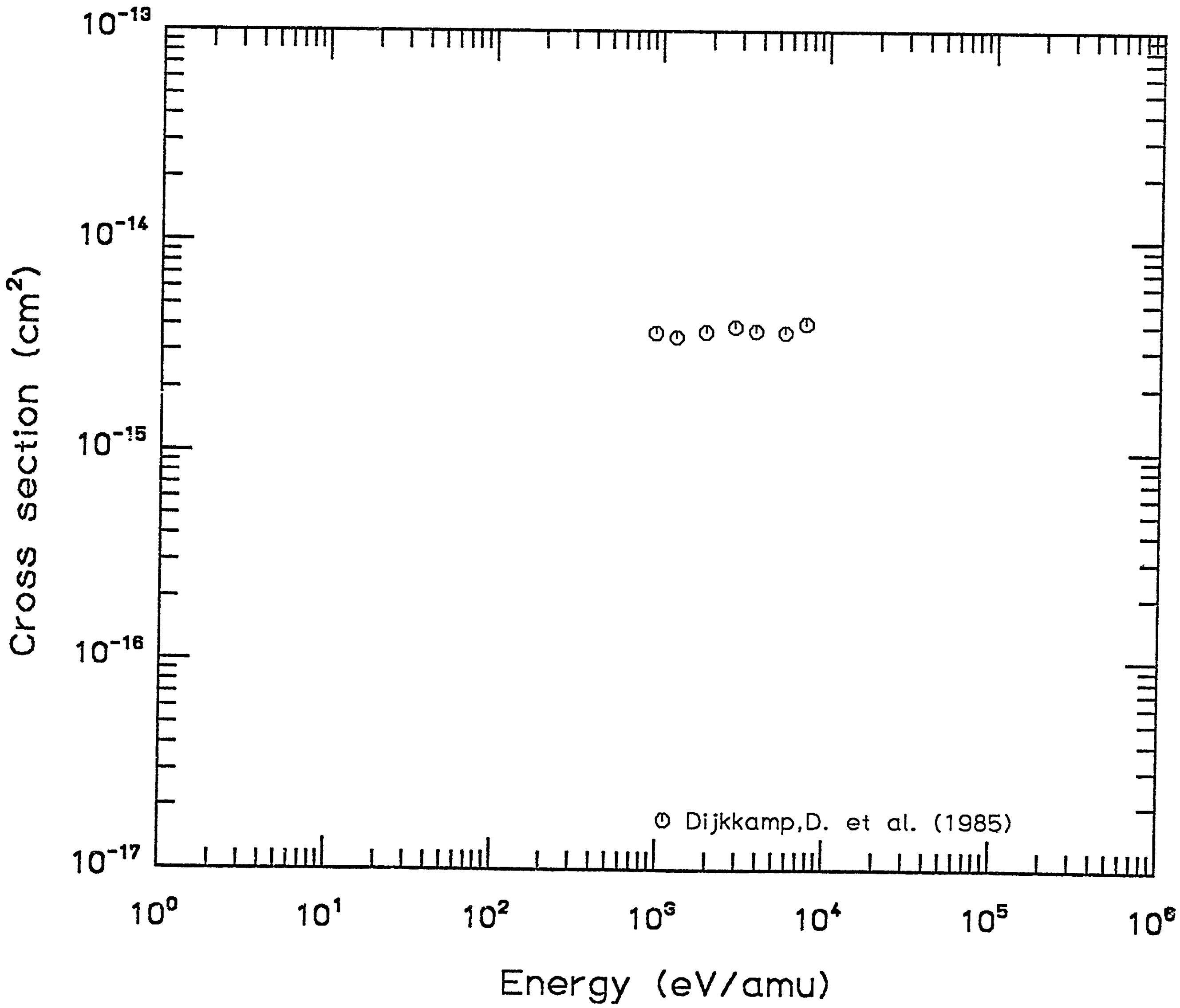


Fig.95 $O^{6+} + H \rightarrow O^{5+}(1s^2 4s) + H^+$

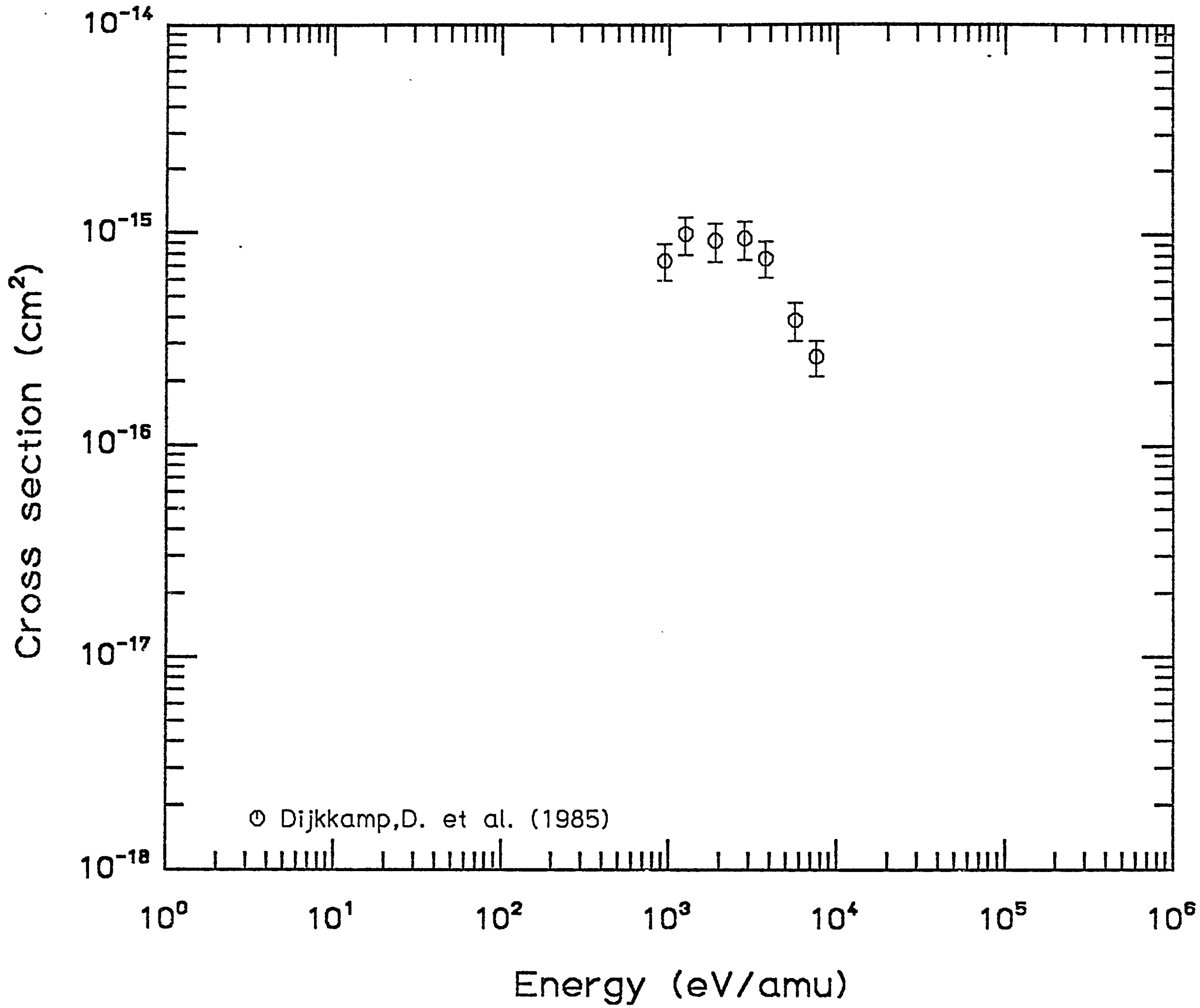


Fig.96 $O^{6+} + H \rightarrow O^{5+}(1s^2 4p) + H^+$

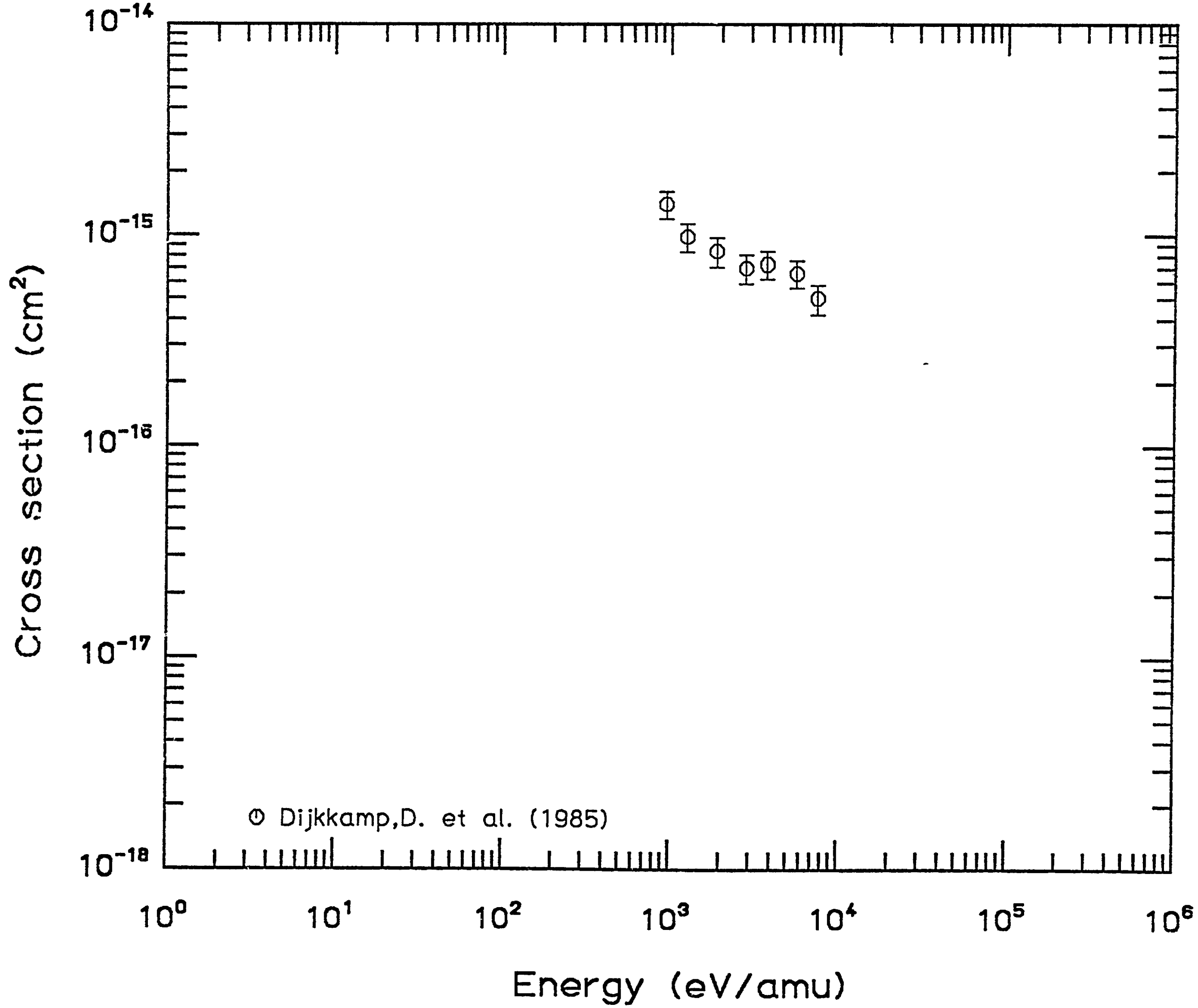


Fig.97 $O^{6+} + H \dashrightarrow O^{5+}(1s^2 4d) + H^+$

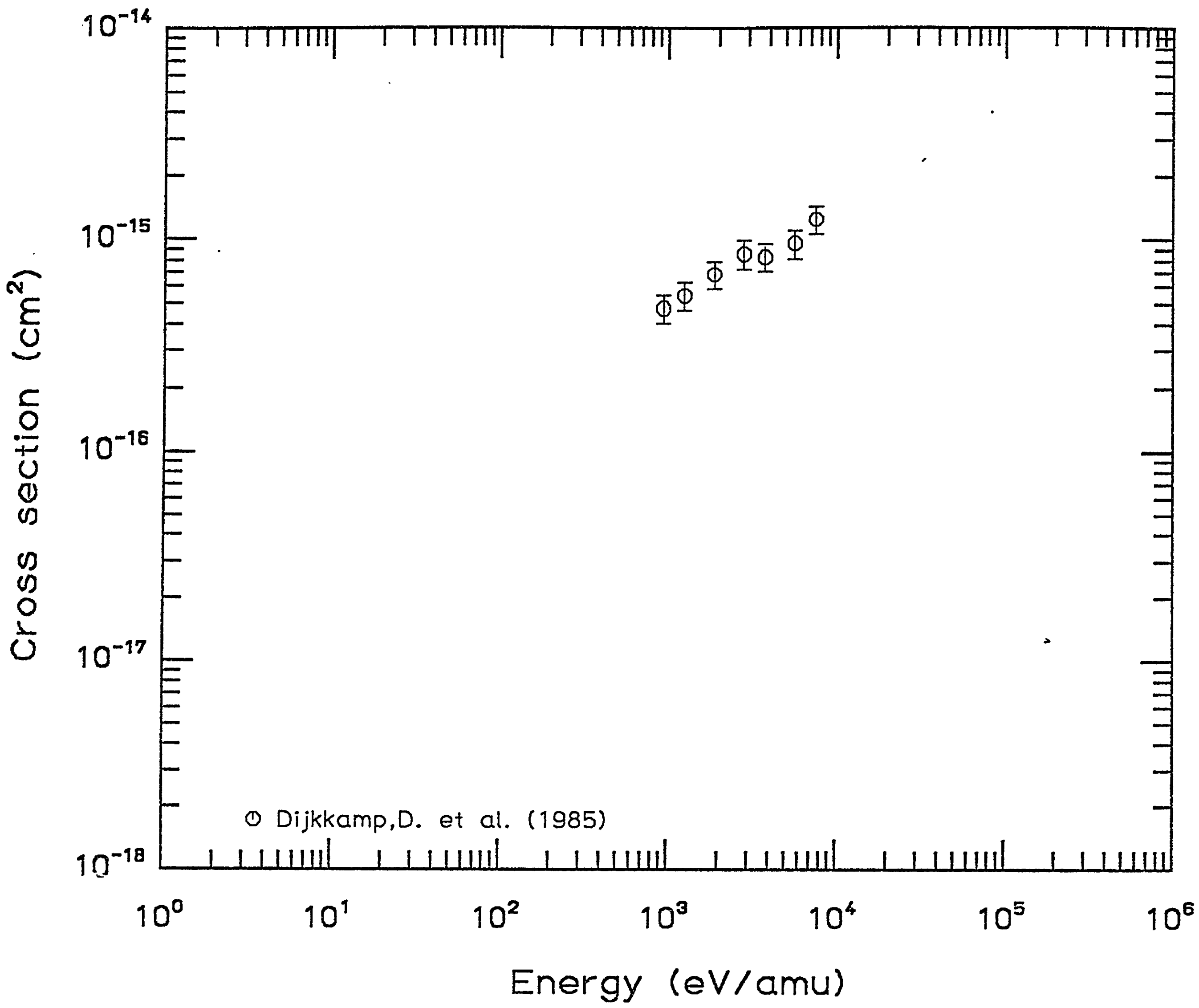
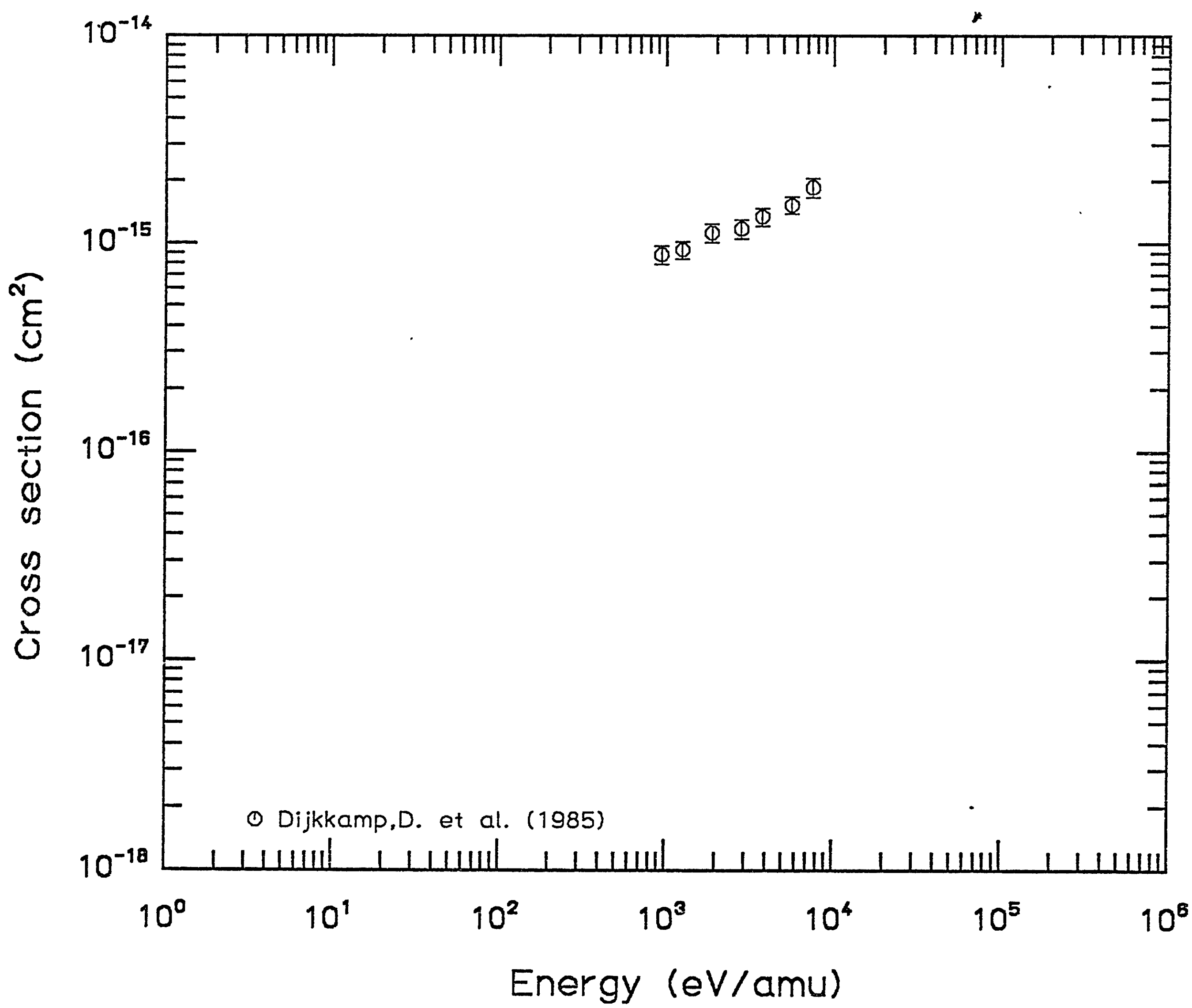


Fig.98 $O^{6+} + H \dashrightarrow O^{5+}(1s^2 4f) + H^+$



IV-4. $O^{4+}(1s^2 2s^2\ {}^1S) + H(1s) \rightarrow O^{3+}(1s^2 2s^2 n\ell) + H^+$

Experimental total cross sections are summarized.[1] Total rate coefficients over the temperature $10^3 - 10^{4.5}$ K were calculated by Butler and Dalgarno[2] using LZ model. No partial cross section measurement has been reported.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. S.E. Butler andf A. Dalgarno, Astrophys. J. 241 (1980) 838

IV-5. $O^{3+}(1s^2 2s^2 2p\ ^2P^0) + H(1s) \rightarrow O^{2+}(1s^2 2s^2 2pn\ell) + H^+$

Total electron capture cross sections are summarized.[1] On the other hand, Butler et al.[2] made their quantal calculation of total rate coefficients over the temperature range 5×10^3 - 5×10^4 K. Then, Heil et al.[3] showed that the most dominant process is $2s^2 2p3p\ ^3D$ state capture followed by $2s^2 2p3p\ ^3S$ and $2s^2 2p3p\ ^1P$ at the energy range 0.27 - 8.1 eV/amu. Further, Bienstock et al.[4] extended their calculation of the ($n\ell$) distribution for $2p3s\ ^1P^0$, $2p3p\ ^1P$, ^3S and ^3D states, using the distorted-wave approximation, over the energy range 0.1 - 5000 eV/amu, showing that the capture into 3ℓ states, in particular $3p\ ^3D$ state, is dominant over the energy range investigated.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. S.E. Butler, T.G.Heil and A. Dalgarno, Astrophys. J. 241 (1980) 442
3. T.G. Heil, S.E. Butler and A. Dalgarno, Phys. Rev. A 27 (1983) 2365
4. S. Bienstock, T.G. Heil and A. Dalgarno, Phys. Rev. A 27 (1983) 2741

Fig.99 O^{3+} + H --> O^{2+}(total) + H^{+}

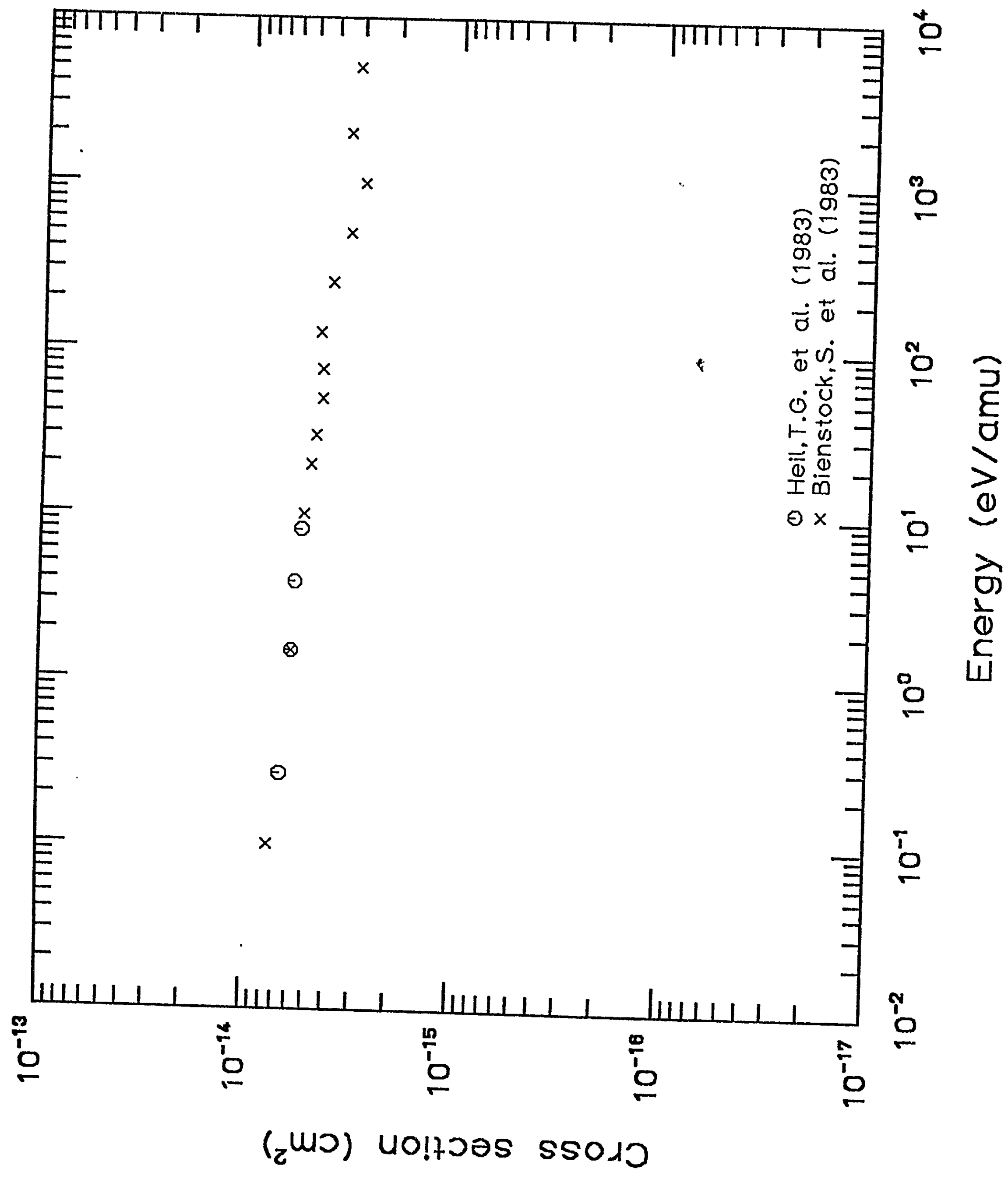


Fig.100 $O^{3+} + H \rightarrow O^{2+}(1s^2 2s^2 2p3s\ ^3P^0) + H^+$

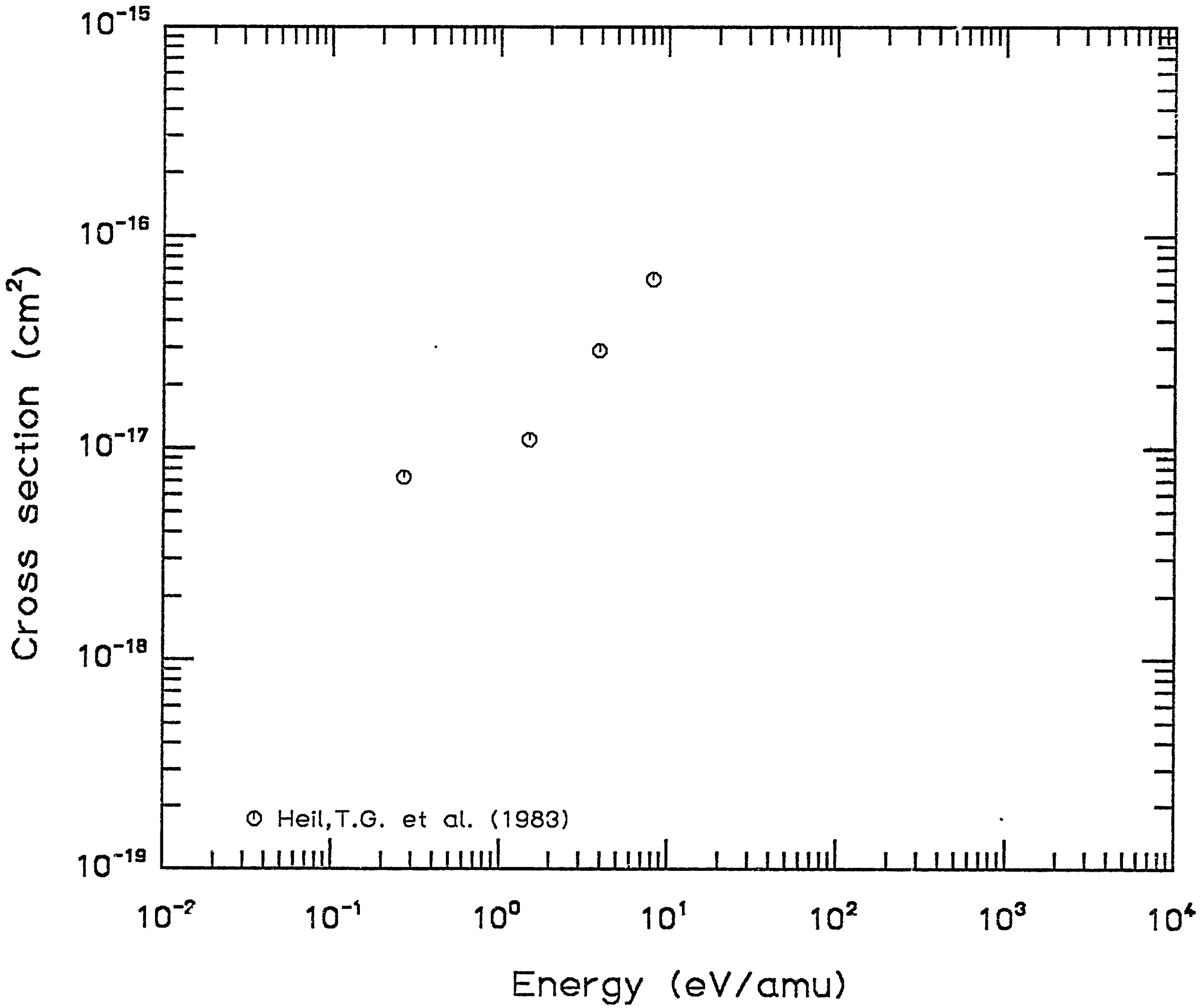


Fig.101 $O^{3+} + H \rightarrow O^{2+}(1s^2 2s^2 2p3s\ ^1P^0) + H^+$

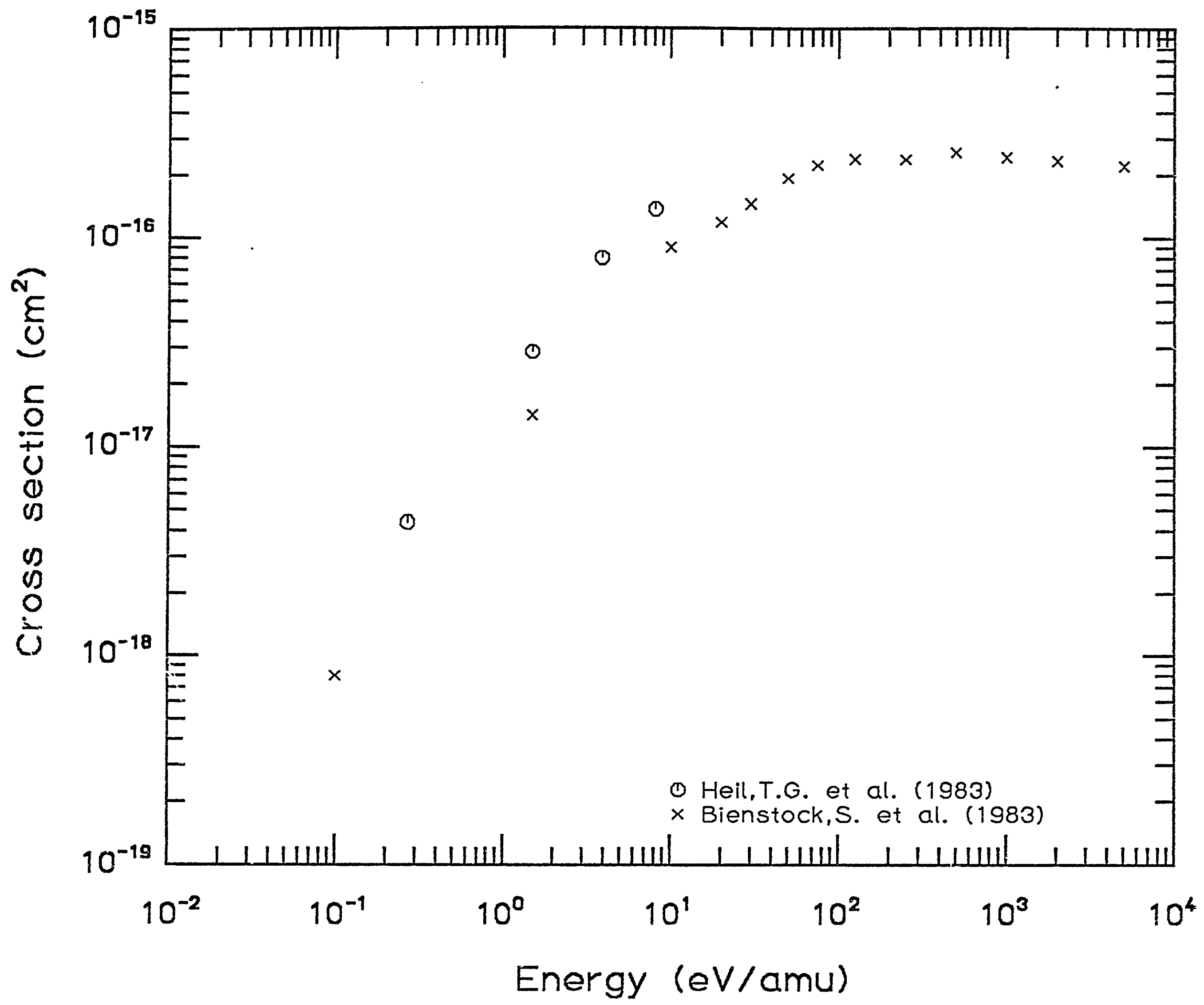


Fig.102 $O^{3+} + H \dashrightarrow O^{2+}(1s^2 2s^2 2p3p\ ^3S) + H^+$

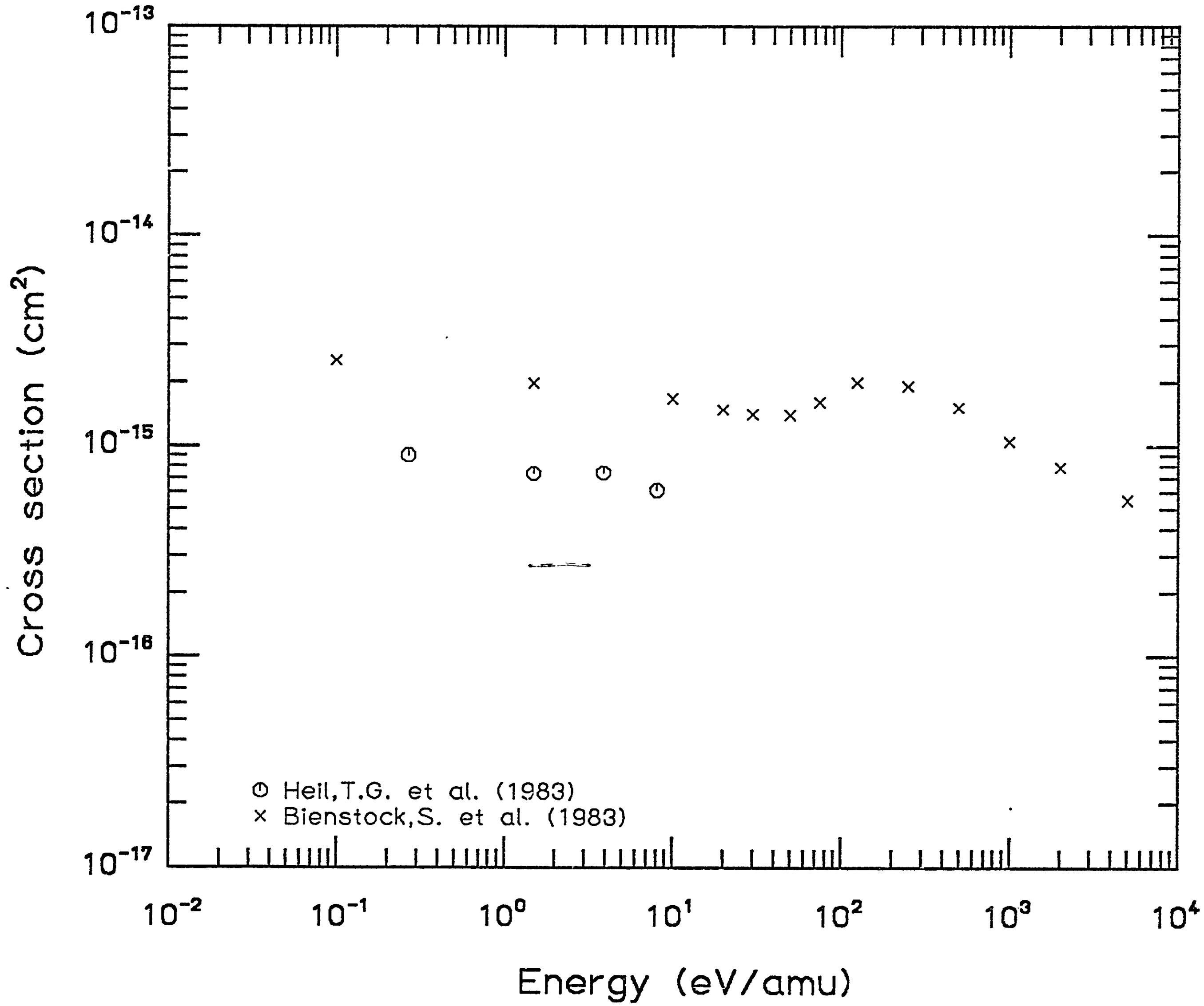
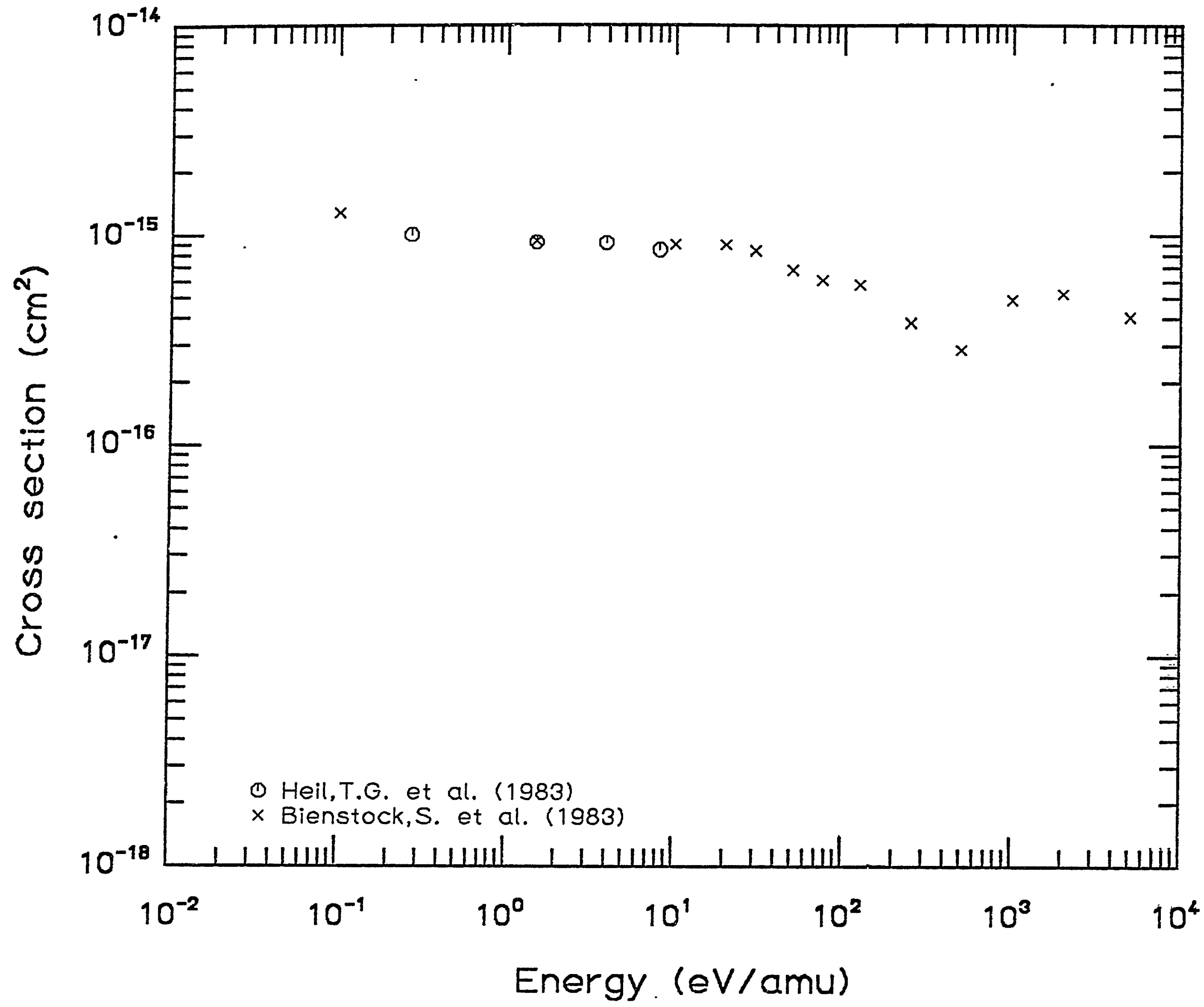


Fig.103 $O^{3+} + H \dashrightarrow O^{2+}(1s^2 2s^2 2p3p\ ^1P) + H^+$



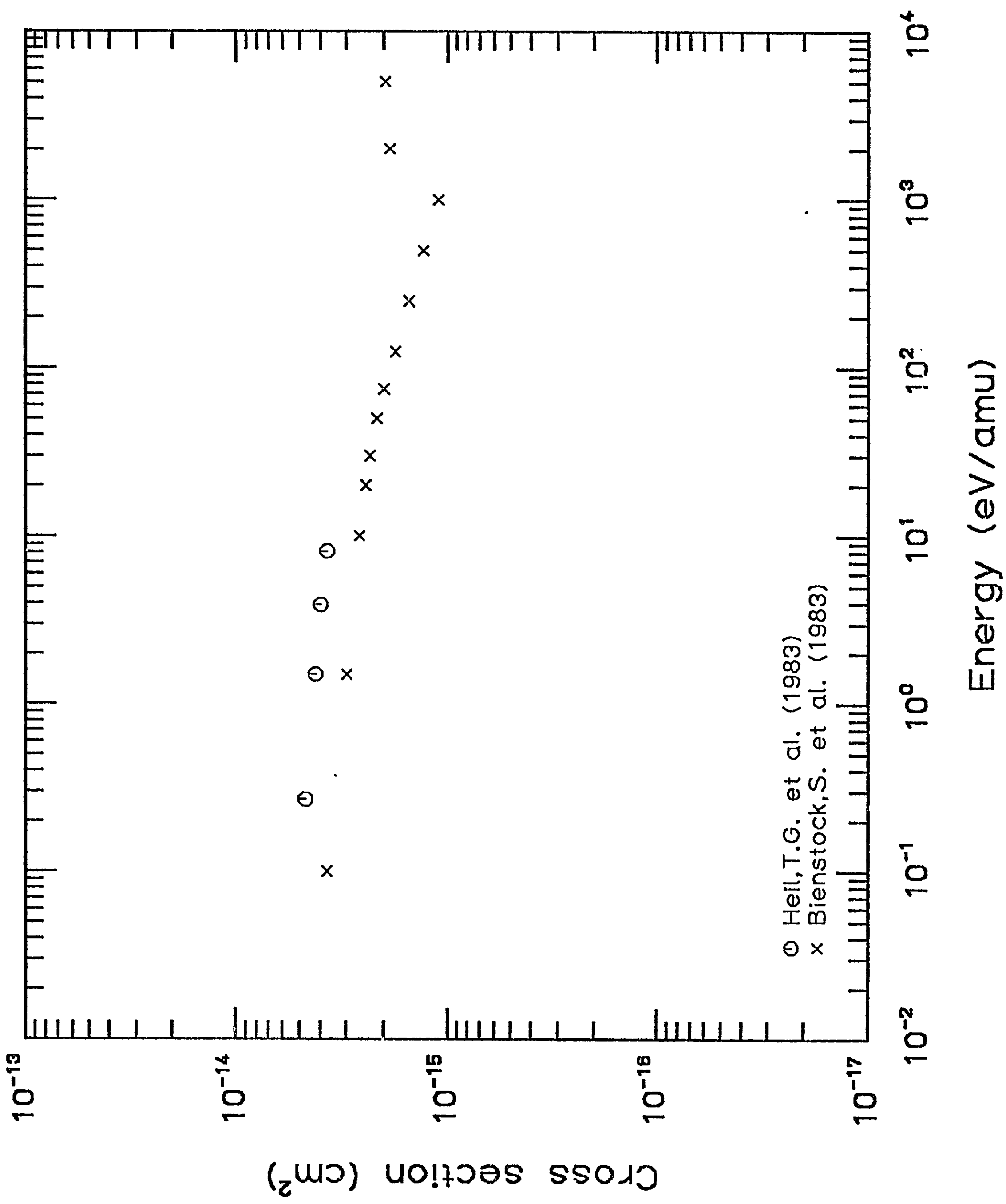


Fig.104 $O^{3+} + H \dashrightarrow O^{2+}(1s^2 2s^2 2p3p\ ^3D) + H^+$

IV-6. $O^{2+}(1s^2 2s^2 2p^2\ ^3P) + H(1s) \rightarrow O^+ + H^+$

Total electron capture cross sections are summarized.[1] No experimental investigation has been reported on the cross sections for $(n\ell)$ distributions. Butler et al.[2] calculated the rate coefficients at the thermal energy using Landau-Zener approximation and showed the following process is dominant:

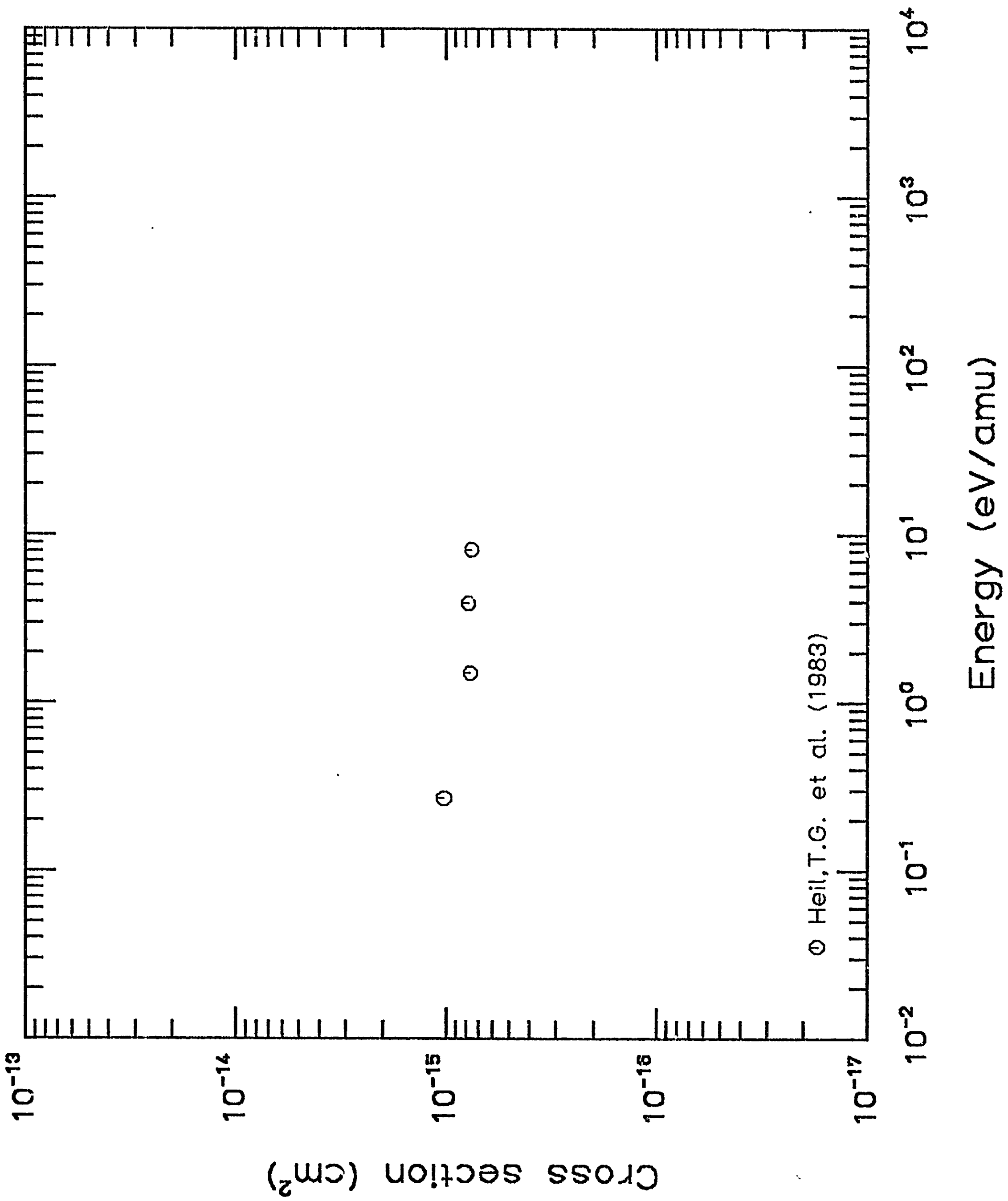
$$O^+(1s^2 2s2p^4\ ^4P) + H^+,$$

that is, this dominant process is one-electron capture into 2p state accompanied by 2s electron excitation into 2p state. Butler et al.[3], using quantal method, calculated total rate coefficients over the temperature $5 \times 10^3 - 5 \times 10^4$ K for the capture into $2s2p^4\ ^4P$ state. Further, Heil et al.[4], based upon molecular treatment, calculated the cross sections for $2s2p^4\ ^4P$ state over the energy range 0.27 - 8.1 eV/amu.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. S.E. Butler, C.F. Bender and A. Dalgarno, Astrophys. J. 230 (1979) L59
3. S.E. Butler, T.G. Heil and A. Dalgarno, Astrophys. J. 241 (1980) 442
4. T.G. Heil, S.E. Butler and A. Dalgarno, Phys. Rev. A 27 (1983) 2365

Fig.105 O^{2+} + H --> $O^+(1s^22s2p^4\ ^4P)$ + H^+



V O^{q+} + H_2 collisions

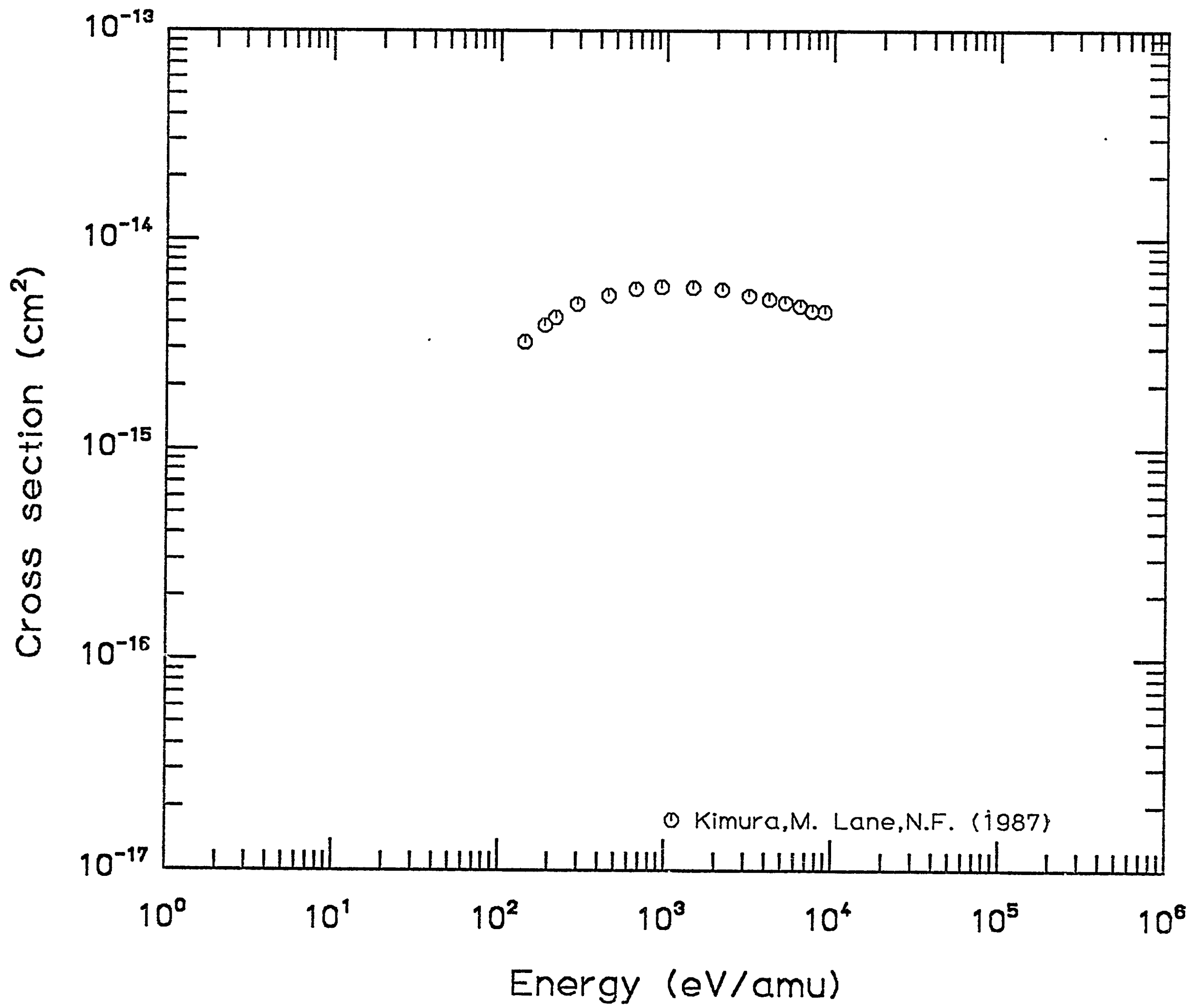
V-1. $O^{8+} + H_2 \rightarrow C^{7+}(n\ell) + H_2^+$

Experimental data for total cross sections for single electron capture are summarized.[1] Total theoretical cross sections have been calculated by Grozdanov and Janev[2] using the tunneling model at the energies 0.12 and 2.76 keV/amu and by Kimura and Lane[3] using the travelling MO method with the indication of the dominant contribution from electron capture into n=5 states. Bliman et al.[4], by observing Lyman series emission lines, determined relative populations in 5s,5p,5d,5f and 5g states, with the most dominant contribution from 5d states followed by that from 5f states at 4.4 keV/amu. Similar photon spectroscopic data are reported by Politis et al.[5] Using the translational energy spectroscopy, Kimura et al.[6] have shown the dominant capture occurs into n=5 states at 0.75 keV/amu. However, no partial cross sections for this system have been reported. No total cross sections for double electron capture was reported yet, either.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. T.P. Grozdanov and R.K. Janev, J. Phys. B 13 (1980) L69
3. M. Kimura and N.F. Lane, Phys. Rev. A 35 (1987) 70
4. S. Bliman, J.J. Bonnet, A. Bordenave-Montesquieu, S. Dousson, M. Druetta, D. Hitz and M. Mayo, Nucl. Instr. Meth. in Phys Res. B 9 (1985) 371
5. M.F. Politis, H. Jouin, M. Bonnefy, J.J. Bonnet, M. Chassevent, A. Fleury, S. Bliman and C. Harel, J. Phys. B 20 (1987) 2267
6. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J.Phys. B 20 (1987) 3873

Fig.106 $O^{8+} + H_2 \dashrightarrow O^{7+}(\text{total}) + H_2^+$



V-2. $O^{7+}(1s) + H_2 \rightarrow O^{6+}(1sn\ell) + H_2^+$

Total cross sections for single electron capture processes, though limited quantities, are available.[1] However, no investigation was reported on the final state distribution of the system except for one work by Kimura et al.[2] who observed that the dominant electron capture occurs into n=4 and 5 states with nearly equal probabilities at around 500 eV/amu using the translational energy spectroscopy. No total sections for double electron capture was reported yet.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873

V-3 $O^{6+}(1s^2) + H_2 \rightarrow O^{5+}(1s^2n\ell) + H_2^{+}$

$\rightarrow O^{4+}(1s^2n\ell n'\ell') + H_2^{2+}$

Total cross sections for single and double electron capture processes are summarized.[1] Baptist et al.[2] determined, using photon spectroscopy, relative populations in ℓ-distributions in n=4 states, which are expected and confirmed experimentally[3] to be dominant channels for single electron capture and have shown that the ℓ-distributions are statistical at 60 keV. The detailed ($n\ell$) distributions over 0.9 - 7.5 keV/amu have been determined , based upon photon spectroscopy, by Dijkkamp et al.[4] who showed that dominant electron capture occurs into 4s states at lower energies, whereas at higher energies 4f states become significant, with the contribution of 10 - 20 % from n=3s states. Their observed average ℓ-distributions $<\ell>$ are well reproduced theoretically using the extended classical over-barrier model over the energy range 1 - 6 keV/amu.[5]

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985) 235
2. R. Baptist, S. Bliman, J.J. Bonnet, G. Chauvet, S. Dousson, D. Hitz, B. Jacquot and E.J. Knystautas, Phys. Letters 93A (1983) 185
3. M. Kimura, N. Kobayashi, S. Ohtani and H. Tawara, J. Phys. B 20 (1987) 3873
4. D. Dijkkamp, D. Ciric, E. Vlieg, A. de Boer and F.J. de Heer, J. Phys. B 18 (1985) 4763
5. J. Burgdorfer, R. Morgenstern and A. Niehaus, J. Phys. B 19 (1986) L607

Fig.107 $O^{6+} + H_2 \dashrightarrow O^{5+}(total) + H_2^+$

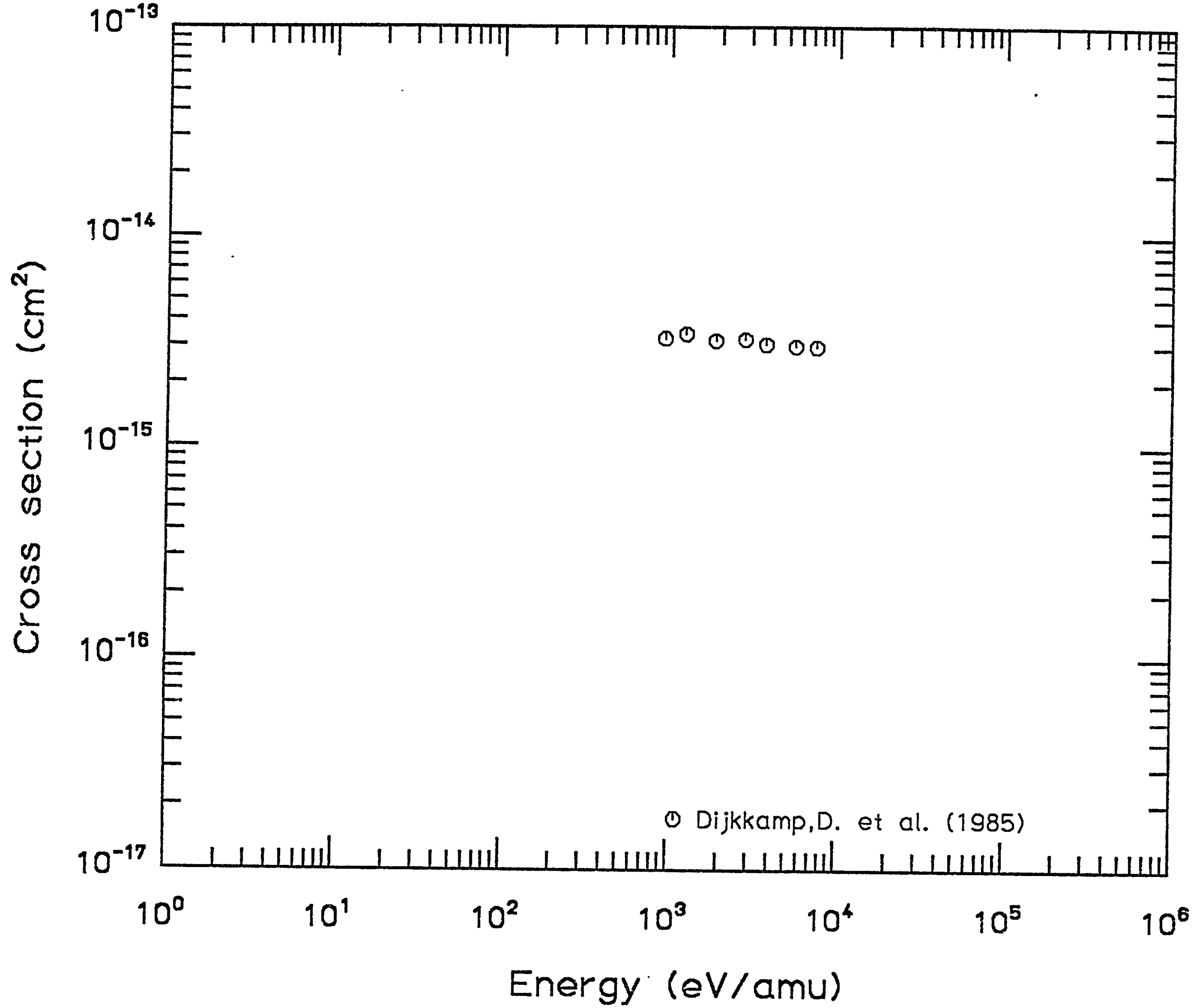


Fig.108 $O^{6+} + H_2 \rightarrow O^{5+}(1s^2 4s) + H_2^+$

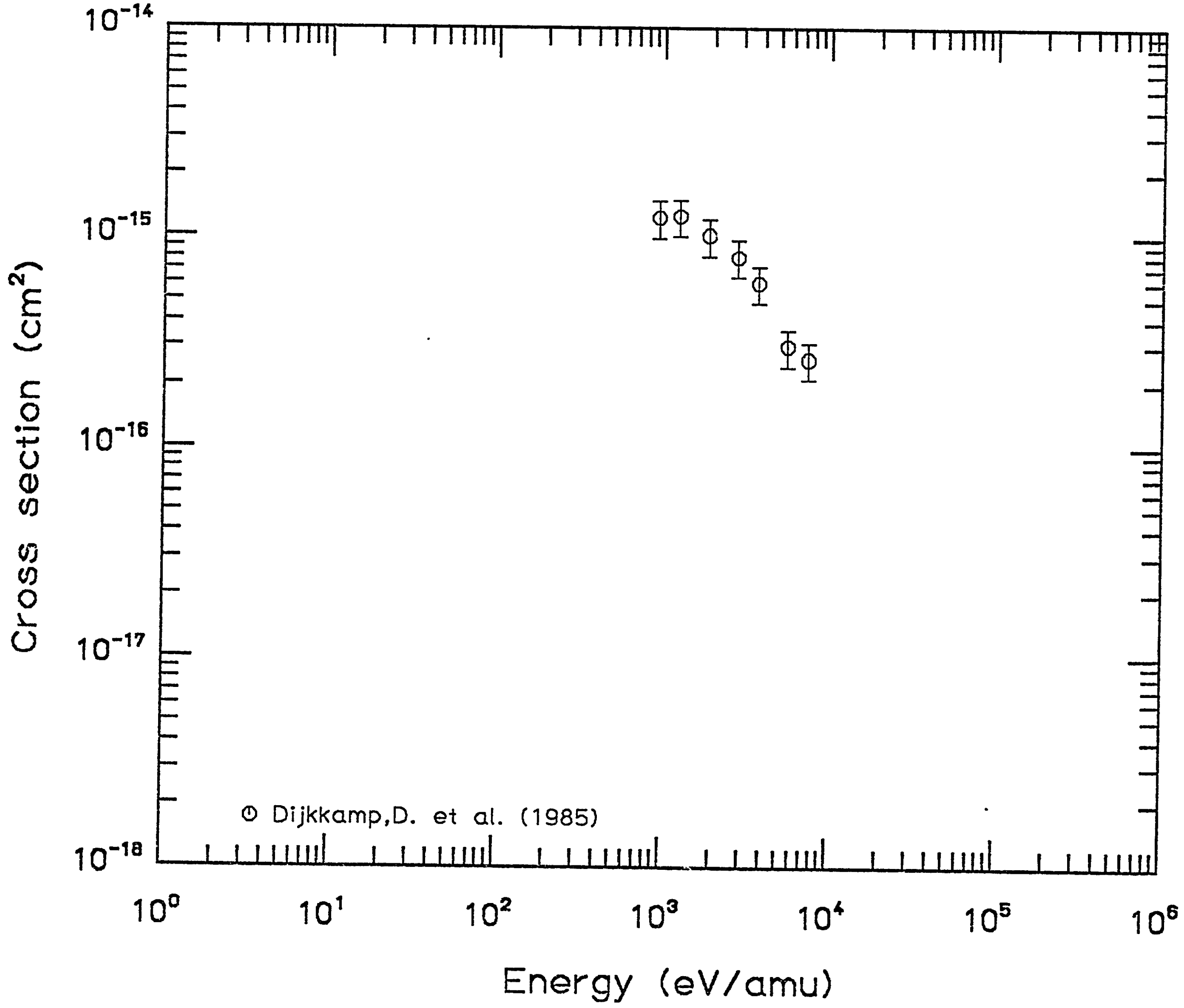


Fig.109 $O^{6+} + H_2 \dashrightarrow O^{5+}(1s^24p) + H_2^+$

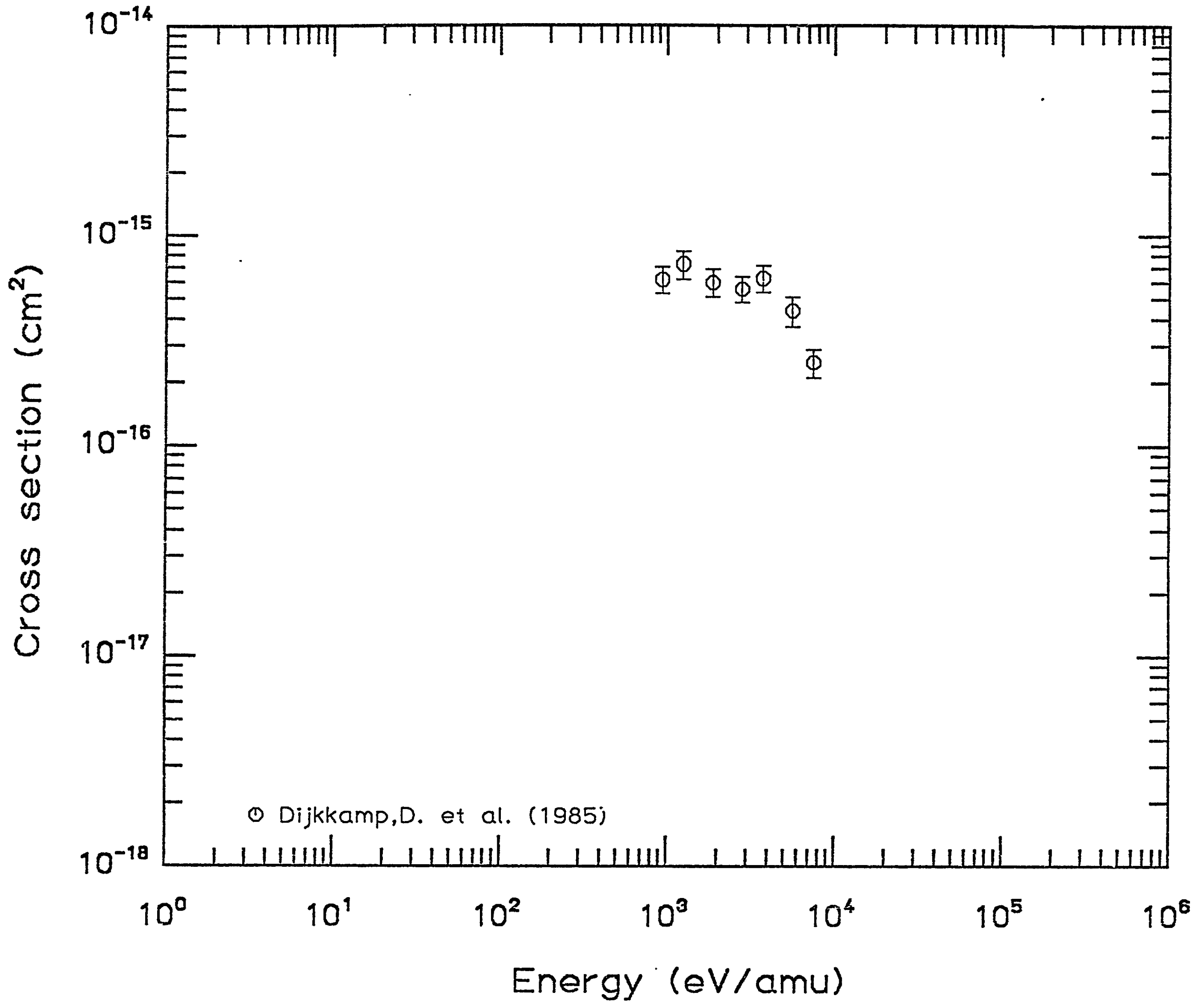


Fig.110 $O^{6+} + H_2 \dashrightarrow O^{5+}(1s^24d) + H_2^+$

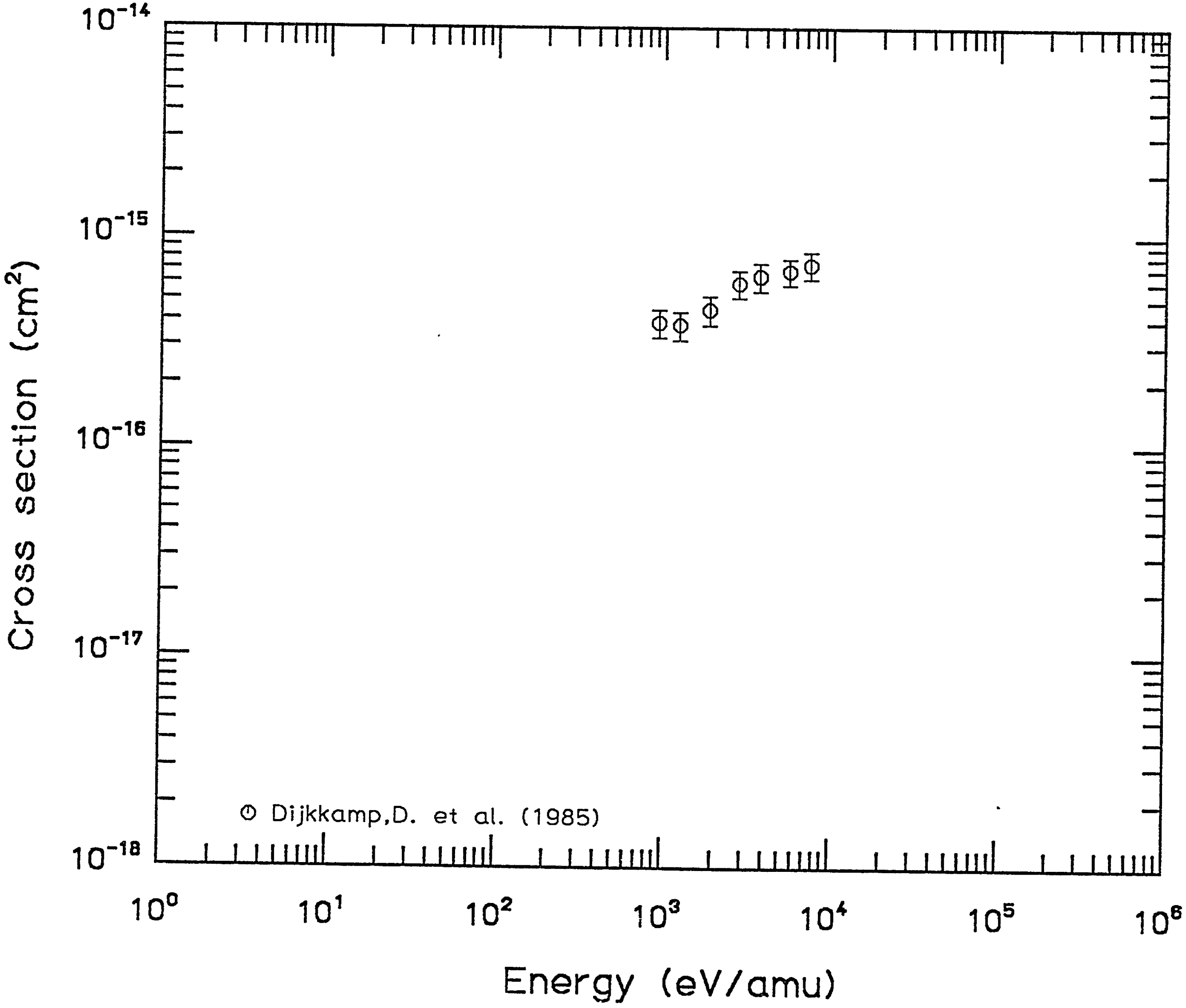
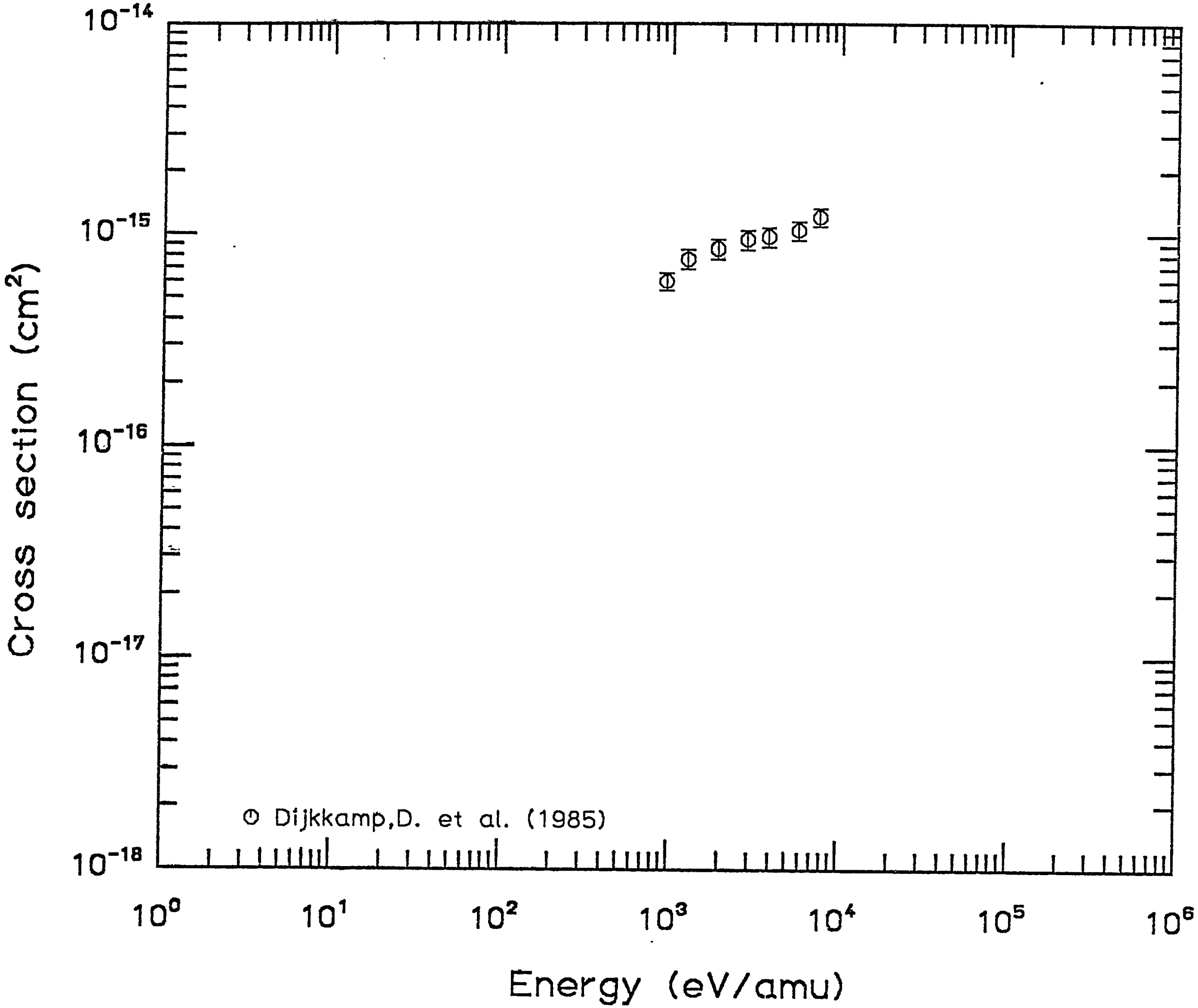


Fig.111 $O^{6+} + H_2 \dashrightarrow O^{5+}(1s^2 4f) + H_2^+$



V-4. $O^{2+}(1s^2 2s^2 2p^2\ {}^3P) + H_2 \rightarrow O^+ + H_2^+$
$\rightarrow O^0 + H_2^{2+}$

Total cross sections for single and double electron capture processes are summarized.[1] Kamber et al.[2], using translational energy spectroscopy, observed a series of peaks of the energy-changed projectiles and found that the most dominant one-electron capture is that into

$1s^2 2s 2p^4\ {}^4P_{5/2}$ state

at their energy of 6 keV. This shows that the dominant electron capture into 2p state is accompanied by 2s electron excitation into 2p state. They did not report any cross section for this process.

References

1. H. Tawara, T. Kato and Y. Nakai, At. Data and Nucl. Data Tables 32 (1985)235
2. E.Y. Kamber, A.G. Brenton, J.H. Beynon and J.B. Hasted, J. Phys. B 18 (1985) 1933

VI O^{q+} + He collisions

VI-1 $O^{8+} + He \rightarrow O^{7+}(n\ell) + He^{+}$

$\rightarrow O^{6+}(n\ell n'\ell') + He^{2+}$

Experimental data of total cross sections for single and double electron capture are summarized[1]. Total cross sections for single electron capture have been calculated by Suzuki et al.[2], using UDWA method, over the energy range 1 - 200 keV/amu and by Kimura and Olson[3] using MO model over 0.2 - 50 keV/amu. Bliman et al.[4] have given their calculated cross sections for single and double electron capture based upon molecular treatment, indicating that at low energies the single electron capture into n = 4 states is dominant with a weak contribution from n = 5 states and the double electron capture into n = 3, n' = 4 and n = 3, n' = 3 states is dominant with n = 4, n' = 4 states becoming significant at higher energies. Another important result of their studies is that the double electron capture is not negligible, over the single electron capture at the keV/amu energy range.

Experimental observation by Ohtani et al.[5] using the translational energy spectroscopy shows the electron is indeed selectively captured into n = 4 states at 0.4 keV/amu. Another experiment of Laurent et al.[6] pointed out the importance of the angular distribution of the charged-changed products : that for dominant n = 4 states is forward-peaked, whereas the contribution to single electron capture from the autoionizing states due to double electron capture becomes important at larger scattering angles. Relative intensities of different ℓ-states in n = 4 states have been measured by Politis et al.[7] at 4.4 keV/amu. However, no absolute measurement of the ($n\ell$) distributions has been reported. Theoretical calculations for ($n\ell$) distributions at higher energies (keV - MeV) by Jain et al.[8] using AO expansion method show that the capture into n = 4 states is dominant at around 30 keV/amu, that into n = 3 until 15 MeV and n = 2 at higher energies. At higher energies the reduction of the cross sections for $m \neq 0$ states is significant, compared th that for m = 0 states, indicating that at higher energies the electron capture needs larger momentum component along the beam direction, which the m = 0 states have indeed.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. H. Suzuki, Y. Kajikawa, N. Toshima, H. Ryufuku and T. Watanabe, Phys. Rev. A 29 (1984) 525
3. M. Kimura and R.E. Olson, J. Phys. B 18 (1985) 2729
4. S. Bliman, D. Hitz, B. Jacquot, C. Harel and A. Salin, J. Phys. 16 (1983) 2849
5. S. Ohtani, Y. Kaneko, M. Kimura, N. Kobayashi, T. Iwai, A. Matsumoto, K. Okuno, S. Takagi, H. Tawara and S. Tsurubuchi, J. Phys. B 15 (1982) L533
6. H. Laurent, P. Roncin, M.N. Gabori and M. Barat, Nucl. Instr. Meth. in Phys. Res. B 26 (1987) 45 ; P. Roncin, M. Barat and H. Laurent, Europhys. Letters 2 (1986) 371
7. M.F. Politis, H. Jouin, M. Bennefoy, J.J. Bonnet, M. Chassevent, A. Fleury, S. Bliman and C. Harel, J. Phys. B 20 (1987) 2267
8. A. Jain, C.D. Lin and W. Fritsch, Phys. Rev. A 34 (1986) 3673

VI-2 $O^{7+}(1s) + He \rightarrow O^{6+}(1sn\ell) + He^{+}$

$\rightarrow O^{5+}(1sn\ell n'\ell') + He^{2+}$

Total cross sections for single and double electron capture processes are summarized[1]. Only a single work has been reported on the $(n\ell)$ distribution of the final states by Tsurubuchi et al.[2] who used translational energy spectroscopy to identify the most dominant electron capture process into $1s4\ell$ states at 500 eV/amu energy range.

No information is available on the $(n\ell)$ distribution of this system yet.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. S. Tsurubuchi, T. Iwai, Y. Kaneko, N. Kobayashi, A. Matsumoto, S. Ohtani, K. Okuno, S. Takagi and H. Tawara, J. Phys. B 15 (1982) L737

VI-3 $O^{6+}(1s^2)$ + He $\rightarrow$ $O^{5+}(1s^2n\ell)$ + He^+
$\rightarrow$ $O^{4+}(1s^2n\ell n'\ell')$ + He^{2+}

Total cross sections for single and double electron capture are summarized.[1] The n-distribution of this system was investigated by Okuno et al.[2], using translational energy spectroscopy, who reported the most dominant electron capture occurs into n = 3 states. Dijkkamp et al.[3], using photon spectroscopy, determined the absolute cross sections for various ($n\ell$) states over the energy range 0.56 - 7.13 keV/amu which show that 3p and 3d states are dominant at lower energies, whereas at higher energies 3s, 3p and 3d states become comparable, with the contribution of 20 % from n = 4 states.

The theoretical calculations of the cross sections of ($n\ell$) distributions have been reported by Fritsch and Lin[4] using AO model over 0.5 - 40 keV/amu and by Shimakura et al.[5] using MO model over 0.14 - 7 keV/amu.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. K. Okuno, H. Tawara, T. Iwai, Y. Kaneko, M. Kimura, N. Kobayashi, A. Matsumoto, S. Ohtani, S. Takagi and S. Tsurubuchi, Phys. Rev. A 28 (1983) 127
3. D. Dijkkamp, D. Ciric, E. Vilieg, A. de Boer and F.J. de Heer, J. Phys. B 18 (1985) 4763
4. W. Fritsch and C.D. Lin, J. Phys. B 19 (1986) 2683
5. N. Shimakura, H. Sato, M. Kimura and T. Watanabe, J. Phys. B 20 (1987) 1801

Fig.112 O^{6+} + He --> O^{5+}(total) + He^{+}

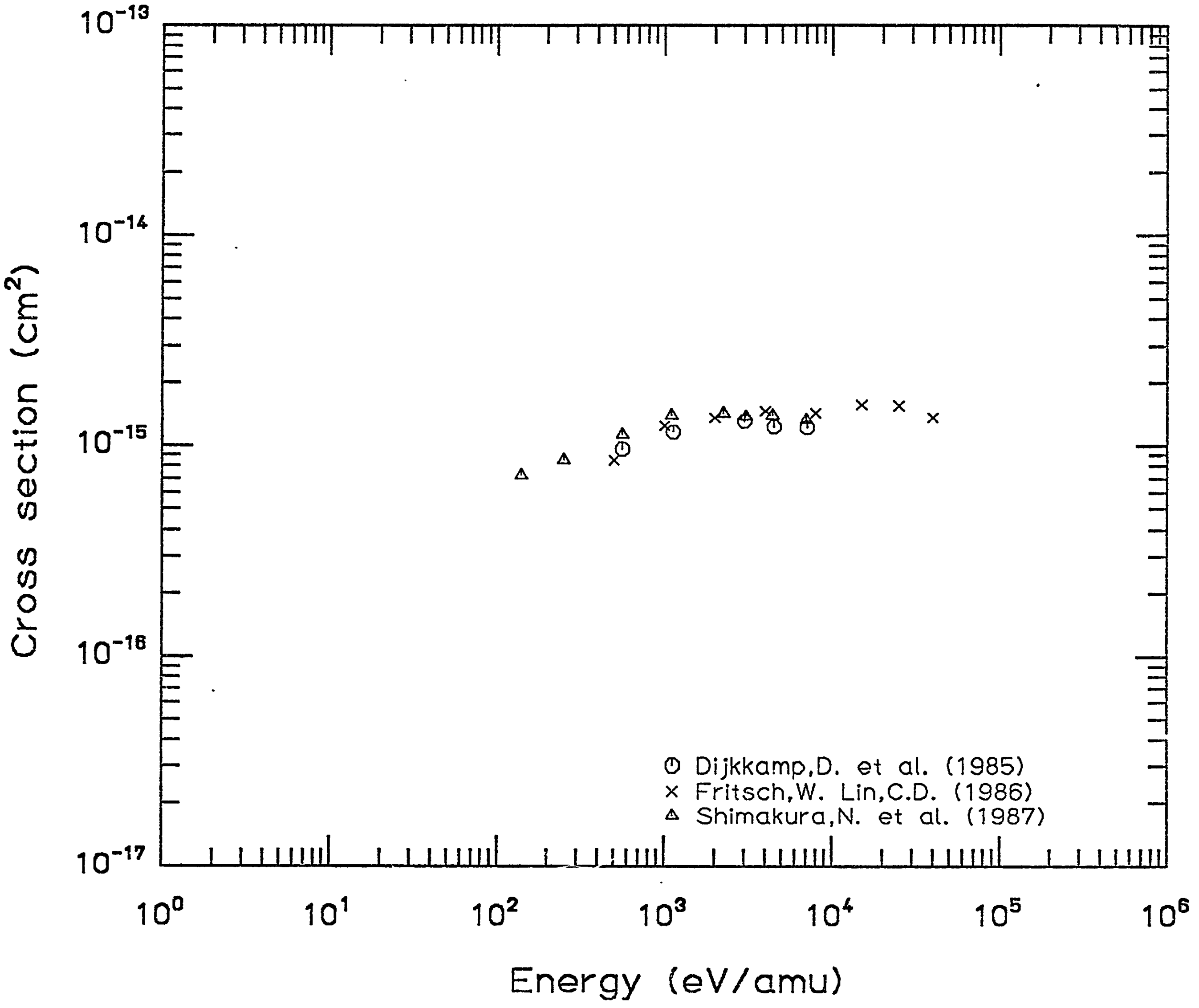


Fig.113 $O^{6+} + He \rightarrow O^{5+}(1s^2 3s) + He^+$

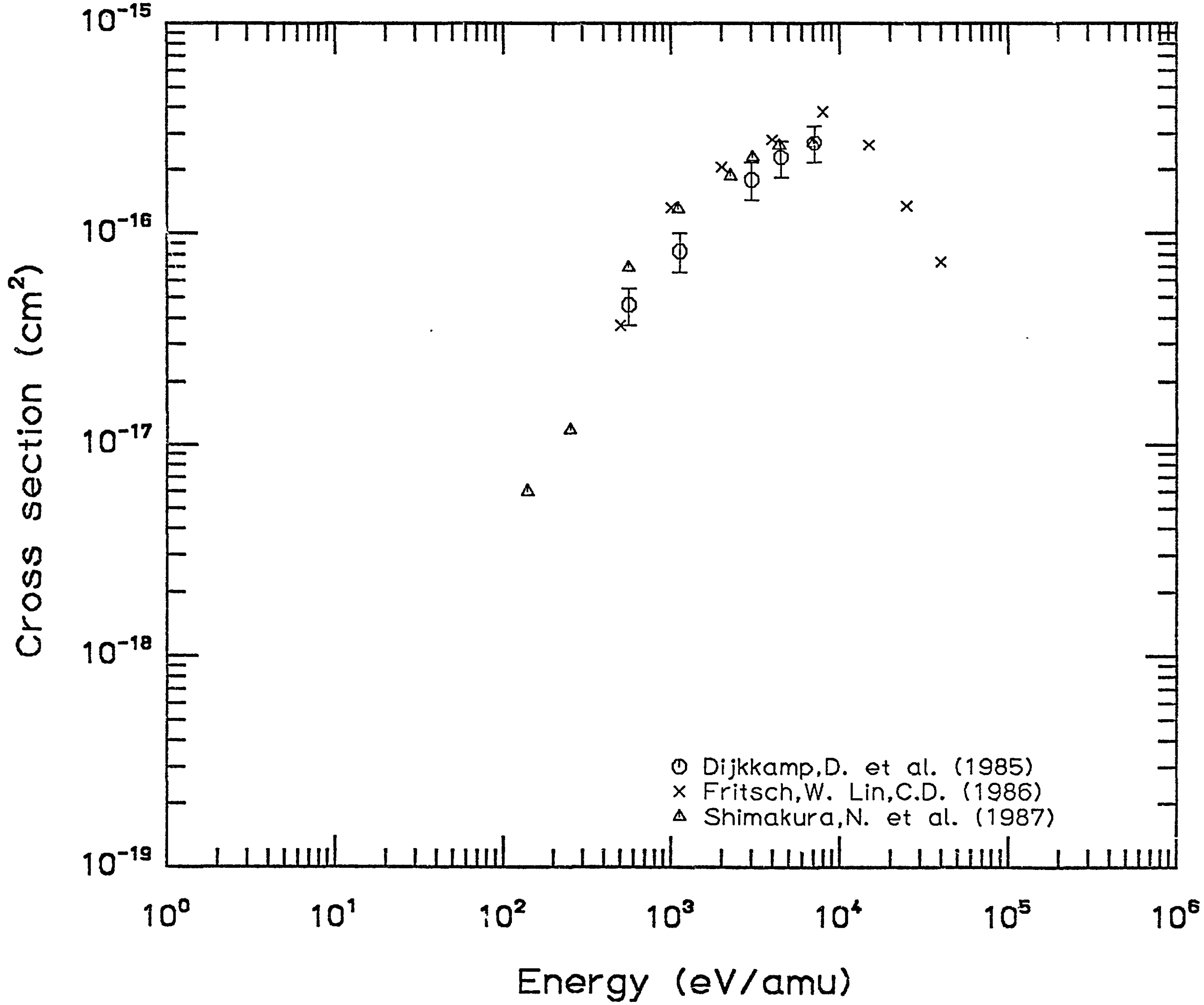


Fig.114 $O^{6+} + He \dashrightarrow O^{5+}(1s^2 3p) + He^+$

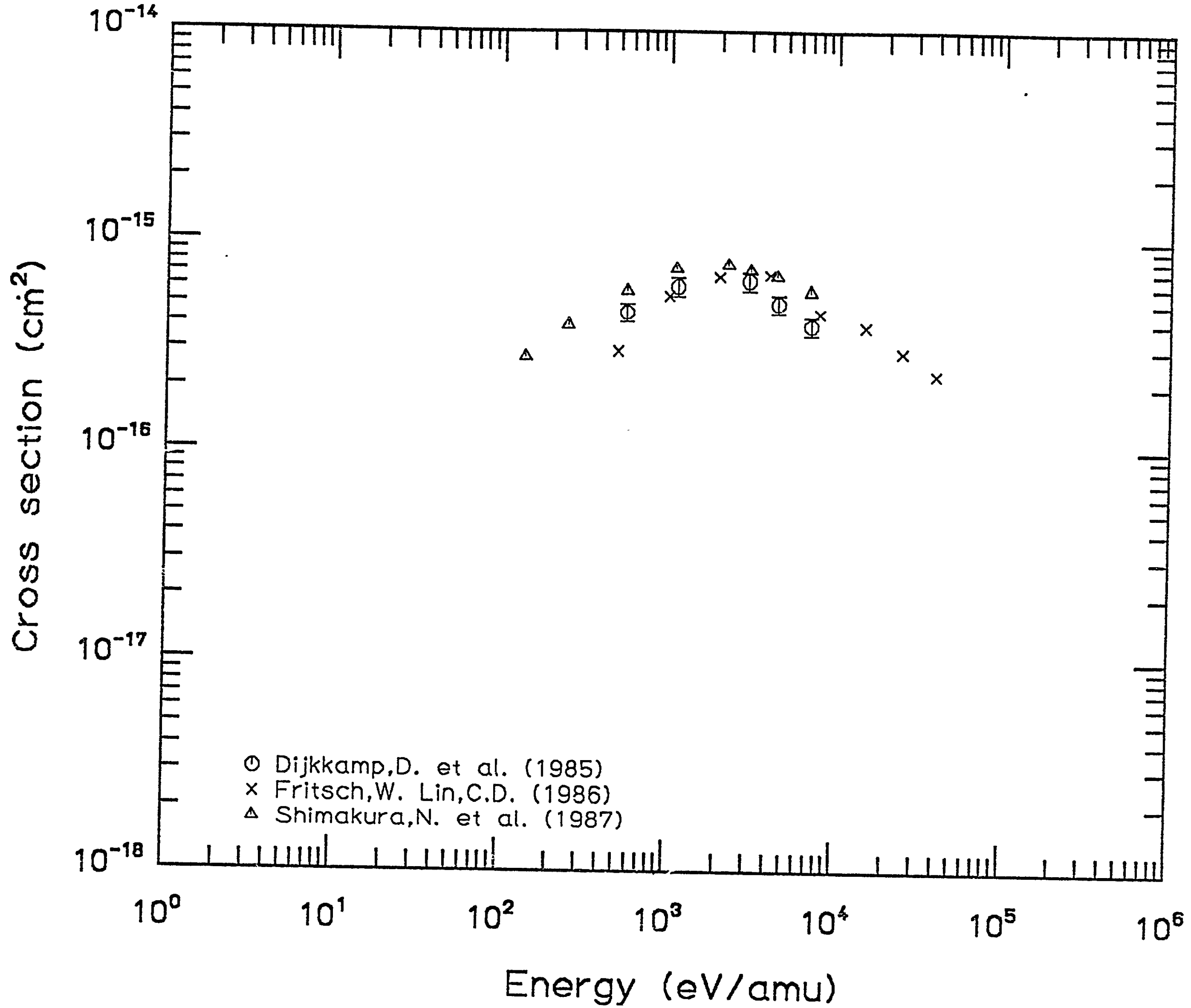


Fig.115 $O^{6+} + He \rightarrow O^{5+}(1s^2 3d) + He^+$

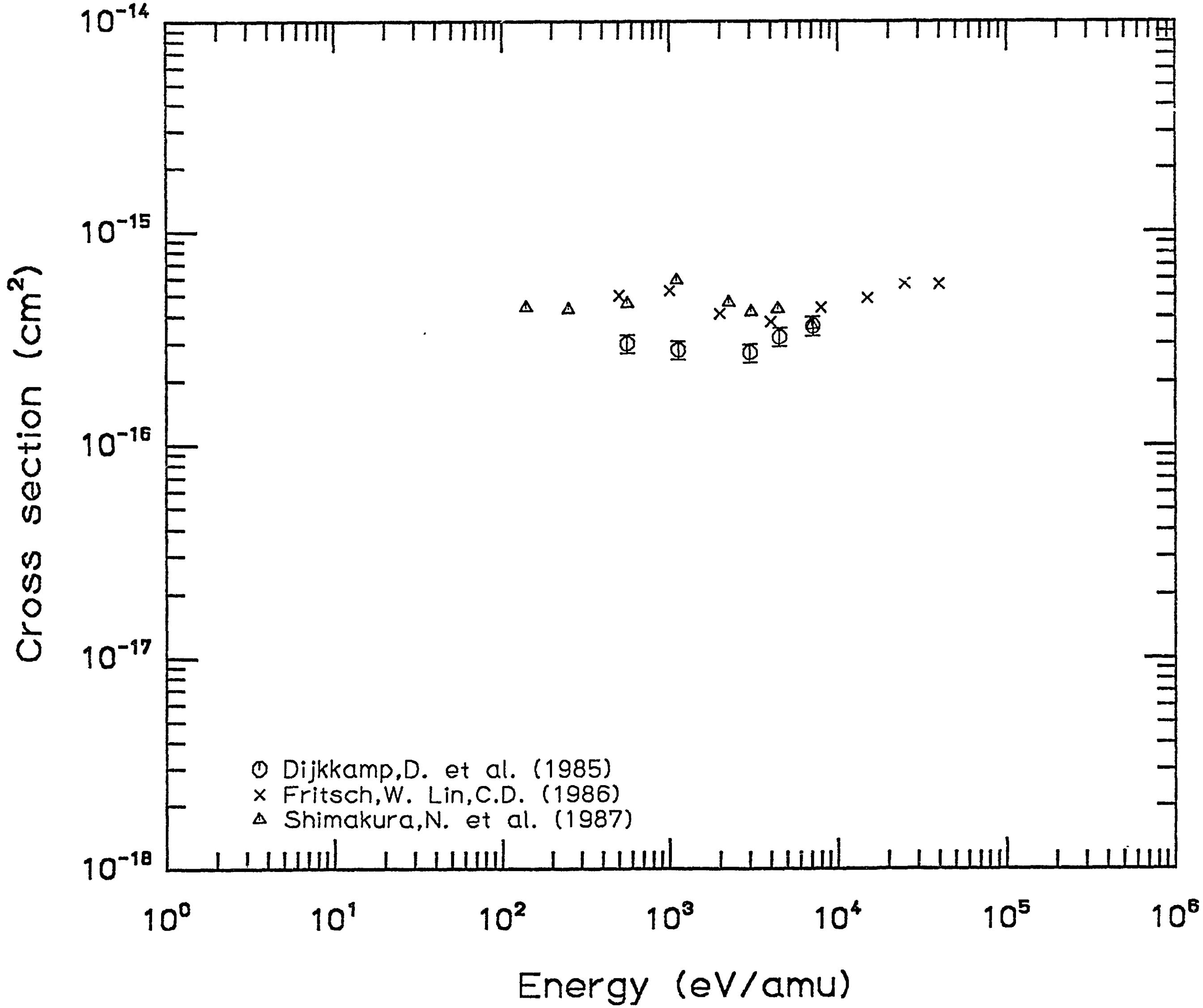


Fig.116 O^{6+} + He --> $O^{5+}(1s^24s)$ + He^+

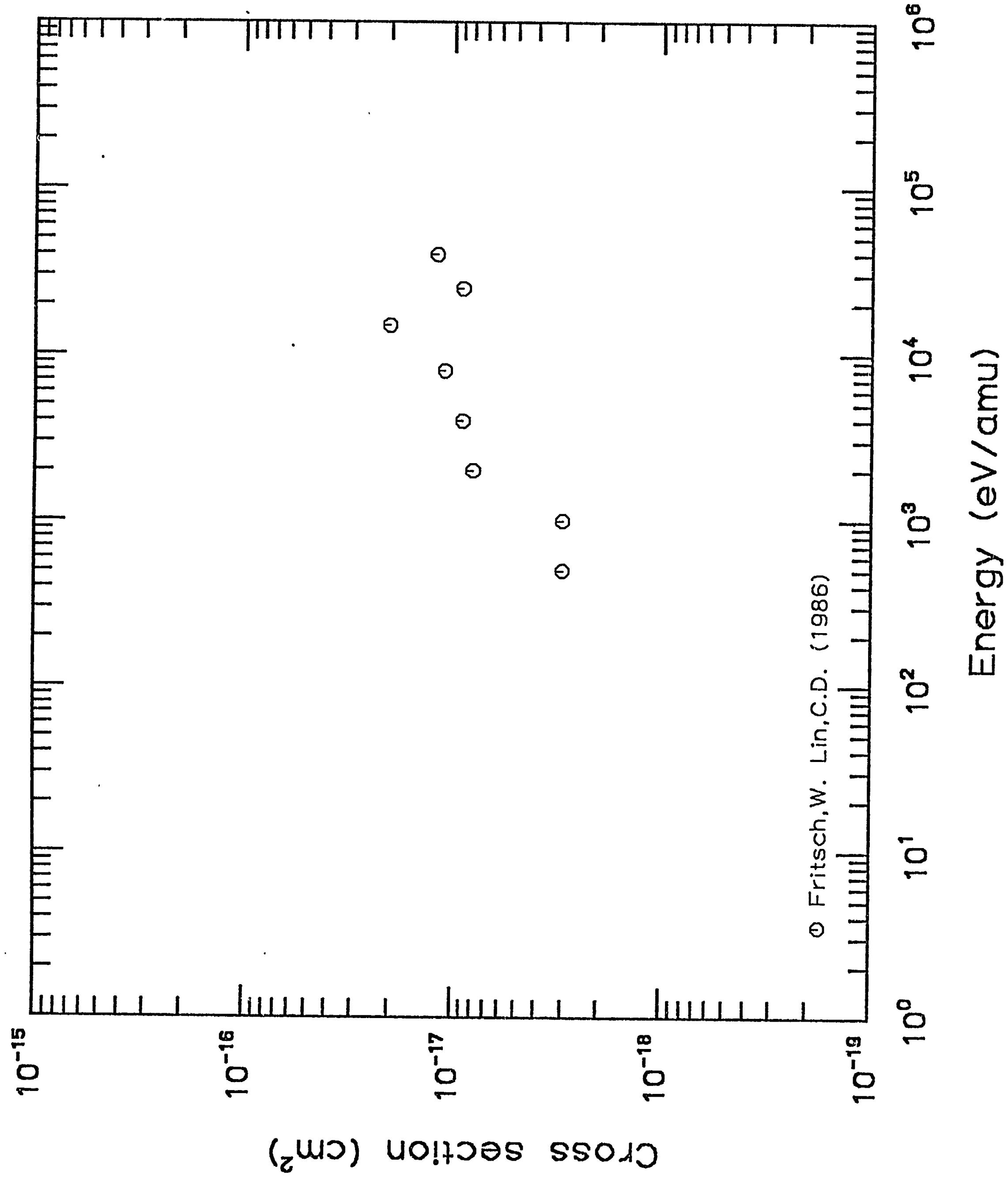


Fig.117 $O^{6+} + He \dashrightarrow O^{5+}(1s^24p) + He^+$

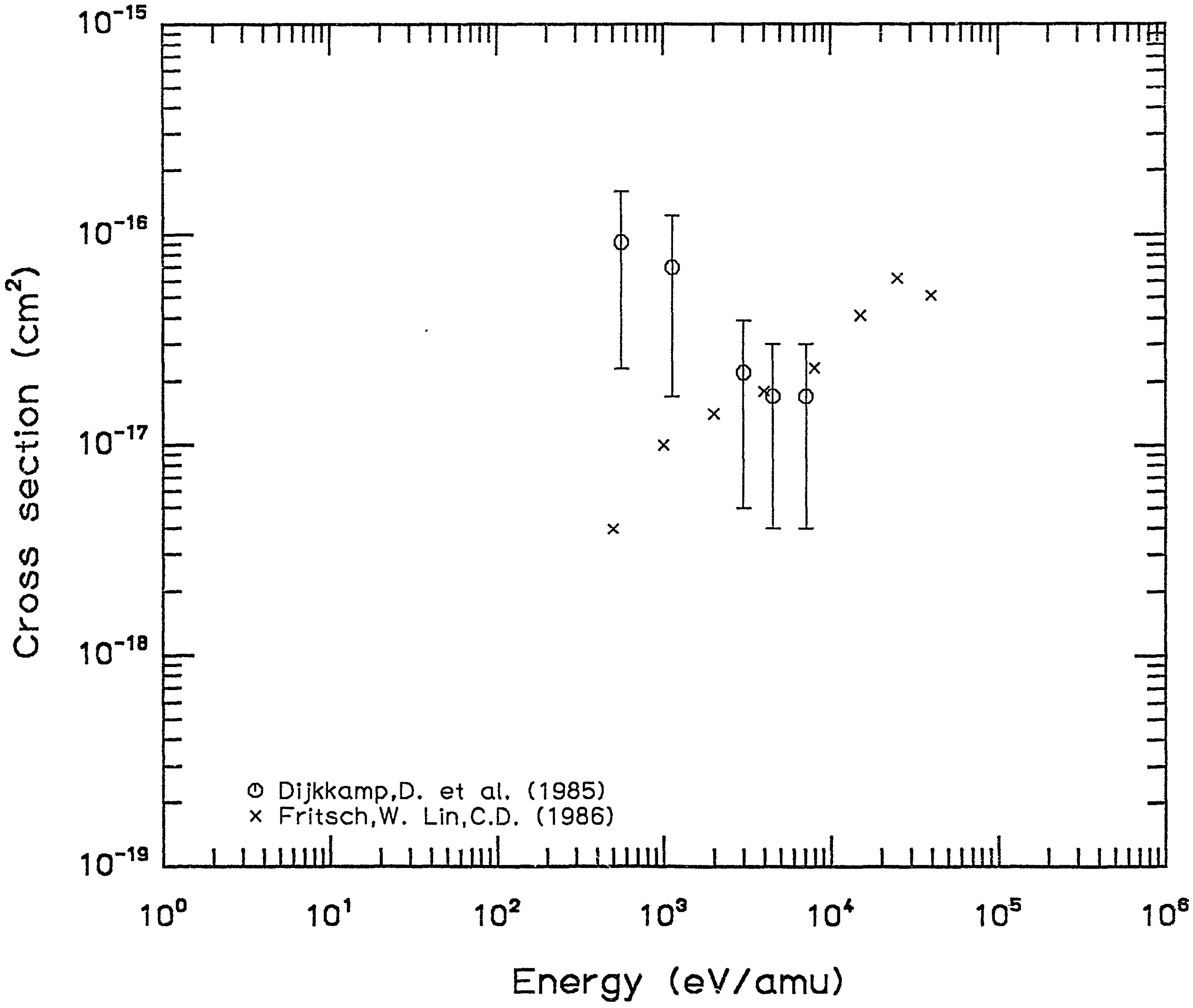


Fig.118 $O^{6+} + He \rightarrow O^{5+}(1s^2 4d) + He^+$

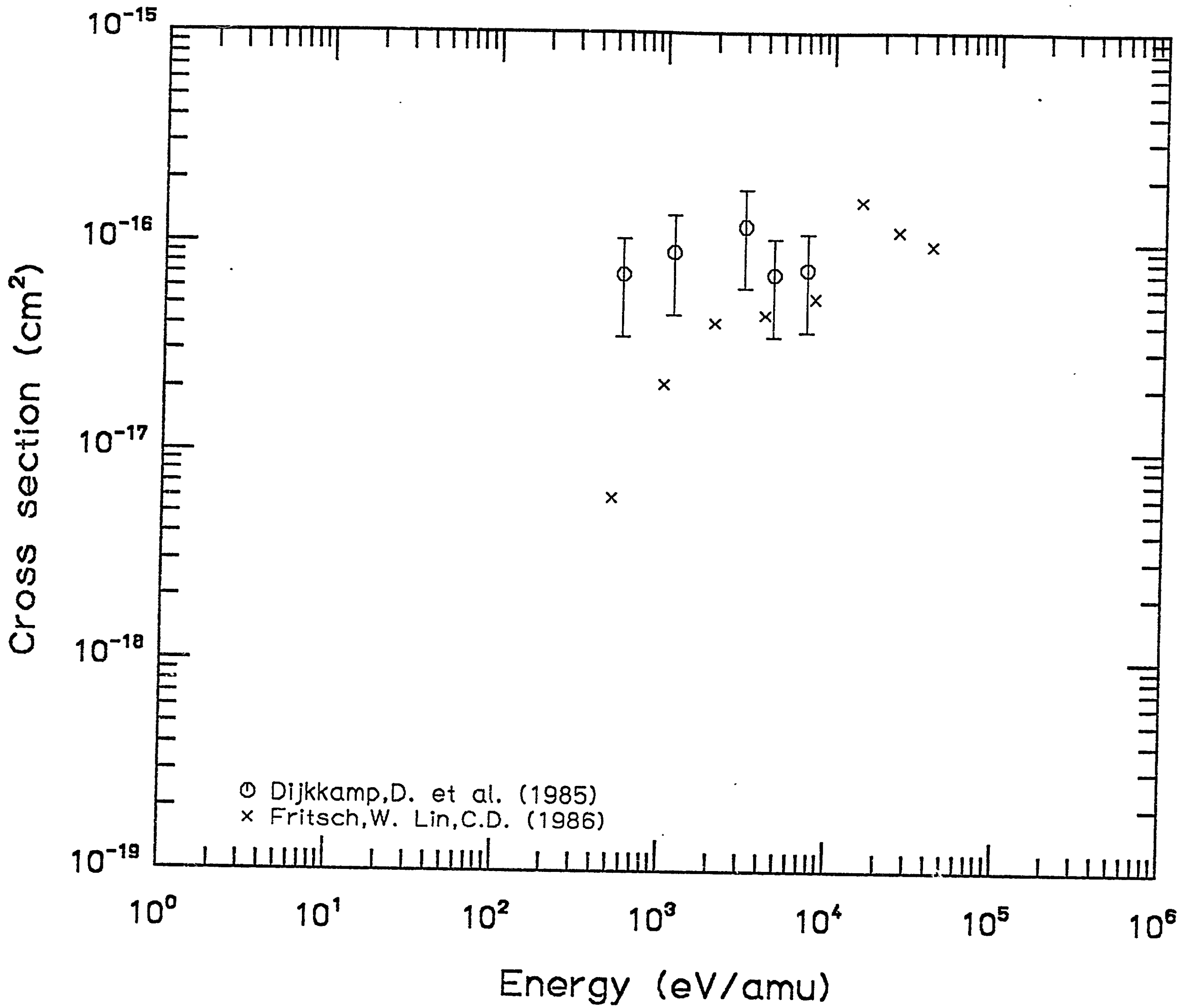
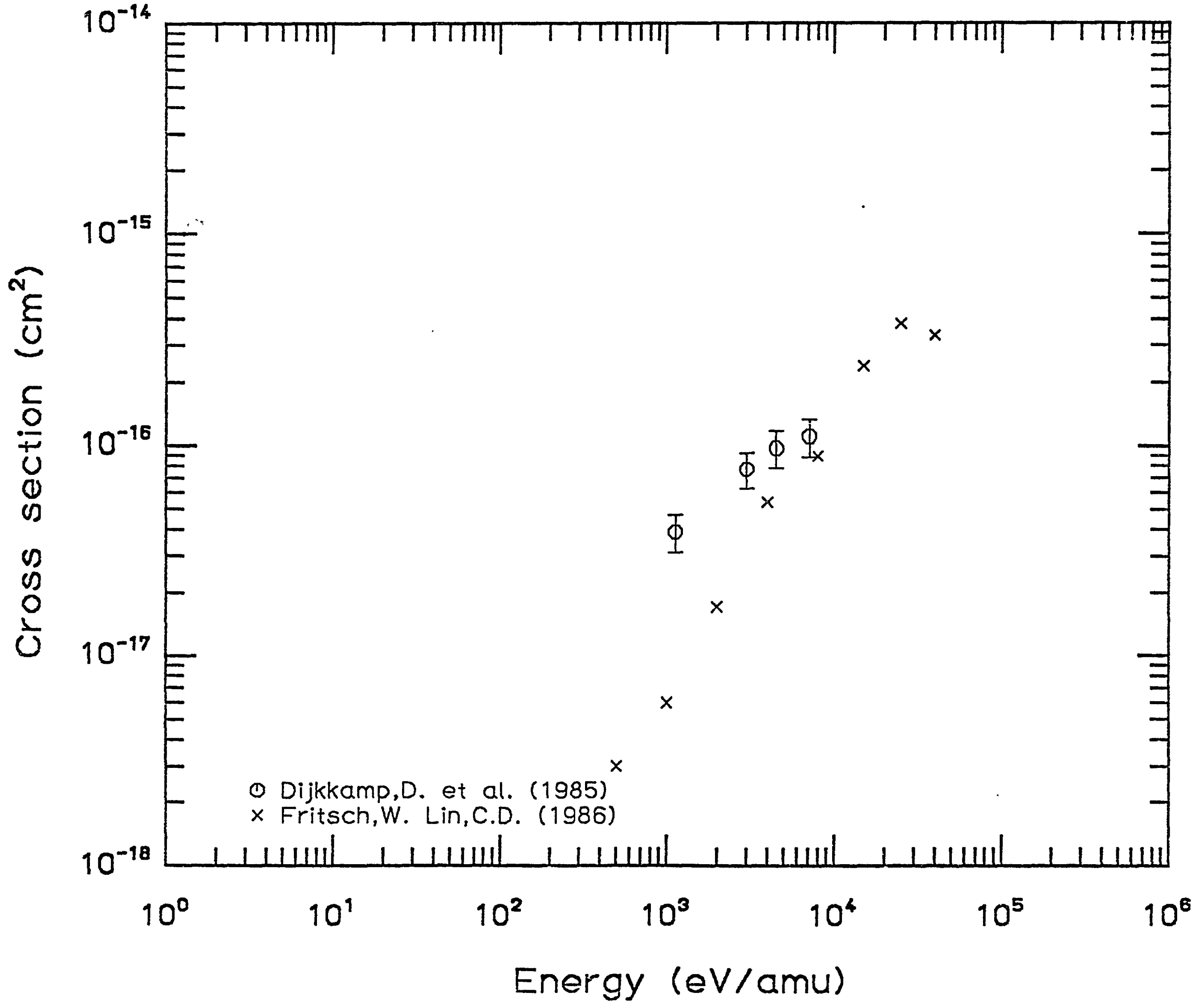


Fig.119 $O^{6+} + He \dashrightarrow O^{5+}(1s^24f) + He^+$



VI-4 $O^{5+}(1s^2 2s\ ^2S) + He \rightarrow O^{4+}(1s^2 2sn\ell) + He^+$

$\rightarrow O^{3+}(1s^2 2sn\ell n'\ell') + He^{2+}$

Total cross sections for single and double electron capture are summarized by Wu et al.[1] However, no investigation of the partial cross sections has been reported. Only a single experiment was made on the observation of the dominant electron capture into n = 3 states at the keV/amu energy range[2], without knowing the ℓ-distribution.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. M. Kimura, T. Iwai, Y. Kaneko, N. Kobayashi, A. Matsumoto, S. Ohtani, K. Okuno, S. Takagi, H. Tawara and S. Tsurubuchi, J. Phys. B 15 (1982) L851

VI-5 $O^{4+}(1s^2 2s^2\ ^1S) + He \rightarrow O^{3+}(1s^2 2s^2 n\ell) + He^+$

$\rightarrow O^{2+}(1s^2 2s^2 n\ell n'\ell') + He^{2+}$

Experimental total cross sections for single electron capture are summarized.[1] However, no experimental studies on the partial cross sections have been reported. The rate coefficients over the temperature $10^3 - 10^{4.5}$ K were calculated by Butler and Dalgarno[2] using LZ model. No total cross sectios for double electron capture was reported yet.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. S.E. Butler and A. Dalgarno, Astrophys. J. 241 (1980) 838

VI-6 $O^{3+}(1s^2 2s^2 2p\ ^2P^0) + He \rightarrow O^{2+}(1s^2 2s^2 2pn\ell) + He^+$

$\rightarrow O^{+}(1s^2 2s^2 2pn\ell n'\ell') + He^{2+}$

Experimental total cross sections for single electron capture are summarized.[1]
Total rate coefficients over the temperature $10^3 - 10^{4.5}$ K were calculated by Butler and Dalgarno[2] using LZ model. However, no work has been reported on the partial cross section measurements.
No total cross section for double electron capture was reported yet.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. S.E. Butler and A. Dalgarno, Astrophys. J. 241 (1980) 838

VI-7 $O^{2+}(1s^2 2s^2 2p^2\ ^3P) + He \rightarrow O^+ + He^+$

$\rightarrow O^\circ + He^{2+}$

Total cross sections for single and double electron capture processes are summarized.[1] Total rates at 300 K were calculated by Dalgarno et al.[2] using the Landau-Zener approximation and Butler et al.[3] calculated total rates over the temperature range 5×10^3 - 5×10^4 K by quantal method. Using the distorted-wave approximation, Bienstock et al.[4] calculated the cross sections for the capture into $2p^3\ ^2p^0$ and $^2D^0$ states over the energy range 1 - 5000 eV/amu and showed that at their energy range the capture into $2p^3\ ^2P^0$ states is dominant, with significant contribution from $^2p^3\ ^2D^0$ state above 500 eV/amu.

On the other hand, Kamber et al.[5], using translational energy spectroscopy, determined that the capture into $2p^3$ $^2D_{5/2}$ state is dominant and also determined relative variation of their intensities over the energy range 1 - 8 keV.

References

1. W.K. Wu, B.A. Huber and K. Wiesemann, At. Data and Nucl. Data Tables
2. A. Dalgarno, S.E. Butler and T.G. Heil, J. Geophys. Res. 85 (1980) 6047
3. S.E. Butler, T.G. Heil and Dalgarno, Astrophys. J. 241 (1980) 442
4. S. Bienstock, T.G. Heil and and A. Dalgarno, Phys. Rev. A 29 (1984) 503
5. E.Y. Kamber, A.G. Brenton, J.H. Hasted, J. Phys. B 18 (1985) 933

Fig.120 $O^{2+} + He \dashrightarrow O^{+}(total) + He^{+}$

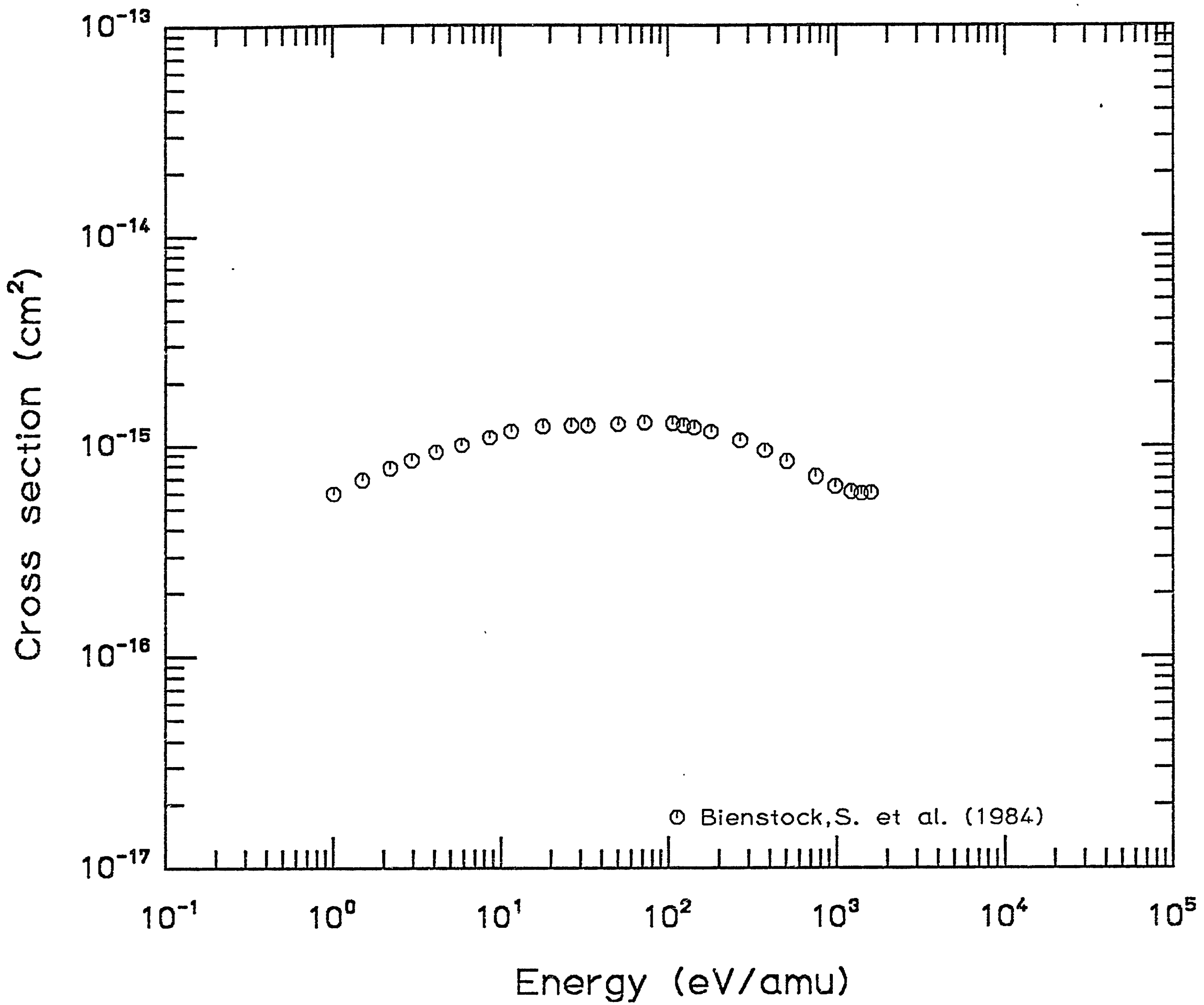


Fig.121 $O^{2+} + He \dashrightarrow O^{+}(1s^2 2s^2 2p^3\ ^2P^0) + He^{+}$

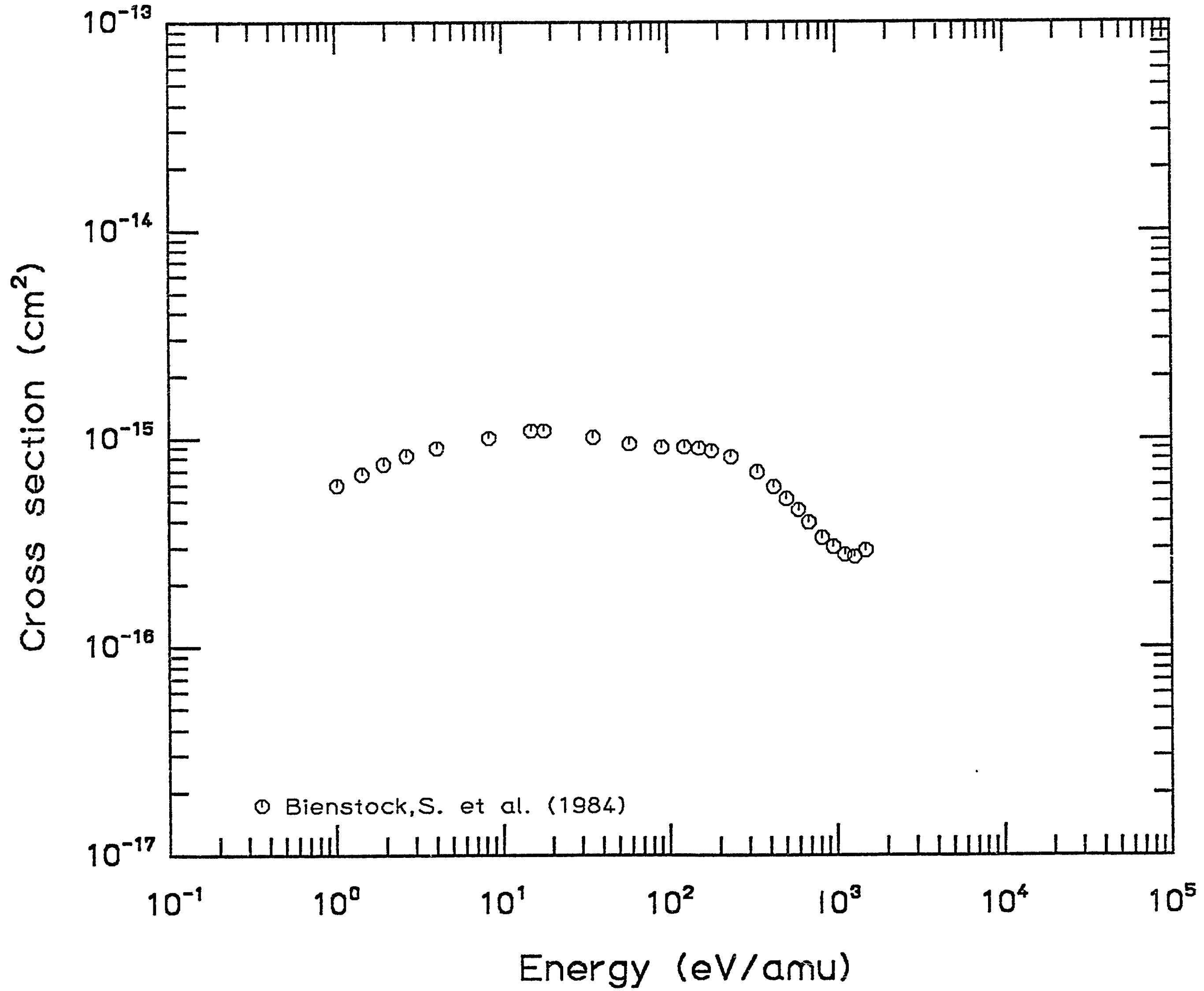
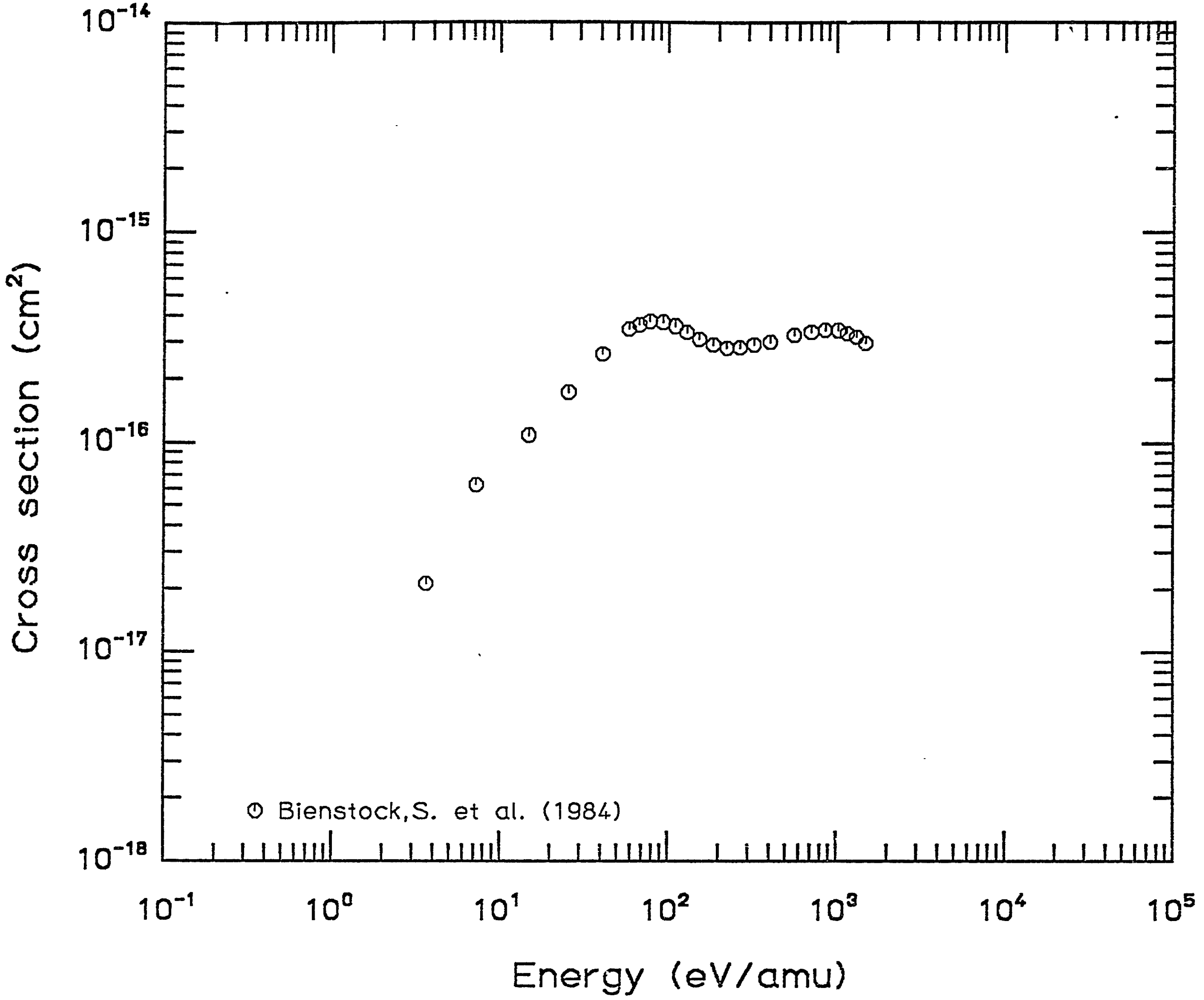


Fig.122 $O^{2+} + He \rightarrow O^{+}(1s^2 2s^2 2p^3\ {}^2D^0) + He^{+}$



LIST OF IPPJ-AM REPORTS

IPPJ-AM-1* "Cross Sections for Charge Transfer of Hydrogen Beams in Gases and Vapors in the Energy Range 10 eV–10 keV"
H. Tawara (1977) [Published in Atomic Data and Nuclear Data Tables 22, 491 (1978)]

IPPJ-AM-2* "Ionization and Excitation of Ions by Electron Impact –Review of Empirical Formulae–"
T. Kato (1977)

IPPJ-AM-3 "Grotrian Diagrams of Highly Ionized Iron FeVIII-FeXXVI"
K. Mori, M. Otsuka and T. Kato (1977) [Published in Atomic Data and Nuclear Data Tables 23, 196 (1979)]

IPPJ-AM-4 "Atomic Processes in Hot Plasmas and X-Ray Emission"
T. Kato (1978)

IPPJ-AM-5* "Charge Transfer between a Proton and a Heavy Metal Atom"
S. Hiraide, Y. Kigoshi and M. Matsuzawa (1978)

IPPJ-AM-6* "Free-Free Transition in a Plasma –Review of Cross Sections and Spectra–"
T. Kato and H. Narumi (1978)

IPPJ-AM-7* "Bibliography on Electron Collisions with Atomic Positive Ions: 1940 Through 1977"
K. Takayanagi and T. Iwai (1978)

IPPJ-AM-8 "Semi-Empirical Cross Sections and Rate Coefficients for Excitation and Ionization by Electron Collision and Photoionization of Helium"
T. Fujimoto (1978)

IPPJ-AM-9 "Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV I. Incidence of He, Li, Be, B and Their Ions"
Kazuhiko Okuno (1978)

IPPJ-AM-10 "Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV II. Incidence of C, N, O and Their Ions"
Kazuhiko Okuno (1978)

IPPJ-AM-11 "Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV III. Incidence of F, Ne, Na and Their Ions"
Kazuhiko Okuno (1978)

IPPJ-AM-12* "Electron Impact Excitation of Positive Ions Calculated in the Coulomb-Born Approximation –A Data List and Comparative Survey–"
S. Nakazaki and T. Hashino (1979)

IPPJ-AM-13 "Atomic Processes in Fusion Plasmas – Proceedings of the Nagoya Seminar on Atomic Processes in Fusion Plasmas Sept. 5-7, 1979"
Ed. by Y. Itikawa and T. Kato (1979)

IPPJ-AM-14 "Energy Dependence of Sputtering Yields of Monatomic Solids"
N. Matsunami, Y. Yamamura, Y. Itikawa, N. Itoh, Y. Kazumata, S. Miyagawa, K. Morita and R. Shimizu (1980)

IPPJ-AM-15 "Cross Sections for Charge Transfer Collisions Involving Hydrogen Atoms"
Y. Kaneko, T. Arikawa, Y. Itikawa, T. Iwai, T. Kato, M. Matsuzawa, Y. Nakai, K. Okubo, H. Ryufuku, H. Tawara and T. Watanabe (1980)

IPPJ-AM-16 "Two-Centre Coulomb Phaseshifts and Radial Functions"
H. Nakamura and H. Takagi (1980)

IPPJ-AM-17 "Empirical Formulas for Ionization Cross Section of Atomic Ions for Electron Collisions –Critical Review with Compilation of Experimental Data–"
Y. Itikawa and T. Kato (1981)

IPPJ-AM-18 "Data on the Backscattering Coefficients of Light Ions from Solids"
T. Tabata, R. Ito, Y. Itikawa, N. Itoh and K. Morita (1981) [Published in Atomic Data and Nuclear Data Tables 28, 493 (1983)]

IPPJ-AM-19 "Recommended Values of Transport Cross Sections for Elastic Collision and Total Collision Cross Section for Electrons in Atomic and Molecular Gases"
M. Hayashi (1981)

IPPJ-AM-20 "Electron Capture and Loss Cross Sections for Collisions between Heavy Ions and Hydrogen Molecules"
Y. Kaneko, Y. Itikawa, T. Iwai, T. Kato, Y. Nakai, K. Okuno and H. Tawara (1981)

IPPJ-AM-21 "Surface Data for Fusion Devices – Proceedings of the U.S–Japan Workshop on Surface Data Review Dec. 14-18, 1981"
Ed. by N. Itoh and E.W. Thomas (1982)

IPPJ-AM-22 "Desorption and Related Phenomena Relevant to Fusion Devices"
Ed. by A. Koma (1982)

IPPJ-AM-23 "Dielectronic Recombination of Hydrogenic Ions"
T. Fujimoto, T. Kato and Y. Nakamura (1982)

IPPJ-AM-24 "Bibliography on Electron Collisions with Atomic Positive Ions: 1978 Through 1982 (Supplement to IPPJ-AM-7)"
Y. Itikawa (1982) [Published in Atomic Data and Nuclear Data Tables 31, 215 (1984)]

IPPJ-AM-25 "Bibliography on Ionization and Charge Transfer Processes in Ion-Ion Collision"
H. Tawara (1983)

IPPJ-AM-26 "Angular Dependence of Sputtering Yields of Monatomic Solids"
Y. Yamamura, Y. Itikawa and N. Itoh (1983)

IPPJ-AM-27 "Recommended Data on Excitation of Carbon and Oxygen Ions by Electron Collisions"
Y. Itikawa, S. Hara, T. Kato, S. Nakazaki, M.S. Pindzola and D.H. Crandall (1983) [Published in Atomic Data and Nuclear Data Tables 33, 149 (1985)]

IPPJ-AM-28 "Electron Capture and Loss Cross Sections for Collisions Between Heavy Ions and Hydrogen Molecules (Up-dated version of IPPJ-AM-20)
H. Tawara, T. Kato and Y. Nakai (1983) [Published in Atomic Data and Nuclear Data Tables 32, 235 (1985)]

IPPJ-AM-29 "Bibliography on Atomic Processes in Hot Dense Plasmas"
T. Kato, J. Hama, T. Kagawa, S. Karashima, N. Miyanaga, H. Tawara, N. Yamaguchi, K. Yamamoto and K. Yonei (1983)

IPPJ-AM-30 "Cross Sections for Charge Transfers of Highly Ionized Ions in Hydrogen Atoms (Up-dated version of IPPJ-AM-15)"
H. Tawara, T. Kato and Y. Nakai (1983) [Published in Atomic Data and Nuclear Data Tables 32, 235 (1985)]

IPPJ-AM-31 "Atomic Processes in Hot Dense Plasmas"
T. Kagawa, T. Kato, T. Watanabe and S. Karashima (1983)

IPPJ-AM-32 "Energy Dependence of the Yields of Ion-Induced Sputtering of Monatomic Solids"
N. Matsunami, Y. Yamamura, Y. Itikawa, N. Itoh, Y. Kazumata, S. Miyagawa, K. Morita, R. Shimizu and H. Tawara (1983) [Published in Atomic Data and Nuclear Data Tables 31, 1 (1984)]

IPPJ-AM-33 "Proceedings on Symposium on Atomic Collision Data for Diagnostics and Modelling of Fusion Plasmas, Aug. 29 – 30, 1983"
Ed. by H. Tawara (1983)

IPPJ-AM-34 "Dependence of the Backscattering Coefficients of Light Ions upon Angle of Incidence"
T. Tabata, R. Ito, Y. Itikawa, N. Itoh, K. Morita and H. Tawara (1984)

IPPJ-AM-35 "Proceedings of Workshop on Synergistic Effects in Surface Phenomena Related to Plasma-Wall Interactions, May 21 – 23, 1984"
Ed. by N. Itoh, K. Kamada and H. Tawara (1984) [Published in Radiation Effects 89, 1 (1985)]

IPPJ-AM-36 "Equilibrium Charge State Distributions of Ions ($Z_1 \geqq 4$) after Passage through Foils – Compilation of Data after 1972"
K. Shima, T. Mikumo and H. Tawara (1985) [Published in Atomic Data and Nuclear Data Tables 34, 357 (1986)]

IPPJ-AM-37 "Ionization Cross Sections of Atoms and Ions by Electron Impact"
H. Tawara, T. Kato and M. Ohnishi (1985) [Published in Atomic Data and Nuclear Data Tables 36, 167 (1987)]

IPPJ-AM-38 "Rate Coefficients for the Electron-Impact Excitations of C-like Ions"
Y. Itikawa (1985)

IPPJ-AM-39 "Proceedings of the Japan-U.S. Workshop on Impurity and Particle Control, Theory and Modeling, Mar. 12 – 16, 1984"
Ed. by T. Kawamura (1985)

IPPJ-AM-40 "Low-Energy Sputterings with the Monte Carlo Program ACAT"
Y. Yamamura and Y. Mizuno (1985)

IPPJ-AM-41 "Data on the Backscattering Coefficients of Light Ions from Solids (a Revision)"
R. Ito, T. Tabata, N. Itoh, K. Morita, T. Kato and H. Tawara (1985)

IPPJ-AM-42 "Stopping Power Theories for Charged Particles in Inertial Confinement Fusion Plasmas (Emphasis on Hot and Dense Matters)"
S. Karashima, T. Watanabe, T. Kato and H. Tawara (1985)

IPPJ-AM-43 "The Collected Papers of Nice Project/IPP, Nagoya"
Ed. by H. Tawara (1985)

IPPJ-AM-44 "Tokamak Plasma Modelling and Atomic Processes"
Ed. by T. Kawamura (1986)

IPPJ-AM-45 Bibliography of Electron Transfer in Ion-Atom Collisions
H. Tawara, N. Shimakura, N. Toshima and T. Watanabe (1986)

IPPJ-AM-46 "Atomic Data Involving Hydrogens Relevant to Edge Plasmas"
H. Tawara, Y. Itikawa, Y. Itoh, T. Kato, H. Nishimura, S. Ohtani, H. Takagi, K. Takayanagi and M. Yoshino (1986)

IPPJ-AM-47 "Resonance Effects in Electron-Ion Collisions"
Ed. by H. Tawara and G. H. Dunn (1986)

IPPJ-AM-48 "Dynamic Processes of Highly Charged Ions (Proceedings)"
Ed. by Y. Kanai and S. Ohtani (1986)

IPPJ-AM-49 "Wavelengths of K X-Rays of Iron Ions"
T. Kato, S. Morita and H. Tawara (1987)

IPPJ-AM-50 "Proceedings of the Japan-U.S. Workshop P-92 on Plasma Material Interaction/High Heat Flux Data Needs for the Next Step Ignition and Steady State Devices, Jan. 26 – 30, 1987"
Ed. by A. Miyahara and K. L. Wilson (1987)

IPPJ-AM-51 "High Heat Flux Experiments on C-C Composite Materials by Hydrogen Beam at the 10MW Neutral Beam Injection Test Stand of the IPP Nagoya"
H. Bolt, A. Miyahara, T. Kuroda, O. Kaneko, Y. Kubota, Y. Oka and K. Sakurai (1987)

IPPJ-AM-52 "Energy Dependence of Ion-Induced Sputtering Yields of Monatomic Solids in the Low Energy Region"
N. Matsunami, Y. Yamamura, N. Itoh, H. Tawara and T. Kawamura (1987)

IPPJ-AM-53 "Data Base on the High Heat Flux Behaviour of Metals and Carbon Materials for Plasma Facing Components – Experiments at the 10 MW Neutral Beam Injection Test Stand of the IPP Nagoya"
H. Bolt, C. D. Croessmann, A. Miyahara, T. Kuroda and Y. Oka (1987)

IPPJ-AM-54 "Final (n, ℓ) State-Resolved Electron Capture by Multiply Charged Ions from Neutral Atoms"
N. Shimakura, N. Toshima, T. Watanabe and H. Tawara (1987)

IPPJ-AM-55 "Atomic Data for Hydrogens in Collisions with Electrons – Addenda to IPPJ-AM-46"
H. Tawara, Y. Itikawa, H. Nishimura and M. Yoshino (1987)

IPPJ-AM-56 "Total and Partial Cross Sections for Electron Capture for C^{q+} (q= 6–2) and O^{q+} (q=8–2) Ions in Collisions with H, H_2 and He Atoms"
H. Tawara (1987)

Available upon request to Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan, except for the reports noted with*.