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ATOMIC AND PLASMA–MATERIAL INTERACTION DATA FOR FUSION

(Supplement to the journal Nuclear Fusion)

VOLUME 4

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1993
AGENCE INTERNATIONALE DE L'ENERGIE ATOMIQUE, VIENNE, 1993
МЕЖДУНАРОДНОЕ АГЕНТСТВО ПО АТОМНОЙ ЭНЕРГИИ, ВЕНА, 1993
ORGANISMO INTERNACIONAL DE ENERGIA ATOMICA, VIENA, 1993

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Printed by the IAEA in Austria
September 1993

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INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1993

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- Elementary collision processes in fusion plasmas involving photons, electrons, ions, atoms and molecules;
- Collision processes of plasma particles with surfaces of fusion relevant materials;
- Plasma-material interaction phenomena, including the thermophysical response of materials.

Each submitted contribution should contain fusion relevant data and information in either of the above areas. Original contributions should provide new data, using well established methods. Review articles should give a critical analysis or evaluation of a wider range of data. They are normally prepared on the invitation of the Scientific Editor or on prior mutual consent. Each submitted contribution is assessed by two independent referees.

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Publisher: International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria

Scientific Editor: R.K. Janev, Atomic and Molecular Data Unit, Division of Physical and Chemical Sciences

Editor: C. Bobeldijk, Division of Publications

Annual subscription price (one issue): Austrian Schillings 350,–
Airmail delivery (optional): Austrian Schillings 40,— to any destination

ATOMIC AND PLASMA-MATERIAL INTERACTION DATA FOR FUSION, VOLUME 4
IAEA, VIENNA, 1993
STI/PUB/23/APID/4

CROSS SECTIONS FOR COLLISION PROCESSES OF HYDROGEN ATOMS WITH ELECTRONS, PROTONS AND MULTIPLY CHARGED IONS

R.K. Janev and J.J. Smith

International Atomic Energy Agency
Vienna, Austria

CONTENTS

Editorial Note

The present volume of Atomic and Plasma-Material Interaction Data for Fusion contains the result of a critical data evaluation of the cross sections of ground state and excited hydrogen atoms colliding with the basic fusion plasma constituents, the electrons and protons, and with the multiply charged ions of major plasma impurities. Because of the specific requirements on the presentation of evaluated material and recommended cross sections, the format and the style of the present volume had to be changed with respect to the standard one. Such deviations from the standard format and style of individual volumes may be expected also in the future due to either the specific form of presented material or some other reasons.

INTRODUCTION

1. Scope and Purpose

The present volume contains recommended cross sections for the inelastic processes of hydrogen atoms in ground and excited states colliding with electrons, protons, He^{2+}, Be^{4+}, B^{5+}, C^{6+}, O^{8+} and other highly charged ions A^{q+} with $q > 8$. The specific electron-impact processes considered are excitation and ionization, while the ion-impact processes include excitation, ionization and charge transfer (electron capture). The considered collision energy range for electron-impact processes is from threshold to several hundred keV. For the ion-impact processes, the energy range considered is typically from a few hundred eV/amu to several MeV/amu. The inelastic processes involving lower excited hydrogen levels (typically below the $n=5$ electronic shell) are treated individually. For the processes involving higher excited hydrogen levels, either generalized semi-empirical formulae or well established scaling relationships for the corresponding cross sections are used. Similarly, the cross sections for ion-atom collision processes with ions in charge states $q > 8$ ($q > 4$ for excitation) are represented by suitable semi-empirical formulae, based on established theoretical scalings.

The primary purpose of the present collection of recommended cross sections is to provide a critically assessed and complete set of collisional data required in the modelling of neutral hydrogen beam penetration in a thermonuclear fusion plasma. This has determined the scope of processes and colliding systems included in our analysis. The collision energy range in which the cross sections for the considered atomic reactions are presented is, however, much broader than that of interest to the beam-plasma interaction studies and the present database should, therefore, also be useful in other plasma research areas.

2. Data Sources and Data Evaluation Criteria

In constructing the recommended cross sections for the reactions considered in the present collection, we have used the experimental and theoretical cross section information available in the journal literature as of December 1992. The cross section data were taken from the original sources, and only in a limited number of reactions secondary data sources (data compendia, evaluated data sets) were used. For the processes involving highly excited hydrogen states, or highly charged ions, the cross sections are based on semi-empirical, or general theoretical formulae. In determining the recommended cross section for a given reaction for which more than one experimental or theoretical data sets (or a combination of them) where available, relative accuracy weightings were given to the individual data sets on the basis of reliability of experimental or theoretical method used and the degree of sophistication of performed measurement or calculation. The mutual consistency of the best available data sets, either experimental or theoretical, served as a guiding criterion for determining the accuracy of the recommended cross section. In the case of reactions for which only one set of experimental or theoretical data in a given energy range was available, the uncertainty of the "recommended" cross section is that quoted in the original data source (if experimental), or estimated on the basis of reliability of the applied method (if theoretical). For a number of reactions, cross section extrapolations were made on the basis of established theoretical scalings, if the resulting cross section uncertainty did not exceed a factor of two. It is believed that for the vast majority of recommended cross sections, the assigned accuracies have been estimated conservatively.

3. Data Presentation

The recommended cross sections are presented in both tabular and graphical form. Each of the recommended cross sections is documented with estimated accuracies for different energy ranges, and with brief comments on the original data used in its determination. The recommended cross sections are additionally represented by analytic fit expressions, which reproduce the recommended data with an rms deviation usually smaller than 3%. For the majority of reactions, the analytic fit functions have a correct asymptotic behaviour, which allows a plausible extension of the cross section beyond the energy range in which the data evaluation was done. Each cross section analytic fit function is supplemented with the values of its fitting parameters and with an indication of its accuracy (rms and maximum deviation).

The analytic fit functions for the recommended cross sections of considered processes are stored in the ALADDIN database system of the International Atomic Energy Agency. The ALADDIN data file, containing the entire cross section information presented here, can be obtained from the IAEA Atomic and Molecular Data Unit on request.

Acknowledgement

We are deeply indebted to a number of colleagues from the atomic collision physics community (in particular to Drs W. Fritsch, A. Salin, R.A. Phaneuf) for critical reading of the manuscript and several useful suggestions.

List of Reactions

List of Abbreviations

CC	Close Coupling method
DW, DWA	Distorted Wave Approximation
DWB2	Distorted Wave-second Born approximation
DWPO	Distorted Wave-Polarized Orbitals approximation
AO	Atomic-Orbital (close-coupling method)
MO	Molecular-Orbital (close-coupling method)
FBA	First Born Approximation
SE	Symmetrized Eikonal approximation
CDW	Continuum Distorted Wave appromimation
CTMC	Classical Trajectory Monte Carlo method
CPBA	Coloumb Projected Born Approximation
EIS-CDW	Eikonal Initial State-Continuum Distorted Wave approximation
UDWA	Unitarized Distorted Wave Approximation

1. Electron Impact Processes

1.1. Excitation

1.1. $e^- + H(1s) \rightarrow e^- + H^*(2s)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.02E+01	1.89E+08	1.14E−17
2.00E+01	2.65E+08	8.46E−18
4.00E+01	3.75E+08	6.73E−18
6.00E+01	4.59E+08	5.46E−18
8.00E+01	5.30E+08	4.57E−18
1.00E+02	5.93E+08	3.92E−18
2.00E+02	8.39E+08	2.27E−18
4.00E+02	1.19E+09	1.22E−18
6.00E+02	1.45E+09	8.38E−19
8.00E+02	1.68E+09	6.37E−19
1.00E+03	1.88E+09	5.13E−19
2.00E+03	2.65E+09	2.61E−19
4.00E+03	3.75E+09	1.31E−19
6.00E+03	4.59E+09	8.79E−20
8.00E+03	5.30E+09	6.60E−20
1.00E+04	5.93E+09	5.28E−20

Threshold energy: $E_{th} = \Delta E = 10.2$ eV

Accuracy: $E < 100$ eV : 10-15 %, or better; $E \geq 100$ eV : 10 %, or better

Comments: (1) For $E > 54.4$ eV the recommended cross section has been determined on the basis of the elaborate multi-state (+ pseudostates) CC calculations of Callaway et al [1] and van Wyngaarden and Walters [2], and the DWB2 results of Kingston and Walters [3]. These cross sections agree to within 10 - 15% for $E < 100$ eV, and better than 10% for $E \geq 100$ eV, with the experimental data of Kauppila et al [4] after their correction (see [2], [5]) for cascading and the relative values put on an absolute scale.

(2) In the energy region 12.23 - 54.4 eV the extended intermediate energy R-matrix results of Scott et al [5] were used along with the CC values of ref. [1]. The derived cross section is consistent to within 10 - 15% with the corrected (see [5]) experimental values of [4].

(3) The cross section from threshold to 12.23 eV has been experimentally determined by Williams [6] and is supported by the variational CC calculations of Callaway [7]. To represent the cross section in this range, the approximations of Callaway and McDowell [8] have been taken.

Analytic fitting function

Cross section: For $10.2 \leq E\,(\mathrm{eV}) \leq 11.56$, $\sigma_{exc} = 10^{-16}\left[0.114 + 0.0575\,(E - \Delta E)\right]$ [cm^2]

For $11.56 \leq E\,(\mathrm{eV}) \leq 12.23$, $\sigma_{exc} = 1.795 \times 10^{-17}$ [cm^2]

For $E \geq 12.23$ eV,

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X}\left[\sum_{j=1}^{5} \frac{A_j}{X^{j-1}} + A_6 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

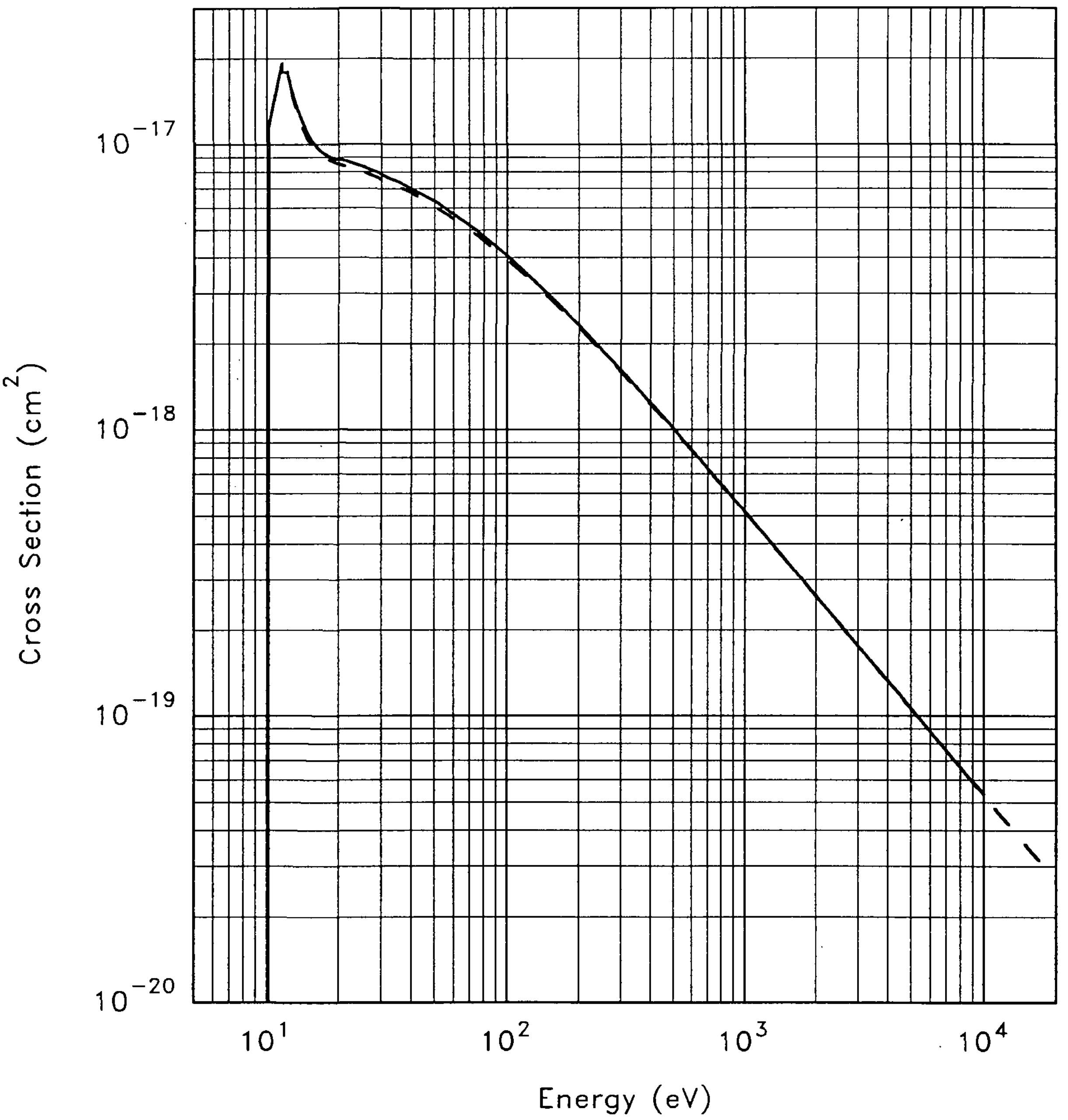
A_1	A_2	A_3	A_4	A_5	A_6
0.88606	−2.7990	5.9451	−7.6948	4.4152	0.0

The rms deviation of the above fit to the recommended cross section for $E \geq 12.23$ eV is 2.1 %. The maximum deviation is 5.3% at 14.1 eV.

ALADDIN evaluation function for cross section: NEEXH1

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (2s)

$$e^{-} + H(1s) \rightarrow e^{-} + H^{*}(2s)$$



Legend:

—— Recommended Cross Section

- – Analytic Fit

1.1.2. $e^- + H(1s) \rightarrow e^- + H^*(2p)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.02E+01	1.89E+08	1.41E−17
2.00E+01	2.65E+08	4.49E−17
4.00E+01	3.75E+08	6.44E−17
6.00E+01	4.59E+08	6.46E−17
8.00E+01	5.30E+08	6.05E−17
1.00E+02	5.93E+08	5.59E−17
2.00E+02	8.39E+08	3.92E−17
4.00E+02	1.19E+09	2.48E−17
6.00E+02	1.45E+09	1.85E−17
8.00E+02	1.68E+09	1.49E−17
1.00E+03	1.88E+09	1.25E−17
2.00E+03	2.65E+09	7.22E−18
4.00E+03	3.75E+09	4.08E−18
6.00E+03	4.59E+09	2.90E−18
8.00E+03	5.30E+09	2.27E−18
1.00E+04	5.93E+09	1.88E−18

Threshold energy: $E_{th} = \Delta E = 10.2$ eV

Accuracy: $E < 100$ eV : 10-15 %, or better; $E \geq 100$ eV : 10 %, or better

Comments: (1) For $E > 54.4$ eV, the large basis (+ pseudostates) CC calculations of Callaway et al [1] and van Wyngaarden and Walters [2] were used in deriving the recommended cross section. These agree to within 5 - 10% with the experimental measurements of Long et al [9], corrected for cascading and other effects (see [2], [5]). For $E \geq 350$ eV, the DWB2 results of Kingston and Walters [3] were used to extend the cross section to higher energies.

(2) In the energy region 12.23 - 54.4 eV, the experimental data of Long et al [9] and the extended intermediate energy R-matrix calculations of Scott et al [5], which agree to approximately 10%, were used.

(3) The cross section from threshold to 12.23 eV has been experimentally determined by Williams [6] and is supported by the variational CC calculations of Callaway [7]. To represent the cross section in this range the approximations of Callaway and McDowell [8] have been taken.

Analytic fitting function

Cross section: For $10.2 \leq E\,(\text{eV}) \leq 11.56$, $\sigma_{exc} = 10^{-16}\left[\,0.141 + 0.129\,(E - \Delta E)\,\right]$ [cm^2]

For $11.56 \leq E\,(\text{eV}) \leq 12.23$, $\sigma_{exc} = 3.23 \times 10^{-17}$ [cm^2]

For $E \geq 12.23$ eV,

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X}\left[\sum_{j=1}^{5} \frac{A_j}{X^{j-1}} + A_6 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

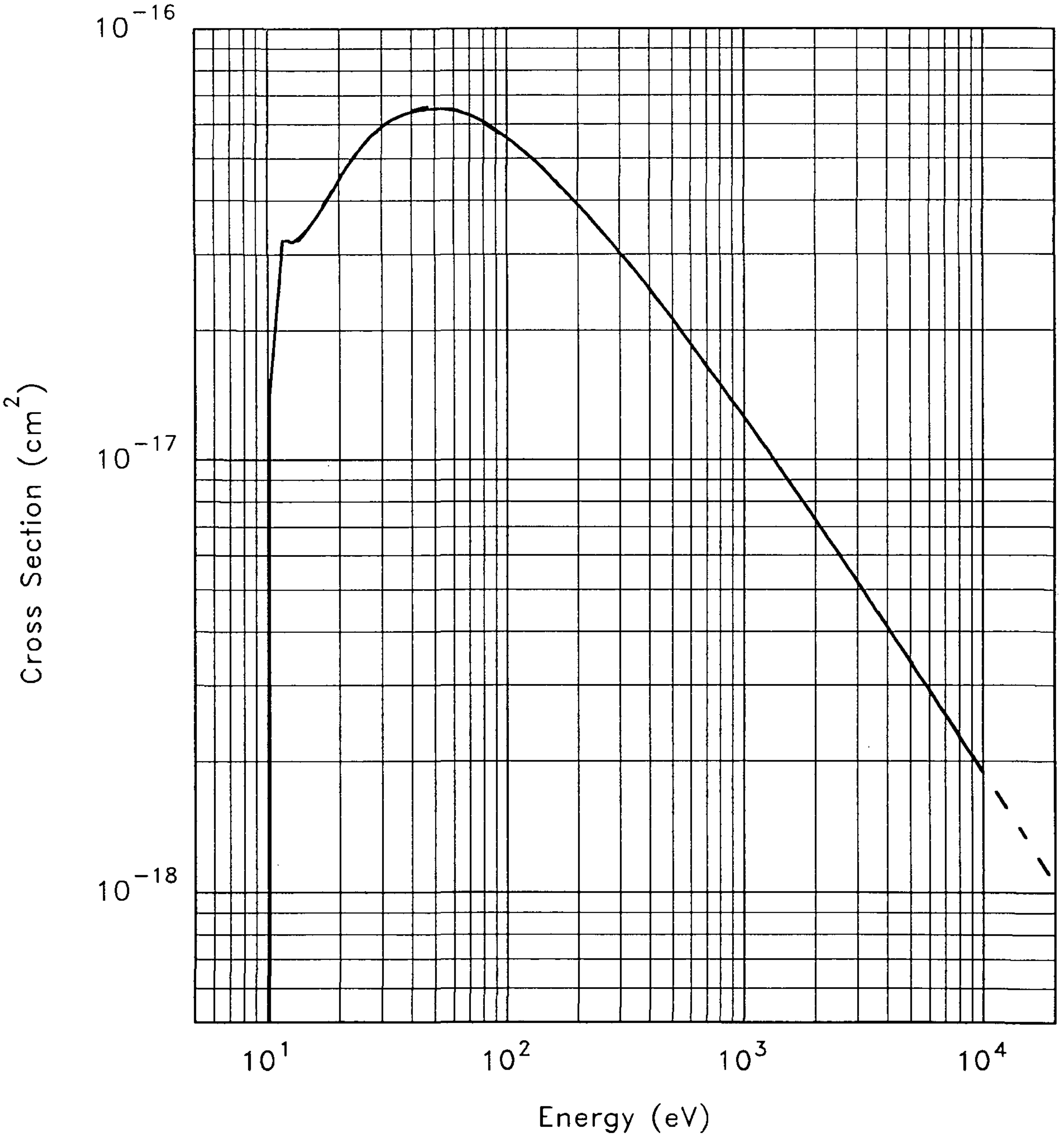
A_1	A_2	A_3	A_4	A_5	A_6
0.43563	−17.995	45.247	−42.229	15.446	4.5146

The rms deviation of the above fit to the recommended cross section for $E \geq 12.23$ eV is 0.4 %. The maximum deviation is 1.2% at 13.8 eV.

ALADDIN evaluation function for cross section: NEEXH1

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (2p)

$e^- + H(1s) \rightarrow e^- + H^*(2p)$



Legend:
—— Recommended Cross Section
- – Analytic Fit

1.1.3. $e^- + H(1s) \rightarrow e^- + H^*(n=2)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.02E+01	1.89E+08	2.55E−17
2.00E+01	2.65E+08	5.33E−17
4.00E+01	3.75E+08	7.12E−17
6.00E+01	4.59E+08	7.01E−17
8.00E+01	5.30E+08	6.51E−17
1.00E+02	5.93E+08	6.00E−17
2.00E+02	8.39E+08	4.15E−17
4.00E+02	1.19E+09	2.61E−17
6.00E+02	1.45E+09	1.94E−17
8.00E+02	1.68E+09	1.55E−17
1.00E+03	1.88E+09	1.31E−17
2.00E+03	2.65E+09	7.50E−18
4.00E+03	3.75E+09	4.22E−18
6.00E+03	4.59E+09	3.00E−18
8.00E+03	5.30E+09	2.35E−18
1.00E+04	5.93E+09	1.94E−18

Threshold energy: $E_{th} = \Delta E = 10.2$ eV

Accuracy: E < 100 eV : 10-15 %, or better; E ≥ 100 eV : 10 %, or better

Comments: The recommended cross section for excitation from the ground state to the n = 2 level is calculated as the sum of the 1s → 2s and 1s → 2p cross sections.

Analytic fitting function

Cross section: For $10.2 \le E\,(\mathrm{eV}) \le 11.56$, $\sigma_{exc} = 10^{-16}\left[\,0.255 + 0.1865\,(E - \Delta E)\,\right]$ [cm^2]

For $11.56 \le E\,(\mathrm{eV}) \le 12.23$, $\sigma_{exc} = 5.025 \times 10^{-17}$ [cm^2]

For $E \ge 12.23$ eV,

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X}\left[\sum_{j=1}^{5} \frac{A_j}{X^{j-1}} + A_6 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

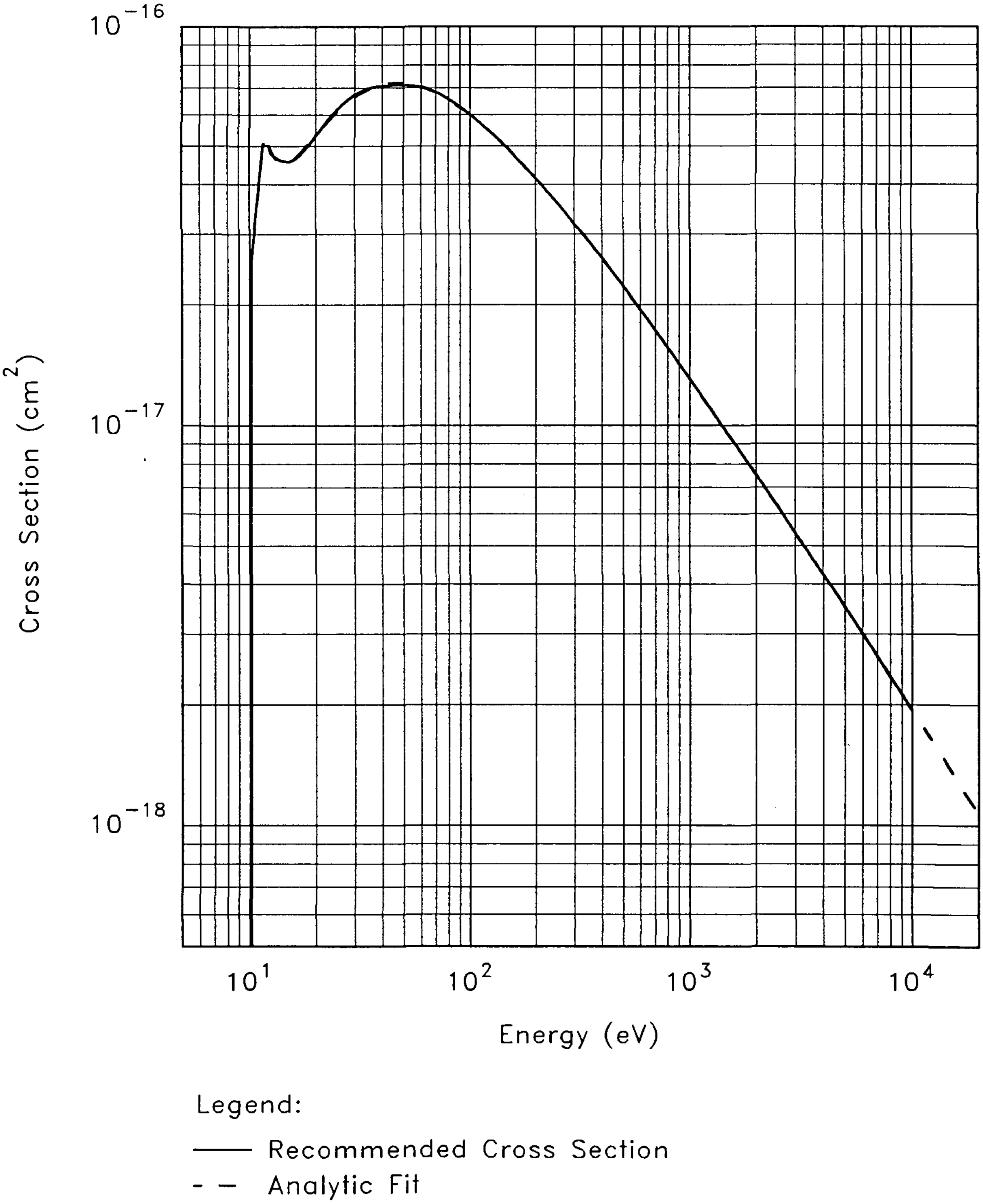
A_1	A_2	A_3	A_4	A_5	A_6
1.4182	−20.877	49.735	−46.249	17.442	4.4979

The rms deviation of the above fit to the recommended cross section for E ≥ 12.23 eV is 0.4 %. The maximum deviation is 1.5% at 23.4 eV.

ALADDIN evaluation function for cross section: NEEXH1

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (n=2)

$e^- + H(1s) \rightarrow e^- + H^*(n=2)$



1.1.4. $e^- + H(1s) \rightarrow e^- + H^*(3s)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.24E+01	2.09E+08	2.25E−18
2.00E+01	2.65E+08	3.12E−18
4.00E+01	3.75E+08	1.04E−18
6.00E+01	4.59E+08	8.93E−19
8.00E+01	5.30E+08	7.99E−19
1.00E+02	5.93E+08	7.12E−19
2.00E+02	8.39E+08	4.41E−19
4.00E+02	1.19E+09	2.44E−19
6.00E+02	1.45E+09	1.68E−19
8.00E+02	1.68E+09	1.27E−19
1.00E+03	1.88E+09	1.03E−19
2.00E+03	2.65E+09	5.17E−20
4.00E+03	3.75E+09	2.58E−20
6.00E+03	4.59E+09	1.72E−20
8.00E+03	5.30E+09	1.29E−20
1.00E+04	5.93E+09	1.03E−20

Threshold energy: $E_{th} = \Delta E = 12.09$ eV

Accuracy: $E < 30$ eV : 20-40 %; $30 \le E$ (eV) ≤ 100 : 10-20 %; $E > 100$ eV : 10 %, or better

Comments: (1) For energies above 100 eV, the recommended cross section was derived on the basis of the crossed beam experimental data of Mahan et al [10] (which include corrections for cascading), DWPO calculations of Syms et al [11], 7-channel eikonal calculations of Flannery and McCann [12] and the orthogonalized Born-Oppenheimer results of Shevelko [13]. All the four sets of data agree within 5% for E > 300 eV.

(2) In the energy range $30 \le E$ (eV) ≤ 100, the recommended cross section is based primarily on the experimental data of Mahan et al [10]. This choice is supported by the multi-state (+ pseudostates) CC calculations of Callaway et al [1] (with inclusion of exchange effects) and Whelan et al [14] (without inclusion of exchange), DWPO calculations [11] and a 7-channel eikonal calculation [12].

(3) In the region below 30 eV, the multi-state CC calculations of Callaway et al [1] and Callaway [7], supported by the recent R-matrix calculations of Aggarwal et al [60] and the algerbraic variational CC calculation of Hata et al [15] were used in determining the recommended cross section. The larger uncertainties in this region reflect the resonant behaviour of the cross section.

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E}\right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

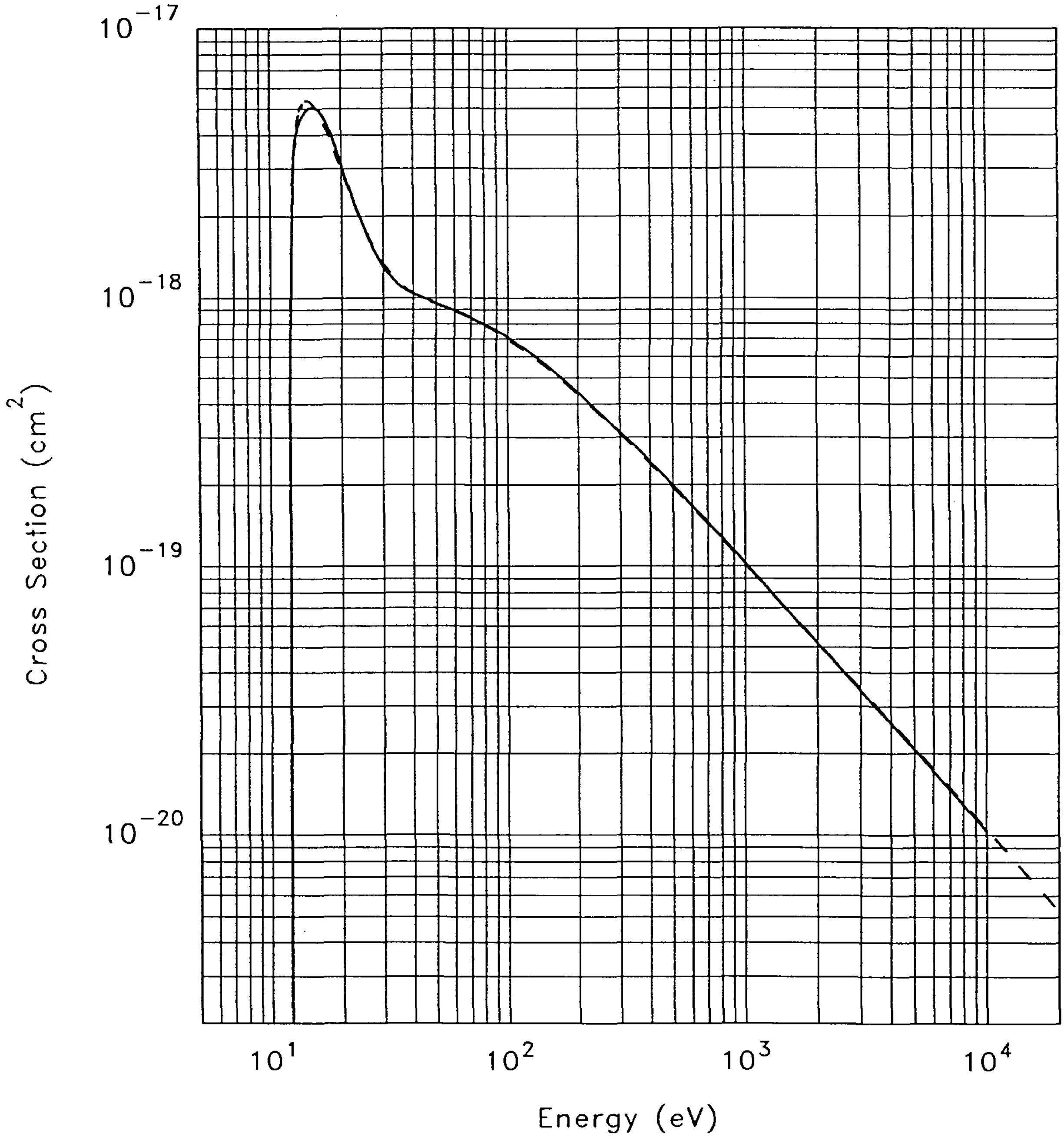
A_1	A_2	A_3	A_4	A_5	A_6
0.17663	−0.42600	0.18342	0.99615	0.0	0.77920

The rms deviation of the above fit to the recommended cross section is 2.7%. The maximum deviation is 11.1% at 13.7 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (3s)

$e^- + H(1s) \rightarrow e^- + H^*(3s)$



Legend:

—— Recommended Cross Section

- – – Analytic Fit

1.1.5. $e^- + H(1s) \rightarrow e^- + H^*(3p)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.24E+01	2.09E+08	4.71E−18
2.00E+01	2.65E+08	9.91E−18
4.00E+01	3.75E+08	1.24E−17
6.00E+01	4.59E+08	1.17E−17
8.00E+01	5.30E+08	1.07E−17
1.00E+02	5.93E+08	9.68E−18
2.00E+02	8.39E+08	6.55E−18
4.00E+02	1.19E+09	4.08E−18
6.00E+02	1.45E+09	3.03E−18
8.00E+02	1.68E+09	2.44E−18
1.00E+03	1.88E+09	2.05E−18
2.00E+03	2.65E+09	1.19E−18
4.00E+03	3.75E+09	6.76E−19
6.00E+03	4.59E+09	4.79E−19
8.00E+03	5.30E+09	3.75E−19
1.00E+04	5.93E+09	3.10E−19

Threshold energy: $E_{th} = \Delta E = 12.09$ eV

Accuracy: E < 35 eV : 20-60 %, or more; 35 ≤ E (eV) ≤ 100 : 10-20 %; E > 100 eV : 10 %, or better

Comments: (1) In the energy region above 100 eV the experimental data of Mahan et al [10] (corrected for cascading and polarisation effects), the DWPO calculations of Syms et al [11], the 7-channel eikonal calculations of Flannery and McCann [12] and the Born-exchange results of Morrison and Rudge [16] and Shevelko [13] all agree to within 10% or better.

(2) In determining the recommended cross section in the energy range between 35 eV and 100 eV we have used the data from sources mentioned in (1) above, along with the multi-state (+ pseudostates) CC calculations of Callaway et al [1] (with inclusion of exchange effects) and Whelan et al [14] (without inclusion of exchange).

(3) In the region below 35 eV, the dispersion of the theoretical cross sections from Refs. [1], [7], [11], [15] and [60] ranges from 20 to 60% and the experimental data of Mahan et al [10] have a quoted uncertainty of 30 - 50%. The uncertainty of the recommended cross section, derived from the above data, is therefore estimated to about 20 - 60%.

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E} \right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X \right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

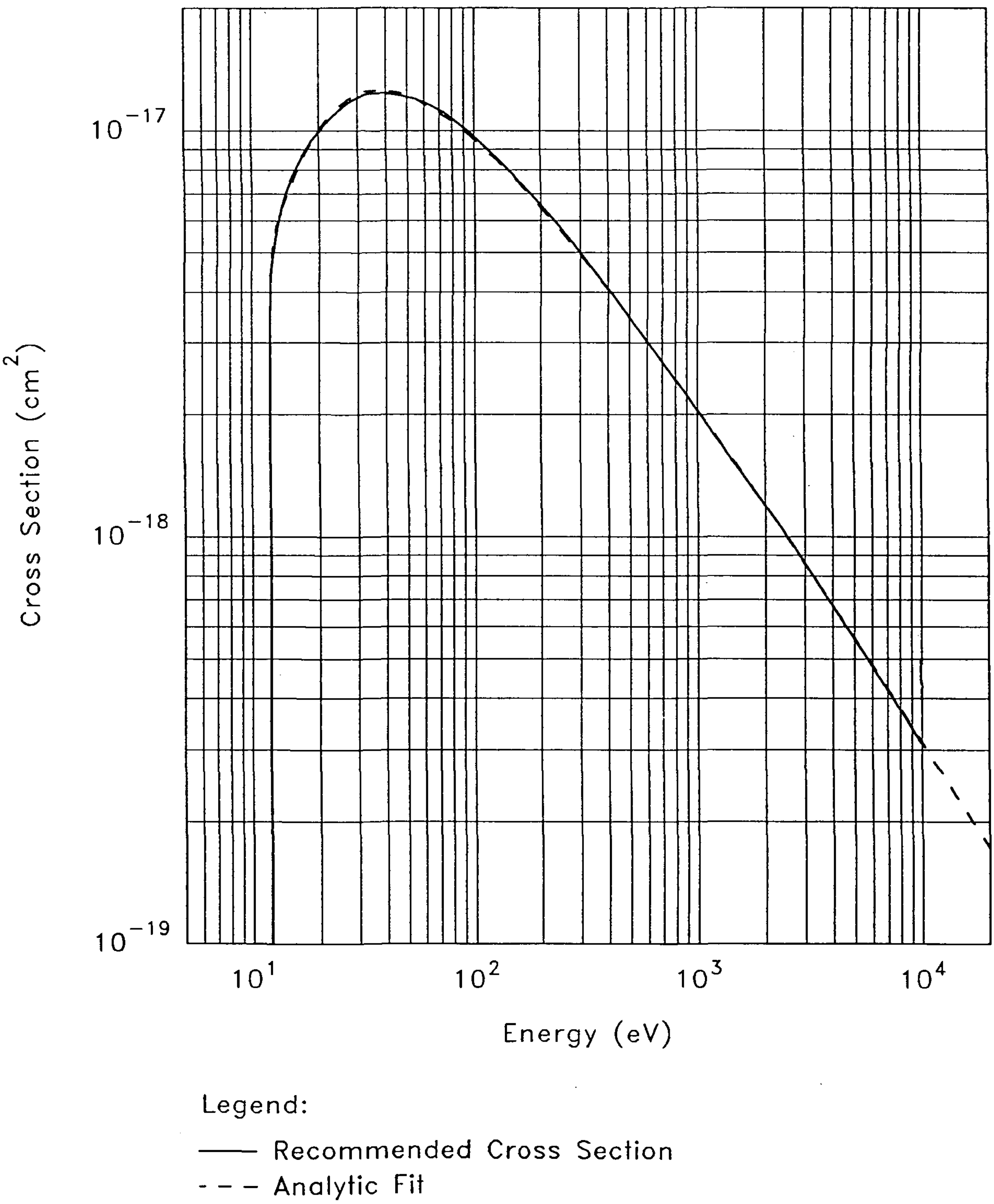
A_1	A_2	A_3	A_4	A_5	A_6
0.014194	−0.34362	0.50609	0.0	0.77738	0.14606

The rms deviation of the above fit to the recommended cross section is 1.3%. The maximum deviation is 5.3% at 12.6 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (3p)

$e^- + H(1s) \rightarrow e^- + H^*(3p)$



1.1.6. $e^- + H(1s) \rightarrow e^- + H^*(3d)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.24E+01	2.09E+08	2.92E−18
2.00E+01	2.65E+08	4.58E−18
4.00E+01	3.75E+08	2.42E−18
6.00E+01	4.59E+08	1.58E−18
8.00E+01	5.30E+08	1.17E−18
1.00E+02	5.93E+08	9.23E−19
2.00E+02	8.39E+08	4.32E−19
4.00E+02	1.19E+09	2.06E−19
6.00E+02	1.45E+09	1.34E−19
8.00E+02	1.68E+09	1.00E−19
1.00E+03	1.88E+09	8.12E−20
2.00E+03	2.65E+09	4.12E−20
4.00E+03	3.75E+09	2.04E−20
6.00E+03	4.59E+09	1.36E−20
8.00E+03	5.30E+09	1.02E−20
1.00E+04	5.93E+09	8.22E−21

Threshold energy: $E_{th} = \Delta E = 12.09$ eV

Accuracy: $E < 35$ eV : 20-40 %; $35 \leq E$ (eV) ≤ 100 : 10-20 %; $E > 100$ eV : 10 %, or better

Comments: (1) In the energy region above 100 eV, the experimental data of Mahan et al [10] (corrected for cascading and polarisation effects) and the the DWPO calculations of Syms et al [11] agree within 10% or better. The DWPO calculations extend smoothly to the orthogonalized Born-Oppenheimer data of Shevelko [13] for energies above 500 eV.

(2) For the energy range between 35 eV and 100 eV, we have used cross sections from the data sources mentioned in (1) above, along with the multi-state (+ pseudostates) CC calculations of Callaway et al [1] (with inclusion of exchange effects), and Whelan et al [14] (without inclusion of exchange).

(3) In the region below 35eV, the theoretical cross sections from Refs. [1], [7], [11], [15] and [60] are consistent with each other to within 20%, but differ from the experimental data point of Mahan et al [10] at E = 18.8 eV by about 40%.

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E} \right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X \right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

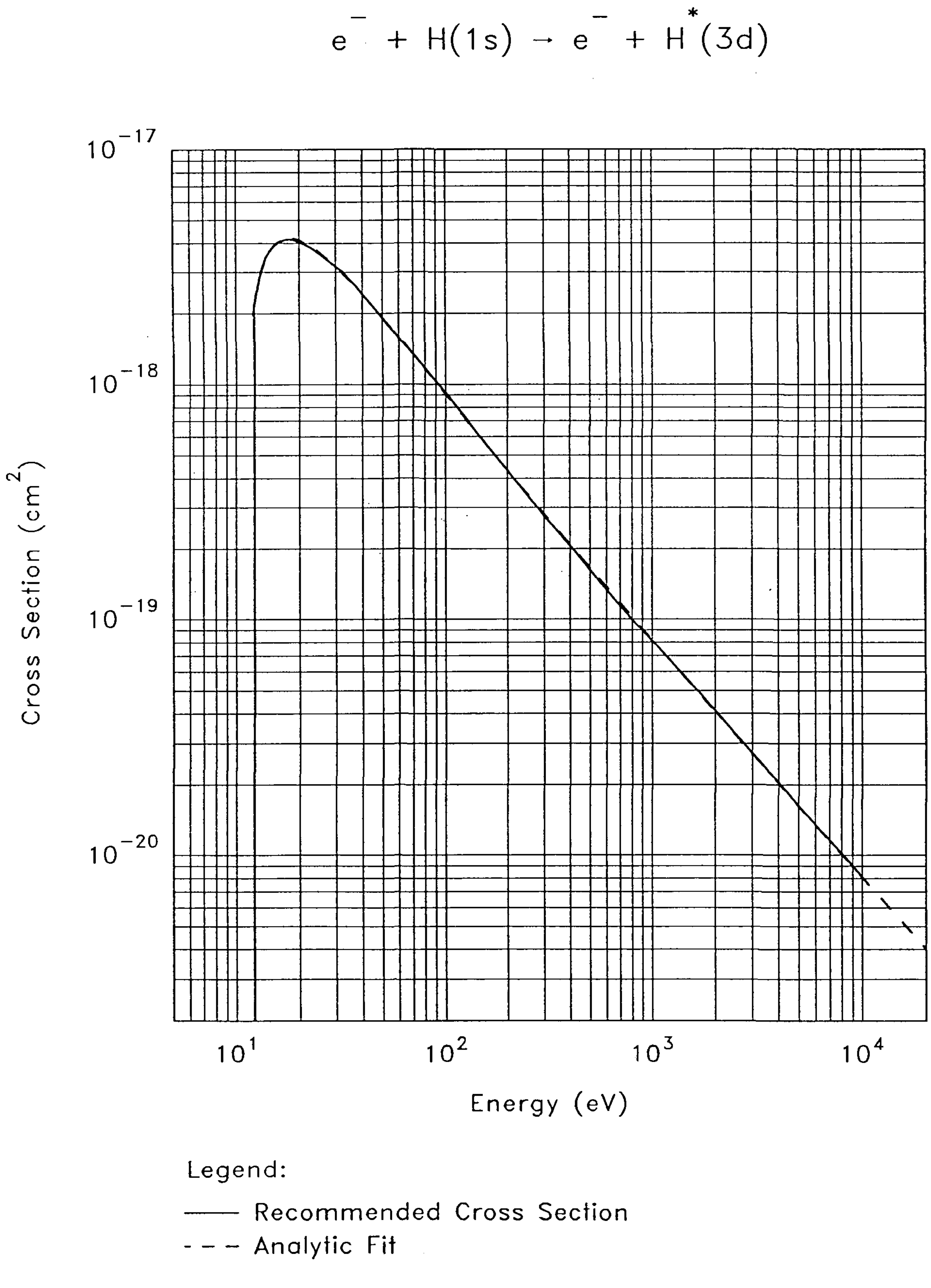
Fitting coefficients

A_1	A_2	A_3	A_4	A_5	A_6
0.13527	0.19672	−0.10712	0.0	0.0	0.35496

The rms deviation of the above fit to the recommended cross section is 1.5%. The maximum deviation is 5.3% at 12.3 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (3d)



$e^- + H(1s) \rightarrow e^- + H^*(3d)$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Cross Section (cm^2)
10^1
10^2
10^3
10^4
Energy (eV)
Legend:
——— Recommended Cross Section
- - - Analytic Fit

1.1.7. $e^- + H(1s) \rightarrow e^- + H^*(n=3)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.24E+01	2.09E+08	1.08E−17
2.00E+01	2.65E+08	1.79E−17
4.00E+01	3.75E+08	1.58E−17
6.00E+01	4.59E+08	1.43E−17
8.00E+01	5.30E+08	1.27E−17
1.00E+02	5.93E+08	1.13E−17
2.00E+02	8.39E+08	7.42E−18
4.00E+02	1.19E+09	4.55E−18
6.00E+02	1.45E+09	3.34E−18
8.00E+02	1.68E+09	2.67E−18
1.00E+03	1.88E+09	2.23E−18
2.00E+03	2.65E+09	1.27E−18
4.00E+03	3.75E+09	7.18E−19
6.00E+03	4.59E+09	5.12E−19
8.00E+03	5.30E+09	3.98E−19
1.00E+04	5.93E+09	3.31E−19

Threshold energy: $E_{th} = \Delta E = 12.09$ eV

Accuracy: $E < 100$ eV : 10-15 %, or better; $E \geq 100$ eV : 10 %, or better

Comments: The recommended cross section for excitation from the ground state to the n = 3 level is generated as the sum of the 1s → 3s, 1s → 3p and 1s → 3d cross sections.

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E} \right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X \right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

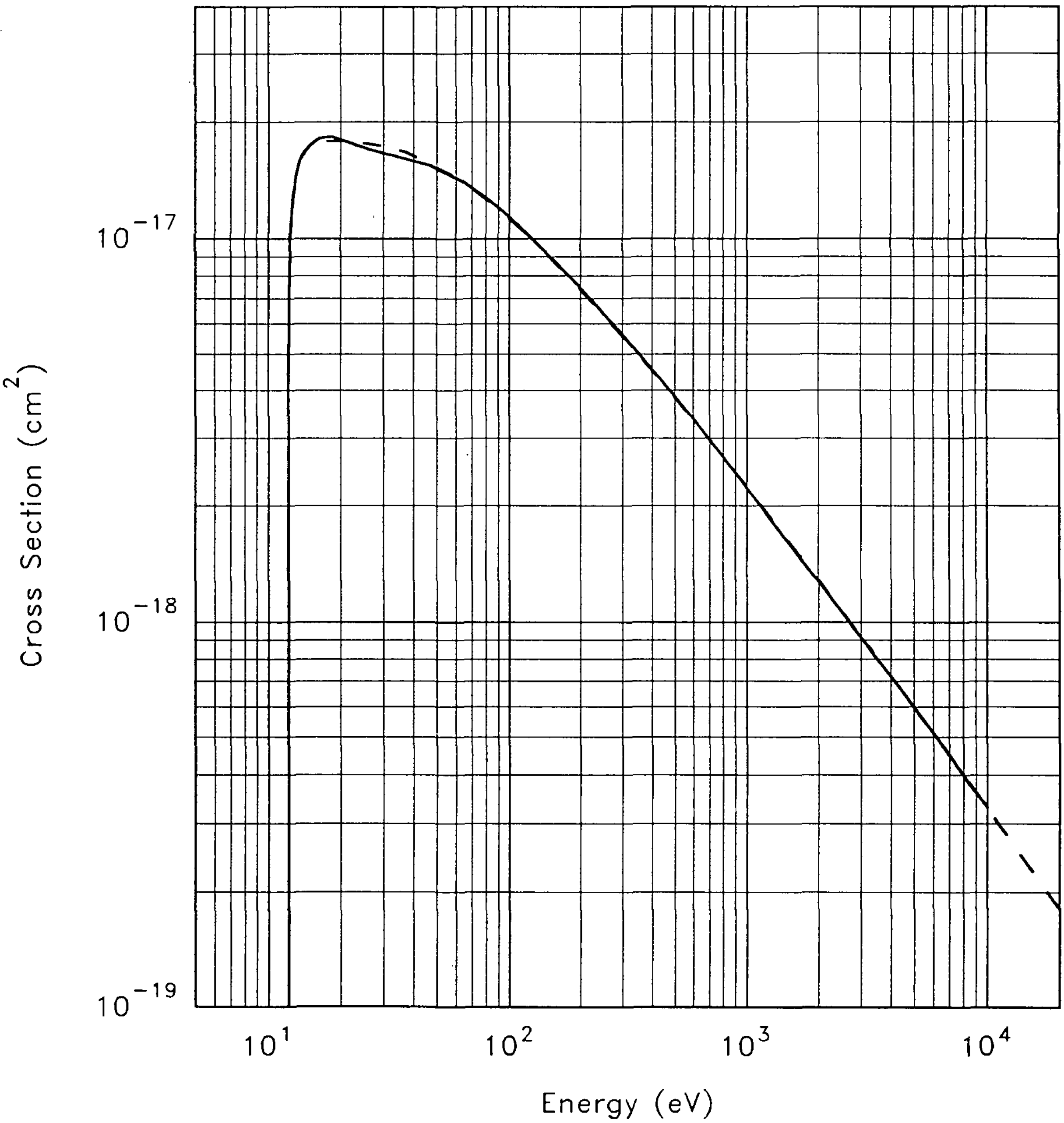
A_1	A_2	A_3	A_4	A_5	A_6
0.42956	−0.58288	1.0693	0.0	0.75448	0.38277

The rms deviation of the above fit to the recommended cross section is 1.0%. The maximum deviation is 5.9% at 12.3 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (n=3)

$e^- + H(1s) \rightarrow e^- + H^*(n=3)$



Legend:

—— Recommended Cross Section

- - Analytic Fit

1.1.8. $e^- + H(1s) \rightarrow e^- + H^*(n=4)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.40E+01	2.22E+08	7.02E−18
2.00E+01	2.65E+08	9.44E−18
4.00E+01	3.75E+08	7.46E−18
6.00E+01	4.59E+08	5.98E−18
8.00E+01	5.30E+08	5.03E−18
1.00E+02	5.93E+08	4.37E−18
2.00E+02	8.39E+08	2.72E−18
4.00E+02	1.19E+09	1.62E−18
6.00E+02	1.45E+09	1.17E−18
8.00E+02	1.68E+09	9.36E−19
1.00E+03	1.88E+09	7.83E−19
2.00E+03	2.65E+09	4.41E−19
4.00E+03	3.75E+09	2.46E−19
6.00E+03	4.59E+09	1.73E−19
8.00E+03	5.30E+09	1.35E−19
1.00E+04	5.93E+09	1.11E−19

Threshold energy: $E_{th} = \Delta E = 12.75$ eV

Accuracy: $E < 40$ eV : 30-60 %; $40 \leq E$ (eV) ≤ 80 : 10-30 %; $E > 80$ eV : 10 %, or better

Comments: (1) For the 1s → n=4 cross section there are no experimental measurements available. The theoretical calculations are limited to the orthogonalized Born-Oppemheimer [13] and Born-Rudge [16] approximations and the 10-state CC calulations with exchange of Edmunds et al [17] (at E =35 eV and 54.4 eV only) and the 15-state R-matrix calculations of Aggarwal et al [60].

(2) In the region above 80 eV, the recommended cross section has been derived from the orthogonalized Born-exchange calculations of Shevelko [13]. In the region below 80 eV, the cross section was determined primarily on the basis of the data of Morrison and Rudge [16] and the R-matrix calculations of Aggarwal et al [60].

(3) We note that the semi-empirical formula of Johnson [18] gives a cross section which is about 20 - 80 % below the recommended cross section in the region $E \leq 40$ eV, and tends towards the recommended cross section with increasing energy.

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E}\right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

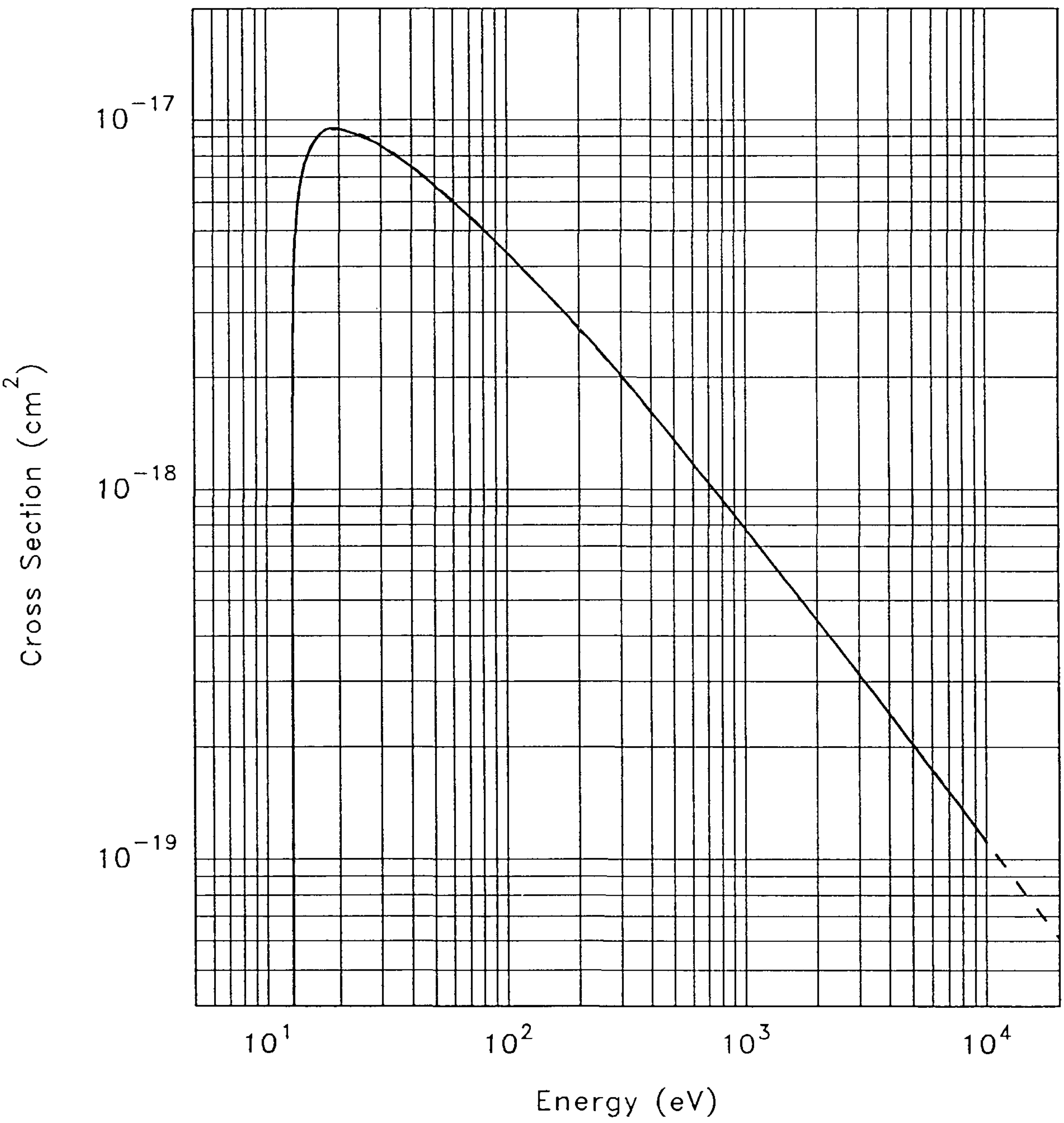
A_1	A_2	A_3	A_4	A_5	A_6
0.24846	0.19701	0.0	0.0	0.24300	0.41844

The rms deviation of the above fit to the recommended cross section is 0.4%. The maximum deviation is 1.1% at 17.5 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (n=4)

$e^- + H(1s) \rightarrow e^- + H^*(n=4)$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

1.1.9. $e^- + H(1s) \rightarrow e^- + H^*(n=5)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.40E+01	2.22E+08	4.62E−18
2.00E+01	2.65E+08	5.99E−18
4.00E+01	3.75E+08	4.36E−18
6.00E+01	4.59E+08	3.21E−18
8.00E+01	5.30E+08	2.58E−18
1.00E+02	5.93E+08	2.20E−18
2.00E+02	8.39E+08	1.33E−18
4.00E+02	1.19E+09	7.77E−19
6.00E+02	1.45E+09	5.69E−19
8.00E+02	1.68E+09	4.56E−19
1.00E+03	1.88E+09	3.79E−19
2.00E+03	2.65E+09	2.12E−19
4.00E+03	3.75E+09	1.19E−19
6.00E+03	4.59E+09	8.37E−20
8.00E+03	5.30E+09	6.52E−20
1.00E+04	5.93E+09	5.37E−20

Threshold energy: $E_{th} = \Delta E = 13.06$ eV

Accuracy: $E < 40$ eV : 30-60 %; $40 \leq E$ (eV) ≤ 80 : 10-30 %; $E > 80$ eV : 10 %, or better

Comments: (1) In the derivation of the 1s → n=5 recommended cross section we have used the orthoganalized Born-Oppenheimer calculations of Shevelko [13], the Born-Rudge calculations of Ref. [16] (available for the 1s → 5s and 1s → 5p transitions and in the energy range below approximately 100 eV) and the R-matrix data of Aggarwal et al [60]. For $E \geq 80$ eV the recommended cross section is based on Ref. [13], while for $E < 80$ eV, the data of Morrison and Rudge [16] were used, complemented with the contributions for the 1s → 5d, 5f transitions taken from Ref. [13], as well as the R-matrix data of Aggarwal et al [60].

(2) The 1s → n=5 cross section calculated from the semi-empirical formula of Johnson [18] is in agreement with the recommended cross section to within 20 - 50 % in the region $E \leq 50$ eV, and for higher energies it approaches the recommended cross section (the two being identical for E larger than 300 eV).

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E} \right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X \right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

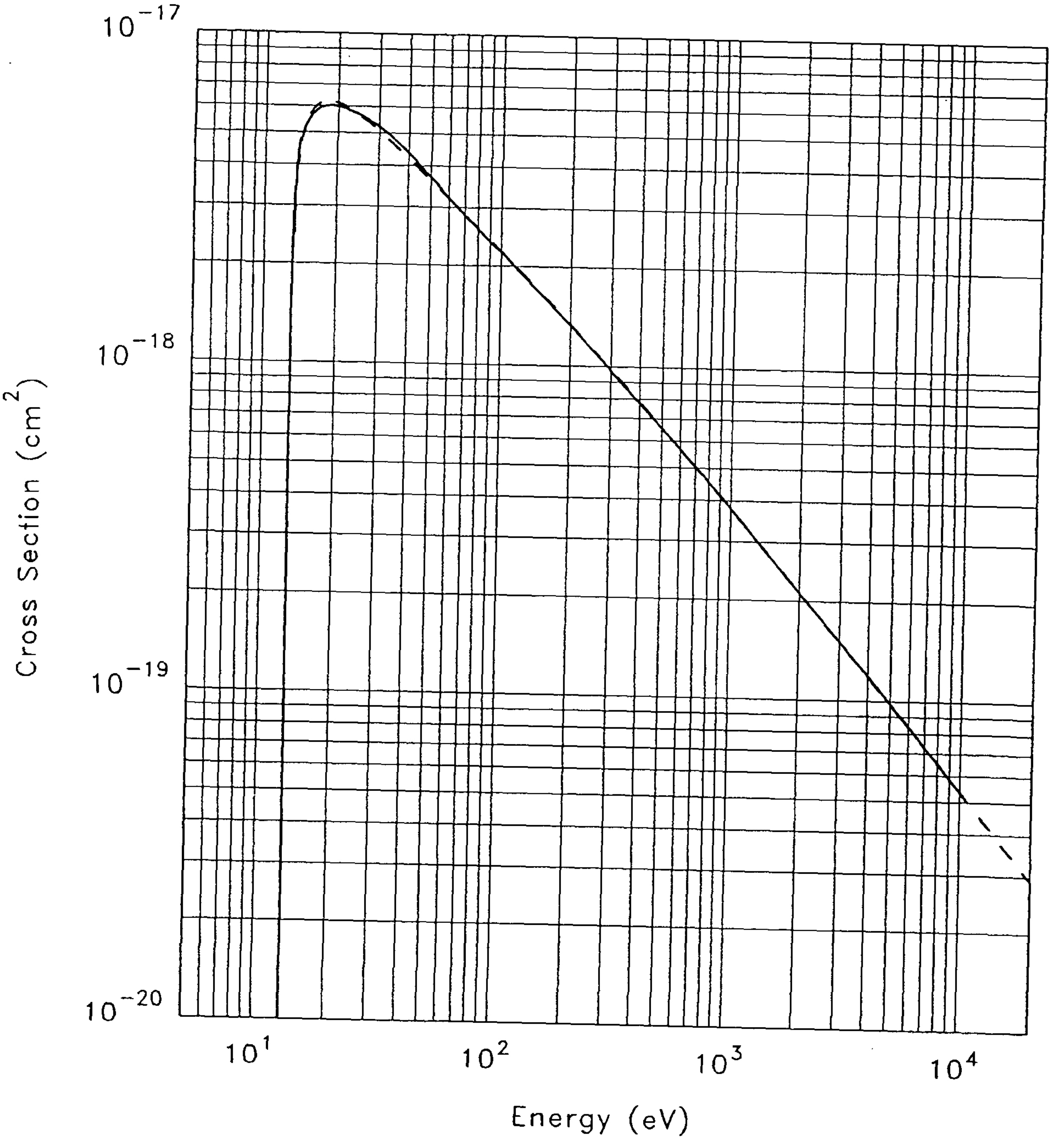
A_1	A_2	A_3	A_4	A_5	A_6
0.13092	0.23581	0.0	0.0	0.11508	0.45929

The rms deviation of the above fit to the recommended cross section is 1.9%. The maximum deviation is 9.8% at 13.4 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (n=5)

$e^- + H(1s) \rightarrow e^- + H^*(n=5)$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

1.1.10. $e^- + H(1s) \rightarrow e^- + H^*(n), n>5$

Energy (eV)	Velocity (cm/s)	Cross sections (cm^2) 1s → n=6	1s → n=8	1s → n=10
1.35E+01	2.18E+08	5.52E−19	2.13E−19	1.05E−19
2.00E+01	2.65E+08	1.13E−18	4.55E−19	2.28E−19
4.00E+01	3.75E+08	1.55E−18	6.32E−19	3.18E−19
6.00E+01	4.59E+08	1.50E−18	6.09E−19	3.07E−19
8.00E+01	5.30E+08	1.36E−18	5.53E−19	2.79E−19
1.00E+02	5.93E+08	1.22E−18	4.97E−19	2.50E−19
2.00E+02	8.39E+08	7.77E−19	3.16E−19	1.59E−19
4.00E+02	1.19E+09	4.58E−19	1.86E−19	9.38E−20
6.00E+02	1.45E+09	3.32E−19	1.35E−19	6.79E−20
8.00E+02	1.68E+09	2.63E−19	1.07E−19	5.38E−20
1.00E+03	1.88E+09	2.19E−19	8.90E−20	4.48E−20
2.00E+03	2.65E+09	1.23E−19	4.99E−20	2.51E−20
4.00E+03	3.75E+09	6.82E−20	2.77E−20	1.39E−20
6.00E+03	4.59E+09	4.81E−20	1.95E−20	9.79E−21
8.00E+03	5.30E+09	3.74E−20	1.52E−20	7.63E−21
1.00E+04	5.93E+09	3.08E−20	1.25E−20	6.27E−21

Threshold energy: $E_{th} = \Delta E_n = 13.6 \left(1 - 1/n^2\right)$, eV

Accuracy: $E < 40$ eV : 40-80 %; $40 \le E$ (eV) ≤ 100 : 20-40 %; $E > 100$ eV : 20 %, or better

Comments: (1) For the 1s → n ≥ 6 excitation cross sections the semi-empirical formula of Johnson [18] is recommended. This formula generates cross sections which in the region E ≥ 100 eV, agree to within 5% with the orthogonalized Born-exchange calculations of Shevelko [13] for n = 6 and 7, and in the region E < 100 eV these cross sections agree to within 5 - 10% with the results of the Born-Rudge approximation, Ref. [16], for n = 10. The ascribed uncertainties for E < 100 eV reflect the uncertainty of the Born-Rudge approximation in this region (estimated on the basis of the n ≤ 5 cross sections).

(2) The general semi-empirical formula of Vriens and Smeets [19] gives results which are consistently smaller than both the recommended cross sections for n ≤ 5 and the results of Johnson's formula for n ≥ 3. For E ≤ 100 eV, the cross sections from Vriens and Smeets formula are by a factor of 1.5 - 3 too small with respect to the recommended cross sections, and only for E ≥ 2 keV they become consistent with the recommended ones.

Analytic expression

Cross Section:

$$\sigma_{exc}(1 \rightarrow n) = \frac{1.76 \times 10^{-16}}{y_n X_n} \left[1 - \exp(-r\, y_n X_n)\right] \times$$

$$\left[A_n \left(\ln X_n + \frac{1}{2X_n}\right) + \left(B_n - A_n \ln \frac{2}{y_n}\right)\left(1 - \frac{1}{X_n}\right)\right] \; [\mathrm{cm}^2],$$

$$y_n = 1 - \left(\frac{1}{n}\right)^2, \qquad X_n = \frac{E\,(\mathrm{eV})}{\Delta E_n}, \qquad r = 0.45,$$

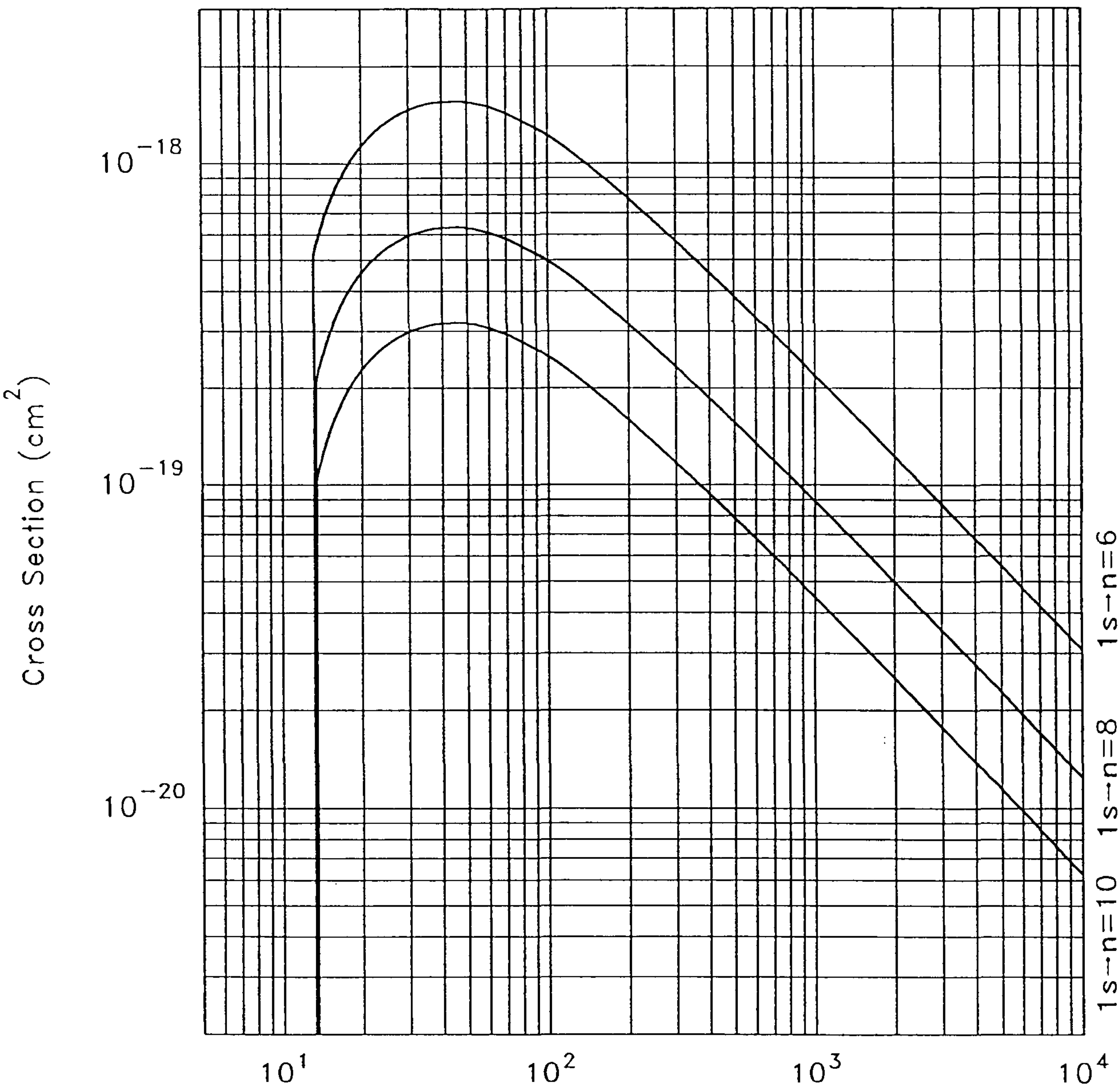
$$A_n = \frac{2 n^2 f_{1n}}{y_n}, \quad (f_{nm} : \text{oscillator strength; see Appendix A.1})$$

$$B_n = \frac{2}{3} n^2 (5 + b_n), \quad b_n = \frac{1}{n}\left(4.0 - \frac{18.63}{n} + \frac{36.24}{n^2} - \frac{28.09}{n^3}\right)$$

ALADDIN evaluation function for cross section: EEXCJN

ALADDIN hierarchical labelling: EXC e H [+0] (1s) e H [+0] (n > 5)

$$e^- + H(1s) \rightarrow e^- + H^*(n),\ n>5$$



Legend:

—— Recommended Cross Section

1.1.11. $e^- + H^*(n=2) \rightarrow e^- + H^*(m=3)$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
2.00E+00	8.39E+07	2.73E−15
4.00E+00	1.19E+08	2.91E−15
6.00E+00	1.45E+08	3.03E−15
8.00E+00	1.68E+08	3.40E−15
1.00E+01	1.88E+08	3.57E−15
2.00E+01	2.65E+08	2.87E−15
4.00E+01	3.75E+08	1.78E−15
6.00E+01	4.59E+08	1.34E−15
8.00E+01	5.30E+08	1.10E−15
1.00E+02	5.93E+08	9.32E−16
2.00E+02	8.39E+08	5.45E−16
4.00E+02	1.19E+09	3.17E−16
6.00E+02	1.45E+09	2.28E−16
8.00E+02	1.68E+09	1.80E−16
1.00E+03	1.88E+09	1.50E−16
2.00E+03	2.65E+09	8.32E−17
4.00E+03	3.75E+09	4.55E−17
6.00E+03	4.59E+09	3.21E−17
8.00E+03	5.30E+09	2.50E−17
1.00E+04	5.93E+09	2.04E−17

Threshold energy: $E_{th} = \Delta E = 1.889$ eV

Accuracy: $E < 30$ eV : 20-40 %; $30 \leq E$ (eV) < 80 : 10-20 %; $E \geq 80$ eV : 10 %, or better

Comments: (1) For energies above 80 eV, the 18 state (7 bound + 11 pseudostates) CC-calculations of Callaway et al [1], extended by the unitarized Born-exchange calculations, are in agreement with the results of the orthogonalized Born-Oppenheimer approximation of Shevelko [13].

(2) In the region $30 \leq E(eV) < 80$, the data of Ref. [1] are supported by the CC-pseudostate and unitarized Born calculations of Whelan et al [14] and Edmunds et al [17]. The recommended cross section in this region is that of Callaway et al [1].

(3) For energies below 30 eV, data are available from the orthogonalized Born-Oppenheimer calculations of Ref [13], variational CC calculations of Hata et al [20] (for $E \leq 2.45$ eV), the 18-state CC calculations of Callaway et al [1] (see also the errata in Ref. [61]) and 15-state R-matrix calculations of Aggarwal et al [60]. The recommended cross section in this region follows the data of Refs. [1] and [60].

Analytic fitting function

Cross section:

$$\sigma_{exc} = \frac{5.984 \times 10^{-16}}{\Delta E\, X} \left[\frac{E - \Delta E}{E}\right]^{A_6} \left[\sum_{j=1}^{4} \frac{A_j}{X^{j-1}} + A_5 \ln X\right] \quad [cm^2],$$

where $X = E/\Delta E$, and ΔE and E are expressed in eV.

Fitting coefficients

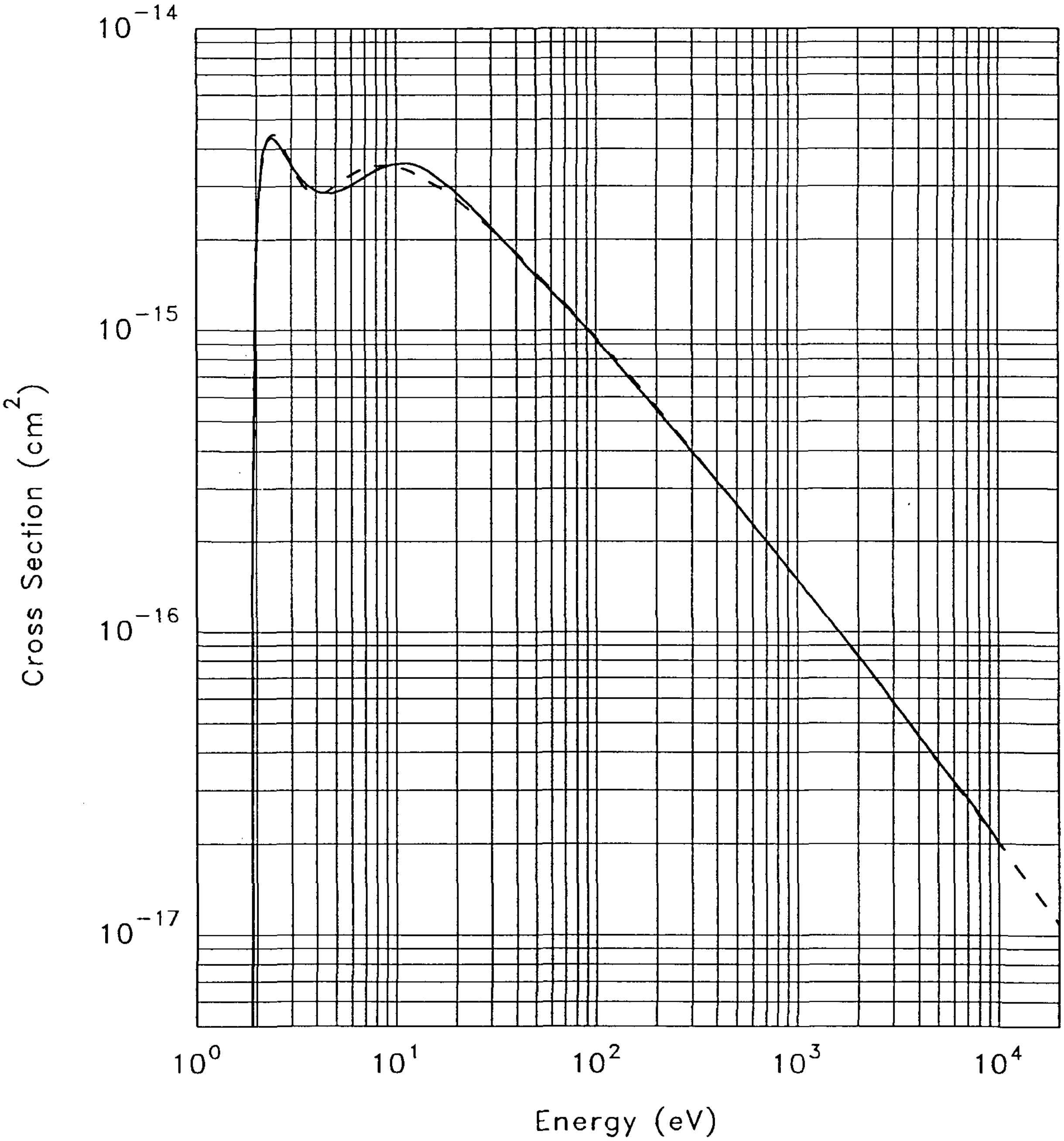
A_1	A_2	A_3	A_4	A_5	A_6
5.2373	119.25	−595.39	816.71	38.906	1.3196

The rms deviation of the above fit to the recommended cross section is 2.4%. The maximum deviation is 8.2% at 6.02 eV.

ALADDIN evaluation function for cross section: NEEXH2

ALADDIN hierarchical labelling: EXC e H [+0] (n=2) e H [+0] (m=3)

$$e^- + H^*(n=2) \rightarrow e^- + H^*(m=3)$$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

1.1.12. $e^- + H^*(n) \rightarrow e^- + H^*(m)$, $n > 1$, $m > n$

Energy (eV)	Velocity (cm/s)	Cross sections (cm^2) n=2 → m=4	n=2 → m=5	n=2 → m=6
4.00E+00	1.19E+08	5.81E−16	1.90E−16	8.56E−17
6.00E+00	1.45E+08	7.31E−16	2.62E−16	1.26E−16
8.00E+00	1.68E+08	7.56E−16	2.78E−16	1.36E−16
1.00E+01	1.88E+08	7.38E−16	2.73E−16	1.34E−16
2.00E+01	2.65E+08	5.51E−16	2.05E−16	1.01E−16
4.00E+01	3.75E+08	3.40E−16	1.26E−16	6.19E−17
6.00E+01	4.59E+08	2.49E−16	9.15E−17	4.50E−17
8.00E+01	5.30E+08	1.98E−16	7.26E−17	3.56E−17
1.00E+02	5.93E+08	1.66E−16	6.05E−17	2.96E−17
2.00E+02	8.39E+08	9.36E−17	3.39E−17	1.65E−17
4.00E+02	1.19E+09	5.22E−17	1.88E−17	9.12E−18
6.00E+02	1.45E+09	3.68E−17	1.32E−17	6.40E−18
8.00E+02	1.68E+09	2.87E−17	1.03E−17	4.98E−18
1.00E+03	1.88E+09	2.37E−17	8.44E−18	4.09E−18
2.00E+03	2.65E+09	1.29E−17	4.58E−18	2.21E−18
4.00E+03	3.75E+09	6.97E−18	2.46E−18	1.19E−18
6.00E+03	4.59E+09	4.86E−18	1.71E−18	8.24E−19
8.00E+03	5.30E+09	3.75E−18	1.32E−18	6.35E−19
1.00E+04	5.93E+09	3.07E−18	1.08E−18	5.19E−19

Threshold Energy: $E_{th} = \Delta E_{nm} = 13.6 \left(1/n^2 - 1/m^2\right)$, eV

Accuracy: $E < 30\,\Delta E_{nm}$: indeterminate; $30\,\Delta E_{nm} \le E < 80\,\Delta E_{nm}$: 20-60 %; $E \ge 80\,\Delta E_{nm}$: 10−20%

Comments: The semi-empirical formulae of Johnson [18] is taken as the recommendation for the cross sections for the $n \rightarrow m$ ($n > 1, m > n$) transitions, excluding $n=2 \rightarrow m=3$ for which a separate cross section has been recommended (see preceeding reaction). This semi-empirical formula correctly reproduces the results of the Born approximation at energies above $80\,\Delta E_{nm}$ eV for a large number of $n \rightarrow m$ transitions from Omidvar [21], and in the region $30\Delta E_{nm} \le E < 80\Delta E_{nm}$ it is consistent to within 20 - 60% with the impact-parameter calculations of Saraph [22] and the classical-model calculations of Percival and Richards [23]. Below approximately $30\Delta E_{nm}$, the Johnson formula for some transitions produces cross sections which are substantially (approximately a factor of 2 to 4) lower than the first Born cross sections. In this region, the semi-empirical formula of Vriens and Smeets [19] gives cross sections about a factor of two lower than those obtained from the formula of Johnson.

Analytic expression

Cross section:

$$\sigma_{exc}(n \rightarrow m) = \frac{1.76 \times 10^{-16}\, n^2}{y_{nm} X_{nm}} \left[1 - \exp\left(-r_n\, y_{nm} X_{nm}\right)\right] \times$$

$$\left[A_{nm}\left(\ln X_{nm} + \frac{1}{2X_{nm}}\right) + \left(B_{nm} - A_{nm} \ln \frac{2n^2}{y_{nm}}\right)\left(1 - \frac{1}{X_{nm}}\right)\right] [\mathrm{cm}^2],$$

$$y_{nm} = 1 - \left(\frac{n}{m}\right)^2, \quad X_{nm} = \frac{E\,(\mathrm{eV})}{\Delta E_{nm}}, \quad r_n = 1.94\, n^{-1.57},$$

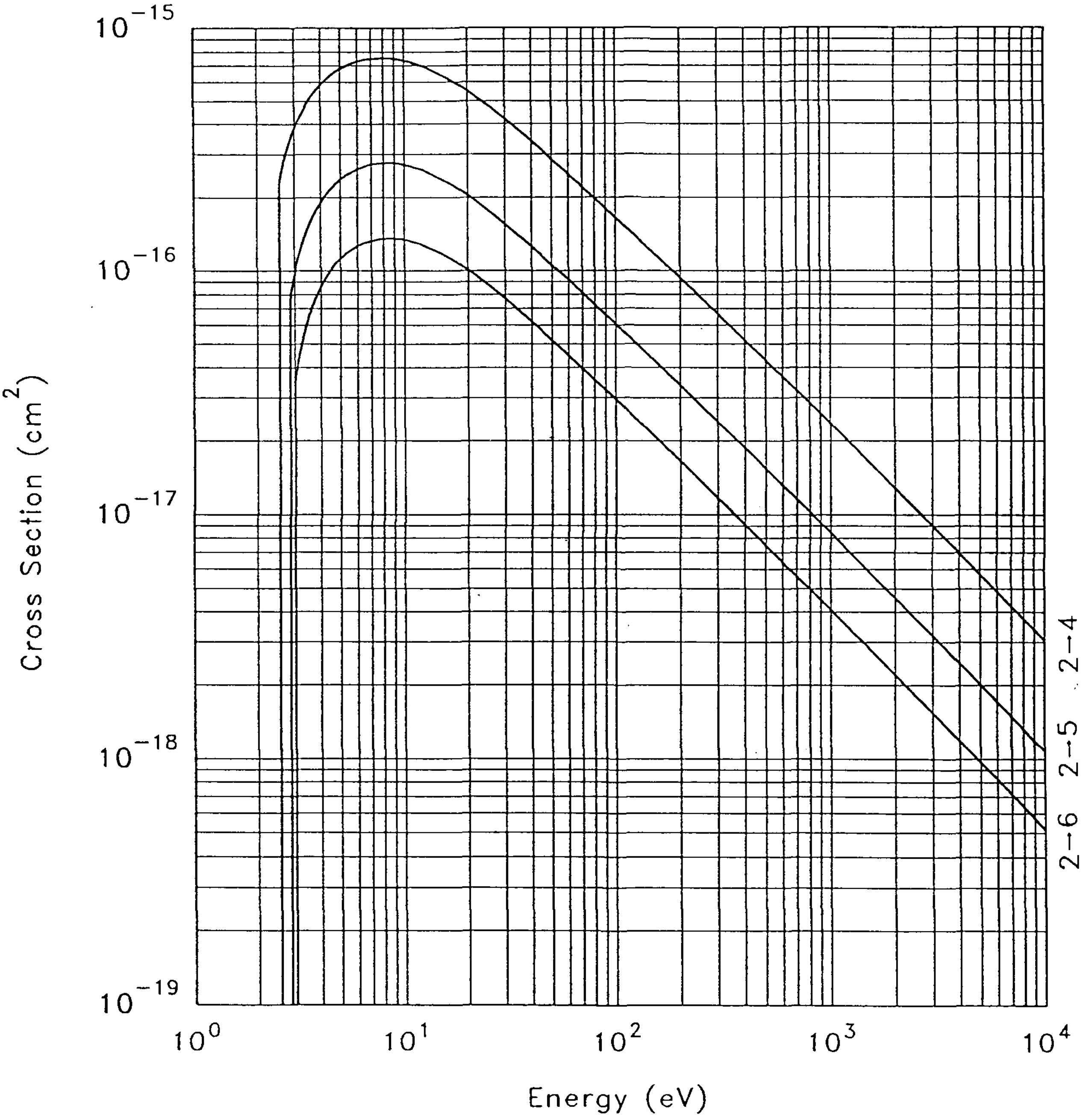
$$A_{nm} = \frac{2n^2 f_{nm}}{y_{nm}}, \quad (\, f_{nm} : \text{oscillator strength ; see Appendix A.1})$$

$$B_{nm} = \frac{4n^4}{m^3 y_{nm}^2}\left(1 + \frac{4}{3y_{nm}} + \frac{b_n}{y_{nm}^2}\right), \quad b_n = \frac{1}{n}\left(4.0 - \frac{18.63}{n} + \frac{36.24}{n^2} - \frac{28.09}{n^3}\right)$$

ALADDIN evaluation function for cross section: EEXCJN

ALADDIN hierarchical labelling: EXC e H [+0] (n>1) e H [+0] (m > n, m > 3)

$e^- + H^*(n) \rightarrow e^- + H^*(m),\ n>1,\ m>n$



Legend:

—— Recommended Cross Section

1. Electron Impact Processes

1.2. Ionization

1.2.1. $e^- + H(1s) \rightarrow e^- + H^+ + e^-$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
1.50E+01	2.30E+08	7.70E−18
2.00E+01	2.65E+08	2.96E−17
4.00E+01	3.75E+08	5.88E−17
6.00E+01	4.59E+08	6.19E−17
8.00E+01	5.30E+08	5.88E−17
1.00E+02	5.93E+08	5.51E−17
2.00E+02	8.39E+08	3.95E−17
4.00E+02	1.19E+09	2.41E−17
6.00E+02	1.45E+09	1.75E−17
8.00E+02	1.68E+09	1.39E−17
1.00E+03	1.88E+09	1.15E−17
2.00E+03	2.65E+09	6.26E−18
4.00E+03	3.75E+09	3.51E−18
6.00E+03	4.59E+09	2.43E−18
8.00E+03	5.30E+09	1.88E−18
1.00E+04	5.93E+09	1.53E−18

Threshold energy: $E_{th} = I = 13.6$ eV

Accuracy: 10 %, or better

Comments: (1) The recommended cross section for $E \leq 4$ keV is based on the recent crossed beams data of Shah et al [24], for which the absolute scale was determined by normalization at high energies to measurements of the electon removal cross section for protons incident on H(1s). At the cross section maximum, the Shah et al values are 17% smaller than the experimental data of Fite and Brackmann [25]. At energies above 200 eV, the two experimental cross sections are in good agreement with each other, and with the results from the Born-Ochkur approximation of Kyle and Omidvar [26] and the orthogonalized Born-Oppenheimer approximation of Shevelko [27].

(2) The present recommended cross section is an update to the cross section recommended by Bell et al [28], which was based on Fite and Brackmann's [25] experimental data.

(3) The expression for the analytic fit to the cross section has been taken in the same form as the one used by Bell et al [28] in their evaluation of electron impact ionization cross sections.

Analytic fitting function

Cross section:

$$\sigma_{ion} = \frac{10^{-13}}{IE} \left[A \ln\left(\frac{E}{I}\right) + \sum_{j=1}^{5} B_j \left(1 - \frac{I}{E}\right)^j \right] \quad [cm^2]$$

where the parameter A is a Bethe coefficient, determined from fitting the high energy cross section with the expression

$$\sigma_{ion} = \frac{10^{-13}}{IE} \left[A \ln(E) + B \right] \quad [cm^2] ,$$

where I and E are expressed in eV.

Fitting parameters

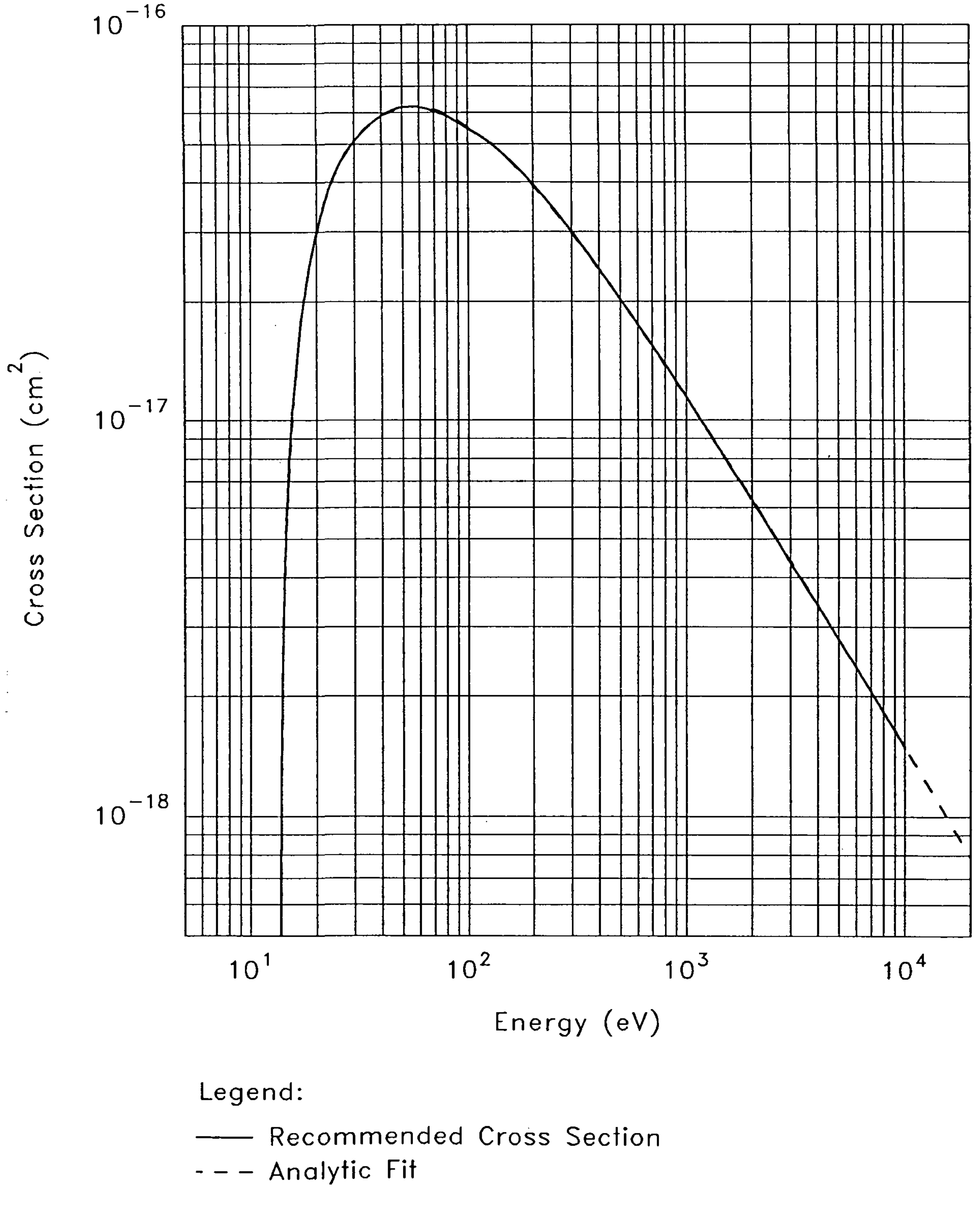
A	B_1	B_2	B_3	B_4	B_5
0.18450	−0.032226	−0.034539	1.4003	−2.8115	2.2986

The rms deviation of the above fit to the recommended cross section is 1.3 %. The maximum deviation is 4.4% at 17.2 eV.

ALADDIN evaluation function for cross section: BELI

ALADDIN hierarchical labelling: ION e H [+0] (1s) e H [+1] e

$e^- + H(1s) \rightarrow e^- + H^+ + e^-$



1.2.2. $e^- + H^*(2s) \rightarrow e^- + H^+ + e^-$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
4.00E+00	1.19E+08	1.09E−16
6.00E+00	1.45E+08	6.19E−16
8.00E+00	1.68E+08	8.42E−16
1.00E+01	1.88E+08	9.35E−16
2.00E+01	2.65E+08	8.59E−16
4.00E+01	3.75E+08	5.78E−16
6.00E+01	4.59E+08	4.34E−16
8.00E+01	5.30E+08	3.50E−16
1.00E+02	5.93E+08	2.99E−16
2.00E+02	8.39E+08	1.78E−16
4.00E+02	1.19E+09	1.01E−16
6.00E+02	1.45E+09	7.14E−17
8.00E+02	1.68E+09	5.58E−17
1.00E+03	1.88E+09	4.60E−17
2.00E+03	2.65E+09	2.53E−17
4.00E+03	3.75E+09	1.35E−17
6.00E+03	4.59E+09	9.32E−18
8.00E+03	5.30E+09	7.19E−18
1.00E+04	5.93E+09	5.82E−18

Threshold energy: $E_{th} = I = 3.4$ eV

Accuracy: $E < 10$ eV : 15-40 %; $10 \leq E$ (eV) < 40 : 10-15 %; $E \geq 40$ eV : 10 %, or better

Comments: (1) The only experimental results for the electron impact ionisation of H(2s) are from the crossed beams measurements of Dixon et al [29] and Koller [30]. The data of Koller [30] cover the energy range from 3.5 to 9.2 eV and have a large absolute uncertainty. The data of Dixon et al [29] cover the energy range from 8.4 to 498.5 eV with only systematic errors quoted of 9 - 13 % for $E \leq 13.5$ eV, and 6 % for higher energies. In the small energy range in which these two experimental datasets overlap, the cross sections are in good accord.

(2) Theoretical results are available from the Born-Ochkur approximations of Prasad [31] and Kyle and Omidvar [26], and from the orthogonalized Born-Oppenheimer approximation of Shevelko [27], and all these data are in consistent accord with each over.

(3) For $E \leq 150$ eV, the recommended cross section is based on the experimental data, and for higher energies, it is based on theoretical calculations.

Analytic fitting function

Cross section:

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln\left(\frac{E}{I}\right) + \sum_{j=1}^{5} B_j \left(1 - \frac{I}{E}\right)^j\right] \quad [cm^2]$$

where the parameter A is a Bethe coefficient, determined from fitting the high energy cross section with the expression

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln(E) + B\right] \quad [cm^2],$$

where I and E are expressed in eV.

Fitting parameters

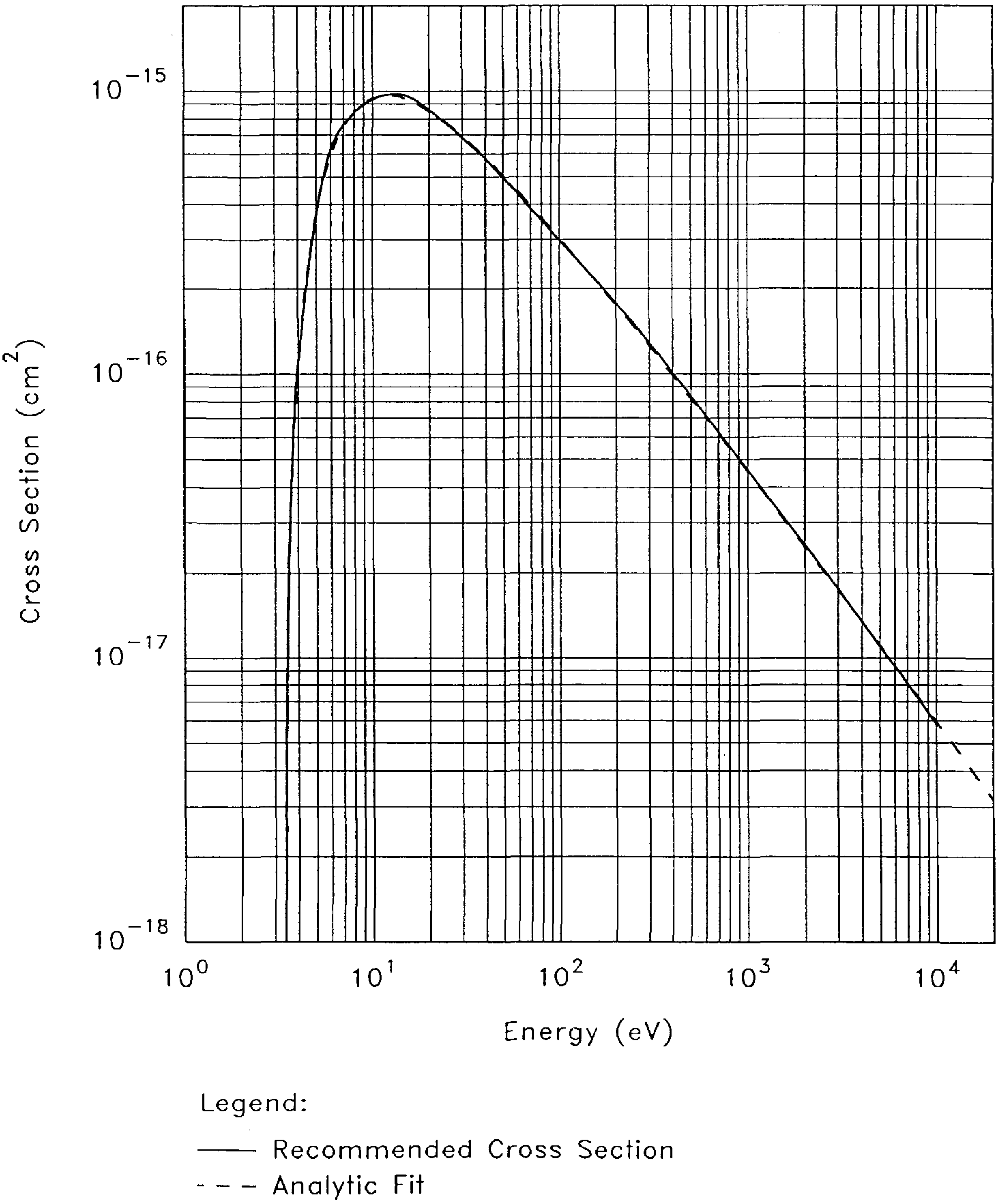
A	B_1	B_2	B_3	B_4	B_5
0.20901	−0.16481	0.13873	0.73025	−0.34957	0.0

The rms deviation of the above fit to the recommended cross section is 2.1 %. The maximum deviation is 6.9% at 3.8 eV.

ALADDIN evaluation function for cross section: BELI

ALADDIN hierarchical labelling: ION e H [+0] (2s) e H [+1] e

$$e^- + H^*(2s) \rightarrow e^- + H^+ + e^-$$



1.2.3. $e^- + H^*(2p) \rightarrow e^- + H^+ + e^-$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
4.00E+00	1.19E+08	2.53E−16
6.00E+00	1.45E+08	9.23E−16
8.00E+00	1.68E+08	1.17E−15
1.00E+01	1.88E+08	1.24E−15
2.00E+01	2.65E+08	1.04E−15
4.00E+01	3.75E+08	6.72E−16
6.00E+01	4.59E+08	4.93E−16
8.00E+01	5.30E+08	3.89E−16
1.00E+02	5.93E+08	3.25E−16
2.00E+02	8.39E+08	1.81E−16
4.00E+02	1.19E+09	9.96E−17
6.00E+02	1.45E+09	6.81E−17
8.00E+02	1.68E+09	5.17E−17
1.00E+03	1.88E+09	4.24E−17
2.00E+03	2.65E+09	2.25E−17
4.00E+03	3.75E+09	1.20E−17
6.00E+03	4.59E+09	8.40E−18
8.00E+03	5.30E+09	6.48E−18
1.00E+04	5.93E+09	5.29E−18

Threshold energy: $E_{th} = I = 3.4$ eV

Accuracy: $E < 10$ eV : 15-40 %; $10 \leq E$ (eV) < 40 : 10-15 %; $E \geq 40$ eV : 10 %, or better

Comments: (1) For ionisation from H(2p) there are no experimental data available. Theoretical results are available from the Born-Ockhur approximations of Prasad [31] and Kyle and Omidvar [26] and from the first Born approximation of Omidvar [32] and Kingston [33]. The recommended cross section has been based on these calculations.

(2) The analogous calculations for the case of H(2s) ionisation agree with the experimental cross sections within the stated accuracies (see the comments for the $\sigma_{ion}(2s)$) , and this has been taken as a criterion for the estimation of the $\sigma_{ion}(2p)$ cross section.

Analytic fitting function

Cross section:

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln\left(\frac{E}{I}\right) + \sum_{j=1}^{5} B_j \left(1 - \frac{I}{E}\right)^j \right] \quad [cm^2]$$

where the parameter A is a Bethe coefficient, determined from fitting the high energy cross section with the expression

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln(E) + B \right] \quad [cm^2] ,$$

where I and E are expressed in eV.

Fitting parameters

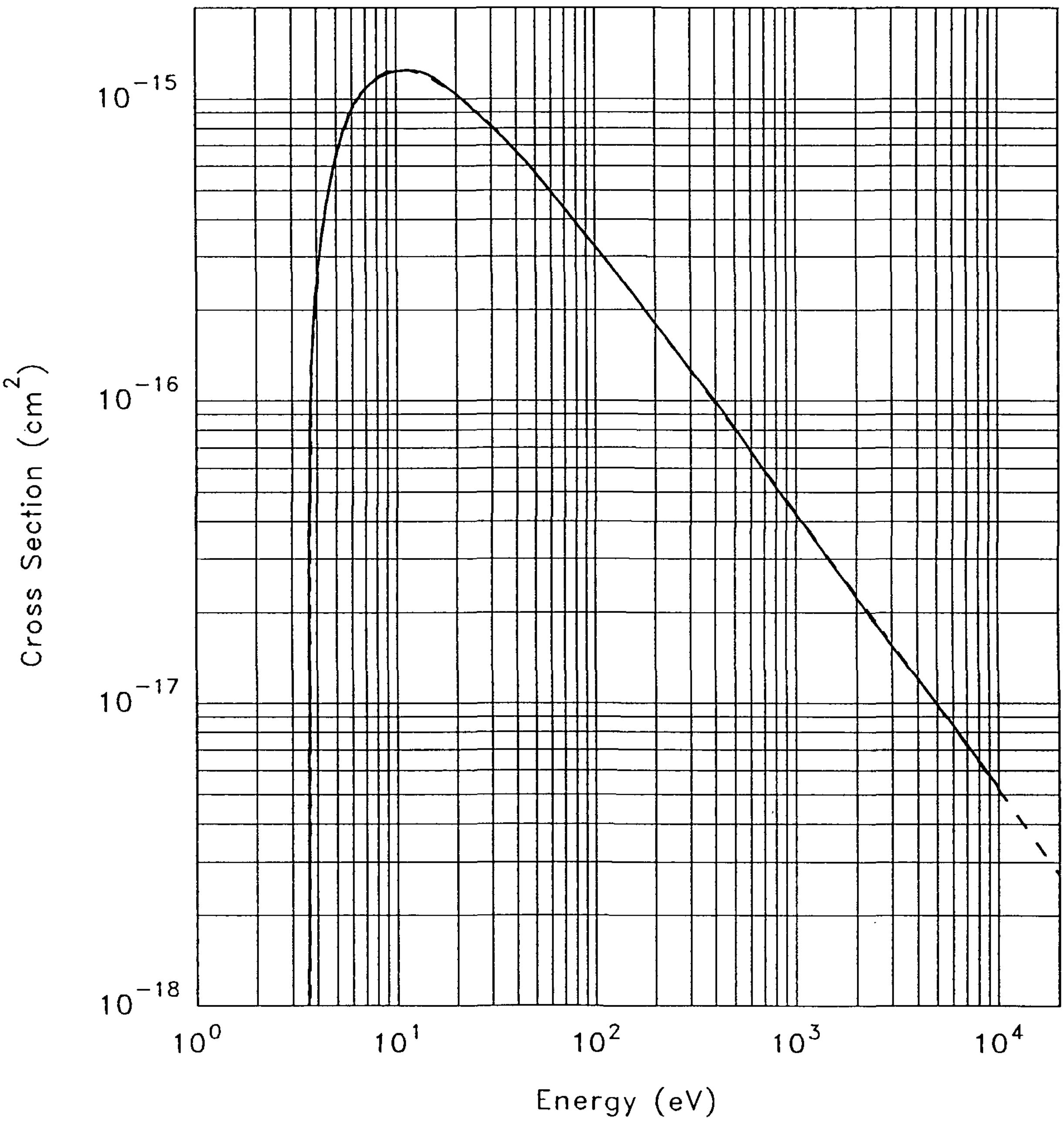
A	B_1	B_2	B_3	B_4	B_5
0.13197	0.033285	0.21332	1.0058	−0.83918	0.29989

The rms deviation of the above fit to the recommended cross section is 1.1%. The maximum deviation is 1.9% at 15.1 eV.

ALADDIN evaluation function for cross section: BELI

ALADDIN hierarchical labelling: ION e H [+0] (2p) e H [+1] e

$$e^- + H^*(2p) \rightarrow e^- + H^+ + e^-$$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

1.2.4. $e^- + H^*(n=2) \rightarrow e^- + H^+ + e^-$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
4.00E+00	1.19E+08	2.19E−16
6.00E+00	1.45E+08	8.51E−16
8.00E+00	1.68E+08	1.08E−15
1.00E+01	1.88E+08	1.16E−15
2.00E+01	2.65E+08	9.92E−16
4.00E+01	3.75E+08	6.49E−16
6.00E+01	4.59E+08	4.83E−16
8.00E+01	5.30E+08	3.84E−16
1.00E+02	5.93E+08	3.20E−16
2.00E+02	8.39E+08	1.80E−16
4.00E+02	1.19E+09	1.00E−16
6.00E+02	1.45E+09	6.89E−17
8.00E+02	1.68E+09	5.28E−17
1.00E+03	1.88E+09	4.33E−17
2.00E+03	2.65E+09	2.32E−17
4.00E+03	3.75E+09	1.24E−17
6.00E+03	4.59E+09	8.64E−18
8.00E+03	5.30E+09	6.67E−18
1.00E+04	5.93E+09	5.43E−18

Threshold energy: $E_{th} = I = 3.4$ eV

Accuracy: E < 10 eV : 15-40 %; 10 ≤ E (eV) < 40 : 10-15 %; E ≥ 40 eV : 10 %, or better

Comments: (1) The average ionization cross section for the n = 2 level has been calculated from the recommended 2s and 2p ionization cross sections. The above accuracies correspond to the estimated accuracies of the constituent cross sections.

(2) We note that the cross section generated from the semi-empirical formula of Johnson [18] agrees well with the first Born cross sections of Omidvar [32] and Kingston [33] for energies above 100 eV (E approximately 30 E_{th}), and in the region around the cross section maximum it is about 50% lower.

Analytic fitting function

Cross section:

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln\left(\frac{E}{I}\right) + \sum_{j=1}^{5} B_j \left(1 - \frac{I}{E}\right)^j \right] \quad [cm^2]$$

where the parameter A is a Bethe coefficient, determined from fitting the high energy cross section with the expression

$$\sigma_{ion} = \frac{10^{-13}}{IE}\left[A \ln(E) + B \right] \quad [cm^2] ,$$

where I and E are expressed in eV.

Fitting parameters

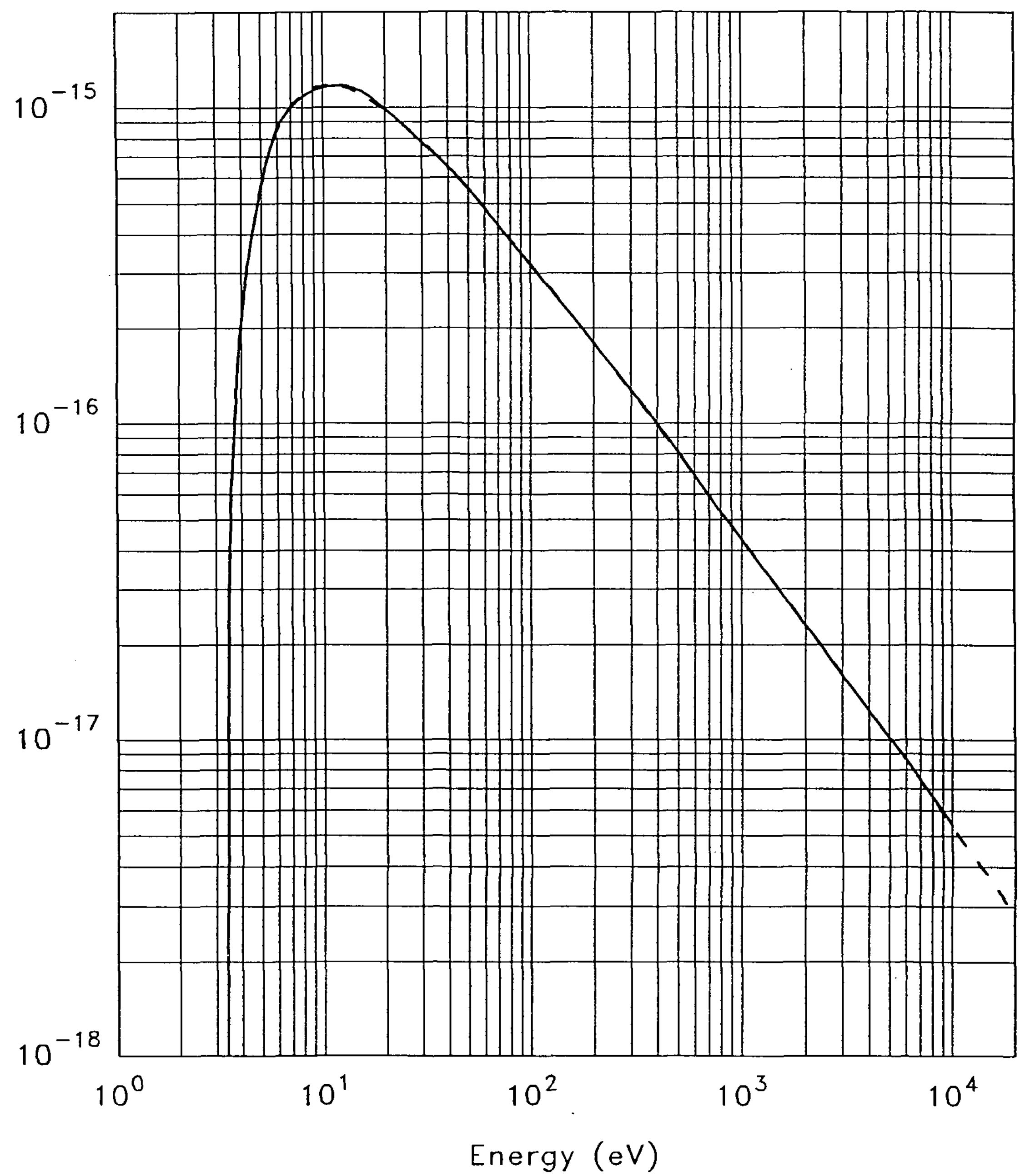
A	B_1	B_2	B_3	B_4	B_5
0.14784	0.0080871	−0.062270	1.9414	−2.1980	0.95894

The rms deviation of the above fit to the recommended cross section is 1.0%. The maximum deviation is 2.4% at 4.5 eV.

ALADDIN evaluation function for cross section: BELI

ALADDIN hierarchical labelling: ION e H [+0] (n=2) e H [+1] e

$e^- + H^*(n=2) \rightarrow e^- + H^+ + e^-$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

1.2.5. $e^- + H^*(n=3) \rightarrow e^- + H^+ + e^-$

Energy (eV)	Velocity (cm/s)	Cross section (cm^2)
2.00E+00	8.39E+07	1.63E−15
4.00E+00	1.19E+08	5.51E−15
6.00E+00	1.45E+08	5.75E−15
8.00E+00	1.68E+08	5.33E−15
1.00E+01	1.88E+08	4.84E−15
2.00E+01	2.65E+08	3.12E−15
4.00E+01	3.75E+08	1.79E−15
6.00E+01	4.59E+08	1.26E−15
8.00E+01	5.30E+08	9.72E−16
1.00E+02	5.93E+08	7.93E−16
2.00E+02	8.39E+08	4.17E−16
4.00E+02	1.19E+09	2.17E−16
6.00E+02	1.45E+09	1.48E−16
8.00E+02	1.68E+09	1.12E−16
1.00E+03	1.88E+09	9.09E−17
2.00E+03	2.65E+09	4.69E−17
4.00E+03	3.75E+09	2.41E−17
6.00E+03	4.59E+09	1.63E−17
8.00E+03	5.30E+09	1.24E−17
1.00E+04	5.93E+09	1.00E−17

Threshold energy: $E_{th} = I = 1.511$ eV

Accuracy: $E < 4$ eV : 20-60 %; $4 \leq E$ (eV) < 30 : 10-20 %; $E \geq 30$ eV : 10 %, or better

Comments: (1) For ionization of the n = 3 level, calculations are available from the first Born approximation by Omidvar [32] and Kingston [33] up to 54.4 eV, and from the orthogonalized Born-Oppenheimer approximation by Shevelko [27]. The recommended cross section in the region above 30 eV is based on the first Born calculations, which can be smoothly extended to energies above 54.4 eV by the cross section obtained by the Johnson formula [18].

(2) In the region below 30 eV, the recommended cross section is based on the Johnson formula results (down to 8 eV), and on the orthogonalized Born-Oppenheimer approximation of Shevelko [27] (below 8 eV).

Analytic fitting function

Cross section:

$$\sigma_{ion} = \frac{10^{-13}}{I\,E}\left[A \ln\left(\frac{E}{I}\right) + \sum_{j=1}^{5} B_j \left(1 - \frac{I}{E}\right)^j\right] \quad [\mathrm{cm}^2]$$

where the parameter A is a Bethe coefficient, determined from fitting the high energy cross section with the expression

$$\sigma_{ion} = \frac{10^{-13}}{I\,E}\left[A \ln(E) + B\right] \quad [\mathrm{cm}^2]\ ,$$

where I and E are expressed in eV.

Fitting parameters

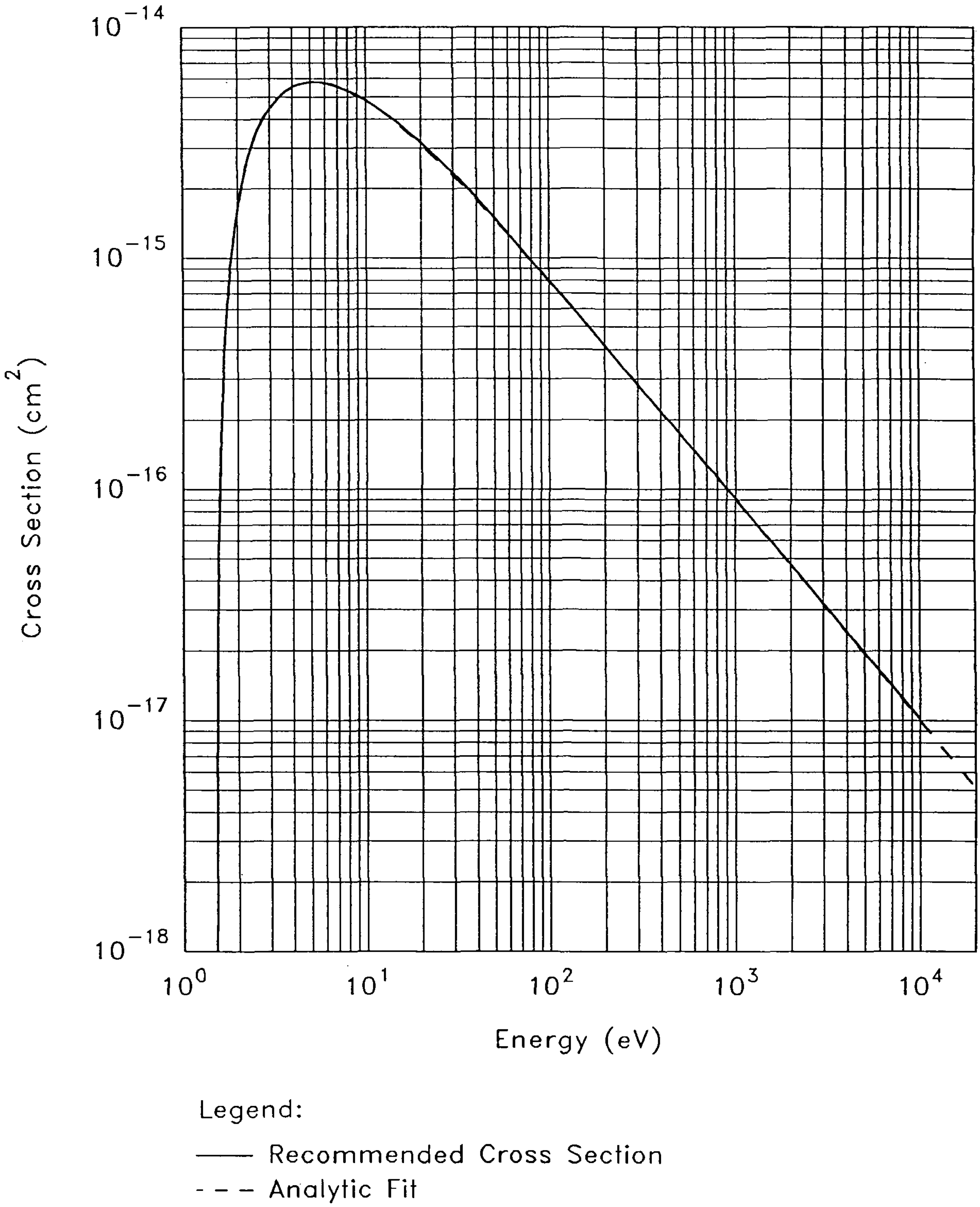
A	B_1	B_2	B_3	B_4	B_5
0.058463	−0.051272	0.85310	−0.57014	0.76684	0.0

The rms deviation of the above fit to the recommended cross section is 0.6%. The maximum deviation is 1.8% at 28.3 eV.

ALADDIN evaluation function for cross section: BELI

ALADDIN hierarchical labelling: ION e H [+0] (n=3) e H [+1] e

$e^- + H^*(n=3) \rightarrow e^- + H^+ + e^-$



1.2.6. $e^- + H^*(n) \rightarrow e^- + H^+ + e^-, n>3$

Energy (eV)	Velocity (cm/s)	Cross sections (cm^2) n=4	n=6	n=10
0.50E+00	4.19E+07		5.25E−15	1.47E−13
1.00E+00	5.93E+07	8.08E−16	2.96E−14	1.90E−13
2.00E+00	8.39E+07	8.68E−15	4.36E−14	1.87E−13
4.00E+00	1.19E+08	1.29E−14	4.23E−14	1.49E−13
6.00E+00	1.45E+08	1.26E−14	3.62E−14	1.17E−13
8.00E+00	1.68E+08	1.14E−14	3.07E−14	9.45E−14
1.00E+01	1.88E+08	1.02E−14	2.63E−14	7.84E−14
2.00E+01	2.65E+08	6.15E−15	1.45E−14	4.11E−14
4.00E+01	3.75E+08	3.31E−15	7.56E−15	2.09E−14
6.00E+01	4.59E+08	2.28E−15	5.13E−15	1.41E−14
8.00E+01	5.30E+08	1.74E−15	3.89E−15	1.06E−14
1.00E+02	5.93E+08	1.41E−15	3.14E−15	8.55E−15
2.00E+02	8.39E+08	7.30E−16	1.61E−15	4.33E−15
4.00E+02	1.19E+09	3.77E−16	8.20E−16	2.19E−15
6.00E+02	1.45E+09	2.55E−16	5.53E−16	1.47E−15
8.00E+02	1.68E+09	1.94E−16	4.18E−16	1.11E−15
1.00E+03	1.88E+09	1.56E−16	3.36E−16	8.92E−16
2.00E+03	2.65E+09	8.03E−17	1.71E−16	4.51E−16
4.00E+03	3.75E+09	4.12E−17	8.73E−17	2.28E−16
6.00E+03	4.59E+09	2.79E−17	5.88E−17	1.53E−16
8.00E+03	5.30E+09	2.11E−17	4.44E−17	1.15E−16
1.00E+04	5.93E+09	1.70E−17	3.57E−17	9.27E−17

Threshold energy: $E_{th} = I_n = 13.6/n^2$, eV

Accuracy: $E < 5 I_n$: 30-100%, or worse; $5 I_n \leq E < 20 I_n$: 10-30 %; $E \geq 20 I_n$: 10%

Comments: For the ionization of $n > 3$ levels the use of the semi-empirical formulae of Johnson [18] is recommended. At energies above (15-20) I_n the results of Johnsons's formula for all levels from $n=4$ to $n=10$ agree within 5 - 10 % with the first Born calcualtions of Omidvar [32] in the region of overlap. In the region $E < 20 I_n$ the results of the Johnson formula are consistent within the above specified uncertainties with the orthogonalized Born-Oppenheimer cross sections from Ref. [27].

Analytic expression

Cross section:

$$\sigma_{ion}(n) = \frac{1.76 \times 10^{-16}}{X_n} \left[1 - \exp(-r_n X_n) \right] \times$$

$$\left[A_n \ln X_n + \left(B_n - A_n \ln 2n^2 \right) \left(1 - \frac{1}{X_n} \right)^2 \right] \; [\mathrm{cm}^2],$$

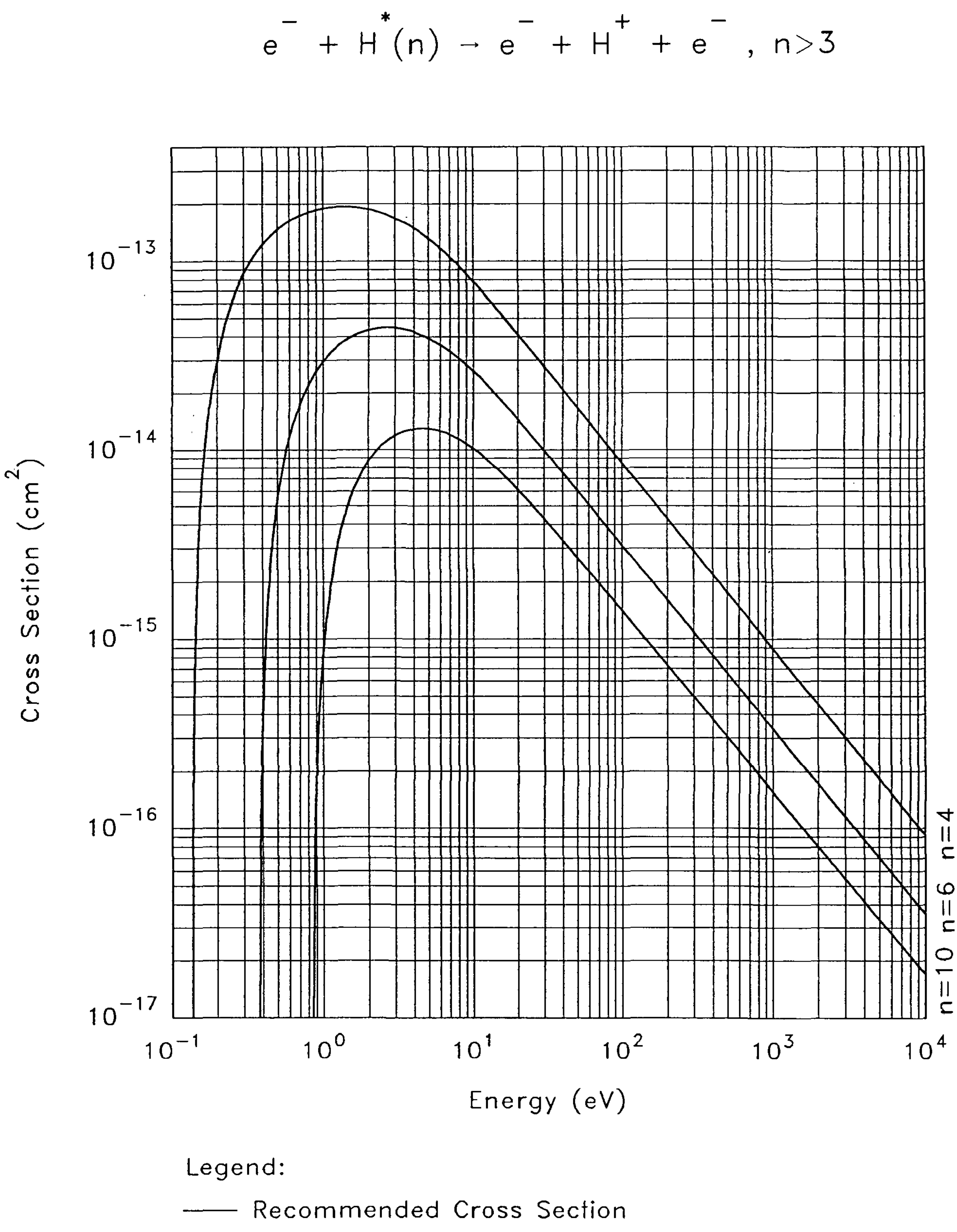
$$y_n = 1 - \left(\frac{1}{n} \right)^2, \qquad X_n = \frac{E\,(\mathrm{eV})}{I_n}, \qquad r_n = 1.94\, n^{-1.57},$$

$$A_n = \frac{2 n^2 f_{1n}}{y_n}, \quad (f_{nm} : \text{oscillator strength ; see Appendix A.1})$$

$$B_n = \frac{2}{3} n^2 (5 + b_n), \quad b_n = \frac{1}{n} \left(4.0 - \frac{18.63}{n} + \frac{36.24}{n^2} - \frac{28.09}{n^3} \right)$$

ALADDIN evaluation function for cross section: EIONJN

ALADDIN hierarchical labelling: ION e H [+0] (n>3) e H [+1] e



$e^- + H^*(n) \rightarrow e^- + H^+ + e^-$, n>3
Cross Section (cm^2)
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Energy (eV)
n=10 n=6 n=4
Legend:
—— Recommended Cross Section

2. Proton Impact Processes

2.1. Excitation

2.1.1. $H^+ + H(1s) \rightarrow H^+ + H^*(2s)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.16E−19
1.00E+03	4.39E+07	4.97E−19
2.00E+03	6.21E+07	1.65E−18
5.00E+03	9.82E+07	5.81E−18
1.00E+04	1.39E+08	4.48E−18
2.00E+04	1.96E+08	9.81E−18
5.00E+04	3.11E+08	1.45E−17
1.00E+05	4.39E+08	8.53E−18
2.00E+05	6.21E+08	4.47E−18
5.00E+05	9.82E+08	1.88E−18
1.00E+06	1.39E+09	9.65E−19
2.00E+06	1.96E+09	4.88E−19
5.00E+06	3.11E+09	1.96E−19

Accuracy: $E < 0.5$ keV/amu : Indeterminate; $0.5 \leq E$ (keV/amu) ≤ 25 : 20-30 % ;
$25 < E$ (keV/amu) < 200 : 10-20 % ; $E \geq 200$ keV/amu : 10 %, or better

Comments: (1) There are two experimental cross section measurements of this reaction in the region 5 - 26 keV/amu (Morgan et al [34] and Chong and Fite [35]). The data of Morgan et al are substantiated by the extensive multi-state (28-36) 3-center expansion calculations of Winter and Lin [36] and 40 AO (+ pseudostates) coupled-state calculations of Fritsch and Lin [37], which in the region 10 - 25 keV/amu agree with each other and with the experimental data to within 10 - 20 %. In the region 5 - 10 keV/amu all three sets of data agree to within 20 - 30 %.

(2) In the region 0.5 - 5 keV/amu, the 10 MO-coupled-state calculations of Kimura and Thorson [38], the 3-center expansion calculations of Winter and Lin [36], the calculations of Lüdde and Dreizler [39] based on solving the time-dependent Schrödinger equation, and the adiabatic calculations of Janev and Krstic [40] all agree to within 5 - 10 %. The assigned accuracy of 20 - 30 % for the recommended cross section may be too conservative.

(3) In the region 25 - 100 keV/amu, the recommended cross section is based on the 70-coupled hydrogenic orbitals calculation of Shakeshaft [41], 40 AO (+ pseudostates) coupled-state calculations of Fritsch and Lin [37], 53 one-center AO coupled-state calculations of Fitchard et al [42] and on the variational calculations of Brendlé et al [43] (at E = 50 and 100 keV/amu). For $E > 100$ keV/amu, the recommended cross section is based on the CPBA calcualtions of Saxena et al [44], the optical model calculations of Lüdde and Dreizler [45] and the FBA calculations of Mandal et al [46].

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)}{E} + \frac{A_3 \exp(-A_4 E)}{E^{A_5}} + \frac{A_6 \exp(-A_7/E)}{1 + A_8 E^{A_9}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

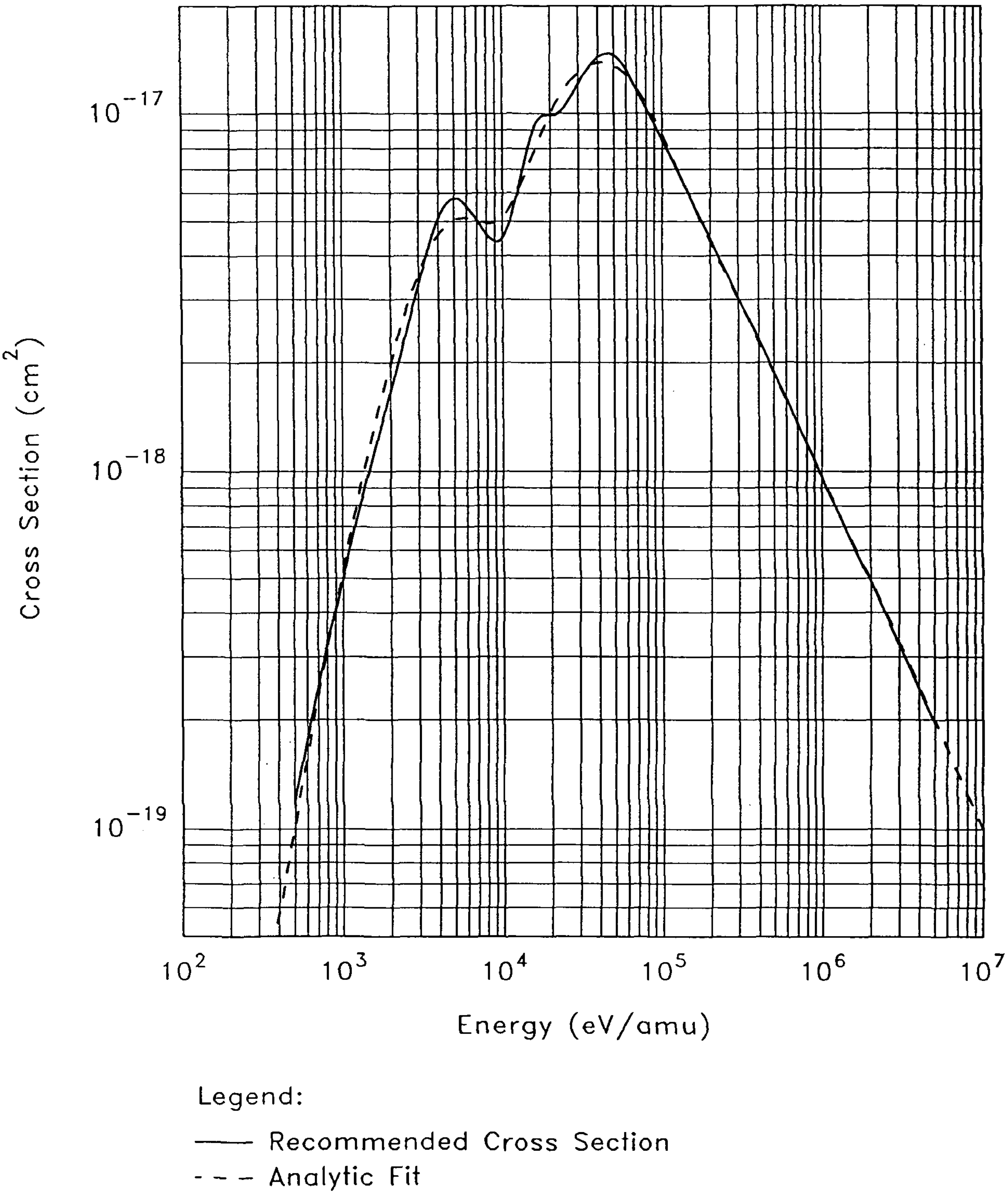
A_1 - A_5	10.082	45.483	9.5185E−04	0.60403	−2.7993
A_6 - A_9	8.7513E−03	12.125	1.1038E−06	3.1597	

The rms deviation of the above fit to the recommended cross section is 7.7%, with a maximum deviation of 21.8% at 2.0 keV/amu.

ALADDIN evaluation function for cross section: HEXC1

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (2s)

$H^+ + H(1s) \rightarrow H^+ + H^*(2s)$



$H^+ + H(1s) \rightarrow H^+ + H^*(2p)$

Energy (eV/amu)	Velocity (cm/s)	sross Section (cm^2)
6.00E+02	3.40E+07	5.60E−18
1.00E+03	4.39E+07	2.30E−17
2.00E+03	6.21E+07	2.89E−17
5.00E+03	9.82E+07	3.05E−17
1.00E+04	1.39E+08	2.35E−17
2.00E+04	1.96E+08	4.12E−17
5.00E+04	3.11E+08	8.57E−17
1.00E+05	4.39E+08	8.15E−17
2.00E+05	6.21E+08	5.94E−17
5.00E+05	9.82E+08	3.36E−17
1.00E+06	1.39E+09	1.99E−17
2.00E+06	1.96E+09	1.15E−17
5.00E+06	3.11E+09	5.30E−18

Accuracy: $E < 0.6$ keV/amu : Indeterminate ; $0.6 \le E$ (keV/amu) < 1 : 50-100 % ;
$1 \le E$ (keV/amu) < 15 : 20-30 % ; $15 \le E$ (keV/amu) < 70 : 15-20 % ;
$E \ge 70$ keV/amu : 12 %, or better

Comments: (1) For $E > 75$ keV/amu the recommended cross section is based on the experimental data of Schartner et al [47] (up to 700 keV/amu) and on the FBA calculations of Mandal et al [46] (which agree with the experiments for $E \ge 300$ keV/amu to within 2 - 5 %).

(2) In the region 30 - 70 keV/amu there are no experimental data and the recommended cross section was determined on the basis of coupled-state calculations of Fritsch and Lin [37] (40 AO + pseudostates), Shakeshaft [48] (24 Sturmian states), the 53 one-center AO coupled-state calculations of Fitchard et al [42], a variational data point at 50 keV/amu by Brendlé et al [43] and on the basis of its consistency with the properly normalized experimental total cross section for $n=2$ of Park et al [49].

(3) For $E = 0.6$ - 30 keV/amu, Lyman−alpha emmission cross section measurements are available from several groups (Morgan et al [34]; Kondow et al [50]; Stebbings et al [51]; Young et al [52]) which to within 5% (the cascading contribution) represent the excitation cross section. In the region ~ 2 - 30 keV/amu the data of Morgan et al [34] and Kondow et al [50] agree with each other, as well as with the elaborate coupled-state calculations of Shakeshaft [41] (70-hydrogenic AOs), Fritsch and Lin [37] (40 AOs + pseudostates), Winter and Lin [36] (28-36 states 3-center expansion), and Lüdde and Dreizler [39] (100-150 Hylleraas-type pseudostate expansion) to within 15 - 30 %.

(4) In the region below 1 keV/amu, the data of Young et al [52] and Stebbings et al [51] (at $E=0.6$ keV/amu) are consistent with each other to within 50 % but inconsistent with the last point of Kondow et al [50] (from deuteron impact) at $E=0.75$ keV/amu.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9 E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

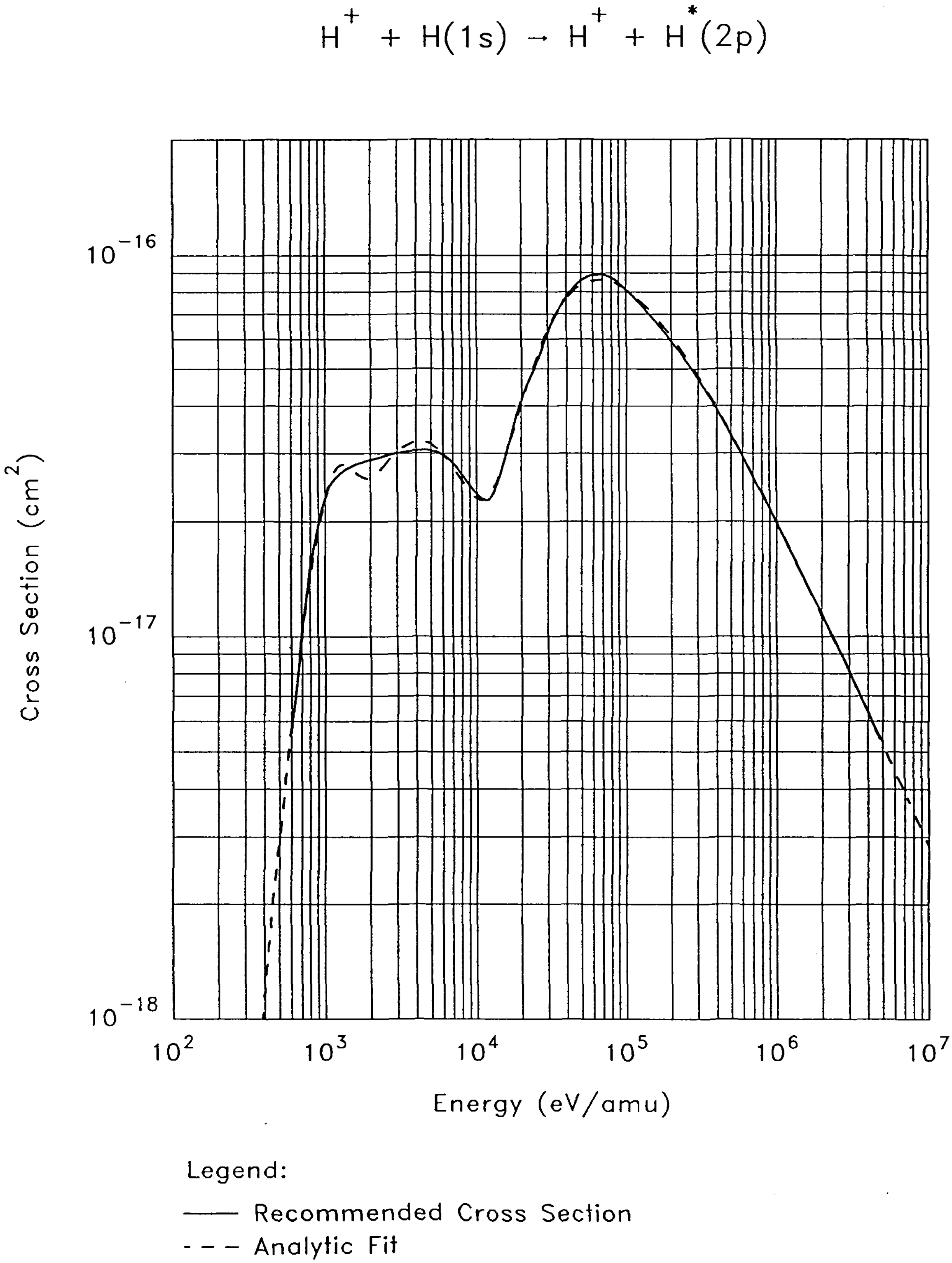
Fitting parameters

A_1 - A_5	33.777	48.717	0.49512	62.880	9.8099
A_6 - A_{10}	−11.310	1.6317E−02	1.5817	4.3511E−03	2.5564

The rms deviation of the above fit to the recommended cross section is 2.5%, with a maximum deviation of 9.7% at 1.82 keV/amu.

ALADDIN evaluation function for cross section: HEXC2

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (2p)


$H^+ + H(1s) \rightarrow H^+ + H^*(2p)$
Cross Section (cm^2)
10^{-16}
10^{-17}
10^{-18}
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
—— Recommended Cross Section
- - - Analytic Fit

2.1.3. $H^+ + H(1s) \rightarrow H^+ + H^*(n=2)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
6.00E+02	3.40E+07	5.77E−18
1.00E+03	4.39E+07	2.34E−17
2.00E+03	6.21E+07	3.04E−17
5.00E+03	9.82E+07	3.63E−17
1.00E+04	1.39E+08	2.80E−17
2.00E+04	1.96E+08	5.10E−17
5.00E+04	3.11E+08	1.00E−16
1.00E+05	4.39E+08	9.00E−17
2.00E+05	6.21E+08	6.38E−17
5.00E+05	9.82E+08	3.55E−17
1.00E+06	1.39E+09	2.09E−17
2.00E+06	1.96E+09	1.20E−17
5.00E+06	3.11E+09	5.50E−18

Accuracy: $E < 0.6$ keV/amu : Indeterminate ; $0.6 \le E$ (keV/amu) < 1 : 50-100 % ; $1 \le E$ (keV/amu) < 15 : 20-30 % ; $15 \le E$ (keV/amu) < 30 : 15-20 % ; $30 \le E$ (keV/amu) < 100 : 10-15 % ; $E \ge 100$ keV/amu : 10 %, or better

Comments: (1) In the region below 15 keV/amu the n = 2 excitation cross section has been constructed as the sum of the recommended σ_{exc} (1s → 2s) and σ_{exc} (1s → 2p).

(2) In the range from 16 to 200 keV/amu there exist total n = 2 relative cross section measurements of Park et al [49]. These data have been normalized to the asymmetric two-centre AO-expansion (51-states) calculations of Ermolaev [53] at 200 keV/amu, which down to 100 keV/amu coincide to within 2 - 3 % with the results of the 53-state one-center AO-expansion calculations of Fitchard et al [42]. This normalization brings the Park et al [49] data in a 10 - 15 % agreement with the 40 AO (+ pseudostates) coupled-state calculations of Fritsch and Lin [37], recent multi-state AO and SE calculations of Reinhold et al [54] and 70-coupled hydrogenic state calculations of Shakeshaft [41] in the range from 20 to 100 keV/amu.

(3) In the region above 200 keV/amu, the recommended cross section follows the data of Ermolaev [53], which for E > 350 keV/amu coincide with the FBA calculations of Mandal et al [46] and the SE calculations of Reinhold et al [54].

(4) The recommended n = 2 cross section is consistent with the sum of the recommended 2s and 2p excitation cross sections.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9E^{A_{10}}} \right] \ [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

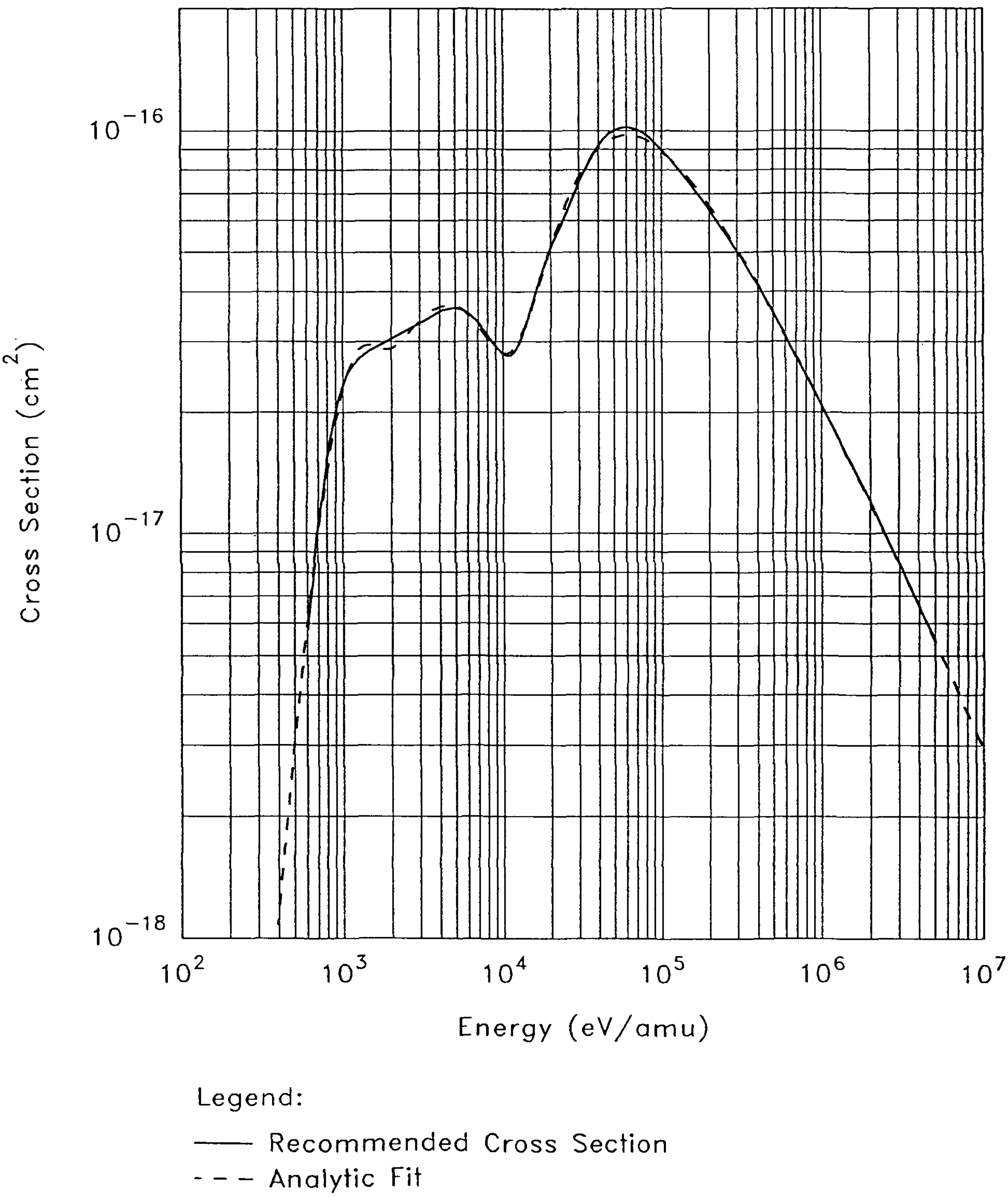
A_1 - A_5	34.433	44.507	0.56870	8.5476	7.8501
A_6 - A_{10}	−9.2217	1.8020E−02	1.6931	1.9422E−03	2.9068

The rms deviation of the above fit to the recommended cross section is 2.4%, with a maximum deviation of 5.9% at 26.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC2

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (n=2)

$H^{+} + H(1s) \rightarrow H^{+} + H^{*}(n=2)$



2.1.4. $H^+ + H(1s) \rightarrow H^+ + H^*(n=3)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	6.24E−20
1.00E+03	4.39E+07	3.63E−19
2.00E+03	6.21E+07	1.30E−18
5.00E+03	9.82E+07	3.75E−18
1.00E+04	1.39E+08	7.12E−18
2.00E+04	1.96E+08	1.30E−17
5.00E+04	3.11E+08	2.10E−17
1.00E+05	4.39E+08	1.76E−17
2.00E+05	6.21E+08	1.18E−17
5.00E+05	9.82E+08	6.32E−18
1.00E+06	1.39E+09	3.73E−18
2.00E+06	1.96E+09	2.13E−18
5.00E+06	3.11E+09	9.89E−19

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 50-100 % ; 5 ≤ E (keV/amu) < 20 : 20-50 % ; 20 ≤ E (keV/amu) ≤ 200 : 10-20 % ; E > 200 keV/amu : 10 %, or better

Comments:

(1) In the energy interval 0.5 to 12 keV/amu, the recommended cross section is based on the results of adiabatic calculations of Janev and Krstic [40]. For energies above 12 keV/amu (up to 25 keV/amu), the adiabatic cross sections [40] agree with the AO coupled-channel data of Fritsch and Lin [37].

(2) In the region from 16 to 200 keV/amu, the relative experimental data of Park et al [49], normalized at E = 200 keV/amu to the asymmetric two-centre AO-expansion (51-states) calculations of Ermolaev [53], agree to within 10 - 20 % with the large basis AO coupled-channel results of Fritsch and Lin [37], Shakeshaft [48], Reinhold et al [54], as well as with the SE calculations (Reinhold et al [54]) above 30 keV/amu.

(3) For energies above 200 keV/amu, the recommended cross section is based on the results of the AO coupled-channel [54], SE [54] and FBA [46] calculations, which are all in complete agreement with each over. At E = 300 and 500 keV/amu, the FBA cross section values for the 3p excitation agree (within 3 %) with the absolute σ (3p) measurements of Schartner et al [47].

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

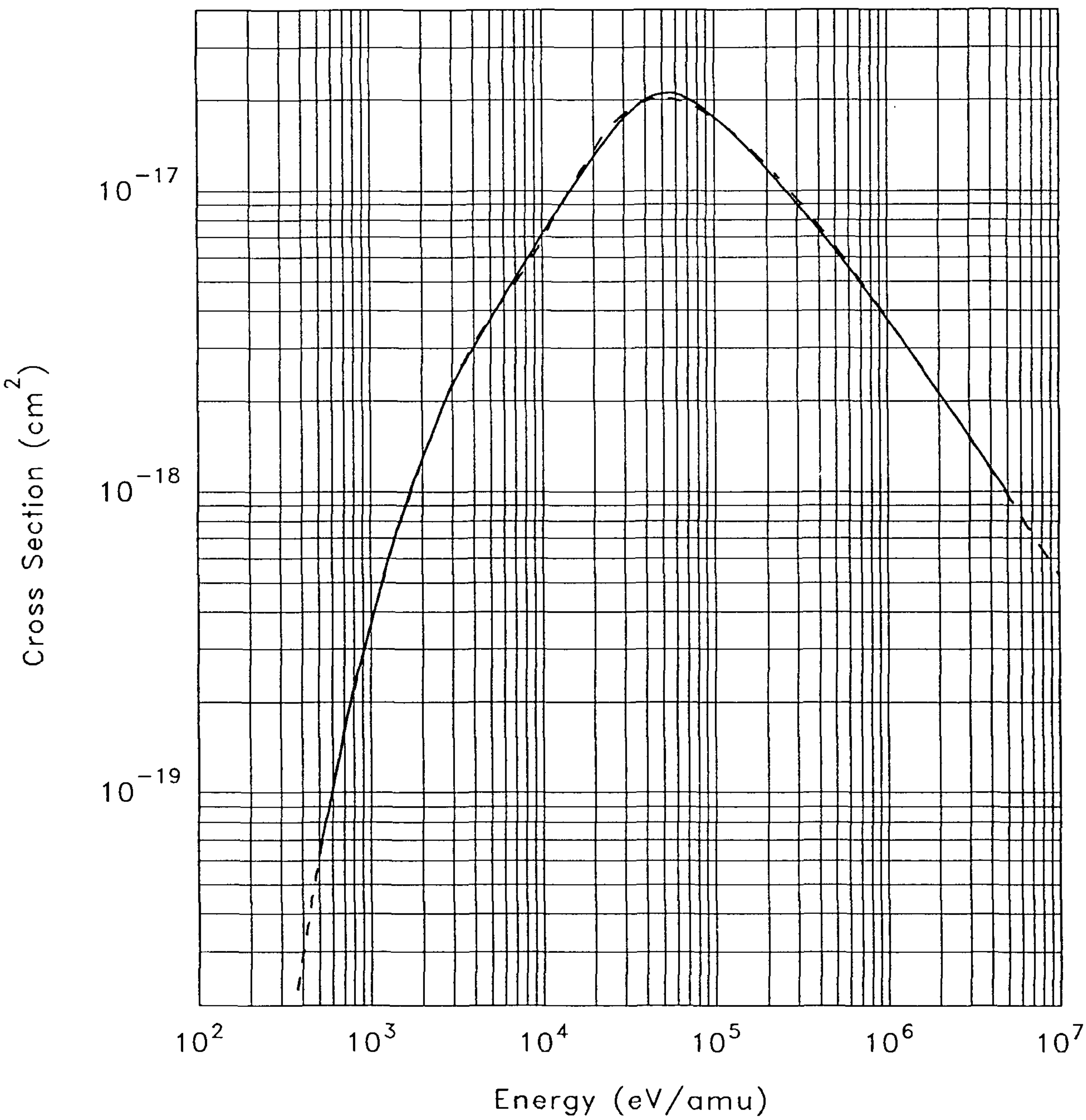
A_1 - A_4	6.1950	35.773	0.54818	5.5162E−03
A_5 - A_8	0.29114	−4.5264	6.0311	−2.0679

The rms deviation of the above fit to the recommended cross section is 2.2%, with a maximum deviation of 5.5% at 24.4 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (n=3)

$H^{+} + H(1s) \rightarrow H^{+} + H^{*}(n=3)$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

2.1.5. $H^+ + H(1s) \rightarrow H^+ + H^*(n=4)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.14E−20
1.00E+03	4.39E+07	6.99E−20
2.00E+03	6.21E+07	2.78E−19
5.00E+03	9.82E+07	1.10E−18
1.00E+04	1.39E+08	2.59E−18
2.00E+04	1.96E+08	5.38E−18
5.00E+04	3.11E+08	8.32E−18
1.00E+05	4.39E+08	6.87E−18
2.00E+05	6.21E+08	4.49E−18
5.00E+05	9.82E+08	2.25E−18
1.00E+06	1.39E+09	1.31E−18
2.00E+06	1.96E+09	7.70E−19
5.00E+06	3.11E+09	3.51E−19

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \leq E$ (keV/amu) < 5 : 30-50 % ;
$5 \leq E$ (keV/amu) < 25 : 20-30 % ; $25 \leq E$ (keV/amu) ≤ 200 : 10-20 % ;
$E > 200$ keV/amu : 10 %, or better

Comments: (1) For energies below 25 keV/amu, the only reliable cross sections for this transition are those from the adiabatic calculations of Janev and Krstic [40]. For energies between 20 and 25 keV/amu these calculations agree well with the SE results of Reinhold et al [54] and with normalized experimental cross section value of Park et al [49] at $E = 25$ keV/amu.

(2) For $25 \leq E$ (keV/amu) ≤ 200, experimental relative cross section data are available from Park et al [49], which when normalized to the large AO-basis coupled-channel calculations of Reinhold et al [54] at $E \approx 120$ keV/amu agree well with the other results of these calculations down to 40 keV/amu and to within 10 - 15 % with the SE data given in the same reference.

(3) The recommended cross section for $E > 200$ keV/amu is based on the SE [54] data, which for $E \geq 400$ keV/amu are in complete agreement with the FBA results [46]. We note that at $E = 300$ and 500 keV/amu, the FBA cross section values for the 4p excitation agree (within 3 %) with the absolute measurements of Schartner et al [47].

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ln(1+A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

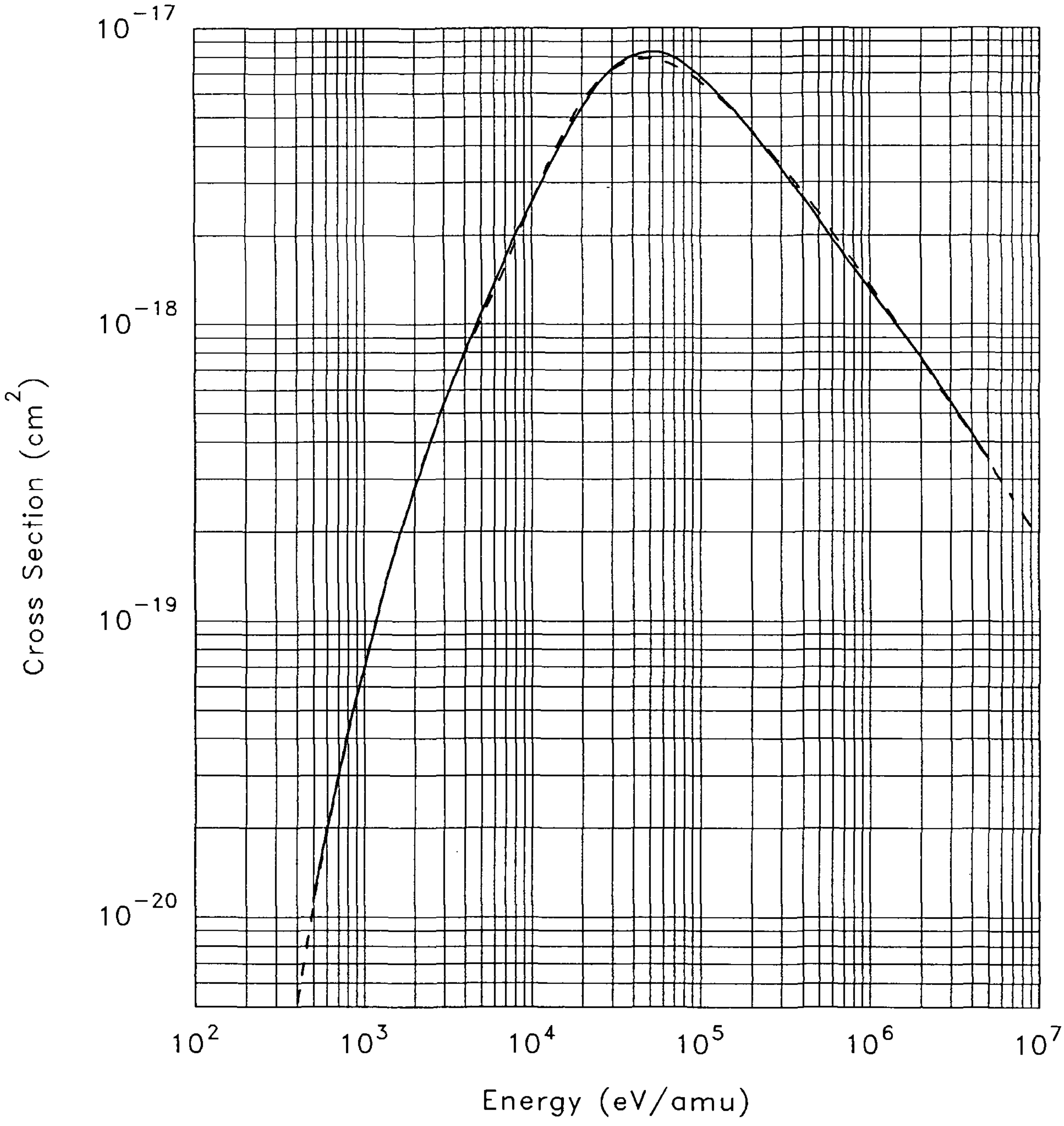
A_1 - A_4	2.0661	34.975	0.91213	5.1335E−04
A_5 - A_8	0.28953	−2.2849	0.11528	−4.8970

The rms deviation of the above fit to the recommended cross section is 2.8%, with a maximum deviation of 6.3% at 63.3 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (n=4)

$$H^{+} + H(1s) \rightarrow H^{+} + H^{*}(n=4)$$



Legend:

—— Recommended Cross Section

2.1.6. $H^+ + H(1s) \rightarrow H^+ + H^*(n=5, n=6)$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) 1s → n=5	1s → n=6
5.00E+02	3.11E+07	4.45E−21	2.50E−21
1.00E+03	4.39E+07	2.74E−20	1.54E−20
2.00E+03	6.21E+07	1.09E−19	6.11E−20
5.00E+03	9.82E+07	4.31E−19	2.42E−19
1.00E+04	1.39E+08	1.01E−18	5.69E−19
2.00E+04	1.96E+08	2.11E−18	1.19E−18
5.00E+04	3.11E+08	3.28E−18	1.84E−18
1.00E+05	4.39E+08	2.81E−18	1.64E−18
2.00E+05	6.21E+08	1.97E−18	1.15E−18
5.00E+05	9.82E+08	1.08E−18	6.22E−19
1.00E+06	1.39E+09	6.43E−19	3.67E−19
2.00E+06	1.96E+09	3.73E−19	2.08E−19
5.00E+06	3.11E+09	1.74E−19	9.68E−20

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 50-100 % ; 5 ≤ E (keV/amu) < 25 : 20-50 % ; 25 ≤ E (keV/amu) ≤ 300 : 10-20 % ; E > 300 keV/amu : 10 %, or better

Comments: (1) The available data on the excitation of the n = 5 and 6 levels are limited to the FBA calculations of Mandal et al [46] and absolute experimental measurements of the 5p and 6p transitions at E = 300 and 500 keV/amu by Schartner et al [47]. The 5p and 6p excitation cross sections of Mandal et al [46] agree well with the experimental data (within 3 %), and on this basis the results of the FBA in the region E ≥ 300 keV/amu, can be recommended with an uncertainty of 10% or better.

(2) In the region from 300 keV/amu to 50 keV/amu, the excitation cross sections for n = 5 and 6 have been constructed on the basis of the semi-empirical formula of Lodge et al [55], normalized to the FBA cross sections at 500 keV/amu. For energies below 50 keV/amu, we have generated the cross sections σ (1s → 5) and σ (1s → 6) by retaining the ratios of σ (1s → 5) / σ (1s → 4) and σ (1s → 6) / σ (1s → 4) the same as the corresponding ones from the region E ≥ 50 keV/amu.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
1s → n=5	1.2449	32.291	0.21176	3.0826E−04	0.31063	−2.4161	0.024664	−6.3726
1s → n=6	0.63771	37.174	0.39265	3.2949E−04	0.25757	−2.2950	0.050796	−5.5986

For the transition 1s → n=5, the rms deviation of the above fit to the recommended cross section is 1.4%, with a maximum deviation of 4.0% at 65.9 keV/amu. For the transition 1s → n=6, the rms deviation of the above fit to the recommended cross section is 1.0%, with a maximum deviation of 3.9% at 7.6 keV/amu.

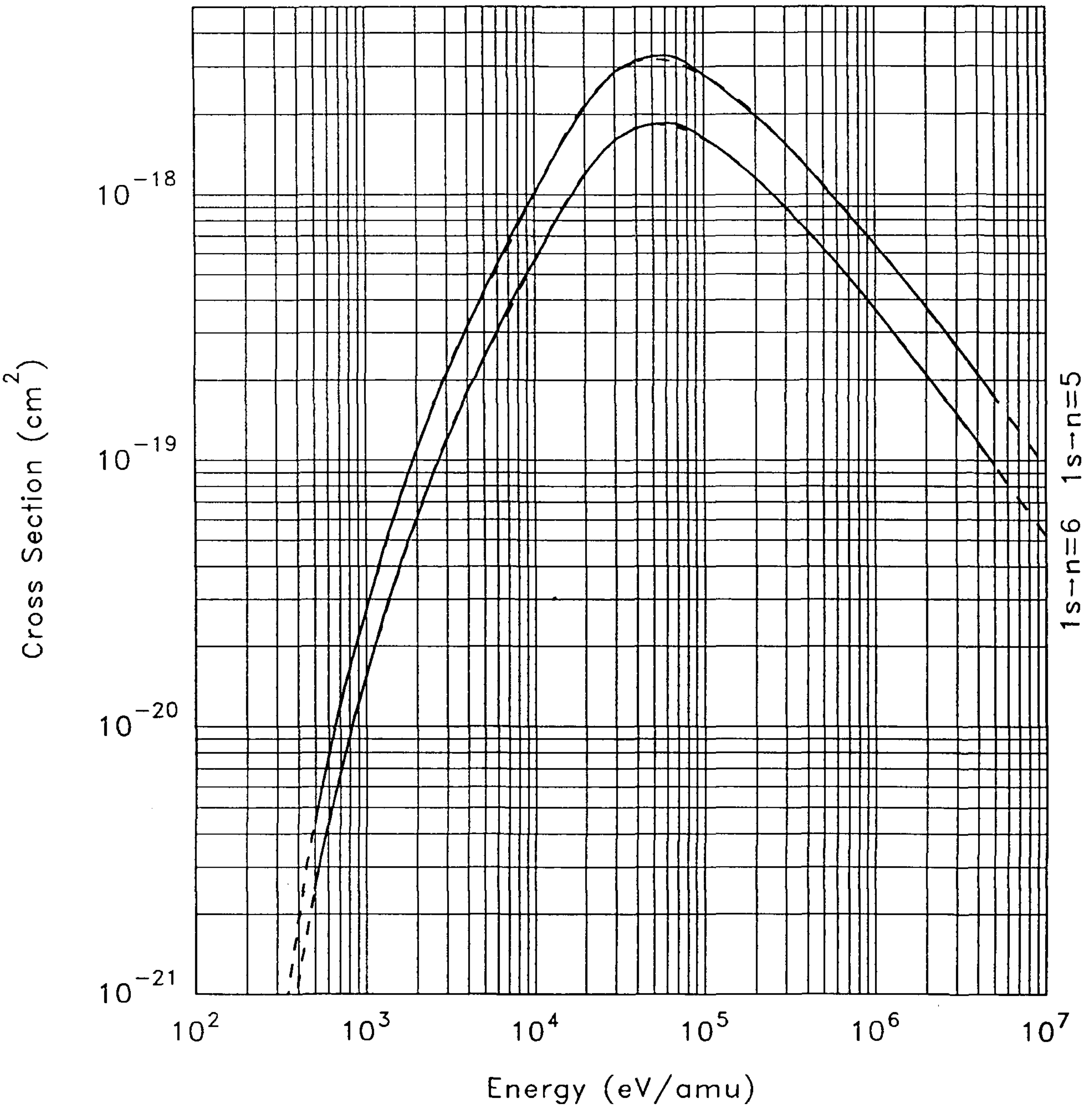
ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling :

EXC H [+1] H [+0] (1s) H [+1] [+0] (n=5), for 1s→n=5

EXC H [+1] H [+0] (1s) H [+1] [+0] (n=6), for 1s→n=6

$H^+ + H(1s) \rightarrow H^+ + H^*(n=5,\ n=6)$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

2.1.7. $H^+ + H(1s) \rightarrow H^+ + H^*(n)$, n>6

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) 1s → n=7	1s → n=8	1s → n=10
5.00E+02	3.11E+07	1.57E−21	1.055−21	5.40E−22
1.00E+03	4.39E+07	9.70E−21	6.50E−21	3.33E−21
2.00E+03	6.21E+07	3.85E−20	2.58E−20	1.32E−20
5.00E+03	9.82E+07	1.52E−19	1.02E−19	5.22E−20
1.00E+04	1.39E+08	3.58E−19	2.40E−19	1.23E−19
2.00E+04	1.96E+08	7.49E−19	5.02E−19	2.57E−19
5.00E+04	3.11E+08	1.12E−18	7.53E−19	3.86E−19
1.00E+05	4.39E+08	9.83E−19	6.58E−19	3.37E−19
2.00E+05	6.21E+08	7.05E−19	4.72E−19	2.42E−19
5.00E+05	9.82E+08	3.87E−19	2.59E−19	1.33E−19
1.00E+06	1.39E+09	2.30E−19	1.54E−19	7.90E−20
2.00E+06	1.96E+09	1.32E−19	8.88E−20	4.54E−20
5.00E+06	3.11E+09	6.18E−20	4.14E−20	2.12E−20

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 50-100 % ;
5 ≤ E (keV/amu) < 25 : 20-50 % ; 25 ≤ E (keV/amu) ≤ 300 : 15-20 % ;
E > 300 keV/amu : 15 %, or better

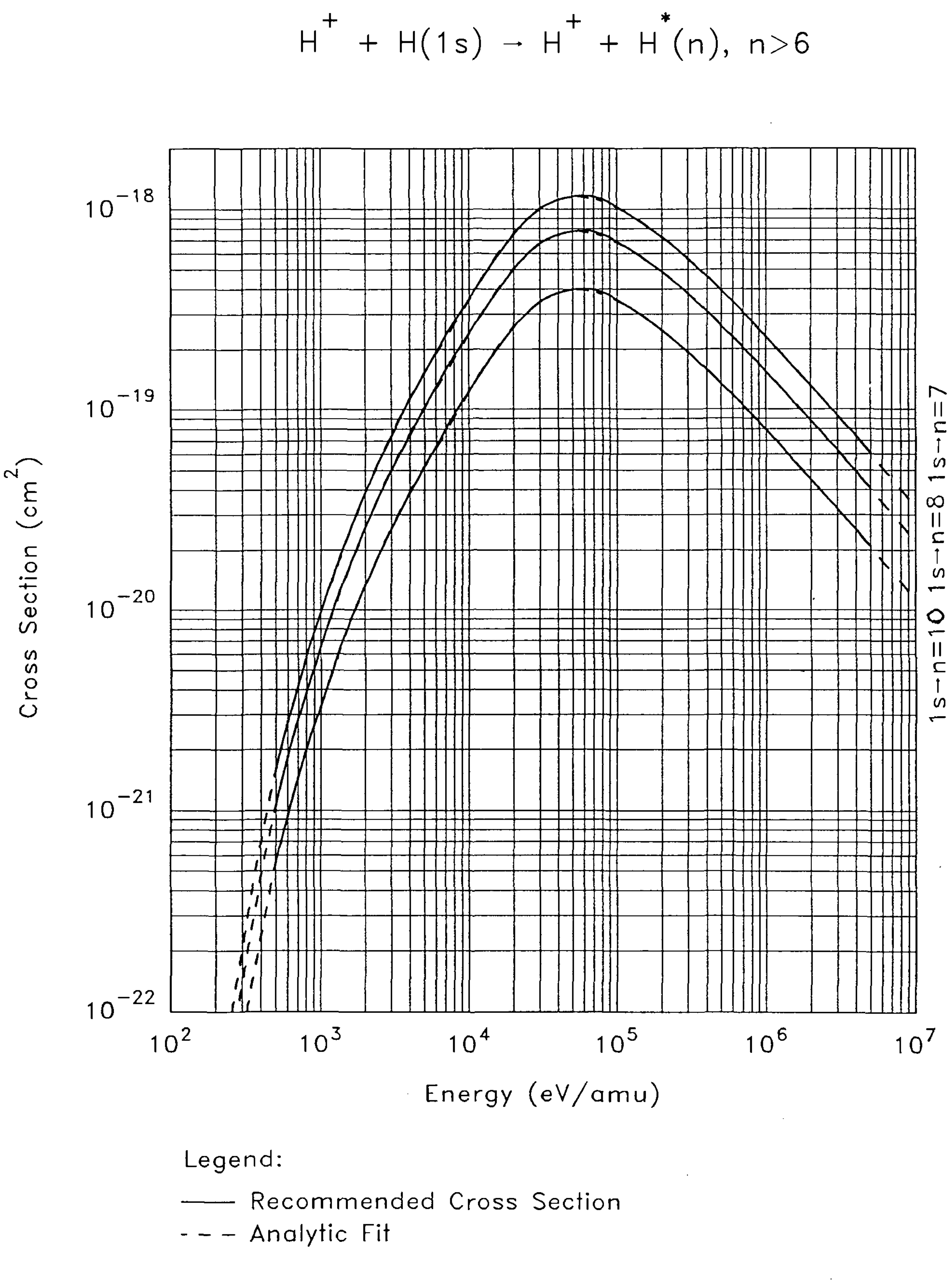
Comments: The cross sections for excitation of n ≥ 7 levels from the ground state can be determined by using the scaling relationship

$$\sigma_{exc}(1s \rightarrow n) = \left(\frac{6}{n}\right)^3 \sigma_{exc}(1s \rightarrow n{=}6), \quad n > 6 \qquad \text{(a)}$$

where $\sigma_{exc}(1s \rightarrow n{=}6)$ is the recommended cross section for excitation to the n = 6 level. The similar relationship $\sigma_{exc}(1s \rightarrow n) = (4/n)^3 \sigma_{exc}(1s \rightarrow n{=}4)$ reproduces the recommended n = 5 and n = 6 excitation cross sections in the entire region from 0.5 keV/amu to 1 MeV/amu, with an accuracy of 2 - 5 %. At energies above 400 keV/amu, the scaling (a) agrees with the FBA results for 7 ≤ n ≤ 20 of Mandal et al [46] to within 10 %. The above prescribed accuracies of $\sigma_{exc}(1s \rightarrow n>6)$ are derived on the basis of those for the n = 6 recommended cross section. The values of the cross sections in the above table are obtained by using the relation (a) and the values of the recommended $\sigma(1s \rightarrow n{=}6)$ cross section.

ALADDIN evaluation function for cross section: HEXC4

ALADDIN hierarchical labelling: EXC H [+1] H [+0] (1s) H [+1] H [+0] (n>6)



$H^+ + H(1s) \rightarrow H^+ + H^*(n)$, n>6
Cross Section (cm^2)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
1s→n=10 1s→n=8 1s→n=7
Legend:
—— Recommended Cross Section
- - - Analytic Fit

2.1.8. $H^+ + H^*(n=2) \rightarrow H^+ + H^*(m)$, $m = 3, 4, 5$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=2 → m=3	n=2 → m=4	n=2 → m=5
5.00E+02	3.11E+07	2.73E−16	2.31E−17	7.89E−18
1.00E+03	4.39E+07	4.54E−16	5.20E−17	1.78E−17
2.00E+03	6.21E+07	6.95E−16	1.04E−16	3.56E−17
5.00E+03	9.82E+07	1.18E−15	2.33E−16	7.99E−17
1.00E+04	1.39E+08	1.68E−15	3.55E−16	1.22E−16
2.00E+04	1.96E+08	2.03E−15	4.35E−16	1.49E−16
5.00E+04	3.11E+08	1.77E−15	3.71E−16	1.26E−16
1.00E+05	4.39E+08	1.33E−15	2.54E−16	8.56E−17
2.00E+05	6.21E+08	8.59E−16	1.52E−16	5.22E−17
5.00E+05	9.82E+08	4.33E−16	7.52E−17	2.60E−17
1.00E+06	1.39E+09	2.49E−16	4.09E−17	1.45E−17
2.00E+06	1.96E+09	1.39E−16	2.23E−17	7.90E−18
5.00E+06	3.11E+09	6.27E−17	1.02E−17	3.38E−18

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 30-50 % ;
5 ≤ E (keV/amu) < 25 : 20-30 % ; 25 ≤ E (keV/amu) ≤ 300 : 10-20 % ;
E > 300 keV/amu : 10 %, or better

Comments : (1) In the absence of experimental information, the recommended cross sections for the n=2 → m=3, 4, 5 transitions have been derived on the basis of theoretical calculations alone. For energies below 20 keV/amu, the recommended cross sections for 2 → 3 and 2 → 4 follow those of the adiabatic calculations of Janev and Krstic [40], which in the range between 15 and 25 keV/amu agree with the SE cross sections of Reinhold et al [54]. The cross section σ (2 → 5) for energies below 20 keV/amu was determined from the relation $\sigma(2 \rightarrow 5) = A\,\sigma(2 \rightarrow 4)$, where A is the ratio of σ (2 → 5) and σ (2 → 4) determined from the region of E about the maxima of the cross sections (20 - 40 keV/amu).

(2) In the energy range between 40 and 200 keV/amu, multi-state AO close-coupling cross sections are available for the above transitions from Reinhold et al [54]. These cross sections agree with the SE approximation from the same reference to within 10 - 30 %.

(3) The SE calculations [54] cover the energy range from 2 keV/amu to 10 MeV/amu. For energies above 300 keV/amu the SE results are expected to be accurate to 10%, or better.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

	A_1	A_2	A_3	A_4	A_5	A_6	Rms Deviation (%)	Maximum Deviation %	at E (keV/amu)
2 → 3	394.51	21.606	0.62426	0.013597	0.16565	−0.8949	1.2	3.4	5.2
2 → 4	50.744	19.416	4.0262	0.014398	0.31584	−1.4799	1.7	4.7	1.7
2 → 5	18.264	18.973	2.9056	0.013701	0.31711	−1.4775	1.6	4.4	1.7

ALADDIN evaluation function for cross section: HEXC3

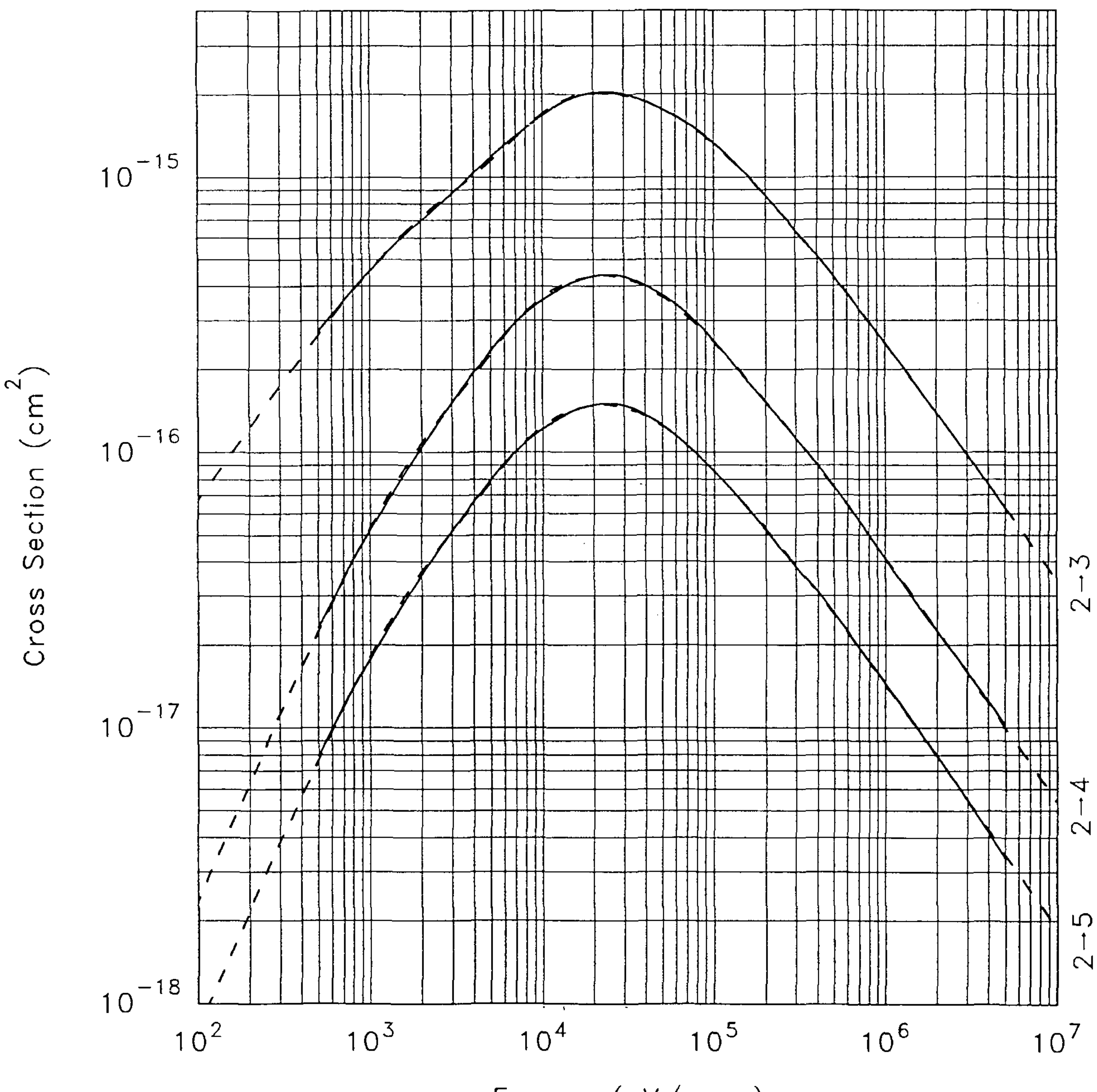
ALADDIN hierarchical labelling :

EXC H [+1] H [+0] (n=2) H [+1] [+0] (m=3), for n=2→m=3

EXC H [+1] H [+0] (n=2) H [+1] [+0] (m=4), for n=2→m=4

EXC H [+1] H [+0] (n=2) H [+1] [+0] (m=5), for n=2→m=5

$H^+ + H^*(n=2) \rightarrow H^+ + H^*(m)$ m=3, 4, 5



Legend:

—— Recommended Cross Section

- - - Analytic Fit

2.1.9. $H^+ + H^*(n=2) \rightarrow H^+ + H^*(m)$, $m > 5$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=2 → m=6	n=2 → m=8	n=2 → m=10
5.00E+02	3.11E+07	3.63E−18	1.15E−18	4.77E−19
1.00E+03	4.39E+07	8.21E−18	2.61E−18	1.08E−18
2.00E+03	6.21E+07	1.64E−17	5.22E−18	2.15E−18
5.00E+03	9.82E+07	3.68E−17	1.17E−17	4.83E−18
1.00E+04	1.39E+08	5.62E−17	1.79E−17	7.38E−18
2.00E+04	1.96E+08	6.87E−17	2.18E−17	9.01E−18
5.00E+04	3.11E+08	5.81E−17	1.85E−17	7.62E−18
1.00E+05	4.39E+08	3.95E−17	1.25E−17	5.18E−18
2.00E+05	6.21E+08	2.41E−17	7.65E−18	3.16E−18
5.00E+05	9.82E+08	1.20E−17	3.81E−18	1.57E−18
1.00E+06	1.39E+09	6.68E−18	2.12E−18	8.77E−19
2.00E+06	1.96E+09	3.64E−18	1.16E−18	4.78E−19
5.00E+06	3.11E+09	1.56E−18	4.95E−19	2.04E−19

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 40-100 % ;
5 ≤ E (keV/amu) < 25 : 25-40 % ; 25 ≤ E (keV/amu) ≤ 300 : 15-25 % ;
E > 300 keV/amu : 15 %, or better

Comments: (1) The cross sections σ (2 → n), n = 6 - 10 can be determined from the relation,

$$\sigma_{exc}(2 \rightarrow n) = A_{2-n}\, \sigma_{exc}(2 \rightarrow 5), \qquad \text{(a)}$$

where σ (2 → 5) is the recommended cross section and A_{2-n} is the ratio σ (2→ n) / σ (2 → 5) , calculated by using the semi-empirical formula of Lodge et al [55] in the energy region above 80 keV/amu. We note that this ratio is, to within 2 - 3%, constant throughout this region.

(2) For the transitions 2 → n, n>10, the cross section can be estimated using the n^{-3}–scaling,

$$\sigma_{exc}(2 \rightarrow n) = \left(\frac{10}{n}\right)^3 \sigma_{exc}(2 \rightarrow 10), \qquad \text{(b)}$$

which is believed to be accurate within 10 - 15 % in the energy range above the cross section maximum. The cross section data in the above table have been generated by using in Eq. (a) the recommended cross section σ (2 → 5). We further note that for the 2 → n transitions with n = 4, 5 the values of the ratio σ (2→ n) / σ (2 → 3) , found from the formula of Lodge et al [55] for E ≥ 80 keV/amu, are practically identical to those obtained from the recommended cross sections.

Values of the coefficients in equation (a)

A_{2-6}	A_{2-7}	A_{2-8}	A_{2-9}	A_{2-10}
0.4610	0.2475	0.1465	0.0920	0.0605

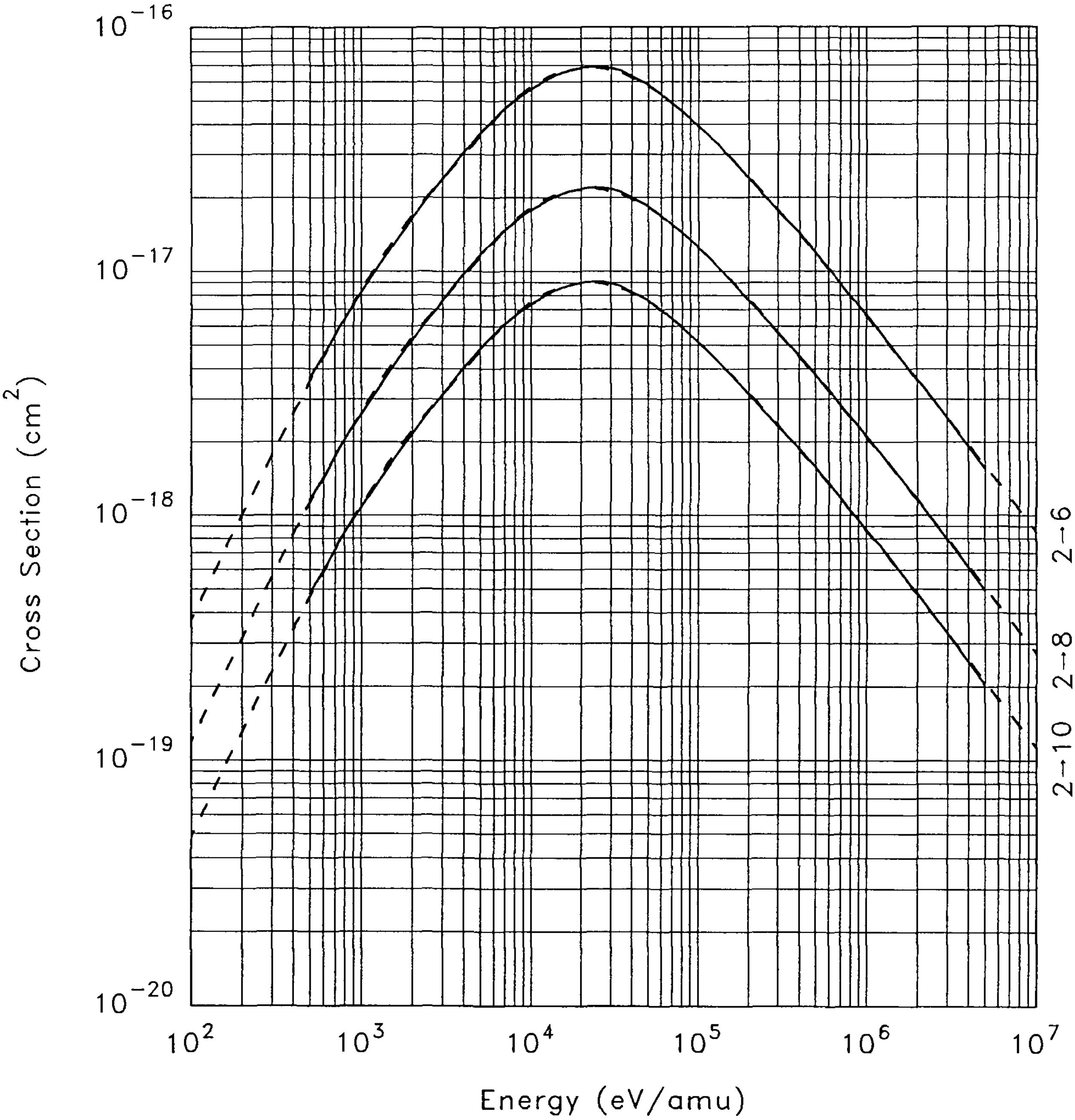
ALADDIN evaluation function for cross section: HEXC5 for n = 6 - 10 and HEXC4 for n>10

ALADDIN hierarchical labelling :

EXC H [+1] H [+0] (n=2) H [+1] [+0] (m), for n=2 → m=6−10

EXC H [+1] H [+0] (n=2) H [+1] [+0] (m>10), for n=2 → m>10

$H^+ + H^*(n=2) \rightarrow H^+ + H^*(m), \quad m > 5$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

2.1.10. $H^+ + H^*(n=3) \rightarrow H^+ + H^*(m)$, $m = 4, 5, 6$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=3 → m=4	n=3 → m=5	n=3 → m=6
5.00E+02	3.11E+07	2.81E−15	4.48E−16	1.60E−16
1.00E+03	4.39E+07	4.94E−15	7.87E−16	2.81E−16
2.00E+03	6.21E+07	7.78E−15	1.24E−15	4.42E−16
5.00E+03	9.82E+07	1.16E−14	1.85E−15	6.59E−16
1.00E+04	1.39E+08	1.41E−14	2.24E−15	7.99E−16
2.00E+04	1.96E+08	1.42E−14	2.27E−15	8.08E−16
5.00E+04	3.11E+08	9.95E−15	1.54E−15	5.58E−16
1.00E+05	4.39E+08	6.24E−15	9.69E−16	3.45E−16
2.00E+05	6.21E+08	3.70E−15	5.73E−16	2.01E−16
5.00E+05	9.82E+08	1.75E−15	2.70E−16	9.49E−17
1.00E+06	1.39E+09	9.66E−16	1.50E−16	5.21E−17
2.00E+06	1.96E+09	5.34E−16	8.27E−17	2.84E−17
5.00E+06	3.11E+09	2.42E−16	3.66E−17	1.30E−17

Accuracy: $E < 0.5$ keV/amu : Indeterminate; $0.5 \le E$ (keV/amu) < 5 : 30-50 %; $5 \le E$ (keV/amu) < 25 : 20-30 %; $25 \le E$ (keV/amu) ≤ 300 : 10-20 %; $E > 300$ keV/amu : 10 %

Comments: (1) There are no experimental data for these transitions. The n=3 → n= 4 recommended cross section is based on the adiabatic calculations of Janev and Krstic [40] for $E \le 15$ keV/amu, and on the SE cross section of Reinhold et al [54] above this energy. In the range from 10 to 20 keV/amu both agree well with each other and with the multi-state AO close-coupling result at E ~ 40 keV/amu of Ref. [54].

(2) For the n=3 → n= 5, 6 transitions, only SE cross section data exist from Reinhold et al [54]. As observed for the n=2 → n= 3, 4 and n=3 → n= 4 transitions, these data are reliable only at energies above ~ 10 - 15 keV/amu. The cross sections for these transitions in the region below this energy were determined by using the relation $\sigma(3 \rightarrow 5, 6) = A_{5,6}\, \sigma(3 \rightarrow 4)$, where $A_{5,6}$, is the ratio of the cross sections $\sigma(3 \rightarrow 5, 6)/\sigma(3 \rightarrow 4)$ determined from the region E about the corresponding cross section maximum (E ~ 15 - 20 keV/amu).

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

	A_1	A_2	A_3	A_4	A_5	A_6	Rms Deviation (%)	Maximum Deviation %	at E (keV/amu)
3 → 4	1247.5	11.319	2.6235	0.068781	0.521176	−1.2722	1.2	3.2	1.0
3 → 5	190.59	11.096	2.9098	0.073307	0.54177	−1.2894	1.1	3.3	1.0
3 → 6	63.494	11.507	4.3417	0.077953	0.53461	−1.2881	1.5	3.4	37.9

ALADDIN evaluation function for cross section: HEXC3

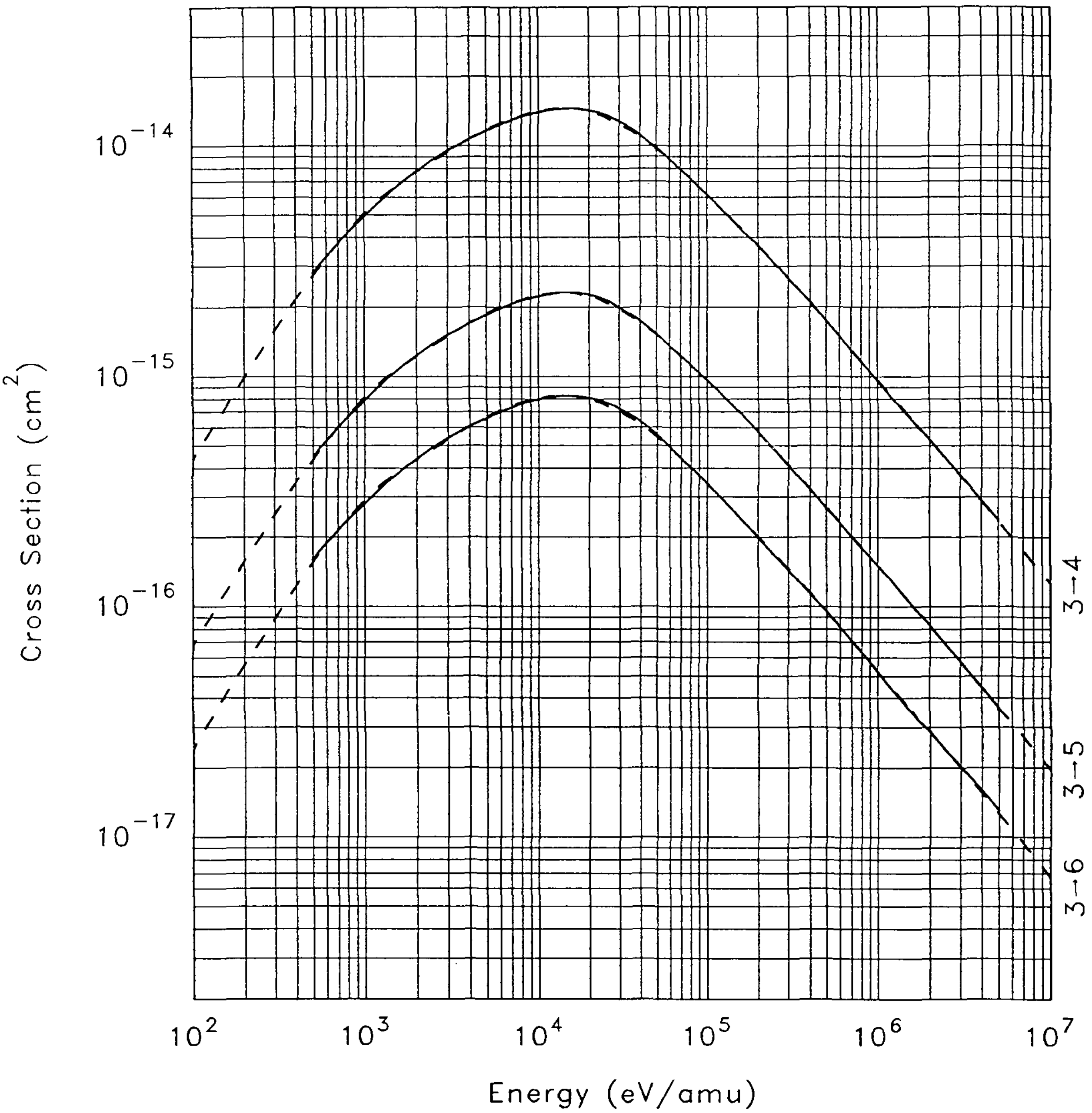
ALADDIN hierarchical labelling:

EXC H [+1] H [+0] (n=3) H [+1] [+0] (m=4), for n=3→m=4

EXC H [+1] H [+0] (n=3) H [+1] [+0] (m=5), for n=3→m=5

EXC H [+1] H [+0] (n=3) H [+1] [+0] (m=6), for n=3→m=6

$H^+ + H^*(n=3) \rightarrow H^+ + H^*(m)$, m=4, 5, 6



Legend:

—— Recommended Cross Section

- - - Analytic Fit

2.1.11. $H^+ + H^*(n=3) \rightarrow H^+ + H^*(m), \quad m > 6$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=3 → m=7	n=3 → m=8	n=3 → m=10
5.00E+02	3.11E+07	7.47E−17	4.07E−17	1.60E−17
1.00E+03	4.39E+07	1.31E−16	7.15E−17	2.81E−17
2.00E+03	6.21E+07	2.06E−16	1.12E−16	4.42E−17
5.00E+03	9.82E+07	3.08E−16	1.68E−16	6.59E−17
1.00E+04	1.39E+08	3.73E−16	2.03E−16	7.99E−17
2.00E+04	1.96E+08	3.78E−16	2.06E−16	8.09E−17
5.00E+04	3.11E+08	2.61E−16	1.42E−16	5.58E−17
1.00E+05	4.39E+08	1.61E−16	8.78E−17	3.45E−17
2.00E+05	6.21E+08	9.38E−17	5.11E−17	2.01E−17
5.00E+05	9.82E+08	4.43E−17	2.41E−17	9.49E−18
1.00E+06	1.39E+09	2.43E−17	1.32E−17	5.21E−18
2.00E+06	1.96E+09	1.33E−17	7.22E−18	2.84E−18
5.00E+06	3.11E+09	6.07E−18	3.31E−18	1.30E−18

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \leq E$ (keV/amu) < 5 : 40-100 % ;
$5 \leq E$ (keV/amu) < 25 : 25-40 % ; $25 \leq E$ (keV/amu) ≤ 300 : 15-25 % ;
$E > 300$ keV/amu : 15 %, or better

Comments: (1) The cross sections σ (3 → n), n = 7 - 10 can be determined from the relation,

$$\sigma_{exc}(3 \rightarrow n) = A_{3-n}\, \sigma_{exc}(3 \rightarrow 6), \qquad \text{(a)}$$

where σ (3 → 6) is the recommended cross section and A_{3-n} is the ratio σ (3→ n) / σ (3 → 6), calculated by using the semi-empirical formula of Lodge et al [55] in the energy region above 80 keV/amu.

(2) For the transitions 3 → n, n>10, the cross section can be estimated using the n^{-3}−scaling,

$$\sigma_{exc}(3 \rightarrow n) = \left(\frac{10}{n}\right)^3 \sigma_{exc}(3 \rightarrow 10), \qquad \text{(b)}$$

which is believed to be accurate within 10 - 15 % in the energy range above the cross section maximum. The cross section data in the above table have been generated by using in eq. (a) the recommended cross section σ (3 → 6).

Values of the coefficients for equation (a)

A_{3-7}	A_{3-8}	A_{3-9}	A_{3-10}
0.4670	0.2545	0.1540	0.1000

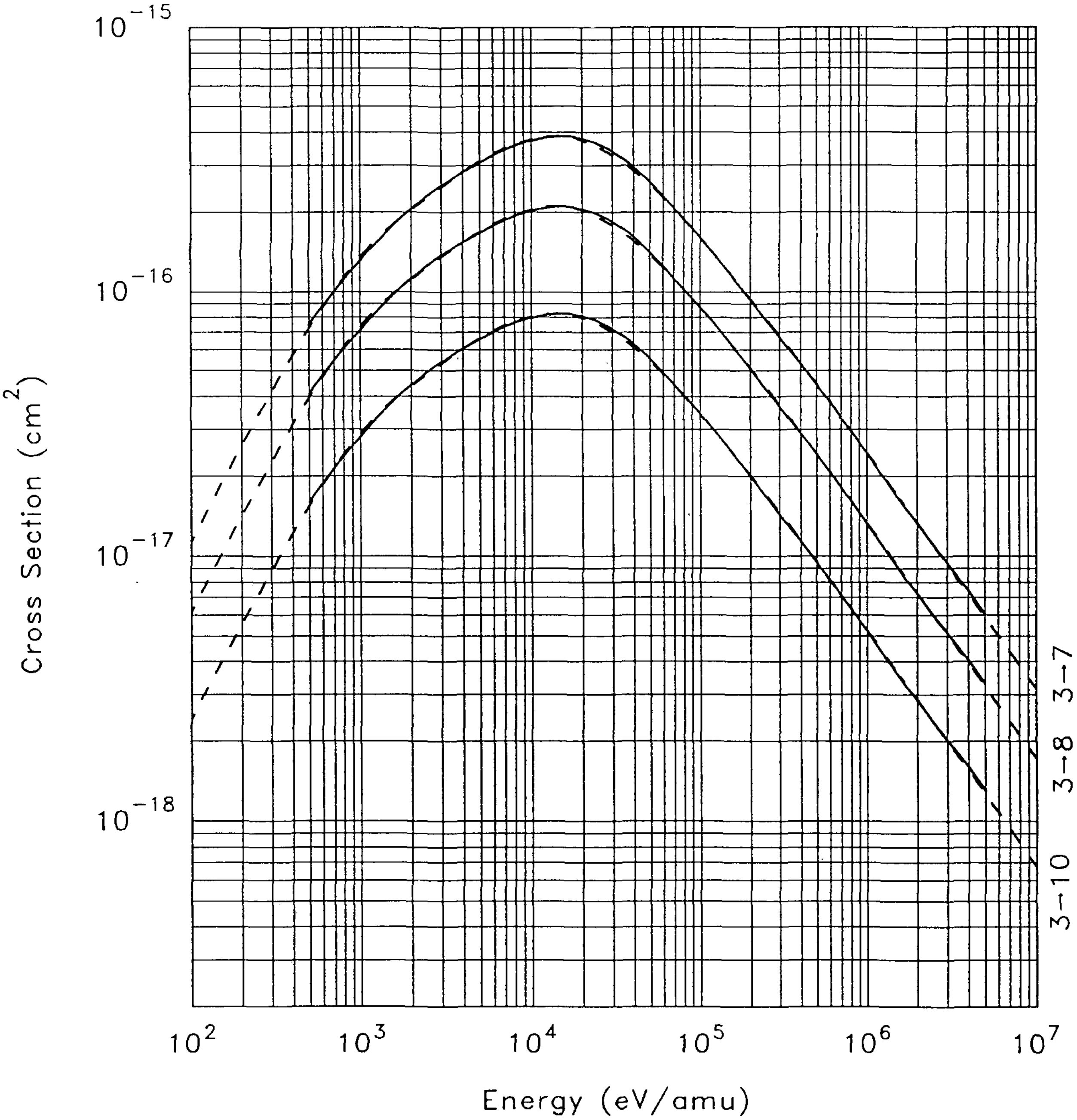
ALADDIN evaluation function for cross section: HEXC5 for n = 7 - 10 and HEXC4 for n>10

ALADDIN hierarchical labelling :

EXC H [+1] H [+0] (n=3) H [+1] [+0] (m), for n=3 → m=7−10

EXC H [+1] H [+0] (n=3) H [+1] [+0] (m>10), for n=3 → m>10

$H^{+} + H^{*}(n=3) \rightarrow H^{+} + H^{*}(m),\ m>6$



Legend:
—— Recommended Cross Section
- - - Analytic Fit

2.1.12. $H^+ + H^*(n) \rightarrow H^+ + H^*(m)$, $n > 3$, $m > n$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=4 → m=5	n=4 → m=6	n=4 → m=7
1.00E+03	4.39E+07	2.01E−14	6.25E−15	2.95E−15
2.00E+03	6.21E+07	2.89E−14	8.46E−15	3.88E−15
5.00E+03	9.82E+07	4.17E−14	1.01E−14	4.20E−15
1.00E+04	1.39E+08	5.00E−14	9.93E−15	3.84E−15
2.00E+04	1.96E+08	4.71E−14	8.30E−15	3.06E−15
5.00E+04	3.11E+08	3.18E−14	5.08E−15	1.80E−15
1.00E+05	4.39E+08	2.03E−14	3.10E−15	1.08E−15
2.00E+05	6.21E+08	1.21E−14	1.79E−15	6.12E−16
5.00E+05	9.82E+08	5.75E−15	8.20E−16	2.77E−16
1.00E+06	1.39E+09	3.18E−15	4.46E−16	1.50E−16
2.00E+06	1.96E+09	1.74E−15	2.40E−16	8.00E−17
5.00E+06	3.11E+09	7.73E−16	1.05E−16	3.47E−17

Accuracy: For the $\Delta n = m - n \leq 6$ transitions : 20 - 25 % for energies above the cross section maximum, and 25 - 40 % below the energy at which the maximum occurs but above $100/n^2$ keV/amu. For the $\Delta n > 6$ transitions, the uncertainty progressively increases and may be larger than 100 %.

Comments: (1) In absence of systematic data for the $n \rightarrow m$ ($m > n > 3$) transitions, the semi-empirical formula of Lodge et al [55] can be used to estimate the cross sections. This formula is given by Eq. (a) below.

(2) The comparison of the recommended data for $n \rightarrow m$ transitions, with $n \leq 3$, with those generated by the Lodge et al formula, indicates that for $\Delta n = m - n \leq 6$ and for energies at and above the cross section maximum, the cross sections calculated from Eq. (a) are accurate to within 20 - 25 %. For $\Delta n > 6$, the uncertainty of the formula can increase considerably, as evident from the comparison with the FBA results for $1 \rightarrow n$ ($\Delta n > 10$) transitions (Mandal et al [46]).

(3) The validity of Eq. (a) is restricted to $E \geq 100/n^2$ keV/amu, with an uncertainty between 20 - 40 % for $\Delta n \leq 6$, and higher for $\Delta n > 6$.

Analytic expression

Cross Section:

$$\sigma_{exc}(n \rightarrow m) = \frac{8.8 \times 10^{-17} n^4}{\varepsilon} \left[ADL + FGH \right] \quad [\,cm^2\,], \tag{a}$$

where, $\varepsilon = \dfrac{E\,(keV\,/\,amu)}{25}$, $\quad s = \Delta n = m - n, \quad D = \exp\left[-1\,/\,(nm\varepsilon^2) \right]$

$$A = \frac{8}{3s}\left(\frac{m}{sn}\right)^3 \left(0.184 - 0.04/s^{2/3}\right)\left(1 - \frac{0.2s}{nm}\right)^{1+2s}, \quad G = 0.5\left(\frac{\varepsilon\, n^2}{m - 1/m}\right)^3$$

$$L = \ln\left(\frac{1 + 0.53\,\varepsilon^2\, n\,(m - 2/m)}{1 + 0.4\varepsilon}\right), \quad F = \left[1 - 0.3sD/(nm)\right]^{1+2s}$$

$$H = \left[C_2\left(z_-, y\right) - C_2\left(z_+, y\right)\right], \quad C_2(z, y) = \frac{z^2 \ln(1 + 2z/3)}{2y + 3z/2}$$

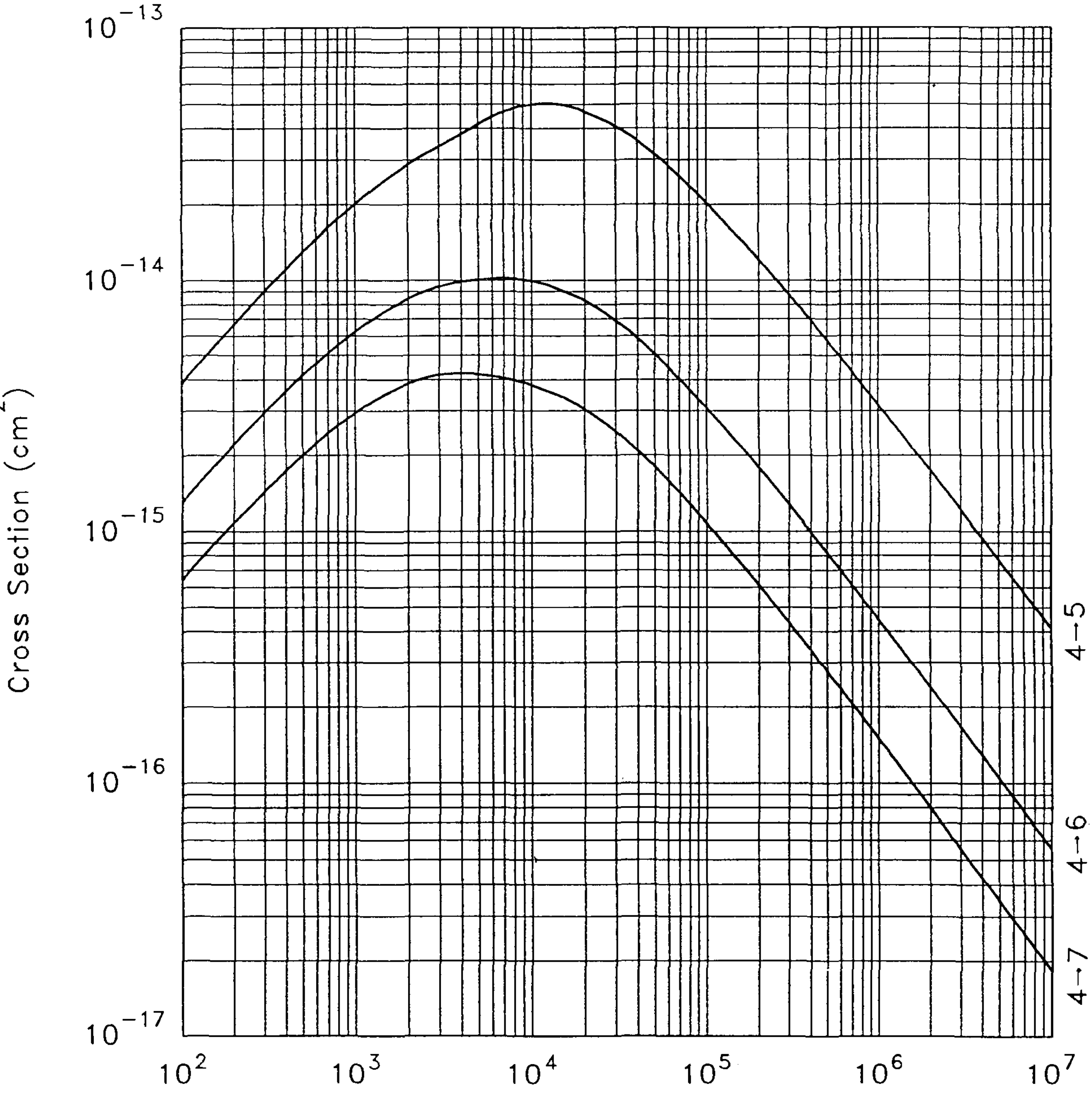
$$z_{\pm} = 2 \Big/ \left\{ \varepsilon\, n^2 \left[\left(2 - n^2/m^2\right)^{1/2} \pm 1 \right] \right\}, \quad y = 1 \Big/ \left[1 - D \ln(18s)/(4s) \right]$$

ALADDIN evaluation function for cross section: HEXCLD

ALADDIN hierarchical labelling :

EXC H [+1] H [+0] (n>3) H [+1] H [+0] (m>n)

$H^+ + H^*(n) \rightarrow H^+ + H^*(m), \quad n>3, \; m>n$



Legend:

—— Recommended Cross Section

2. Proton Impact Processes

2.2. Ionization

2.2.1. $H^+ + H(1s) \rightarrow H^+ + H^+ + e^-$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.46E−20
1.00E+03	4.39E+07	1.46E−19
2.00E+03	6.21E+07	1.02E−18
5.00E+03	9.82E+07	6.24E−18
1.00E+04	1.39E+08	1.94E−17
2.00E+04	1.96E+08	6.73E−17
5.00E+04	3.11E+08	1.43E−16
1.00E+05	4.39E+08	1.10E−16
2.00E+05	6.21E+08	6.99E−17
5.00E+05	9.82E+08	3.48E−17
1.00E+06	1.39E+09	1.94E−17
2.00E+06	1.96E+09	1.05E−17
5.00E+06	3.11E+09	4.62E−18

Accuracy: $E < 0.2$ keV/amu : Indeterminate ; $0.2 \leq E$ (keV/amu) < 2 : 20 % ;
$2 \leq E$ (keV/amu) < 5 : 20-30 % ; $5 \leq E$ (keV/amu) < 10 : 10-20 % ;
$E \geq 10$ keV/amu : 10 %; or better

Comments: (1) The recommended cross section below 2 keV/amu is based on the adiabatic calculations of Janev and Krstic [40] and the 150 molecular orbital coupled-channel calculations of Kimura and Thorson (quoted in M. Kimura and N. F. Lane, Adv. At. Mol. Phys. 26, 79 (1990)), which agree within 5%. In the range 2-5 keV/amu the result of adiabatic calculations [40] is consistent with the 3-center atomic orbital expansion close-coupling calculations of Winter and Lin [77] as well as with the adiabatic calculations of Ovchinnikov [78] within 20 - 30%, and at E ~ 9keV/amu they agree with the experimental point of Shah et al [80].

(2) In the energy region from ~ 10 keV/amu to 1.5 MeV/amu the recommended cross section is based on the experimental data of Shah et al [79,80], which agree with the experimental data of Park et al [81] (renormalized as in Winter and Lin [77]) in the region around the cross section maximum. The theoretical calculations of Fritsch and Lin [37] (2-center AO + pseudostates expansion), Fainstein et al [82] (EIS-CDW approximation) and Ermolaev [53] (2-centre asymmetric AO expansion) all agree with each other and with the experimental data in the region above 20 keV/amu.

(3) The scaled electron impact ionization cross section measurements of Shah et al [24] smoothly overlap and extend the proton-impact data in the region above 1 MeV/amu. The scaled electron-impact data are in excellent agreement with the above mentioned calculations [53,82].

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \qquad [cm^2]$$

where E is expressed in keV/amu.

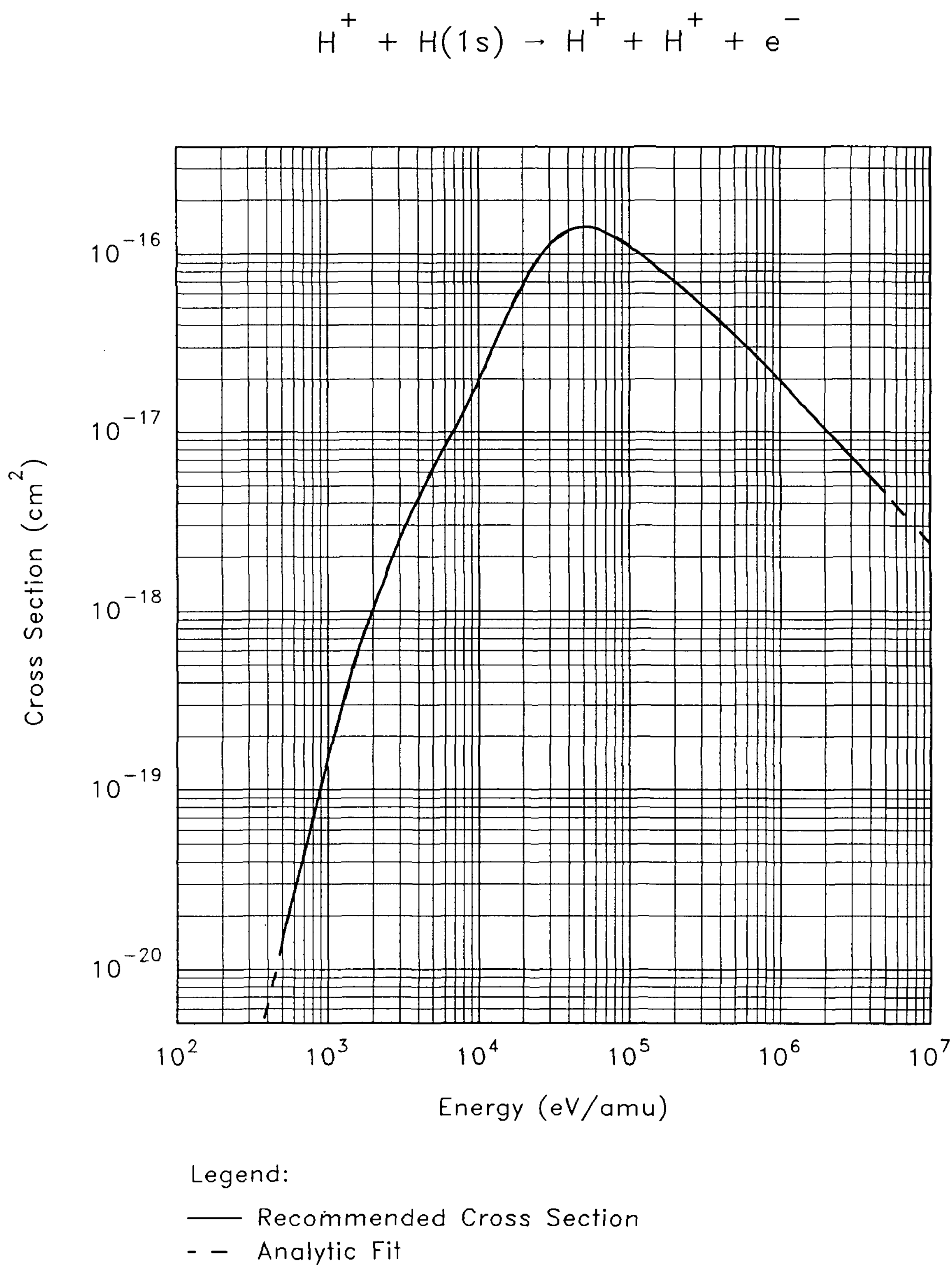
Fitting parameters

A_1 - A_4	12.899	61.897	9.2731E+03	4.9749E−04
A_5 - A_8	3.9890E−02	−1.5900	3.1834	−3.7154

The rms deviation of the above fit to the recommended cross section is 1.7%, with a maximum deviation of 4.1% at 0.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION H [+1] H [+0] (1s) H [+1] H [+1] e


H+ + H(1s) → H+ + H+ + e−
10−16
10−17
10−18
10−19
10−20
Cross Section (cm2)
102
103
104
105
106
107
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

2.2.2. $H^+ + H^*(n=2) \rightarrow H^+ + H^+ + e^-$

Energy (eV/amu)	Velocity (cm/s)	Cross Section (cm^2)
5.00E+02	3.11E+07	2.06E−17
1.00E+03	4.39E+07	6.97E−17
2.00E+03	6.21E+07	2.14E−16
5.00E+03	9.82E+07	8.20E−16
1.00E+04	1.39E+08	2.03E−15
2.00E+04	1.96E+08	3.54E−15
5.00E+04	3.11E+08	2.82E−15
1.00E+05	4.39E+08	1.71E−15
2.00E+05	6.21E+08	9.35E−16
5.00E+05	9.82E+08	3.99E−16
1.00E+06	1.39E+09	2.13E−16
2.00E+06	1.96E+09	1.12E−16
5.00E+06	3.11E+09	4.84E−17

Accuracy: $E < 0.2$ keV/amu : Indeterminate ; $0.2 \le E$ (keV/amu) < 5 : 30-40% ; $5 \le E$ (keV/amu) < 10 : 20-30 % ; $10 \le E$ (keV/amu) < 200 : 10-20 % ; $E \ge 200$ keV/amu : 10 %.

Comments: (1) In the energy range below 10 keV/amu, the recommended cross section follows the result of the adiabatic calculations of Janev and Krstic [40], which at 10 keV/amu agree with the theoretical EIS-CDW result [82] and with the scaled CTMC data of Olson [101].

(2) In the energy region above 10 keV/amu, the recommended ionization cross section represents the results of EIS-CDW calculations [82].

Analytic fitting function data

Cross Section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

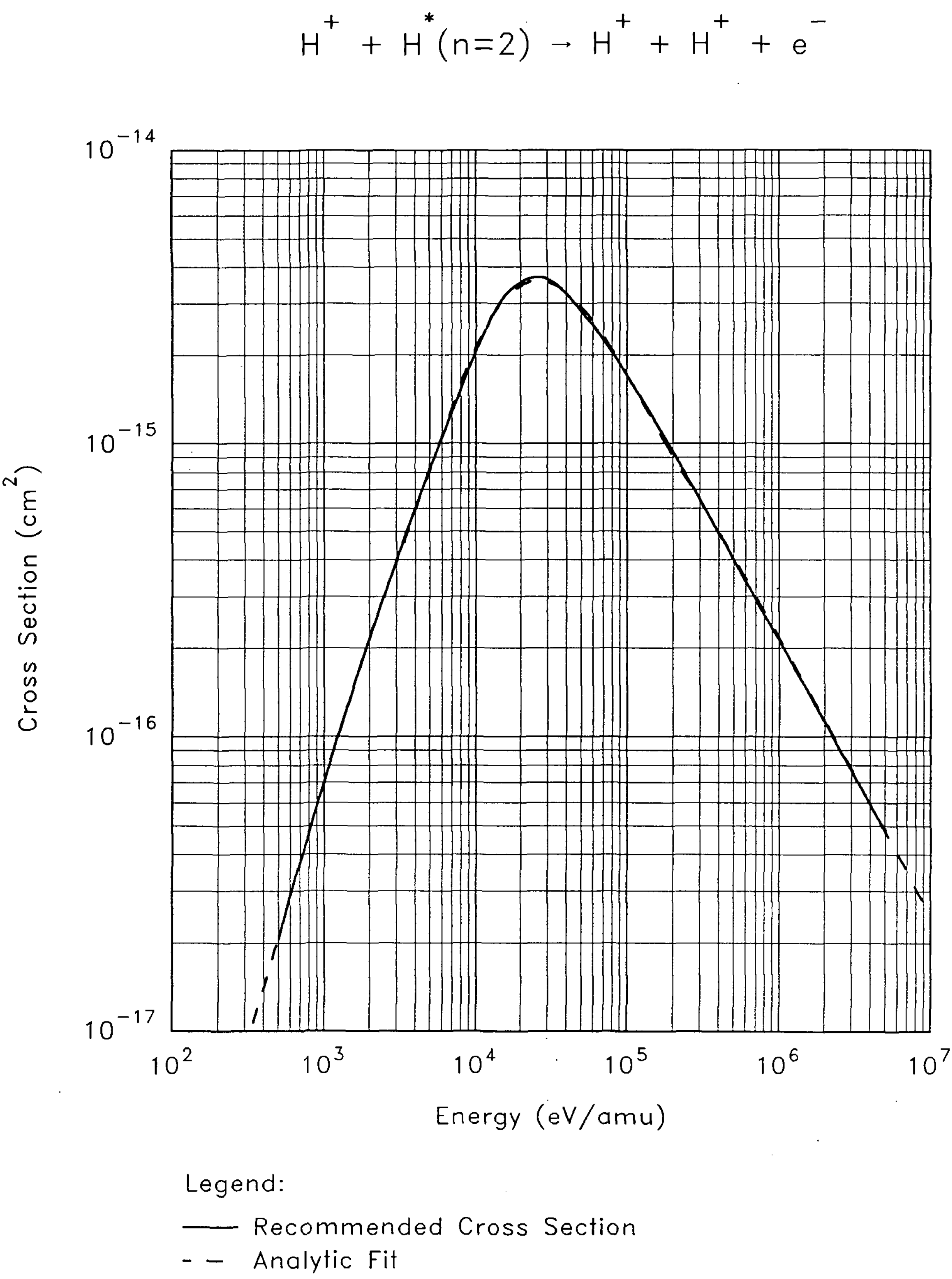
Fitting parameters

A_1 - A_4	107.63	29.860	1.0176E+06	6.9713E−03
A_5 - A_8	2.8448E−02	−1.8000	4.7852E−02	−0.20923

The rms deviation of the above fit to the recommended cross section is 2.1%, with a maximum deviation of 4.9% at 9.3 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION H [+1] H [+0] (n=2) H [+1] H [+1] e



$H^+ + H^*(n=2) \rightarrow H^+ + H^+ + e^-$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Cross Section (cm^2)
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

2.2.3. $H^+ + H^*(n=3) \rightarrow H^+ + H^+ + e^-$

Energy (eV/amu)	Velocity (cm/s)	Cross Section (cm^2)
5.00E+02	3.11E+07	9.21E−16
1.00E+03	4.39E+07	2.29E−15
2.00E+03	6.21E+07	4.95E−15
5.00E+03	9.82E+07	1.13E−14
1.00E+04	1.39E+08	1.67E−14
2.00E+04	1.96E+08	1.38E−14
5.00E+04	3.11E+08	7.24E−15
1.00E+05	4.39E+08	3.93E−15
2.00E+05	6.21E+08	2.14E−15
5.00E+05	9.82E+08	9.49E−16
1.00E+06	1.39E+09	5.15E−16
2.00E+06	1.96E+09	2.73E−16
5.00E+06	3.11E+09	1.14E−16

Accuracy: $E < 0.2$ keV/amu : Indeterminate ; $0.2 \le E$ (keV/amu) < 10 : 30-40% ;
$E \ge 10$ keV/amu : 30 %, or better

Comments: (1) In the energy range below 10 keV/amu, the recommended cross section represents the data of adiabatic calculations of Ref [40], which in the range from 4 to 80 keV/amu agree with the scaled CTMC calculation of Olson [101].

(2) In the energy region above 10 keV/amu, the ionization cross section has been constructed by using the scaling relationships,

$$\sigma_{ion}(n=3, E_3) = \left(\frac{3}{2}\right)^4 \sigma_{ion}(n=2, E), \quad E_3 = \left(\frac{2}{3}\right)^2 E$$

where $\sigma_{ion}(n=2)$ is the recommended proton-impact ionization cross section for $n=2$.

Analytic fitting function data

Cross Section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1+A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

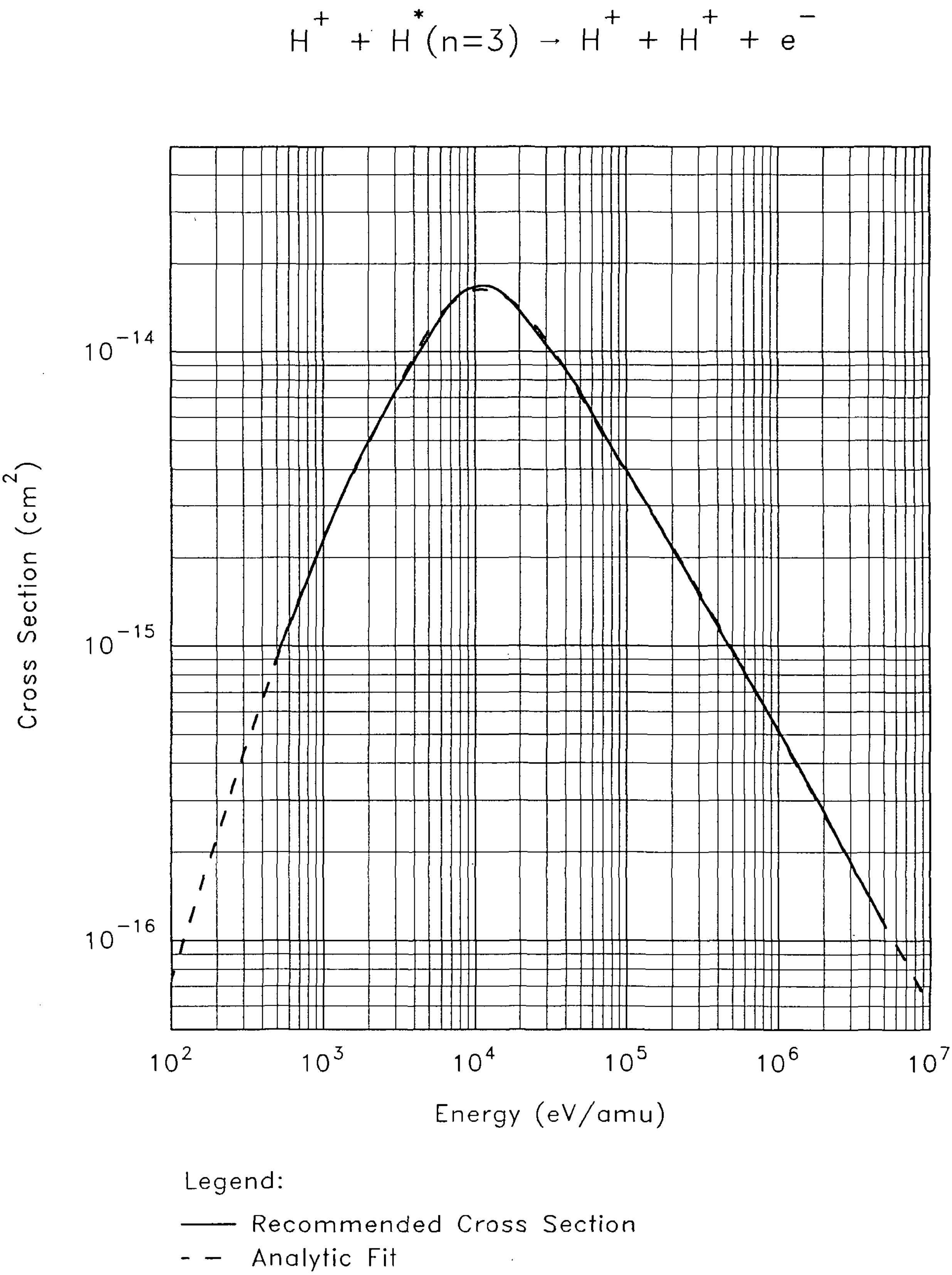
Fitting parameters

A_1 - A_4	336.26	13.608	4.9910E+03	3.0560E−01
A_5 - A_8	6.4364E−02	−0.14924	3.1525	−1.6314

The rms deviation of the above fit to the recommended cross section is 1.8%, with a maximum deviation of 4.7% at 4.9 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION H [+1] H [+0] (n=3) H [+1] H [+1] e



$H^+ + H^*(n=3) \rightarrow H^+ + H^+ + e^-$
Cross Section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

2.2.4. $H^+ + H^*(n) \rightarrow H^+ + H^+ + e^-, n > 3$

Energy E_n (eV/amu)	Velocity V_n (cm/s)	Cross sections (cm^2) n=4	n=5	n=6
5.00E+02	3.11E+07	6.34E−15	2.60E−14	7.81E−14
1.00E+03	4.39E+07	1.37E−14	5.22E−14	1.56E−13
2.00E+03	6.21E+07	2.74E−14	9.86E−14	2.47E−13
5.00E+03	9.82E+07	5.03E−14	1.23E−13	2.25E−13
1.00E+04	1.39E+08	4.69E−14	8.91E−14	1.38E−13
2.00E+04	1.96E+08	3.02E−14	4.98E−14	7.50E−14
5.00E+04	3.11E+08	1.35E−14	2.28E−14	3.47E−14
1.00E+05	4.39E+08	7.58E−15	1.26E−14	1.89E−14
2.00E+05	6.21E+08	4.14E−15	6.76E−15	1.00E−14
5.00E+05	9.82E+08	1.80E−15	2.91E−15	4.31E−15
1.00E+06	1.39E+09	9.49E−16	1.53E−15	2.25E−15
2.00E+06	1.96E+09	4.97E−16	7.98E−16	1.18E−15
5.00E+06	3.11E+09	2.10E−16	3.37E−16	4.95E−16

Accuracy: $E < 5\,(3/n)^2$ keV/amu : 100% or larger; $5\,(3/n)^2 \le E(\text{keV/amu}) \le 20\,(3/n)^2$: 50 - 100 %; $E > 20\,(3/n)^2$ keV/amu : 50%, or better

Comments: In absence of accurate cross section data for proton-impact ionization of $H^*(n)$ for $n > 3$, one can use the classical scaling relationships

$$\sigma_{ion}(n, E_n) = \left(\frac{n}{3}\right)^4 \sigma_{ion}(n = 3, E), \quad E_n = \left(\frac{3}{n}\right)^2 E$$

This scaling is not expected to be valid in scaled energy region below the cross section maximum, which appears approximately at $E_n^{max} \sim 100/n^2$ (keV/amu). The values of the cross sections in the above table are taken from the analytic fit for the $\sigma_{ion}(n=3)$ cross section.

Analytic fitting function data

Cross Section:

$$\sigma_{ion} = 10^{-16} \left(\frac{n}{3}\right)^4 A_1 \left[\frac{\exp(-A_2 / E_n)\, \ln(1 + A_3 E_n)}{E_n} + \frac{A_4 \exp(-A_5 E_n)}{E_n^{A_6} + A_7 E_n^{A_8}} \right] \ [cm^2]$$

where $E_n = (3/n)^2 E$ is expressed in keV/amu.

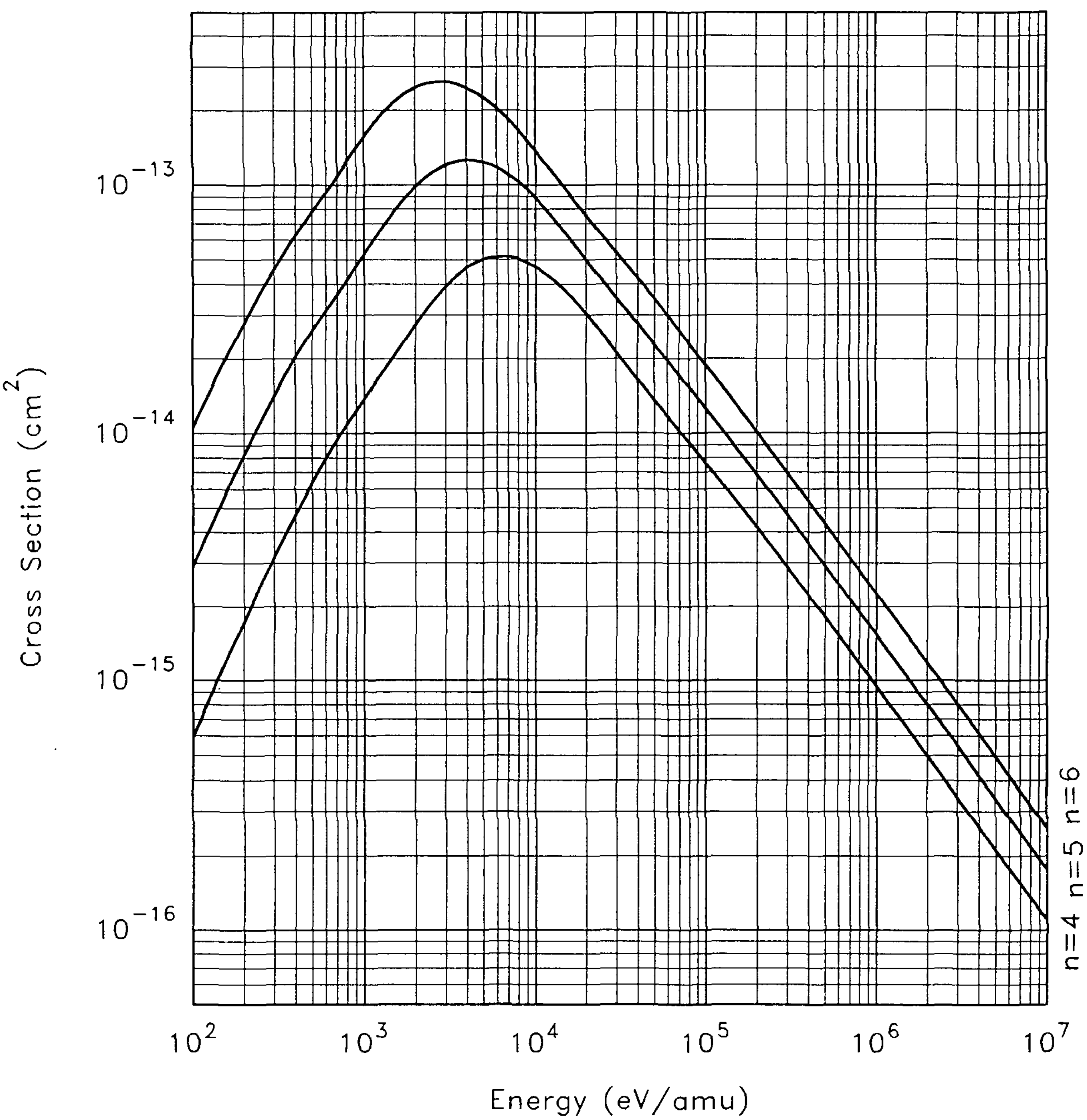
Fitting parameters

A_1 - A_4	336.26	13.608	4.9910E+03	3.0560E−01
A_5 - A_8	6.4364E−02	−0.14924	3.1525	−1.6314

ALADDIN evaluation function for cross section: HIONN

ALADDIN hierarchical labelling: ION H [+1] H [+0] (n>3) H [+1] H [+1] e

$$H^{+} + H^{*}(n) \rightarrow H^{+} + H^{+} + e^{-} \quad , n > 3$$



Legend:

—— Recommended Cross Section

2. Proton Impact Processes

2.3. Electron Capture

2.3.1. $H^+ + H(1s) \rightarrow H + H^+$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.20E−01	4.79E+05	4.96E−15
2.00E−01	6.21E+05	4.70E−15
5.00E−01	9.82E+05	4.33E−15
1.00E+00	1.39E+06	4.10E−15
2.00E+00	1.96E+06	3.83E−15
5.00E+00	3.11E+06	3.46E−15
1.00E+01	4.39E+06	3.17E−15
2.00E+01	6.21E+06	2.93E−15
5.00E+01	9.82E+06	2.65E−15
1.00E+02	1.39E+07	2.44E−15
2.00E+02	1.96E+07	2.22E−15
5.00E+02	3.11E+07	1.97E−15
1.00E+03	4.39E+07	1.71E−15
2.00E+03	6.21E+07	1.44E−15
5.00E+03	9.82E+07	1.10E−15
1.00E+04	1.39E+08	7.75E−16
2.00E+04	1.96E+08	4.45E−16
5.00E+04	3.11E+08	9.93E−17
1.00E+05	4.39E+08	1.01E−17
2.00E+05	6.21E+08	6.09E−19
5.00E+05	9.82E+08	6.03E−21
1.00E+06	1.39E+09	1.57E−22
2.00E+06	1.96E+09	3.78E−24
5.00E+06	3.11E+09	2.56E−26
1.00E+07	4.39E+09	5.99E−28

Accuracy: $1 \times 10^{-4} < E$ (keV/amu) $\leq 1 \times 10^{-2}$: 10 % ; $1 \times 10^{-2} < E$ (keV/amu) ≤ 1 : 10-15 % ; $1 < E$ (keV/amu) $\leq 1 \times 10^{2}$: 5-10 % ; $1 \times 10^{2} < E$ (keV/amu) $\leq 2 \times 10^{3}$: 10-20 % : $2 \times 10^{3} < E$ (keV/amu) $\leq 1 \times 10^{4}$: 20-40 %

Comments: (1) The cross section for this reaction is for electron capture into all final states of the projectile.

(2) The recommended cross section in the energy range from 0.12 eV/amu to 400 keV/amu was taken from the recent evaluation of Barnett [62], based on the extensive experimental measurements available [63 - 74]. For energies above 400 keV/amu, the recommended cross section is based on the experimental data of Hvelplund et al [69] and Schwab et al [73], as well as on the results of second-order theoretical calculations from Belkic et al [75] (CDW) and Decker and Eichler [76] (DWB2).

Analytic fitting function

Cross section:

$$\sigma_{cx} = \frac{10^{-16} A_1 \ln(A_2/E + A_6)}{1 + A_3 E + A_4 E^{3.5} + A_5 E^{5.4}} \qquad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

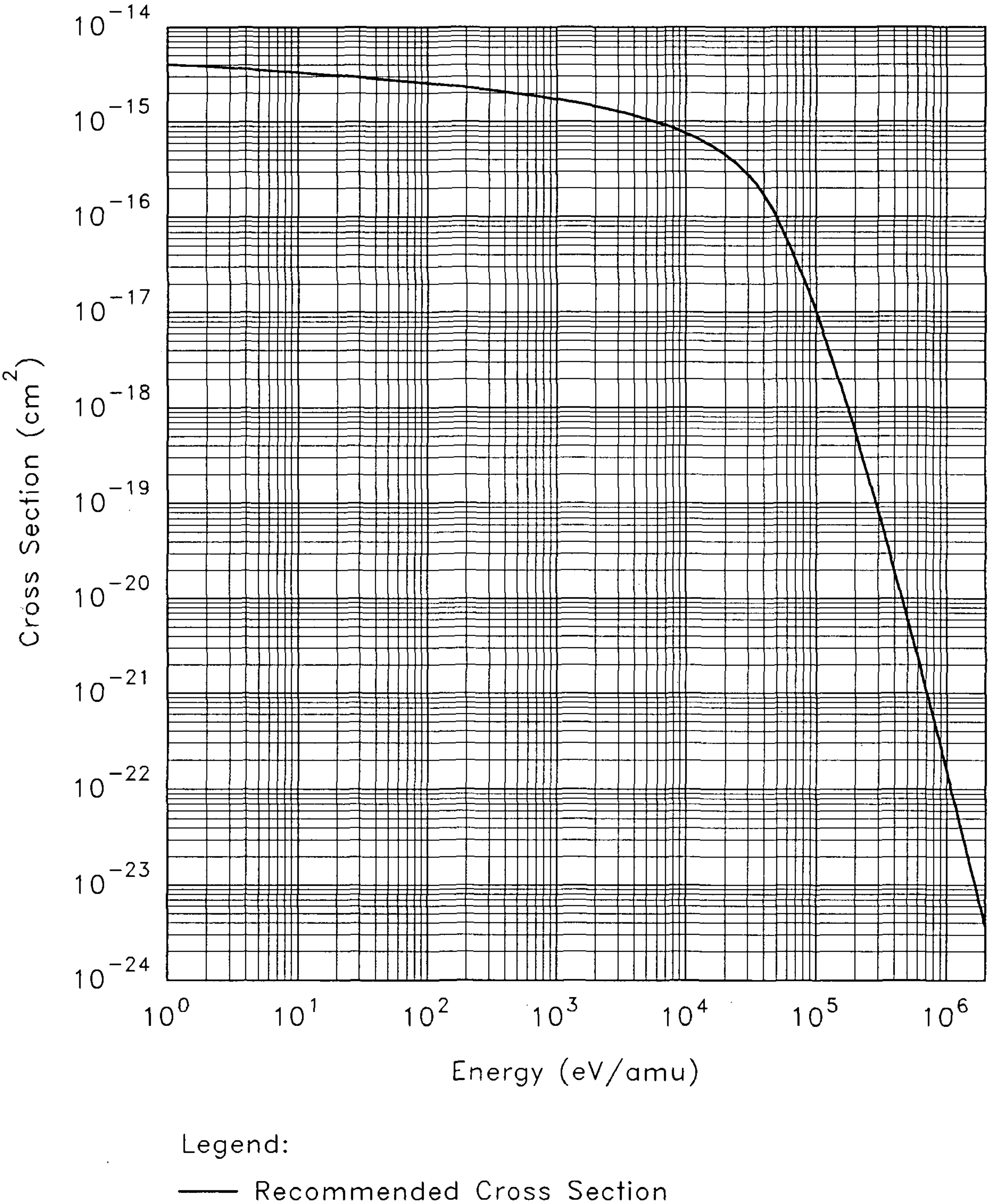
A_1	A_2	A_3	A_4	A_5	A_6
3.2345	235.88	0.038371	3.8068E−06	1.1832E−10	2.3713

The rms deviation of the above fit to the recommended cross section is 2.3%, with a maximum deviation of 5.4% at 1.2 keV/amu.

ALADDIN evaluation function for cross section: HCX1

ALADDIN hierarchical labelling: CX H [+1] H [+0] (1s)

$H^+ + H(1s) \rightarrow H + H^+$



$H^+ + H^*(n) \rightarrow H + H^+$, n>1

Scaled Energy, En^2 (eV/amu)	Scaled Velocity, vn (cm/s)	Scaled Cross sections, σ_{cx} / n^4 (cm^2) n=2	n=3	n ≥ 4
1.00E+01	4.39E+06	1.26E−15	6.91E−16	5.45E−16
2.00E+01	6.21E+06	1.19E−15	6.70E−16	5.36E−16
5.00E+01	9.82E+06	1.09E−15	6.43E−16	5.27E−16
1.00E+02	1.39E+07	1.03E−15	6.23E−16	5.23E−16
2.00E+02	1.96E+07	9.59E−16	6.01E−16	5.16E−16
5.00E+02	3.11E+07	8.62E−16	5.74E−16	5.08E−16
1.00E+03	4.39E+07	7.92E−16	5.54E−16	5.00E−16
2.00E+03	6.21E+07	7.25E−16	5.34E−16	4.91E−16
5.00E+03	9.82E+07	6.32E−16	5.07E−16	4.81E−16
1.00E+04	1.39E+08	5.45E−16	4.77E−16	4.69E−16
2.00E+04	1.96E+08	4.03E−16	3.85E−16	3.82E−16
5.00E+04	3.11E+08	9.93E−17	9.93E−17	9.93E−17
1.00E+05	4.39E+08	1.01E−17	1.01E−17	1.01E−17
2.00E+05	6.21E+08	6.09E−19	6.09E−19	6.09E−19

Accuracy: $En^2 < 0.1$ keV/amu : 30-40 %; $0.1 \le En^2$ (keV/amu) < 40 : 20-30 % ;
$En^2 \ge 40$ keV/amu : 20 %, or better

Comments: (1) The presented cross sections are for electron capture from a given target n-shell to all states of the projectile. The dominant contribution, particularly for the lower values of n, comes from the resonant n → n capture.

(2) For reduced (scaled) energies En^2 below 10 keV/amu, the recommended cross sections are based on the quantal calculations of Bates and Reid [97] (two-state model for n = 2-5), Malaviya [98] (8-state model for n = 2), and for the high values of n (n > 5) on the classical model for over-barrier transitions (Smirnov [99] and Janev et al [100]).

(3) For reduced energies between 25 and 100 keV/amu, the recommended cross sections are based on the CTMC calculations of Olson [101] (for all n). The calculations of Eichler [102] for n = 2 to n = 10 are consistent withe the CTMC results in this energy range and provide a smooth extension of the data down to approximately 10 keV/amu in the low energy region and up to 300 keV/amu at high energies. For energies above 200 keV/amu we assume that the n^4 - cross section scaling is accurate to within 10 - 20 % for all n states (including the ground state).

Analytic fitting function

Cross section:

$$\frac{\sigma_{cx}}{n^4} = \frac{10^{-16} A_1 \ln(A_2/\tilde{E} + A_4)}{1 + A_3\tilde{E} + 3.0842 \times 10^{-6}\tilde{E}^{3.5} + 1.1832 \times 10^{-10}\tilde{E}^{5.4}} \quad [cm^2]$$

where $\tilde{E} = En^2$ is expressed in keV/amu.

Fitting parameters

	A_1	A_2	A_3	A_4	Rms % Deviation	Maximum Deviation %	at $\tilde{E}$ (keV/amu)
n = 2	0.92750	6.5040E+03	1.3405E−02	20.699	1.7	5.7	9.6E+03
n = 3	0.37271	2.7645E+06	1.5720E−03	1.4857E+03	2.7	7.8	38.6
n ≥ 4	0.21336	1.0E+10	1.8184E−03	1.3426E+06	2.7	9.0	10.5

ALADDIN evaluation function for cross section: HCX1

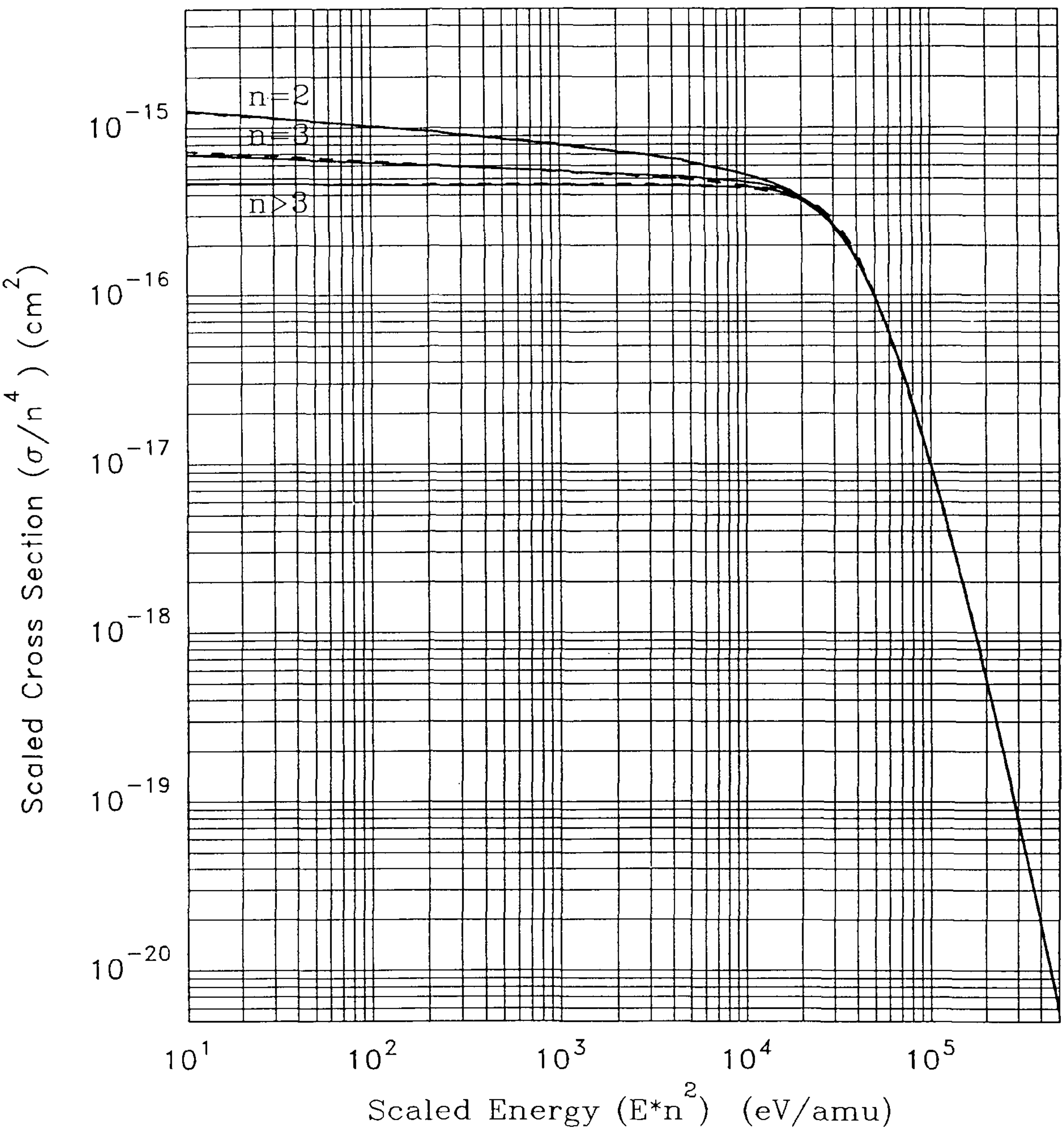
ALADDIN hierarchical labelling:

CX H [+1] H [+0] (n=2), for n=2

CX H [+1] H [+0] (n=3), for n=3

CX H [+1] H [+0] (n>3), for n>=4

$$H^+ + H^*(n) \rightarrow H + H^+, \; n>1$$



Legend:

—— Recommended Cross Section

- - - Analytic Fit

3. Collision Processes with He^{2+}

3.1. Excitation

3.1.1. $He^{2+} + H(1s) \rightarrow He^{2+} + H^*(n=2)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	3.35E−19
1.00E+03	4.39E+07	1.83E−18
2.00E+03	6.21E+07	6.88E−18
5.00E+03	9.82E+07	2.97E−17
1.00E+04	1.39E+08	3.13E−17
2.00E+04	1.96E+08	4.93E−17
5.00E+04	3.11E+08	1.75E−16
1.00E+05	4.39E+08	2.36E−16
2.00E+05	6.21E+08	2.06E−16
5.00E+05	9.82E+08	1.25E−16
1.00E+06	1.39E+09	7.80E−17
2.00E+06	1.96E+09	4.61E−17
5.00E+06	3.11E+09	2.17E−17

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \le E$ (keV/amu) < 4 : 20-40 % ;
$4 \le E$ (keV/amu) ≤ 200 : 10-20 % ; $E > 200$ keV/amu : 10 %

Comments: (1) For energies below 15 keV/amu the recommended cross section is taken from the adiabatic calculations by Krstic and Janev [56], which in the energy range between 15 and 40 keV/amu agree with the 2-center AO close-coupling calculations of Fritsch et al [57] and Bransden et al [58] within the above stated accuracies. The 2-center AO calculations [57,58] were used to generate the recommended cross section up to 200 keV/amu. We note that the cross section of Fritsch et al exhibits an additional weak oscillation around the recommended one in the energy region around 4 keV/amu, which has been accounted for in the above stated uncertainty.

(2) In the region above 200 keV/amu, the recommended cross section is based on the single-center AO close-coupling calculations by Bransden et al [58] and Reinhold et al [54], (up to 800 keV/amu), and on the q-scaled (q = 2, for He^{2+}) proton-impact semi-empirical formula of Lodge et al [55]
$\sigma(He^{2+}; E) = 2\sigma(H^+; E/2)$.

(3) The q-scaled proton-impact recommended cross section for the 1s → n = 2 transition, according to the relation (q = 2) $\sigma(He^{2+}; E) = 2\sigma(H^+; E/2)$, agrees with the present recommended cross section within 10 - 40 % in the energy range 20 - 100 keV/amu, and within 3 - 5 % in the region above 200 keV/amu.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\,\ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9 E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

A_1 - A_5	177.69	64.506	0.10807	2.1398E−04	0.73358
A_6 - A_{10}	−2.9773	7.5603E−02	18.997	2.4352E−03	3.4085

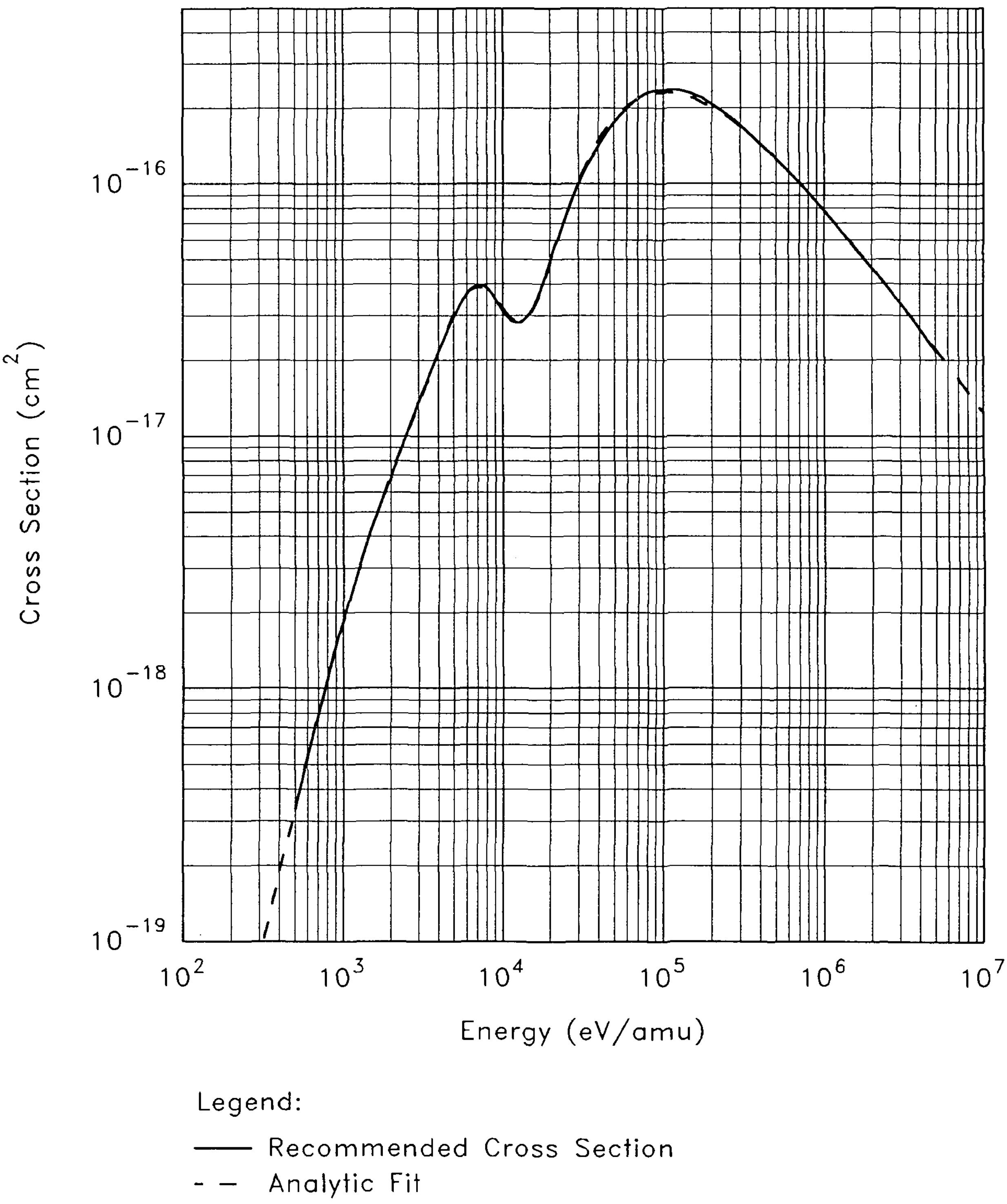
The rms deviation of the above fit to the recommended cross section is 1.8%, with a maximum deviation of 5.3% at 41.6 keV/amu.

ALADDIN evaluation function for cross section: HEXC2

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (1s) He [+2] H [+0] (n=2)

$He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n=2)$



3.1.2. $He^{2+} + H(1s) \rightarrow He^{2+} + H^*(n=3)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	9.69E−21
1.00E+03	4.39E+07	1.13E−19
2.00E+03	6.21E+07	9.72E−19
5.00E+03	9.82E+07	8.59E−18
1.00E+04	1.39E+08	8.65E−18
2.00E+04	1.96E+08	1.13E−17
5.00E+04	3.11E+08	4.48E−17
1.00E+05	4.39E+08	5.24E−17
2.00E+05	6.21E+08	4.10E−17
5.00E+05	9.82E+08	2.37E−17
1.00E+06	1.39E+09	1.40E−17
2.00E+06	1.96E+09	8.01E−18
5.00E+06	3.11E+09	3.59E−18

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 2 : 30-60 % ; 2 ≤ E (keV/amu) < 15 : 20-30 % ; 15 ≤ E (keV/amu) < 200 : 15-20 % ; E > 200 keV/amu : 10-15 %

Comments: (1) In the energy region below 80 keV/amu, the recommended cross section is based on the results of two-centre multi-state AO calculations of Fritsch et al [57], and on the adiabatic superpromotion model calculations of Krstic and Janev [56] (for E < 1.5 keV/amu). In the energy range between 16 and 66 keV/amu, the calculations of Fritsch et al agree to within 10 - 15 % with the Balmer-alpha emission cross section of Donnelly et al [59].

(2) The recommended cross section for E > 100 keV/amu is based on the single-center AO close-coupling of Reinhold et al [54] (up to 800 keV/amu), and on the q-scaled (q = 2, for He^{2+}) proton-impact excitation formula of Lodge et al [55].

(3) We note that the q-scaled recommended cross section for proton impact excitation of the 1s → n = 3 transition, according to the relation (q = 2) $\sigma(He^{2+}; E) = 2\sigma(H^+; E/2)$, agrees with the recommended He^{2+} - impact 1s → n = 3 excitation cross section within 10 - 30 % in the energy range 10 - 100 keV/amu, and within 3 - 5 % for energies above 200 keV/amu.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

A_1 - A_5	18.775	73.938	3.2231	1.2879E−04	0.75301
A_6 - A_{10}	−4.1638	2.3660E−01	20.927	1.6636E−03	3.6319

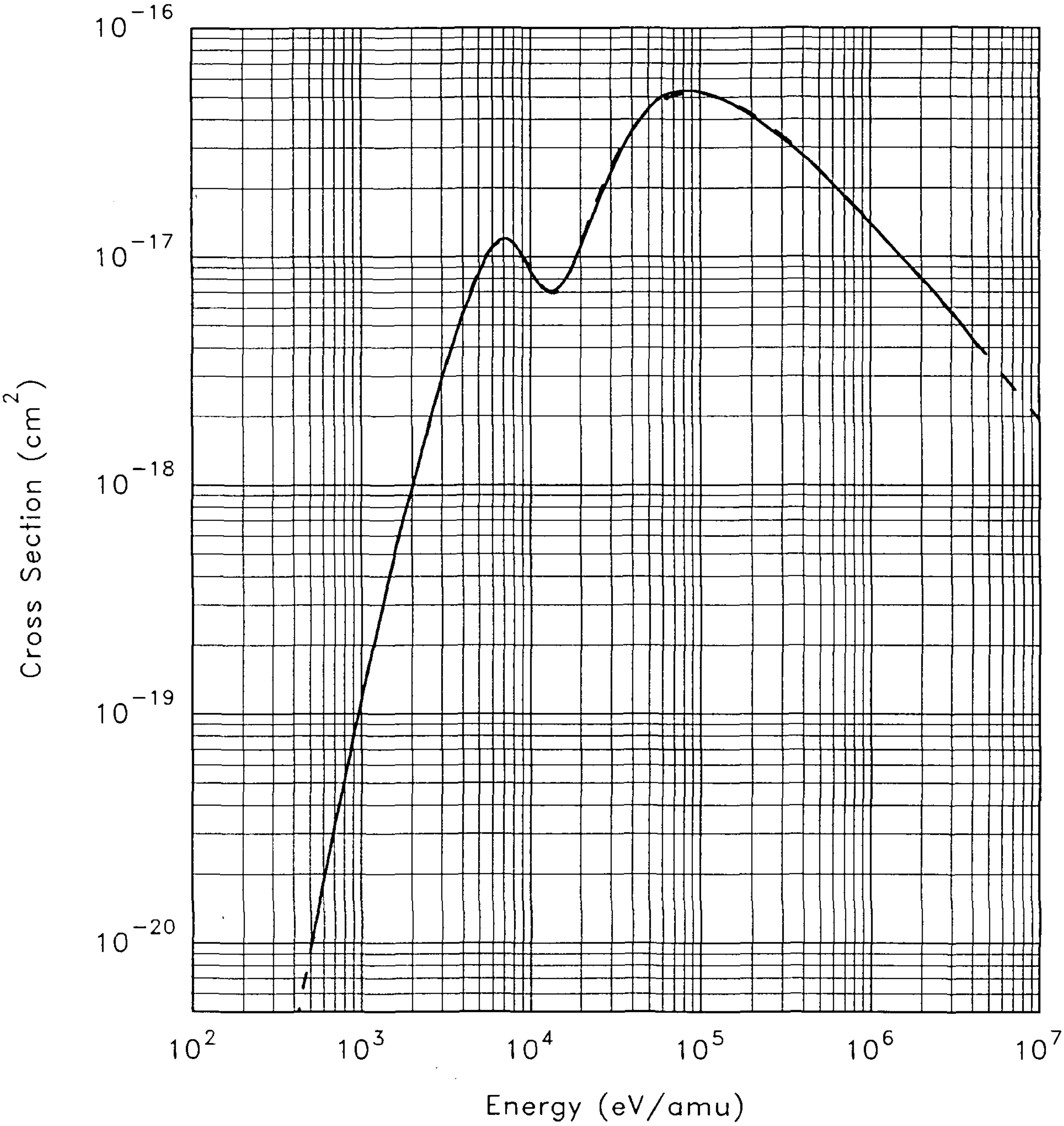
The rms deviation of the above fit to the recommended cross section is 2.0%, with a maximum deviation of 5.9% at 25.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC2

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (1s) He [+2] H [+0] (n=3)

$He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n=3)$



Legend:

—— Recommended Cross Section

- – Analytic Fit

3.1.3. $He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n=4)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.93E−21
1.00E+03	4.39E+07	2.46E−20
2.00E+03	6.21E+07	2.70E−19
5.00E+03	9.82E+07	3.31E−18
1.00E+04	1.39E+08	3.46E−18
2.00E+04	1.96E+08	5.09E−18
5.00E+04	3.11E+08	1.87E−17
1.00E+05	4.39E+08	2.00E−17
2.00E+05	6.21E+08	1.53E−17
5.00E+05	9.82E+08	8.21E−18
1.00E+06	1.39E+09	4.77E−18
2.00E+06	1.96E+09	2.69E−18
5.00E+06	3.11E+09	1.25E−18

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 10 : 40-80 % ; 10 ≤ E (keV/amu) ≤ 200 : 20-40 % ; E > 200 keV/amu : 15-20 %

Comments: (1) In the energy region below 50 keV/amu, the σ (1s → 4) cross section has been obtained from the recommended σ (1s → 3) cross section by using the relationship: $\sigma(1s \rightarrow 4) = (3/4)^3 \sigma(1s \rightarrow 3)$. In the energy region below 8 keV/amu, the ratio of this cross section and that obtained by Krstic and Janev [56] using the adiabatic superpromotion model remains approximately the same as the ratio of the corresponding cross sections for the 1s →n=3 transition.

(2) The recommended cross section for E > 80 keV/amu is based on the multi-state single-center AO close-coupling calculations of Reinhold et al [54] (up to 800 keV/amu), and on the q-scaled proton-impact excitation formula of Lodge et al [55] : $\sigma(He^{2+}; E) = 2\sigma(H^{+}; E/2)$.

(3) We note that the q-scaled recommended cross section for proton impact excitation of the 1s → n=4 transition, according to the relation (q=2) $\sigma(He^{2+}; E) = 2\sigma(H^{+}; E/2)$, agrees with the present recommended cross section within 10 - 40 % in the energy range 10 - 150 keV/amu, and to 3 - 5 % for E > 200 keV/amu.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1+A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1+A_9E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

A_1 - A_5	5.5094	68.504	12.621	7.7669E−05	0.53813
A_6 - A_{10}	−4.1788	4.0349E−02	16.213	5.4493E−09	9.5011

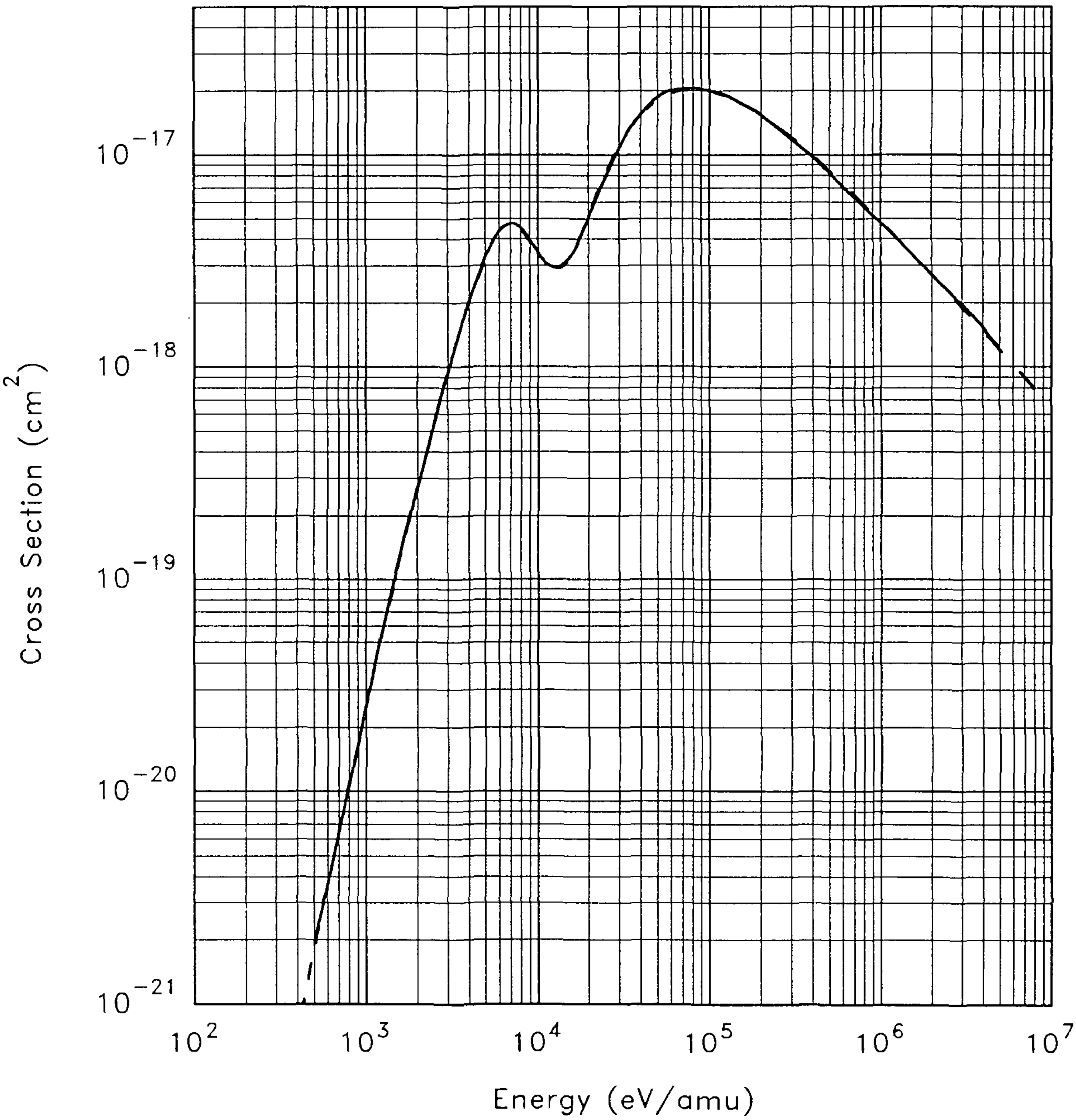
The rms deviation of the above fit to the recommended cross section is 2.1%, with a maximum deviation of 6.2% at 0.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC2

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (1s) He [+2] H [+0] (n=4)

$$He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n=4)$$



Legend:

—— Recommended Cross Section

- – Analytic Fit

3.1.4. $He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n)$, n>4

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) 1s → n=5	1s → n=6	1s → n=7
5.00E+02	3.11E+07	2.43E−21	1.56E−21	9.80E−22
1.00E+03	4.39E+07	1.23E−20	7.49E−21	4.72E−21
2.00E+03	6.21E+07	5.63E−20	3.25E−20	2.04E−20
5.00E+03	9.82E+07	3.23E−19	1.81E−19	1.14E−19
1.00E+04	1.39E+08	8.50E−19	4.82E−19	3.04E−19
2.00E+04	1.96E+08	2.02E−18	1.12E−18	7.08E−19
5.00E+04	3.11E+08	5.11E−18	2.85E−18	1.80E−18
1.00E+05	4.39E+08	6.40E−18	3.67E−18	2.31E−18
2.00E+05	6.21E+08	5.59E−18	3.25E−18	2.05E−18
5.00E+05	9.82E+08	3.49E−18	2.02E−18	1.27E−18
1.00E+06	1.39E+09	2.18E−18	1.25E−18	7.88E−19
2.00E+06	1.96E+09	1.29E−18	7.34E−19	4.62E−19
5.00E+06	3.11E+09	6.17E−19	3.46E−19	2.18E−19

Accuracy: $E \leq 10$ keV/amu : Indeterminate ; $10 < E$ (keV/amu) ≤ 80 : 30 - 50 % ; $80 < E$ (keV/amu) ≤ 200 : 15 - 30 % ; $E > 200$ keV/amu : 15%, or better

Comments: (1) The cross sections for the 1s → n ($n \geq 5$) excitation of hydrogen atoms by He^{2+} −impact, with accuracies indicated above, can be obtained by scaling the corresponding recommended excitation cross section by proton impact according to the relation

$$\sigma_n (He^{2+} ; E) = 2\, \sigma_n (H^+ ; E/2) \qquad \text{(a)}$$

(2) Within the same accuracy as shown above the 1s → n ($n \geq 5$) excitation cross sections in the energy region above 10 keV/amu can be obtained using the scaling relationship (a) to the proton-impact excitation cross sections generated by the semi-empirical formula of Lodge et al [55].

(3) The cross sections for the excitation to n = 5 and n = 6 can be obtained in analytic form by applying the scaling (a) to the analytic fit function of corresponding proton-impact cross sections (see reaction 2.1.6, p. 52)

$$\sigma_{exc}(n=5,6) = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\, \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu and the values of parameters A_i are :

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
1s → n=5	4.9796	64.582	0.10588	2.8878E−05	0.15531	−2.4161	1.6389E−03	−6.3726
1s → n=6	2.55080	74.348	0.19625	3.3570E−05	0.12878	−2.2950	5.1445E−03	−5.5986

(4) Cross sections for the 1s → n ($n \geq 7$) levels can be obtained by using in Eq. (a) the formula of Lodge et al [55] for $\sigma_n (H^+ ; E/2)$. For approximate estimates of σ_{exc} ($n \geq 7$) one can also use the n^{-3}−scaling

$$\sigma_{exc}(1s \rightarrow n) = \left(\frac{6}{n}\right)^3 \sigma_{exc} (1s \rightarrow n=6), \qquad n \geq 7 .$$

ALADDIN evaluation function for cross section: HEXC3 for n = 5 - 6 and HEXC4 for n>6

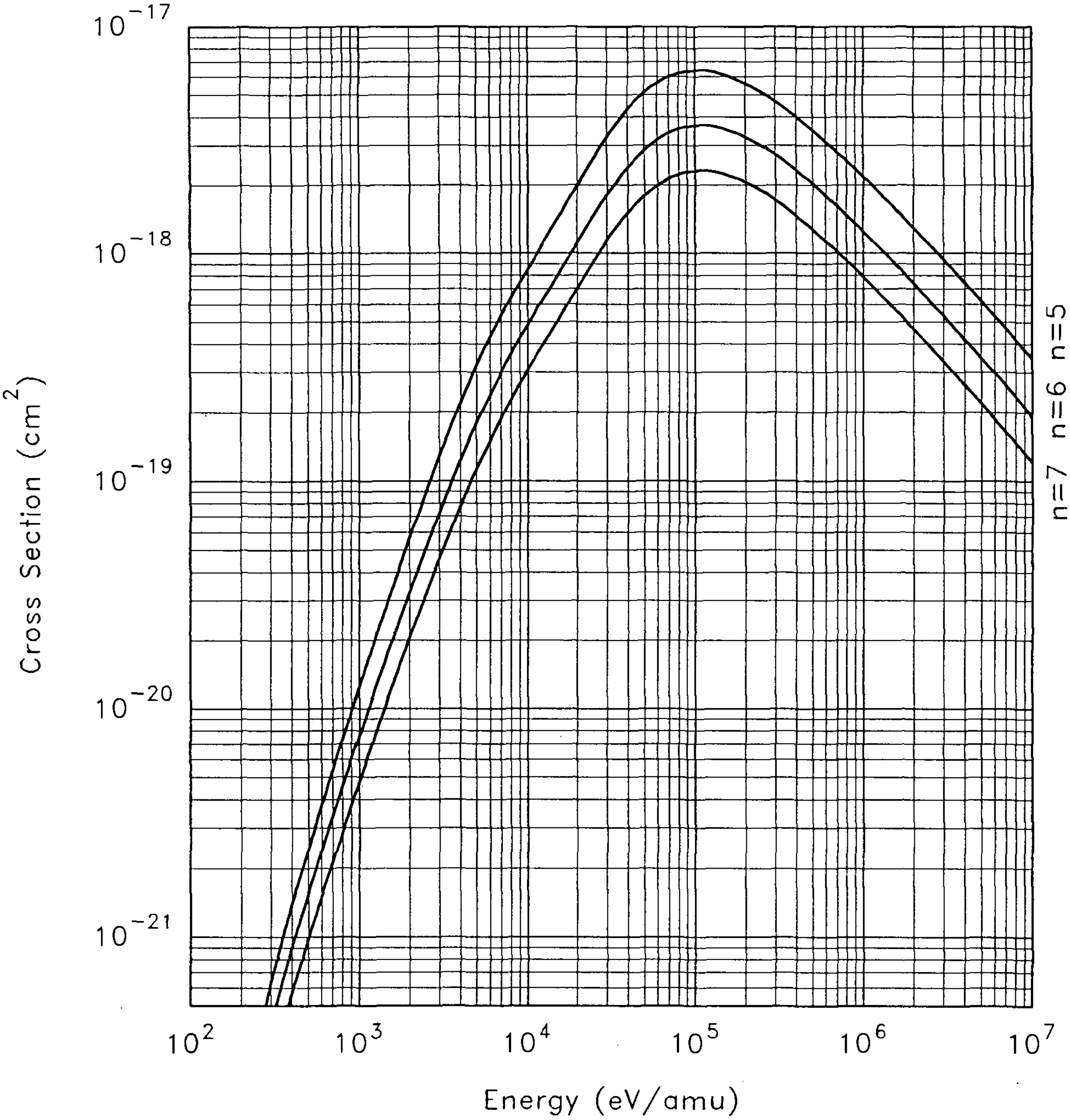
ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (1s) He [+2] [+0] (n=5), for 1s→n=5

EXC He [+2] H [+0] (1s) He [+2] [+0] (n=6), for 1s→n=6

EXC He [+2] H [+0] (1s) He [+2] H [+0] (n>6), for 1s→n>6

$$He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(n),\ n>4$$



Legend:

—— Recommended Cross Section

3.1.5. $He^{2+} + H^*(n=2) \rightarrow He^{2+} + H^*(m=3)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.14E−16
1.00E+03	4.39E+07	3.46E−16
2.00E+03	6.21E+07	8.44E−16
5.00E+03	9.82E+07	2.17E−15
1.00E+04	1.39E+08	3.63E−15
2.00E+04	1.96E+08	5.01E−15
5.00E+04	3.11E+08	5.12E−15
1.00E+05	4.39E+08	3.99E−15
2.00E+05	6.21E+08	2.86E−15
5.00E+05	9.82E+08	1.56E−15
1.00E+06	1.39E+09	9.24E−16
2.00E+06	1.96E+09	5.25E−16
5.00E+06	3.11E+09	2.27E−16

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \leq E$ (keV/amu) < 20 : 30 - 50 % ; $20 \leq E$ (keV/amu) ≤ 100 : 25 - 30 % ; $E > 100$ keV/amu : 15 - 20 %

Comments: (1) In the energy region below 10 keV/amu, the recommended cross section follows the data of adiabatic superpromotion model calculations of Krstic and Janev [56].

(2) For energies above 10 keV/amu, the recommended cross section represents the q-scaled (q=2) proton-impact recommended cross section $\sigma(He^{2+}; E) = 2\sigma(H^+; E/2)$ for the $n=2 \rightarrow m=3$ excitation. At the energy of 70 keV/amu, this cross section agrees with the result of AO-close-coupling calculations of Reinhold et al [54] to 15%.

(3) The q-scaled proton impact formula of Lodge et al [55] gives cross sections which for energies above 10 keV/amu agree to within 2-5 % with the present recommended cross section.

Analytic fitting function

Cross Section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

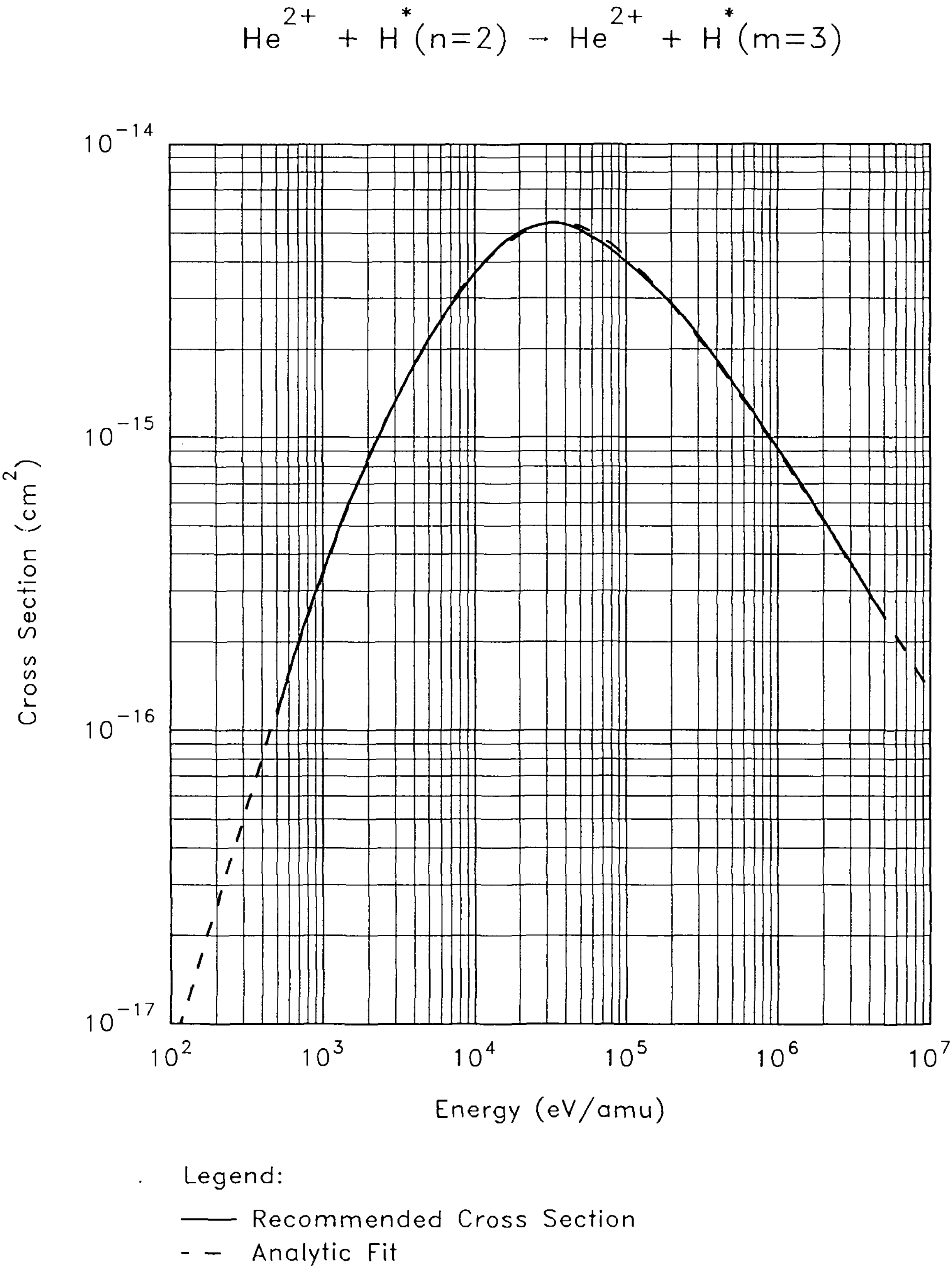
A_1	A_2	A_3	A_4	A_5	A_6
1864.3	19.395	0.13899	2.4502E−03	0.29660	−1.7558

The rms deviation of the above fit to the recommended cross section is 2.1%, with a maximum deviation of 6.8% at 0.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (n=2) He [+2] H [+0] (m=3)



$He^{2+} + H^*(n=2) \rightarrow He^{2+} + H^*(m=3)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Cross Section (cm^2)
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

3.1.6. $He^{2+} + H^{*}(n=2) \rightarrow He^{2+} + H^{*}(m=4)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.27E−17
1.00E+03	4.39E+07	3.84E−17
2.00E+03	6.21E+07	9.48E−17
5.00E+03	9.82E+07	2.63E−16
1.00E+04	1.39E+08	4.85E−16
2.00E+04	1.96E+08	7.44E−16
5.00E+04	3.11E+08	8.69E−16
1.00E+05	4.39E+08	7.02E−16
2.00E+05	6.21E+08	4.72E−16
5.00E+05	9.82E+08	2.44E−16
1.00E+06	1.39E+09	1.43E−16
2.00E+06	1.96E+09	8.13E−17
5.00E+06	3.11E+09	3.75E−17

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 40 - 80 % ; 5 ≤ E (keV/amu) ≤ 20 : 30 - 40 % ; 20 < E (keV/amu) ≤ 200 : 20 - 30 % ; E > 200 keV/amu : 15 - 20 %

Comments:
(1) In the energy region above 10 keV/amu, the q-scaled (q = 2) formula of Lodge et al [55], $\sigma(He^{2+}; E) = 2\sigma(H^{+}; E/2)$, gives results which are to within 2-5% in agreement with the q-scaled recommended data for the proton-impact n=2→m=4 excitation transition. At an energy E = 70 keV/amu, these data agree to 20% with the AO close-coupling result of Reinhold et al [54].

(2) In the energy region below 10 keV/amu, the q-scaled recommended cross section data increasingly disagree with the data from the q-scaled Lodge et al formula, but in the region below 5 keV/amu they agree with the adiabatic superpromotion model calculations of Krstic and Janev [56] within 40-80%.

(3) The q-scaled recommended proton-impact n=2→m=4 excitation cross section was taken as recommended at all considered energies.

Analytic fitting function

Cross Section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

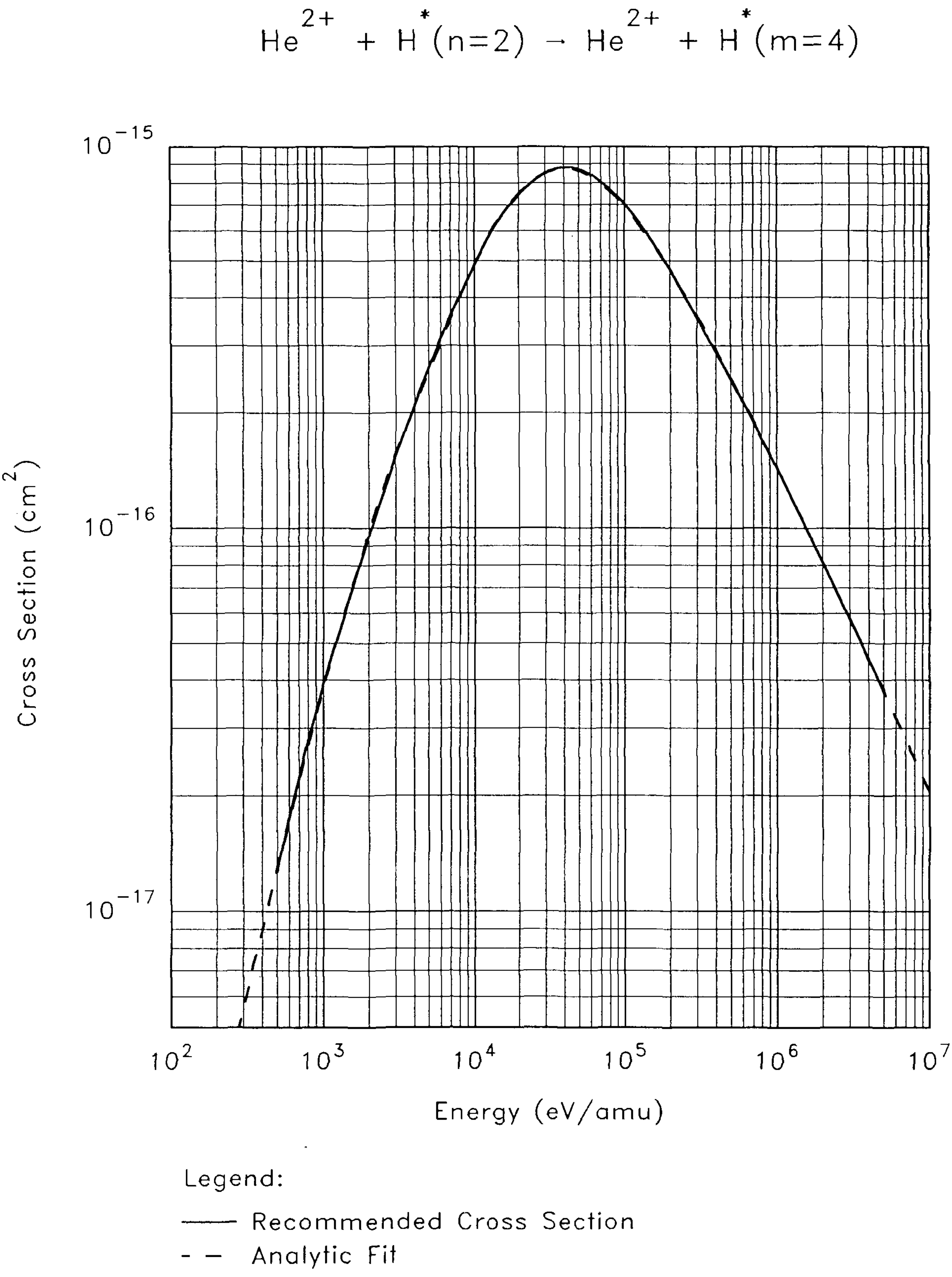
A_1	A_2	A_3	A_4	A_5	A_6
246.18	27.764	0.39876	1.9381E−03	0.23304	−1.7165

The rms deviation of the above fit to the recommended cross section is 1.2, with a maximum deviation of 3.9% at 2.0 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling:

EXC He [+2] H [+0] (n=2) He [+2] H [+0] (m=4)



$He^{2+} + H^{*}(n=2) \rightarrow He^{2+} + H^{*}(m=4)$
10^{-15}
10^{-16}
10^{-17}
Cross Section (cm^2)
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
—— Recommended Cross Section
- - Analytic Fit

3.1.7. $He^{2+} + H^*(n=2) \rightarrow He^{2+} + H^*(m=5)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	5.96E−18
1.00E+03	4.39E+07	1.53E−17
2.00E+03	6.21E+07	3.64E−17
5.00E+03	9.82E+07	8.93E−17
1.00E+04	1.39E+08	1.56E−16
2.00E+04	1.96E+08	2.49E−16
5.00E+04	3.11E+08	2.96E−16
1.00E+05	4.39E+08	2.49E−16
2.00E+05	6.21E+08	1.71E−16
5.00E+05	9.82E+08	8.92E−17
1.00E+06	1.39E+09	5.12E−17
2.00E+06	1.96E+09	2.86E−17
5.00E+06	3.11E+09	1.29E−17

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 40 - 100 % ; 5 ≤ E (keV/amu) ≤ 20 : 30 - 40 % ; 20 < E (keV/amu) ≤ 200 : 20 - 30 % ; E > 200 keV/amu : 20 %, or better

Comments: (1) In the absence of any theoretical or experimental data for this excitation transition, its cross section can be constructed by scaling the corresponding proton-impact excitation cross section according to

$$\sigma_{2\rightarrow5}(He^{2+}; E) = 2\,\sigma_{2\rightarrow5}(H^+; E/2) \qquad \text{(a).}$$

(2) The assigned cross section uncertainties reflect those of the proton-impact n=2→m=5 excitation cross section, and are consistent with the uncertainties of the He^{2+}−impact cross section for the n=2→m=4 excitation transition.

(3) The cross section below is derived from the analytic fit function for the H^+−impact n=2→m=5 excitation cross section (see reaction 2.1.8, p. 56) by using the scaling relation (a).

Analytic fitting function

Cross section:

$$\sigma_{exc}(2\rightarrow5) = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu and the values of parameters A_i are:

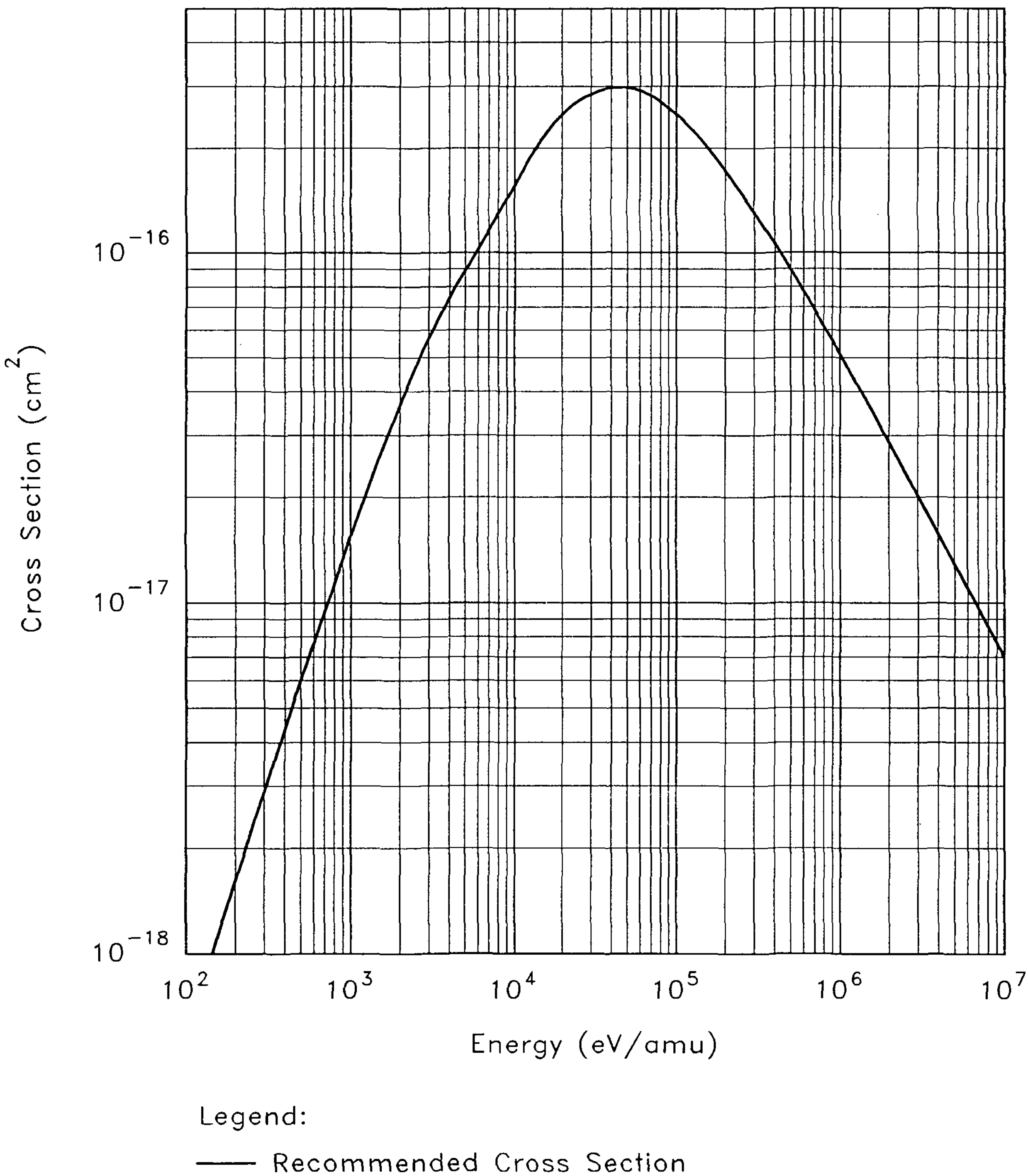
A_1	A_2	A_3	A_4	A_5	A_6
73.056	37.946	1.4528	2.4601E−03	0.15855	−1.4775

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (n=2) He [+2] H [+0] (m=5)

$He^{2+} + H^*(n=2) \rightarrow He^{2+} + H^*(m=5)$



3.1.8. $He^{2+} + H^*(n=2) \rightarrow He^{2+} + H^*(m), \quad m > 5$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=2 → m=6	n=2 → m=8	n=2 → m=10
5.00E+02	3.11E+07	2.75E−18	8.73E−19	3.61E−19
1.00E+03	4.39E+07	7.07E−18	2.25E−18	9.28E−19
2.00E+03	6.21E+07	1.68E−17	5.34E−18	2.21E−18
5.00E+03	9.82E+07	4.12E−17	1.31E−17	5.40E−18
1.00E+04	1.39E+08	7.17E−17	2.28E−17	9.41E−18
2.00E+04	1.96E+08	1.15E−16	3.65E−17	1.51E−17
5.00E+04	3.11E+08	1.37E−16	4.34E−17	1.79E−17
1.00E+05	4.39E+08	1.15E−16	3.65E−17	1.51E−17
2.00E+05	6.21E+08	7.91E−17	2.51E−17	1.04E−17
5.00E+05	9.82E+08	4.11E−17	1.31E−17	5.40E−18
1.00E+06	1.39E+09	2.36E−17	7.50E−18	3.10E−18
2.00E+06	1.96E+09	1.32E−17	4.19E−18	1.73E−18
5.00E+06	3.11E+09	5.94E−18	1.89E−18	7.80E−19

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \leq E$ (keV/amu) < 5 : 40-100 % ;
$5 \leq E$ (keV/amu) < 20 : 30-40 % ; $20 \leq E$ (keV/amu) ≤ 200 : 20-30 % ;
$E > 200$ keV/amu : 20 %; or better

Comments : (1) The cross sections for the n=2 → ≥6 He^{2+}−impact excitation transitions can be obtained (within the accuracies specified above) by scaling the corresponding proton-impact excitation cross sections : $\sigma_{exc}(He^{2+}; E) = 2\ \sigma_{exc}(H^+; E/2)$. This procedure gives:

(2) For the n=2 → m=6−10 transitions, the cross section can be represented as:

$$\sigma_{exc}(2 \rightarrow m) = A_{2-m}\, \sigma_{exc}(2 \rightarrow 5), \qquad (a)$$

where $\sigma_{exc}(2 \rightarrow 5)$ is the recommended cross section for the 2 → 5 transition, and the coefficients A_{2-m} are given in the table below.

(3) For the transitions 2 → m, m>10, the cross section can be estimated using the m^{-3}−scaling,

$$\sigma_{exc}(2 \rightarrow m) = \left(\frac{10}{m}\right)^3 \sigma_{exc}(2 \rightarrow 10), \quad m > 10, \qquad (b)$$

Values of the coefficients for equation (a)

A_{2-6}	A_{2-7}	A_{2-8}	A_{2-9}	A_{2-10}
0.4610	0.2475	0.1465	0.0920	0.0605

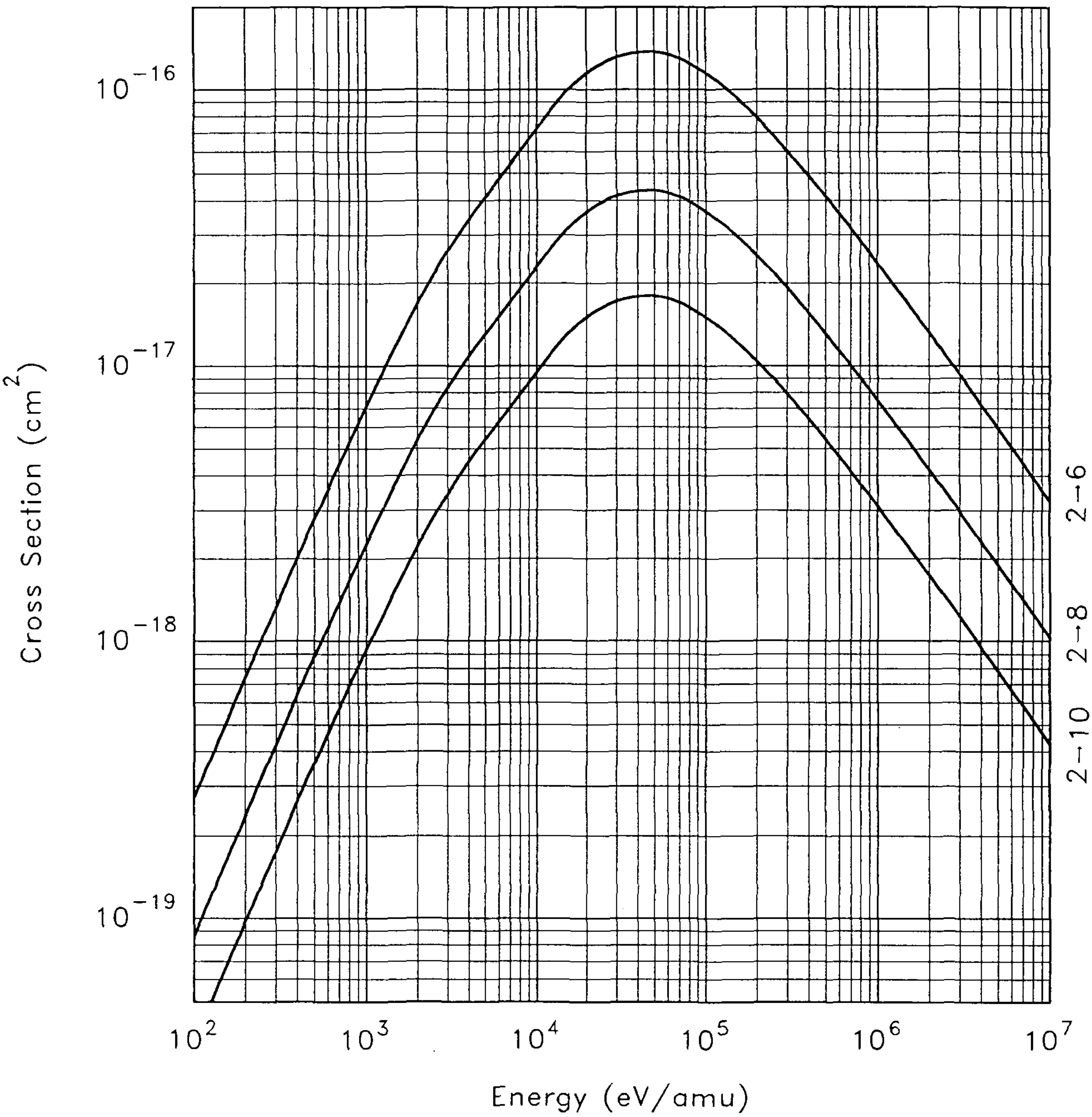
ALADDIN evaluation function for cross section: HEXC5 for n = 6-10 and HEXC4 for n>10

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (n=2) He [+2] [+0] (m), for n=2 → m=6−10

EXC He [+2] H [+0] (n=2) He [+2] [+0] (m>10), for n=2 → m>10

$He^{2+} + H^{*}(n=2) \rightarrow He^{2+} + H^{*}(m),\ m>5$



Legend:

—— Recommended Cross Section

3.1.9. $He^{2+} + H^*(n=3) \rightarrow He^{2+} + H^*(m), \quad m = 4, 5, 6$

Energy	Velocity	Cross sections (cm^2)		
(eV/amu)	(cm/s)	n=3 → m=4	n=3 → m=5	n=3 → m=6
5.00E+02	3.11E+07	2.58E−15	4.08E−16	1.45E−16
1.00E+03	4.39E+07	5.48E−15	8.72E−16	3.10E−16
2.00E+03	6.21E+07	1.02E−14	1.63E−15	5.80E−16
5.00E+03	9.82E+07	1.71E−14	2.73E−15	9.72E−16
1.00E+04	1.39E+08	2.36E−14	3.76E−15	1.34E−15
2.00E+04	1.96E+08	2.83E−14	4.52E−15	1.62E−15
5.00E+04	3.11E+08	2.66E−14	4.21E−15	1.51E−15
1.00E+05	4.39E+08	1.94E−14	3.05E−15	1.09E−15
2.00E+05	6.21E+08	1.24E−14	1.94E−15	6.87E−16
5.00E+05	9.82E+08	6.19E−15	9.61E−16	3.39E−16
1.00E+06	1.39E+09	3.50E−15	5.43E−16	1.91E−16
2.00E+06	1.96E+09	1.94E−15	3.01E−16	1.05E−16
5.00E+06	3.11E+09	8.73E−16	1.35E−16	4.70E−17

Accuracy: $E < 0.5$ keV/amu : Indeterminate ; $0.5 \le E$ (keV/amu) < 5 : 40-100 % ;
$5 \le E$ (keV/amu) < 20 : 30-40 % ; $20 \le E$ (keV/amu) ≤ 200 : 20-30 % ;
$E > 200$ keV/amu : 20 %; or better

Comments: (1) There are no experimental data or theoretical calculations for these excitation transitions. The cross sections for these processes can be obtained (within the above assigned accuracies) by q-scaling (q = 2) the corresponding proton-impact excitation cross sections according to $\sigma_{exc}(He^{2+}; E) = 2\,\sigma_{exc}(H^+; E/2)$. The only theoretical cross section value for the n=3 → m= 4 transition obtained at 70 keV/amu by the AO close coupling method (Reinhold et al [54]) agrees to 15% with the q-scaled proton-impact cross section.

(2) The q-scaled proton-impact excitation formula of Lodge et al [55] gives results which in the region above 10 keV/amu agree to 2-5% with the scaled proton impact data.

(3) The cross sections given below are obtained by q-scaling the cross sections 2.1.10 (p. 60)

Analytic fitting function

Cross section:

$$\sigma_{exc}(3 \rightarrow m) = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\,\ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} \right] \quad [cm^2]$$

where E is expressed in keV/amu and the values of parameters A_i are:

	A_1	A_2	A_3	A_4	A_5	A_6
3 → 4	4990.0	22.638	1.3118	0.014239	0.260596	−1.2722
3 → 5	762.36	22.192	1.4549	0.014996	0.27088	−1.2894
3 → 6	253.89	23.014	2.1708	0.015960	0.26730	−1.2881

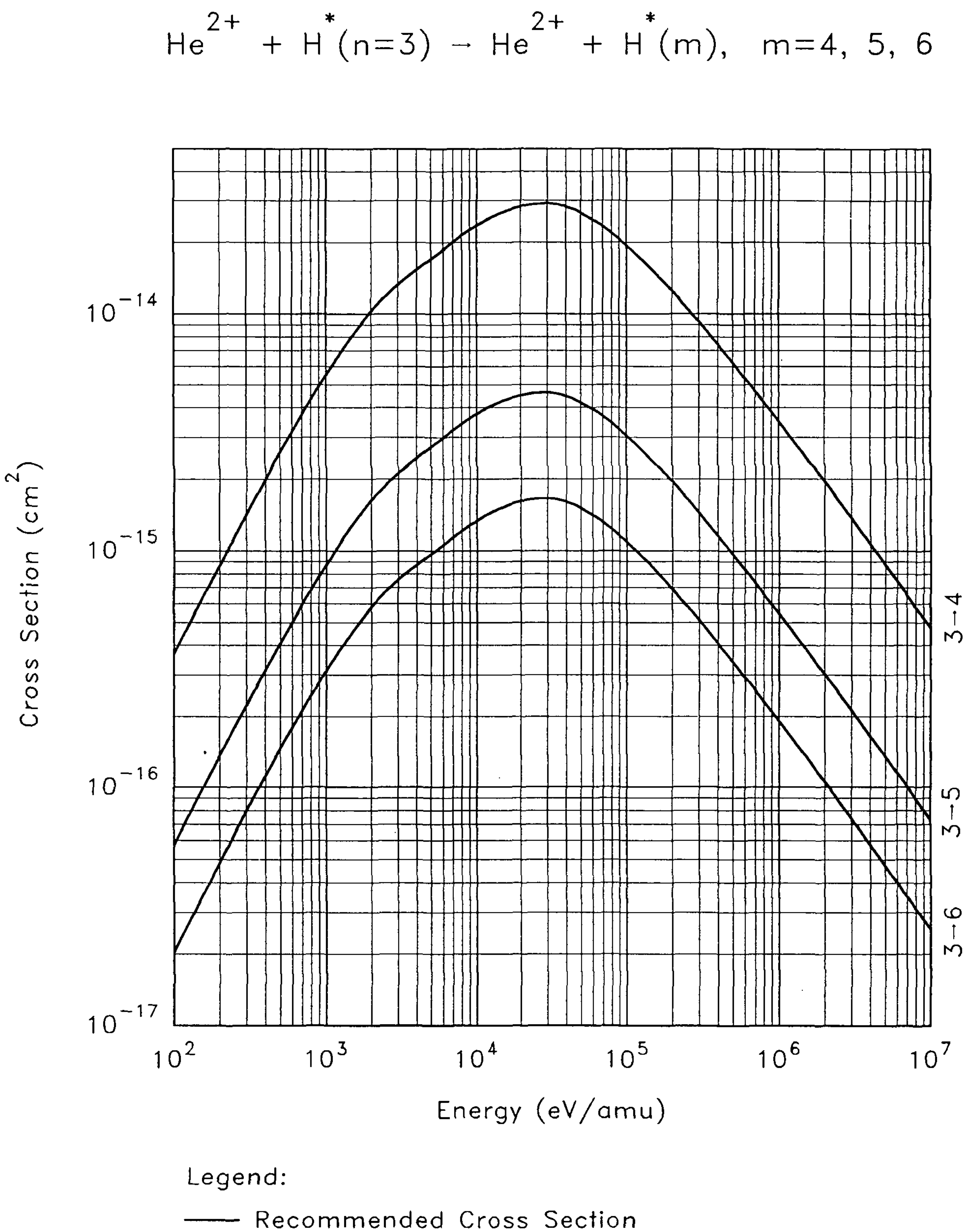
ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (n=3) He [+2] [+0] (m=4), for n=3→m=4

EXC He [+2] H [+0] (n=3) He [+2] [+0] (m=5), for n=3→m=5

EXC He [+2] H [+0] (n=3) He [+2] [+0] (m=6), for n=3→m=6


$He^{2+} + H^{*}(n=3) \to He^{2+} + H^{*}(m)$, m=4, 5, 6
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Cross Section (cm^2)
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
3→4
3→5
3→6
Legend:
—— Recommended Cross Section

3.1.10. $He^{2+} + H^*(n=3) \rightarrow He^{2+} + H^*(m)$, $m > 6$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=3 → m=7	n=3 → m=8	n=3 → m=10
5.00E+02	3.11E+07	6.78E−17	3.69E−17	1.45E−17
1.00E+03	4.39E+07	1.45E−16	7.89E−17	3.10E−17
2.00E+03	6.21E+07	2.71E−16	1.48E−16	5.80E−17
5.00E+03	9.82E+07	4.54E−16	2.47E−16	9.72E−17
1.00E+04	1.39E+08	6.24E−16	3.40E−16	1.34E−16
2.00E+04	1.96E+08	7.54E−16	4.11E−16	1.62E−16
5.00E+04	3.11E+08	7.03E−16	3.83E−16	1.51E−16
1.00E+05	4.39E+08	5.07E−16	2.76E−16	1.09E−16
2.00E+05	6.21E+08	3.21E−16	1.75E−16	6.87E−17
5.00E+05	9.82E+08	1.58E−16	8.63E−17	3.39E−17
1.00E+06	1.39E+09	8.90E−17	4.85E−17	1.91E−17
2.00E+06	1.96E+09	4.91E−17	2.68E−17	1.05E−17
5.00E+06	3.11E+09	2.19E−17	1.20E−17	4.70E−18

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 5 : 40-100 % ;
5 ≤ E (keV/amu) < 20 : 30-40 % ; 20 ≤ E (keV/amu) ≤ 200 : 20-30 % ;
E > 200 keV/amu : 20 %, or better

Comments: (1) The cross sections $\sigma(3 \rightarrow m)$, m = 7 - 10 can be determined from the relation,

$$\sigma_{exc}(3 \rightarrow m) = A_{3-m}\,\sigma_{exc}(3 \rightarrow 6), \qquad \text{(a)}$$

where $\sigma(3 \rightarrow 6)$ is the cross section for the He^{2+} −impact n=3 → m=6 transition, and A_{3-m} have the same values as for the corresponding proton-impact reactions (c.f. reaction 2.1.11, p. 62) and are given in the table below.

(2) For the transitions 3 → m, m>10, the cross section can be estimated using the m^{-3}−scaling,

$$\sigma_{exc}(3 \rightarrow m) = \left(\frac{10}{m}\right)^3 \sigma_{exc}(3 \rightarrow 10), \qquad \text{(b)}$$

which is believed to be accurate within 10 - 15 % in the energy range above the cross section maximum.

Values of the coefficients for equation (a)

A_{3-7}	A_{3-8}	A_{3-9}	A_{3-10}
0.4670	0.2545	0.1540	0.1000

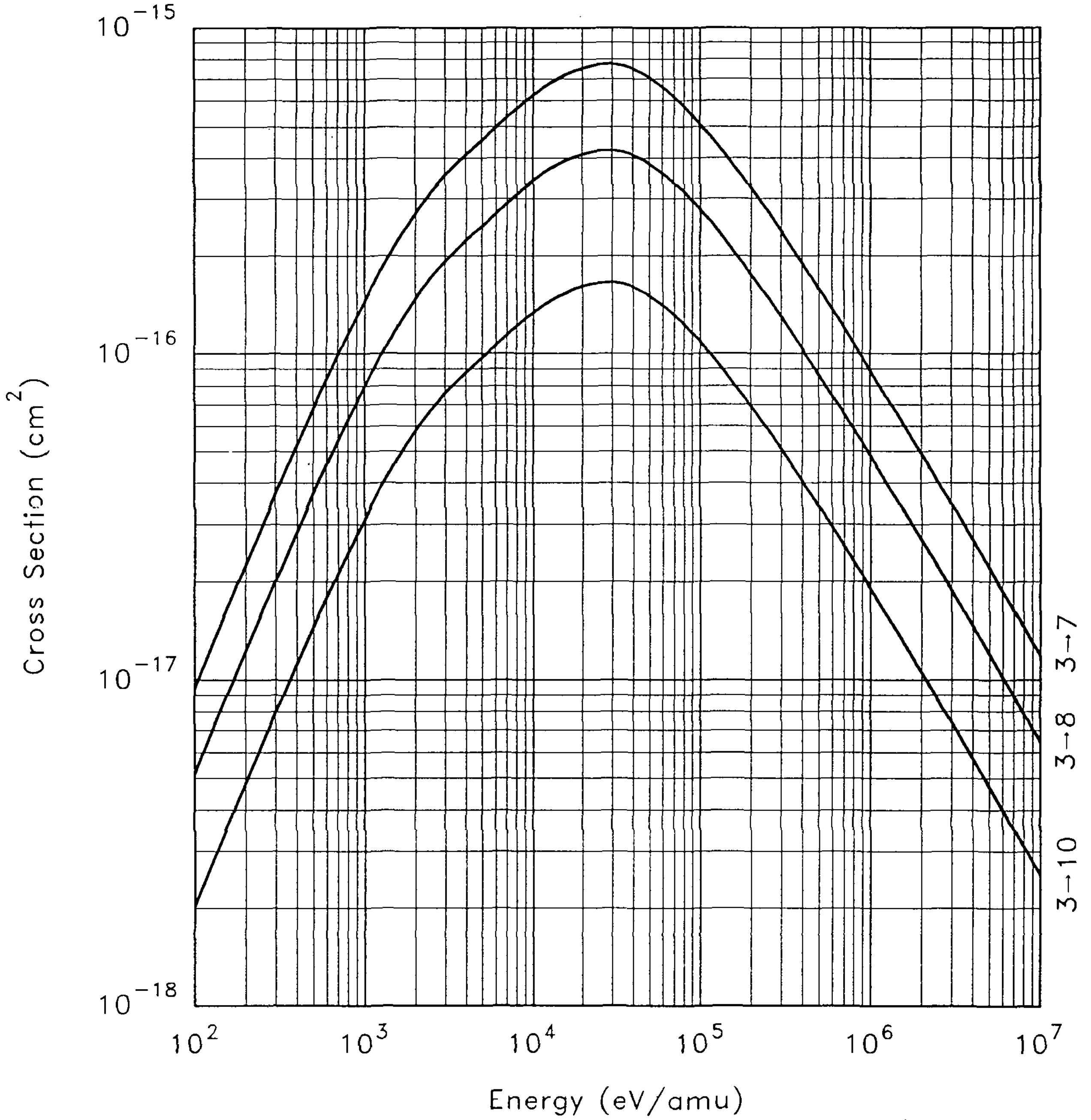
ALADDIN evaluation function for cross section: HEXC5 for n = 7 - 10 and HEXC4 for n>10

ALADDIN hierarchical labelling:

EXC He [+2] H [+0] (n=3) He [+2] [+0] (m), for n=3 → m=7−10

EXC He [+2] H [+0] (n=3) He [+2] [+0] (m>10), for n=3 → m>10

$He^{2+} + H^{*}(n=3) \rightarrow He^{2+} + H^{*}(m),\ m>6$



Legend:

—— Recommended Cross Section

3.1.11. $He^{2+} + H^{*}(n) \rightarrow He^{2+} + H^{*}(m)$, $n > 3$, $m > n$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=4 → m=5	n=4 → m=6	n=4 → m=7
1.00E+03	4.39E+07	2.59E−14	8.34E−15	4.01E−15
2.00E+03	6.21E+07	4.03E−14	1.25E−14	5.90E−15
5.00E+03	9.82E+07	6.35E−14	1.81E−14	8.19E−15
1.00E+04	1.39E+08	8.33E−14	2.02E−14	8.40E−15
2.00E+04	1.96E+08	1.00E−13	1.99E−14	7.68E−15
5.00E+04	3.11E+08	8.80E−14	1.51E−14	5.49E−15
1.00E+05	4.39E+08	6.36E−14	1.02E−14	3.59E−15
2.00E+05	6.21E+08	4.07E−14	6.20E−15	2.15E−15
5.00E+05	9.82E+08	2.03E−14	2.97E−15	1.01E−15
1.00E+06	1.39E+09	1.15E−14	1.64E−15	5.55E−16
2.00E+06	1.96E+09	6.37E−15	8.91E−16	2.99E−16
5.00E+06	3.11E+09	2.86E−15	3.92E−16	1.31E−16

Accuracy: For the $\Delta n = m - n \leq 6$ transitions : 25 - 30 % for energies above the cross section maximum, and 30 - 40 % below the energy at which the maximum occurs and above $50/n^2$ keV/amu. For the $\Delta n > 6$ transitions, the uncertainty progressively increases and may be larger than 100 %.

Comments: (1) In absence of systematic data for the $n \rightarrow m$ ($m > n > 3$) transitions, the q-scaled ($q = 2$) proton-impact excitation semi-empirical formula of Lodge et al [55] can be used to estimate the cross sections with an accuracy as assessed above.

(3) The validity of the q-scaled ($q = 2$) formula of Lodge et al is limited to $E \geq 50$ keV/amu.

Analytic expression

Cross section:

$$\sigma_{exc}(n \rightarrow m) = \frac{1.76 \times 10^{-16} n^4}{\varepsilon} \left[ADL + FGH \right] \quad [cm^2], \qquad (a)$$

where, $\varepsilon = \dfrac{E\,(keV/amu)}{50}$, $\quad s = \Delta n = m - n$, $\quad D = \exp\left[-1/(nm\varepsilon^2) \right]$

$$A = \frac{8}{3s}\left(\frac{m}{sn}\right)^3 \left(0.184 - 0.04/s^{2/3}\right)\left(1 - \frac{0.2s}{nm}\right)^{1+2s}, \quad G = 0.5\left(\frac{\varepsilon n^2}{m - 1/m}\right)^3$$

$$L = \ln\left(\frac{1 + 0.53\,\varepsilon^2 n\,(m - 2/m)}{1 + 0.4\varepsilon}\right), \quad F = \left[1 - 0.3sD/(nm)\right]^{1+2s}$$

$$H = \left[C_2\left(z_-, y\right) - C_2\left(z_+, y\right)\right], \quad C_2(z, y) = \frac{z^2 \ln(1 + 2z/3)}{2y + 3z/2}$$

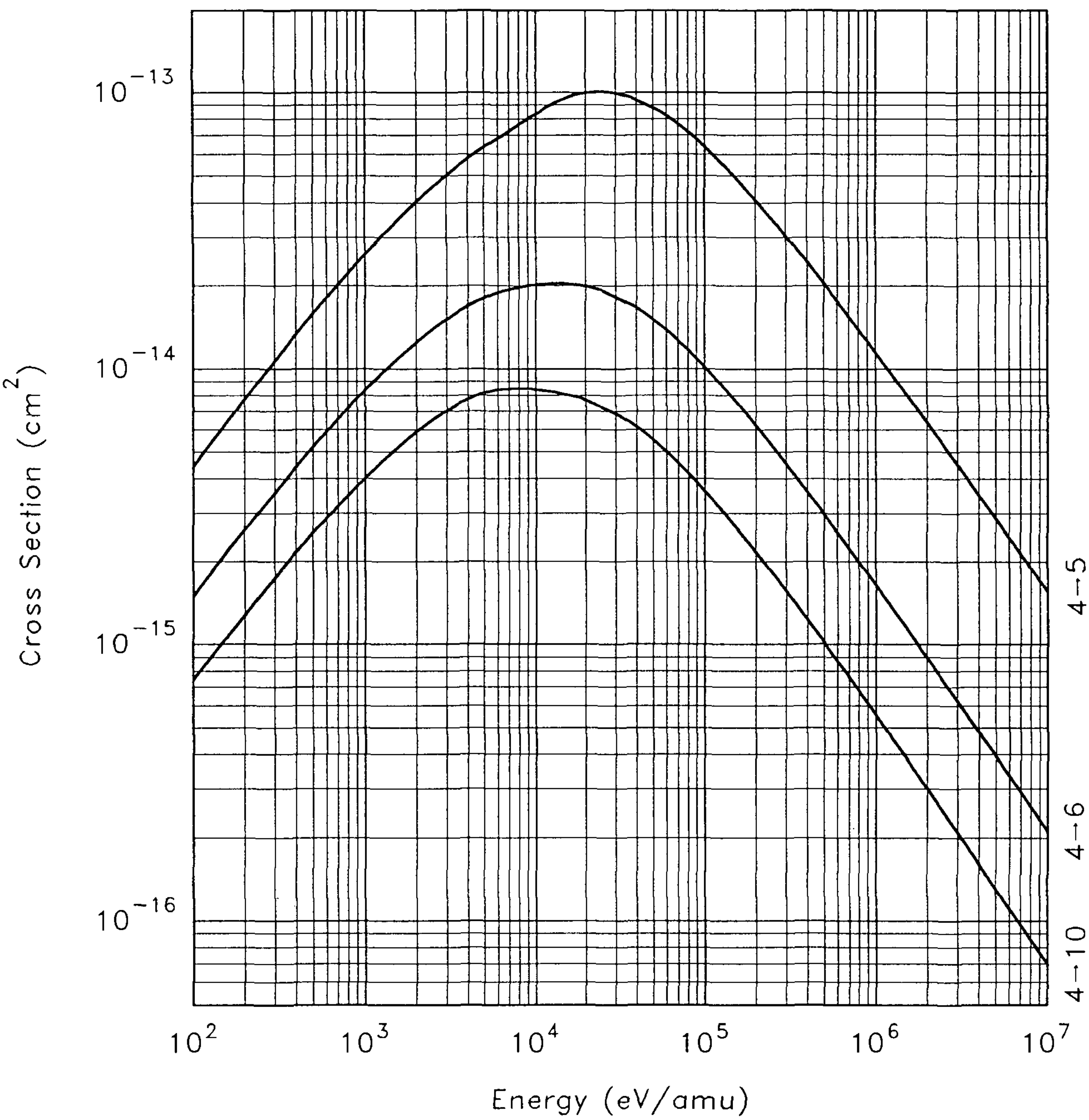
$$z_{\pm} = 2 \Big/ \left\{ \varepsilon n^2 \left[\left(2 - n^2/m^2\right)^{1/2} \pm 1 \right] \right\}, \quad y = 1 \Big/ \left[1 - D \ln(18s)/(4s) \right]$$

ALADDIN evaluation function for cross section: HEXCLD

ALADDIN hierarchical labelling :

EXC He [+2] H [+0] (n>3) He [+2] H [+0] (m>n)

$$He^{2+} + H^{*}(n) \rightarrow He^{2+} + H^{*}(m), \quad m>3, \ m>n$$



Legend:

—— Recommended Cross Section

3. Collision Processes with He^{2+}

3.2. Ionization

3.2.1. $He^{2+} + H(1s) \rightarrow He^{2+} + H^{+} + e^{-}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+02	3.11E+07	1.73E−22
1.00E+03	4.39E+07	1.02E−20
2.00E+03	6.21E+07	2.07E−19
5.00E+03	9.82E+07	3.60E−18
1.00E+04	1.39E+08	1.59E−17
2.00E+04	1.96E+08	7.54E−17
5.00E+04	3.11E+08	4.07E−16
1.00E+05	4.39E+08	3.74E−16
2.00E+05	6.21E+08	2.49E−16
5.00E+05	9.82E+08	1.31E−16
1.00E+06	1.39E+09	7.43E−17
2.00E+06	1.96E+09	4.18E−17
5.00E+06	3.11E+09	1.89E−17

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 3 : 50-100 % ; 3 ≤ E (keV/amu) < 10 : 20-50 % ; 10 ≤ E (keV/amu) < 30 : 10-20 % ; E ≥ 30 keV/amu : 10 %, or better

Comments: (1) For energies below 20 keV/amu, the cross section has been generated from the results of the adabatic calculations of Grozdanov and Solov'ev [83] and Krstic and Janev [56], which for energies between 12 and 20 keV/amu practically coincide with the 2-center 34 AO + pseudostates coupled state calculations of Shingal and Lin [84].

(2) In the energy interval from ~ 20 keV/amu to 600 keV/amu there are experimental cross section data from Shah et al [79,80] for this reaction. The calculations of Shingal and Lin [84] are in agreement with these data up to approximately 200 keV/amu. Above this energy, the experimental data agree with the EIS-CDW calculations of Crothers and McCann [85] and the Glauber approximation results of McGuire [86], which extend up to 1 MeV/amu.

(3) The recommended cross section above 1 MeV/amu has been generated by using the semi-empirical formula of Gillespie [87].

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

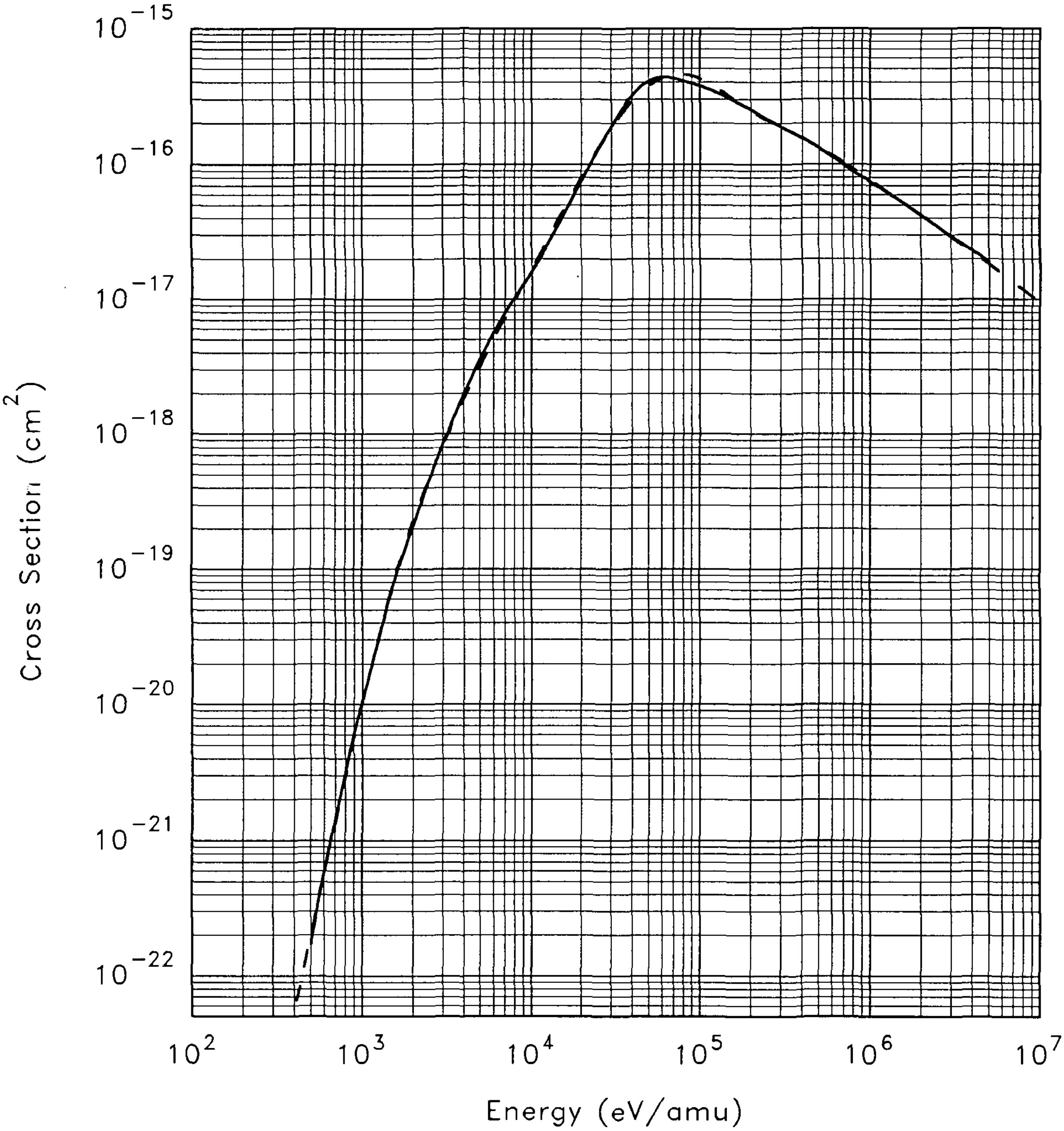
A_1 - A_4	40.498	112.61	1.5496E+06	1.4285E−05
A_5 - A_8	4.1163E−02	−2.6347	4.0589	−5.9204

The rms deviation of the above fit to the recommended cross section is 5.9%, with a maximum deviation of 15.3% at 0.5 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION He [+2] H [+0] (1s) He [+2] H [+1] e

$He^{2+} + H(1s) \rightarrow He^{2+} + H^{+} + e^{-}$



Legend:

—— Recommended Cross Section

- – Analytic Fit

3.2.2. $He^{2+} + H^*(n = 2, 3) \rightarrow He^{2+} + H^+ + e^-$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=2	n=3
5.00E+02	3.11E+07	1.08E−17	1.41E−15
1.00E+03	4.39E+07	6.16E−17	4.74E−15
2.00E+03	6.21E+07	3.00E−16	1.21E−14
5.00E+03	9.82E+07	1.62E−15	2.82E−14
1.00E+04	1.39E+08	4.46E−15	2.99E−14
2.00E+04	1.96E+08	6.19E−15	1.98E−14
5.00E+04	3.11E+08	3.46E−15	8.68E−15
1.00E+05	4.39E+08	1.83E−15	4.50E−15
2.00E+05	6.21E+08	9.64E−16	2.34E−15
5.00E+05	9.82E+08	4.09E−16	1.01E−15
1.00E+06	1.39E+09	2.17E−16	5.28E−16
2.00E+06	1.96E+09	1.14E−16	2.80E−16
5.00E+06	3.11E+09	4.81E−17	1.18E−16

Accuracy: E < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E (keV/amu) < 2 : 40-100 % ; 2 ≤ E (keV/amu) < 10 : 30-40 % ; 10 ≤ E (keV/amu) < 100 : 20-30 % ; E ≥ 100 keV/amu : 20 %

Comments: (1) In the energy region below 6 keV/amu for n = 3 and 15 keV/amu for n = 2, the recommended cross sections σ_{ion} (n=2) and σ_{ion} (n=3) are based on the results of the superpromotion model calculations of Krstic and Janev [56].

(2) For energies above 8 keV/amu for n = 3 and 20 keV/amu for n = 2, the cross sections σ_{ion} (n=2) and σ_{ion} (n=3) are constructed by using the CTMC data of Olson [101] (up to 100 keV/amu) and the q-scaled (q = 2) proton-impact ionization recommended cross sections. In the energy range where the two sets of data overlap (8-100 keV/amu for n = 3 and 20-100 keV/amu for n = 2), they agree within 10% for n = 2 and 10-20% for n = 3.

(3) In the energy region above the cross section maximum (E_{max} ~ 6.7 keV/amu for n = 3 and E_{max} ~ 15 keV/amu for n = 2) σ (n = 3) and σ (n = 2) satisfy the relation

$$\sigma_{ion}(n = 3, E_3) = \left(\frac{3}{2}\right)^4 \sigma_{ion}(n = 2, E_2), \quad E_3 = \left(\frac{2}{3}\right)^2 E_2$$

to within 5-10%. Their E_{max} values are approximately given by $E^n_{max} = 60\, n^{-2}$.

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
n=2	1.0901	26.473	1.0224E+06	5.7286E−03	0.040151	−2.4092	0.014897	−0.23786
n=3	250.10	7.9018	2.1448E+06	0.33041	0.093012	−0.49446	0.63357	−2.7261

For the n = 2 cross section the rms deviation of the above fit to the recommended cross section is 3.8%, with a maximum deviation of 9.6% at 5.4 keV/amu. For the n = 3 cross section the rms deviation of the above fit to the recommended cross section is 2.1%, with a maximum deviation of 4.7% at 7.7 keV/amu.

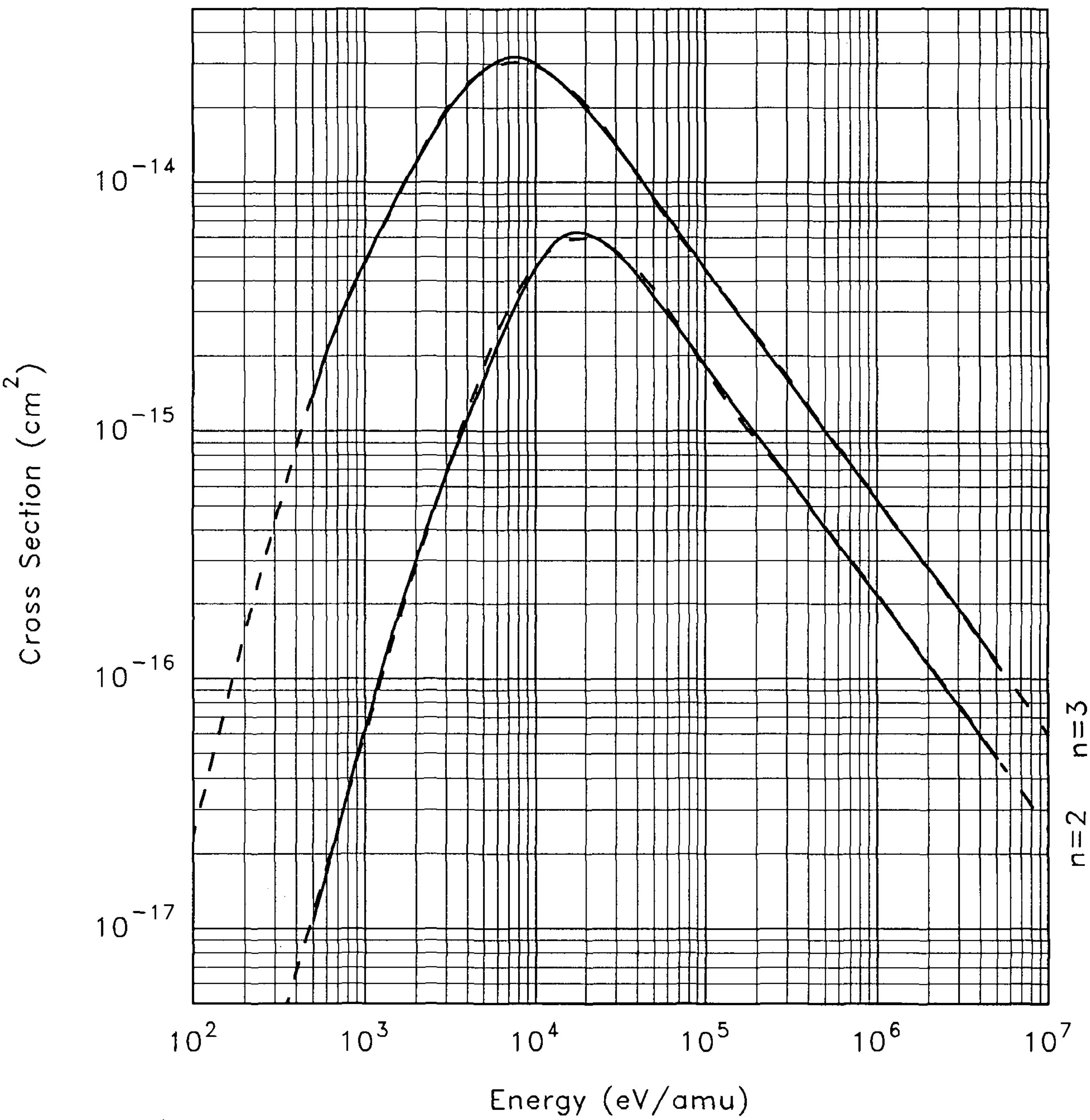
ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling :

ION He [+2] H [+0] (n=2) He [+2] H [+1] e, for n=2

ION He [+2] H [+0] (n=3) He [+2] H [+1] e, for n=3

$He^{2+} + H^{*}(n=2, 3) \rightarrow He^{2+} + H^{+} + e^{-}$



Legend:

—— Recommended Cross Section

- – Analytic Fit

3.2.3. $He^{2+} + H^*(n) \rightarrow He^{2+} + H^+ + e^-, n > 3$

Energy E_n (eV/amu)	Velocity V_n (cm/s)	Cross sections (cm^2) n=4	n=5	n=6
5.00E+02	3.11E+07	1.26E−14	5.75E−14	1.95E−13
1.00E+03	4.39E+07	3.29E−14	1.40E−13	3.97E−13
2.00E+03	6.21E+07	7.20E−14	2.24E−13	4.85E−13
5.00E+03	9.82E+07	9.48E−14	2.00E−13	3.27E−13
1.00E+04	1.39E+08	7.05E−14	1.18E−13	1.70E−13
2.00E+04	1.96E+08	3.79E−14	5.87E−14	8.66E−14
5.00E+04	3.11E+08	1.56E−14	2.56E−14	3.82E−14
1.00E+05	4.39E+08	8.40E−15	1.36E−14	2.02E−14
2.00E+05	6.21E+08	4.45E−15	7.16E−15	1.05E−14
5.00E+05	9.82E+08	1.88E−15	3.01E−15	4.42E−15
1.00E+06	1.39E+09	9.77E−16	1.56E−15	2.28E−15
5.00E+06	3.11E+09	2.10E−16	3.35E−16	4.90E−16

Accuracy: $E < 1 \times n^{-2}$ keV/amu : Indeterminate ; $1 \times n^{-2} \leq E$ (keV/amu) $< 10 \times n^{-2}$: 50 - 100 % ;
$10 \times n^{-2} \leq E$ (keV/amu) $< 100 \times n^{-2}$: 30 - 50 % ;
$100 \times n^{-2} \leq E$ (keV/amu) $\leq 10^3 \times n^{-2}$: 20 - 30 % ;
$E > 10^3 \times n^{-2}$ keV/amu : 20 %

Comments: (1) In the absence of accurate cross section data for ionization of the $n \geq 4$ hydrogen levels by alpha particle impact, the following classical scaling relationship can be used to estimate the cross section

$$\sigma_{ion}(n, E_n) = \left(\frac{4}{3}\right)^4 \sigma_{ion}(3, E), \quad E_n = \left(\frac{3}{n}\right)^2 E \tag{a}$$

where $\sigma_{ion}(3, E)$ is the recommended ionization cross section for $He^{2+} - H^*$ (n=3) collisions.

(2) The scaling relationships (a) are not expected to be valid for energies significantly below the energy of the cross section maximum, $E_{max} \sim 60/n^2$ keV/amu.

(3) The values of the cross sections in the above table are taken from the analytic fit for the σ_{ion} (n=3) cross section.

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} \left(\frac{n}{3}\right)^4 A_1 \left[\frac{\exp(-A_2/E_n) \ln(1 + A_3 E_n)}{E_n} + \frac{A_4 \exp(-A_5 E_n)}{E_n^{A_6} + A_7 E_n^{A_8}} \right] \ [cm^2]$$

where $E_n = (3/n)^2 E$ is expressed in keV/amu.

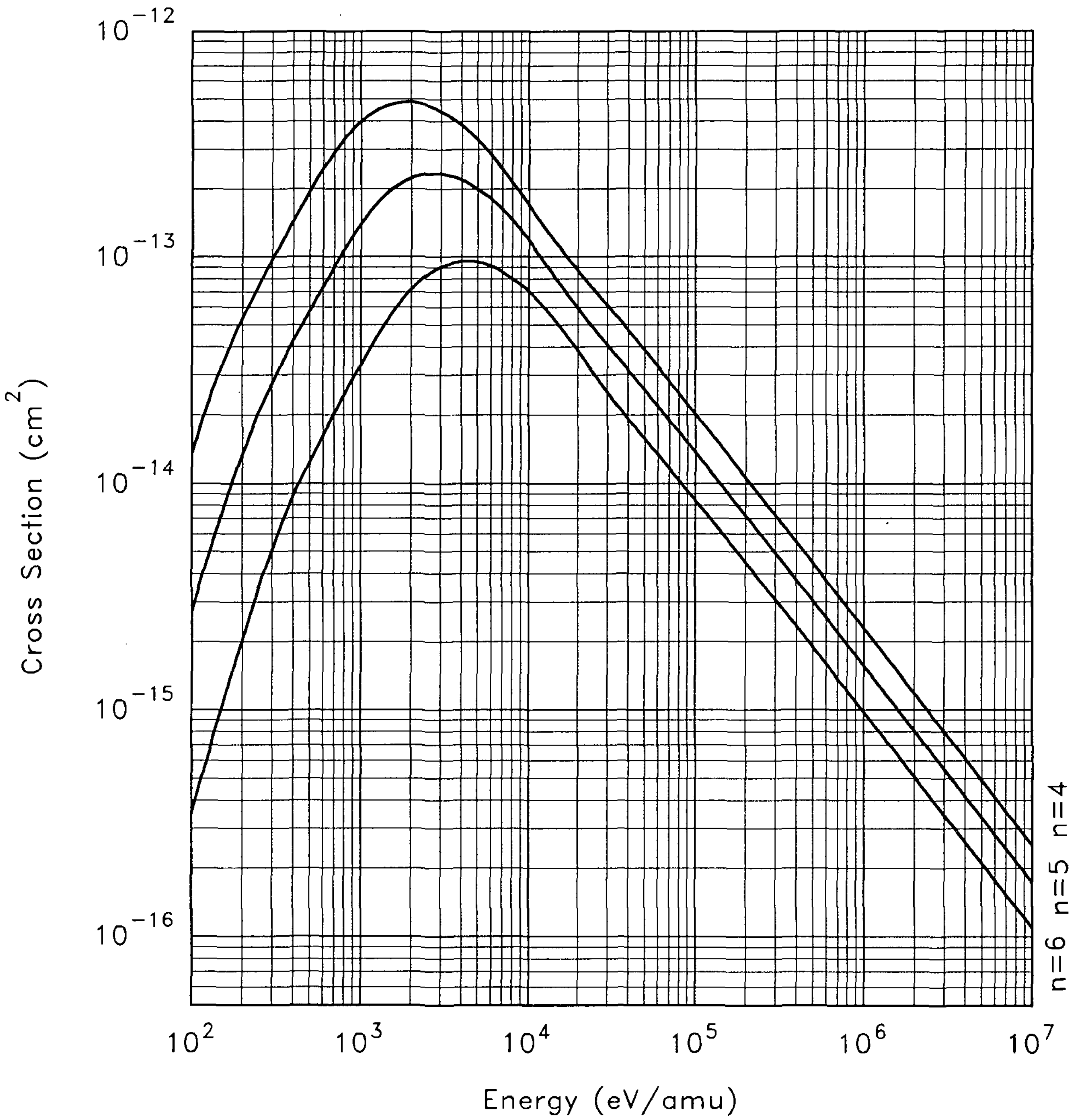
Fitting parameters

$A_1 - A_4$	250.10	7.9018	2.1448E+06	0.33041
$A_5 - A_8$	0.093012	−0.49446	0.63357	−2.7621

ALADDIN evaluation function for cross section: HIONN

ALADDIN hierarchical labelling: ION He [+2] H [+0] (n>3) He [+2] H [+1] e

$He^{2+} + H^{*}(n) \rightarrow He^{2+} + H^{+} + e^{-}$, $n>3$



Legend:

—— Recommended Cross Section

3.3. Electron capture

3.3.1. $He^{2+} + H(1s) \rightarrow He^{+} + H^{+}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+02	1.39E+07	5.00E−19
2.00E+02	1.96E+07	4.58E−18
5.00E+02	3.11E+07	4.99E−17
1.00E+03	4.39E+07	2.18E−16
2.00E+03	6.21E+07	5.82E−16
5.00E+03	9.82E+07	1.13E−15
1.00E+04	1.39E+08	1.24E−15
2.00E+04	1.96E+08	1.14E−15
5.00E+04	3.11E+08	3.46E−16
1.00E+05	4.39E+08	5.24E−17
2.00E+05	6.21E+08	4.61E−18
5.00E+05	9.82E+08	1.05E−19
1.00E+06	1.39E+09	3.64E−21

Accuracy: $E < 0.1$ keV/amu : Indeterminate ; $0.1 \le E$ (keV/amu) < 0.6 : 20-60 % ;
$0.6 \le E$ (keV/amu) < 2 : 10-20 % ; $E \ge 2$ keV/amu : 10 %

Comments: (1) The cross section represented includes electron capture to all final states of He^{+}.

(2) In the energy region below 0.6 keV/amu, the data of theoretical calculations by Kimura and Thorson [88] (10-molecular state expansion), van Hemert et al [89] (time-dependent quantum-mechanical close-coupling method), Errea et al [90] (10-molecular state expansion), Winter [91] (24-34 state triple center expansion) and Krstic and Janev [56] (adiabatic superpromotion method) have a dispersion of about 50 - 60 %. The recommended cross section in this region is based on the data of Krstic and Janev [56] and van Hemert et al [89] and is consistent with the experimental value at approximately 0.5 keV/amu from Nutt et al [92]. We note that the present recommended cross section in the region below 0.6 keV/amu is larger than that adopted by Barnett [62], the difference increasing as the energy decreases, reaching a factor of 2.5 at $E = 0.1$ keV/amu.

(3) In the energy region above 0.6 keV/amu, the recommended cross section is based on the experimental data by Nutt et al [92], Shah and Gilbody [93], Olson et al [94] and Hvelplund and Andersen [69], which are supported by a large number of fairly accurate theoretical calculations [58, 84, 95, 96]. In this region the recommended cross section is in agreement with the evaluated cross section of Barnett [62].

Analytic fitting function

Cross section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)}{1 + A_3 E^{A_4} + A_5 E^{3.5} + A_6 E^{5.4}} + \frac{A_7 \exp(-A_8 E)}{E^{A_9}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

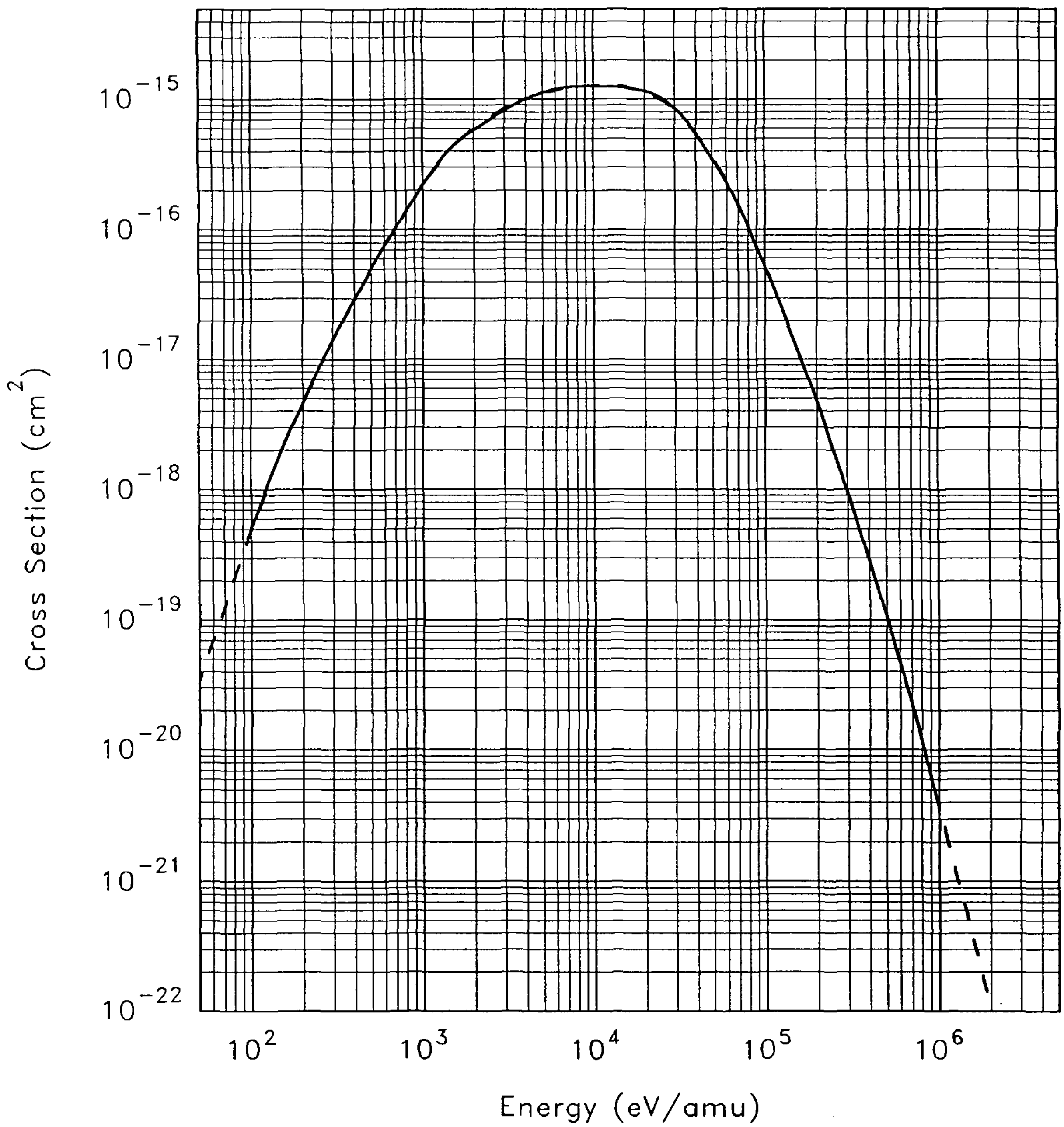
A_1 - A_5	17.438	2.1263	2.1401E−03	1.6498	2.6259E−06
A_6 - A_9	2.4226E−11	15.665	7.9193	−4.4053	

The rms deviation of the above fit to the recommended cross section is 1.6%, with a maximum deviation of 4.3% at 2.5 keV/amu.

ALADDIN evaluation function for cross section: HCX2

ALADDIN hierarchical labelling: CX He [+2] H [+0] (1s)

$He^{2+} + H(1s) \rightarrow He^{+} + H^{+}$



Legend:

—— Recommended Cross Section

- – Analytic Fit

3.3.2. $He^{2+} + H^{*}(n=2) \rightarrow He^{+} + H^{+}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+01	4.39E+06	3.03E−16
2.00E+01	6.21E+06	4.74E−16
5.00E+01	9.82E+06	8.60E−16
1.00E+02	1.39E+07	1.49E−15
2.00E+02	1.96E+07	2.62E−15
5.00E+02	3.11E+07	5.61E−15
1.00E+03	4.39E+07	9.48E−15
2.00E+03	6.21E+07	1.29E−14
5.00E+03	9.82E+07	1.17E−14
1.00E+04	1.39E+08	6.37E−15
2.00E+04	1.96E+08	1.45E−15
5.00E+04	3.11E+08	7.20E−17
1.00E+05	4.39E+08	5.09E−18
2.00E+05	6.21E+08	1.85E−19

Accuracy: $E < 0.1$ keV/amu : Indeterminate ; $0.1 \le E$ (keV/amu) < 2 : 40-80 % ; $2 \le E$ (keV/amu) < 20 : 30-40 % ; $20 \le E$ (keV/amu) < 100 : 20-30 % ; $E \ge 100$ keV/amu : 20 %, or better;

Comments: (1) In the energy region below 2 keV/amu, the recommended cross section is based on the calculations of Krstic and Janev [56] using the adiabatic superpromotion model. Within the above assigned accuracy, the result of these calculations for capture from the 2s state agree with the multistate close-coupling calculations of Jouin and Harel [106].

(2) In the region above 2 keV/amu, the recommended cross section is based on the CTMC calculations of Shultz et al [104] (up to E = 50 keV/amu), and on the semi-empirical scaling relationship of Janev [107].

Analytic fitting function

Cross section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)}{1 + A_3 E^{A_4} + A_5 E^{3.5} + A_6 E^{5.4}} + \frac{A_7 \exp(-A_8 E)}{E^{A_9}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

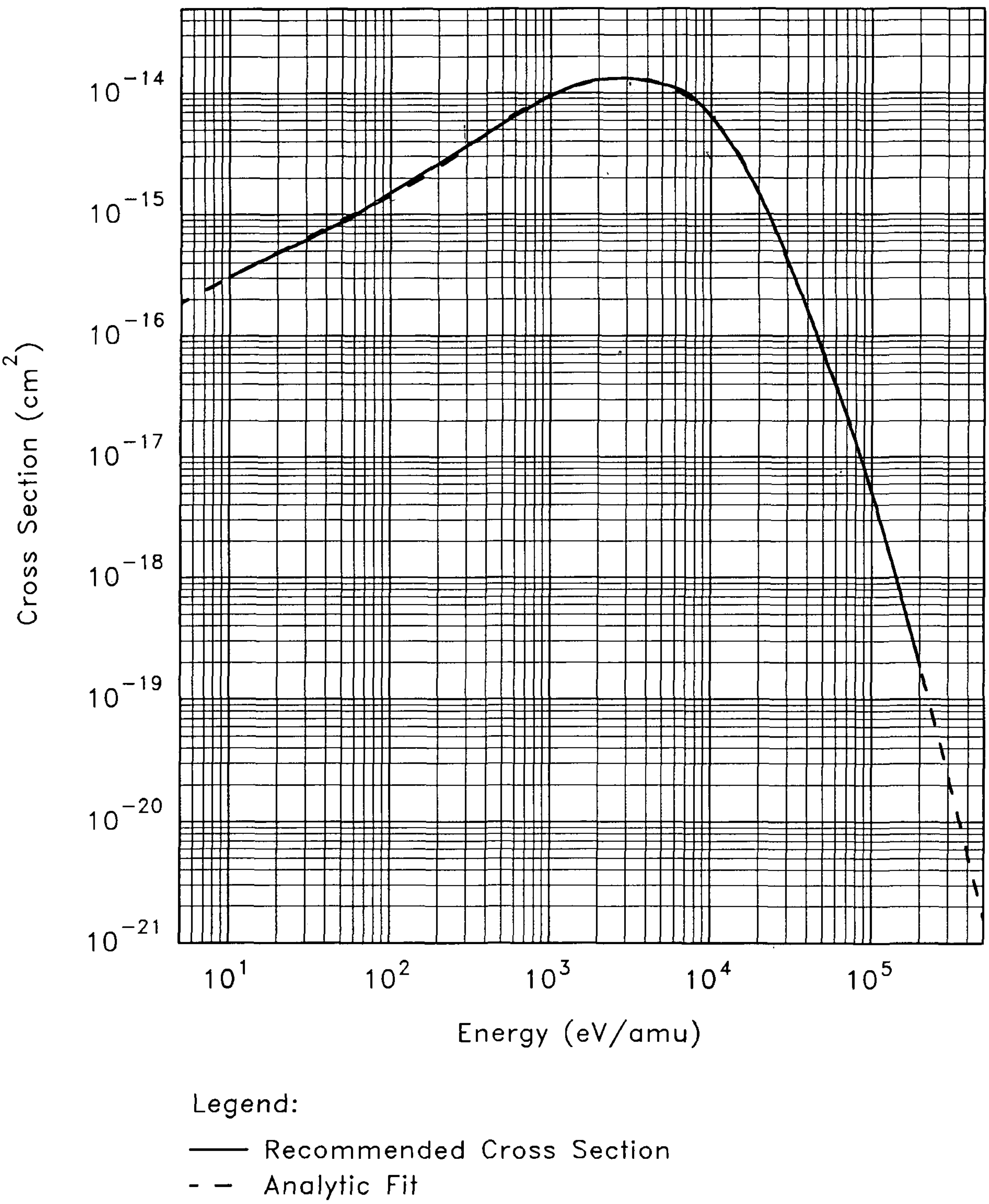
A_1 - A_5	88.508	0.78429	3.2903E−02	1.7635	7.3265E−05
A_6 - A_9	1.4418E−08	0.80478	0.22349	−0.68604	

The rms deviation of the above fit to the recommended cross section is 2.2%, with a maximum deviation of 7.6% at 0.02 keV/amu.

ALADDIN evaluation function for cross section: HCX2

ALADDIN hierarchical labelling: CX He [+2] H [+0] (n=2)

$He^{2+} + H^{*}(n=2) \rightarrow He^{+} + H^{+}$



3.3.3. $He^{2+} + H^*(n) \rightarrow He^+ + H^+$, n>2

Scaled Energy, En^2 (eV/amu)	Scaled Velocity, vn (cm/s)	Scaled Cross section , σ_{cx} / n^4 (cm^2)
1.00E+01	4.39E+06	9.36E−16
2.00E+01	6.21E+06	9.34E−16
5.00E+01	9.82E+06	9.28E−16
1.00E+02	1.39E+07	9.20E−16
2.00E+02	1.96E+07	9.14E−16
5.00E+02	3.11E+07	9.10E−16
1.00E+03	4.39E+07	9.08E−16
2.00E+03	6.21E+07	9.02E−16
5.00E+03	9.82E+07	8.94E−16
1.00E+04	1.39E+08	8.88E−16
2.00E+04	1.96E+08	7.58E−16
5.00E+04	3.11E+08	2.72E−16
1.00E+05	4.39E+08	4.86E−17
2.00E+05	6.21E+08	4.60E−18
5.00E+05	9.82E+08	1.06E−19

Accuracy: $En^2 < 1$ keV/amu : 40-60 %, $1 \leq En^2$ (keV/amu) < 25 : 30-40 % ;
$25 \leq En^2$ (keV/amu) < 200 : 20-30 % ; $En^2 \geq 200$ keV/amu : 20 %, or better

Comments: (1) The presented cross section is for electron capture from a given target n-shell to all He^+ states.

(2) In the reduced (scaled) energy En^2 range from 0.02 to 70 keV/amu, there are experimental cross section data by Burniaux et al [103] for capture from the groups of states with (n,n') = 8-9, (n,n') = 10-14, (n,n') = 15-19 and (n,n') = 20-24. The recommended cross section in the reduced energy region below 70 keV/amu is based on the experimental data with n < 20, and the assigned accuracies reflect the dispersion of the experimental data. Within this accuracy, the eikonal-approximation calculations of Eichler [102] for capture from n = 8 and 9 in the reduced energy range 6 - 40 keV/amu and the CTMC data of Olson [101] (all n) in the range 25 - 80 keV/amu are consistent with the experimental data and recommended cross section.

(3) For $En^2 > 80$ keV/amu, the recommended cross section is based on the CTMC results for n = 2 (Shultz et al [104]) available up to $En^2 \approx 200$ keV/amu, and on the semi-empirical scaling relationship of Janev [107].

Analytic fitting function

Cross section:

$$\frac{\sigma_{cx}}{n^4} = \frac{7.04 \times 10^{-16} A_1 \left\{ 1 - \exp\left[-\frac{4}{3A_1} \left(1 + \tilde{E}^{A_2} + A_3 \tilde{E}^{3.5} + A_4 \tilde{E}^{5.4} \right) \right] \right\}}{1 + \tilde{E}^{A_2} + A_3 \tilde{E}^{3.5} + A_4 \tilde{E}^{5.4}} \quad [cm^2]$$

where $\tilde{E} = En^2$ is expressed in keV/amu.

Fitting parameters

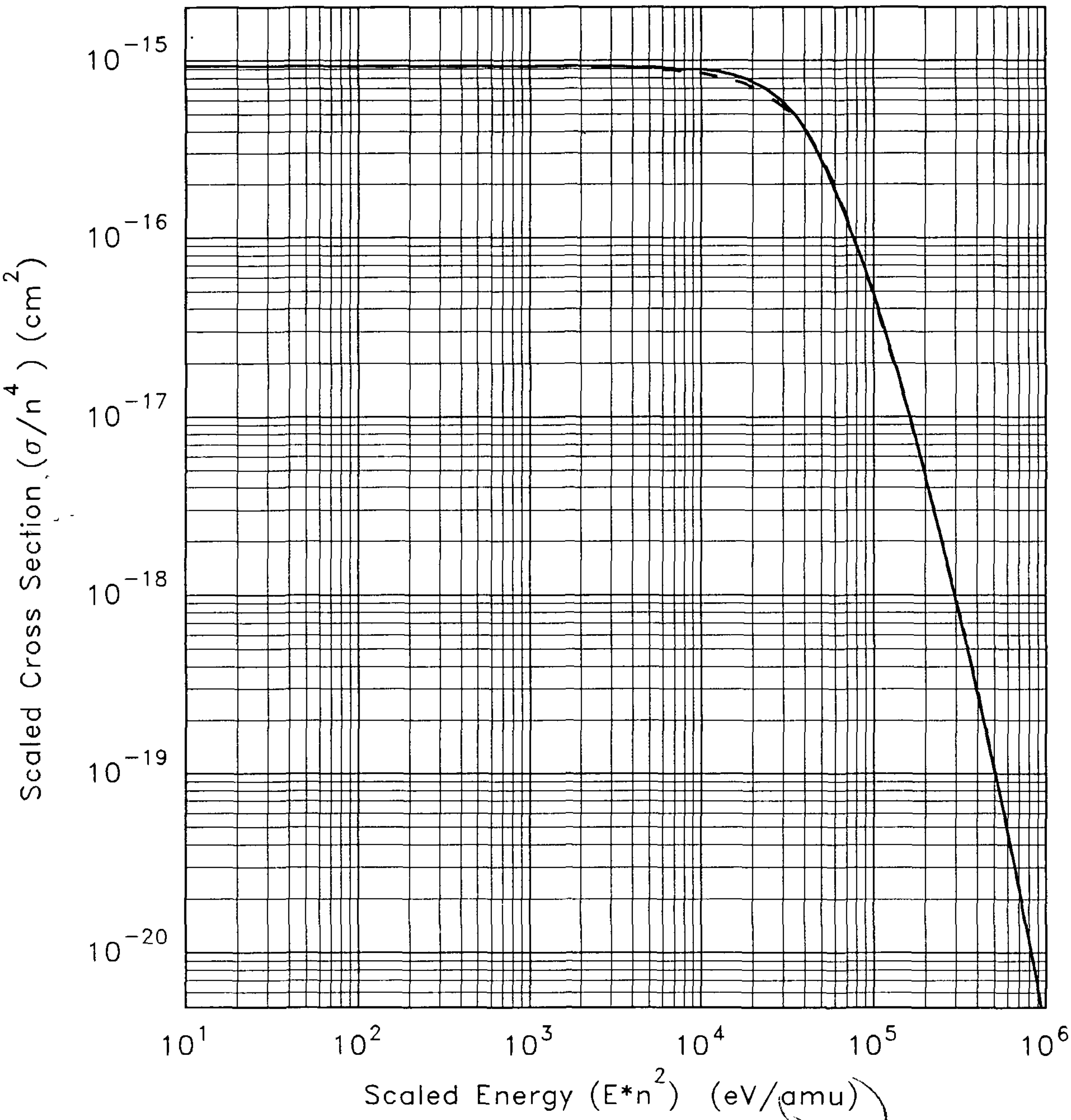
A_1	A_2	A_3	A_4
2.0032E+02	1.4591	2.0384E−04	2.0000E−09

The rms deviation of the above fit to the recommended cross section is 2.4%, with a maximum deviation of 6.4% at E = 10.4 keV/amu.

ALADDIN evaluation function for cross section: HCX3

ALADDIN hierarchical labelling: CX He [+2] H [+0] (n>2) check in new system

$He^{2+} + H^{*}(n) \rightarrow He^{+} + H^{+}$, n>2



Legend:

—— Recommended Cross Section

- – Analytic Fit

4. Collision Processes with Highly Charged Ions

4.1. Excitation

4.1.1. $Be^{4+} + H(1s) \rightarrow Be^{4+} + H^*(n=2)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.03E+03	4.39E+07	9.81E−20
2.00E+03	6.21E+07	6.15E−19
5.00E+03	9.82E+07	6.77E−18
1.00E+04	1.39E+08	1.64E−17
2.00E+04	1.96E+08	4.02E−17
5.00E+04	3.11E+08	2.46E−16
1.00E+05	4.39E+08	3.98E−16
2.00E+05	6.21E+08	4.54E−16
5.00E+05	9.82E+08	3.80E−16
1.00E+06	1.39E+09	2.53E−16
2.00E+06	1.96E+09	1.56E−16
5.00E+06	3.11E+09	7.55E−17

Accuracy: $E < 2$ keV/amu : Indeterminate ; $2 \leq E$ (keV/amu) < 20 : 30-80 % ;
$20 \leq E$ (keV/amu) < 200 : 20-30 % ; $E > 200$ keV/amu : 15-20 %

Comments: (1) In the energy region below 100 keV/amu cross section calculations for this reaction have been performed in the adiabatic superpromotion model [108] and by using the AO-based two-centre expansion method [109]. The recommended cross section in this region follows the results of very extensive coupled channel calculations of Ref. [109].

(2) In the region above 100 keV/amu, the recommended cross section was constructed by using the q-scaled proton impact data $\sigma(Be^{4+}; E) = 4\,\sigma(H^+; E/4)$.

(3) In the energy range 60 - 250 keV/amu, the recommended cross section is consistent with the q-scaled CTMC data of Ref. [54].

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9 E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

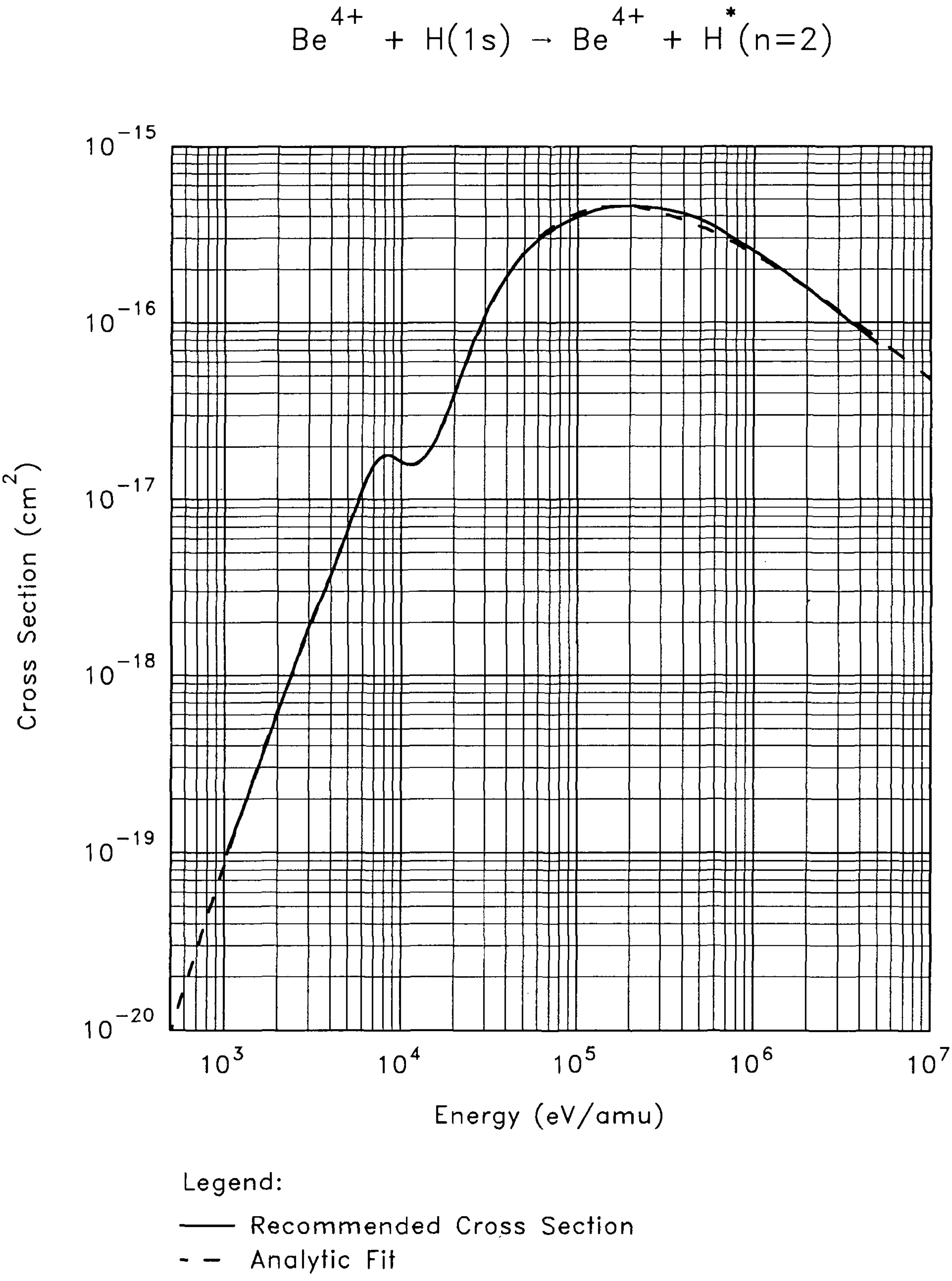
Fitting parameters

A_1 - A_5	961.80	70.386	1.4001E−02	1.2080E−06	0.31849
A_6 - A_{10}	−3.3516	7.2090E−03	30.194	2.4780E−08	8.4206

The rms deviation of the above fit to the recommended cross section is 3.0%, with a maximum deviation of 8.5% at 484.9 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: EXC Be [+4] H [+0] (1s) Be [+4] H [+0] (n=2)



$Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{*}(n=2)$
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Cross Section (cm^2)
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

4.1.2. $Be^{4+} + H(1s) \rightarrow Be^{4+} + H^*(n=3)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+03	4.39E+07	6.53E−21
2.00E+03	6.21E+07	8.03E−20
5.00E+03	9.82E+07	2.35E−18
1.00E+04	1.39E+08	6.36E−18
2.00E+04	1.96E+08	1.04E−17
5.00E+04	3.11E+08	8.36E−17
1.00E+05	4.39E+08	1.18E−16
2.00E+05	6.21E+08	1.10E−16
5.00E+05	9.82E+08	7.28E−17
1.00E+06	1.39E+09	4.70E−17
2.00E+06	1.96E+09	2.84E−17
5.00E+06	3.11E+09	1.34E−17

Accuracy: E < 3 keV/amu : Indeterminate ; 3 ≤ E (keV/amu) < 20 : 30-80 % ;
20 ≤ E (keV/amu) < 200 : 20-30 % ; E ≥ 200 keV/amu : 15-20 %

Comments: (1) In the energy region below 100 keV/amu, the recommended cross section follows the results of very extensive coupled channel calculations of Ref. [109].

(2) For energies above 100 keV/amu, the recommended cross section was constructed by using the q-scaled He^{2+} -impact excitation cross section data :
$\sigma(Be^{4+}, E) = 2\sigma(He^{2+}, E/2)$.

(3) In the energy range 60 - 250 keV/amu, the recommended cross section is consistent with the q-scaled CTMC data of Ref. [54].

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

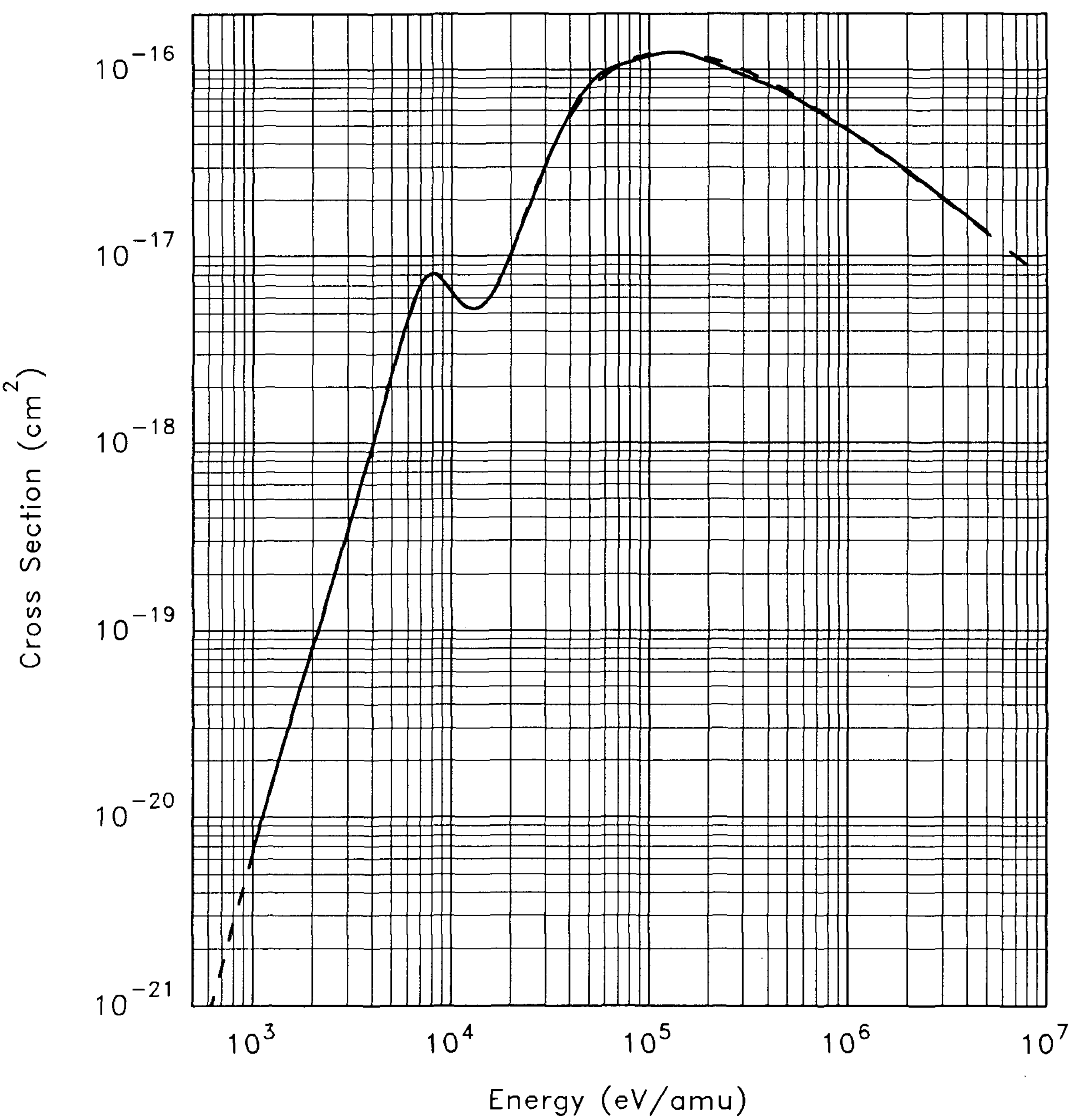
A_1 - A_5	95.728	90.975	0.21980	9.6493E−07	0.36229
A_6 - A_{10}	−4.1912	3.5870E−02	28.681	5.1187E−09	9.1415

The rms deviation of the above fit to the recommended cross section is 2.5%, with a maximum deviation of 7.8% at 204.1 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: EXC Be [+4] H [+0] (1s) Be [+4] H [+0] (n=3)

$Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{*}(n=3)$



Legend:

—— Recommended Cross Section

- – Analytic Fit

4.1.3. $Be^{4+} + H(1s) \rightarrow Be^{4+} + H^*(n=4)$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+03	4.39E+07	2.81E−21
2.00E+03	6.21E+07	3.45E−20
5.00E+03	9.82E+07	1.08E−18
1.00E+04	1.39E+08	2.61E−18
2.00E+04	1.96E+08	4.68E−18
5.00E+04	3.11E+08	3.24E−17
1.00E+05	4.39E+08	4.33E−17
2.00E+05	6.21E+08	4.09E−17
5.00E+05	9.82E+08	2.70E−17
1.00E+06	1.39E+09	1.67E−17
2.00E+06	1.96E+09	9.80E−18
5.00E+06	3.11E+09	4.54E−18

Accuracy: E < 3 keV/amu : Indeterminate ; 3 ≤ E (keV/amu) < 50 : 50-100 % ; 50 ≤ E (keV/amu) < 200 : 30-50 % ; E ≥ 200 keV/amu : 20-30 %

Comments: (1) In the energy region below 50 keV/amu, the recommended cross section for this reaction has been constructed by using the relation $\sigma(1 \rightarrow 4) = (3/4)^3 \sigma(1 \rightarrow 3)$, where $\sigma(1 \rightarrow 3)$ is the recommended cross section for 1 → n=3 excitation by Be^{4+}. An analogous relation was found to connect the 1 → n=2,3 excitation cross sections in the same energy region with an accuracy of 10 - 15 %.

(2) In the energy region above 100 keV/amu, the recommended cross section was constructed by using the q-scaled He^{2+} -impact excitation cross section for the same transition : $\sigma(Be^{4+}, E) = 2\sigma(He^{2+}, E/2)$.

(3) In the energy range 50 - 250 keV/amu, the recommended cross section is consistent with the q-scaled CTMC data of Ref. [54] well within the assigned accuracy.

Analytic fitting function

Cross section:

$$\sigma_{exc} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6}} + \frac{A_7 \exp(-A_8/E)}{1 + A_9E^{A_{10}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

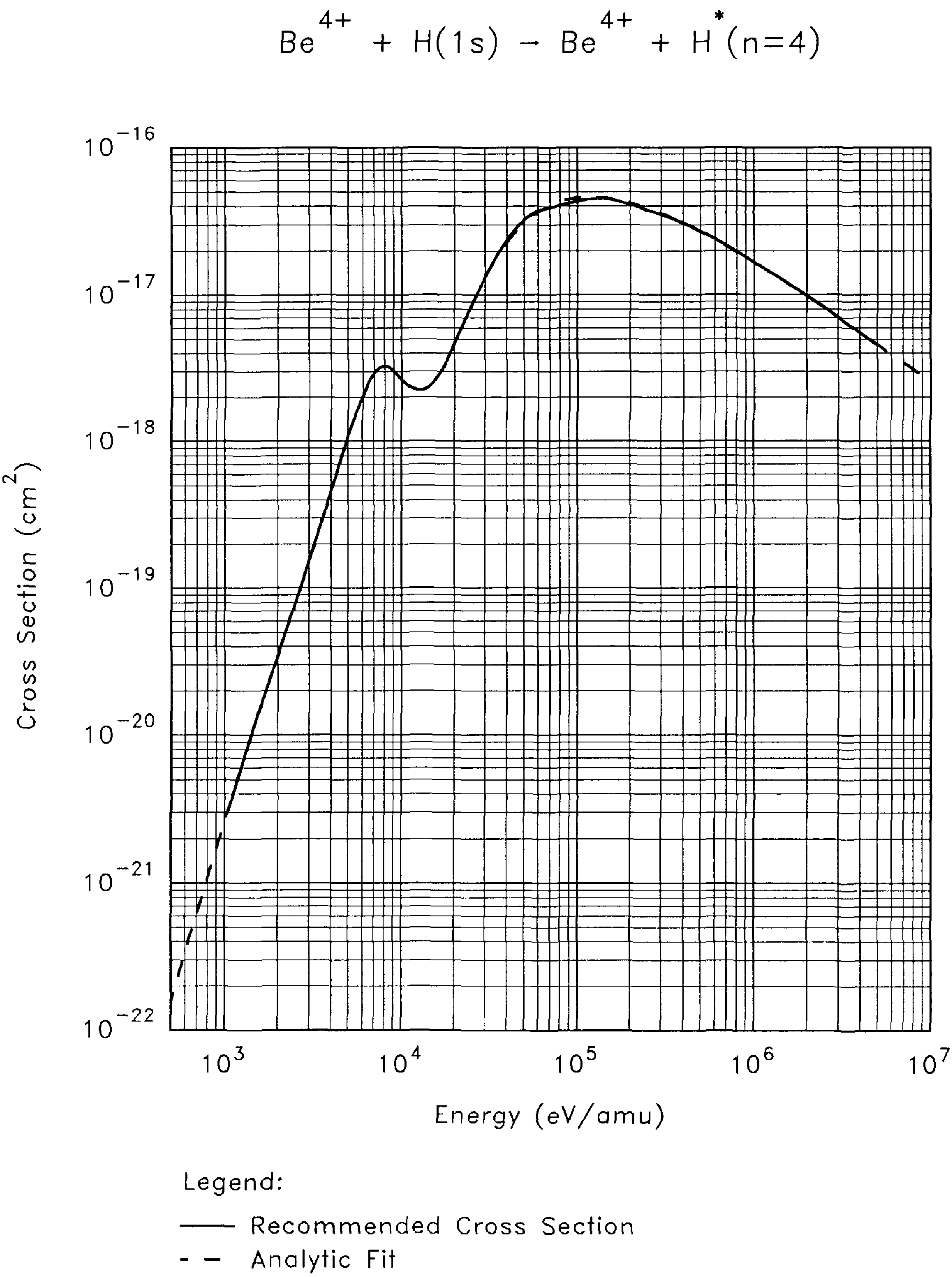
Fitting parameters

A_1 - A_5	32.190	86.307	0.27496	1.1909E−06	0.38748
A_6 - A_{10}	−4.3014	3.2598E−02	26.395	1.5743E−08	8.6415

The rms deviation of the above fit to the recommended cross section is 1.5%, with a maximum deviation of 6.0% at 95.8 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: EXC Be [+4] H [+0] (1s) Be [+4] H [+0] (n=4)


$Be^{4+} + H(1s) \rightarrow Be^{4+} + H^*(n=4)$
Cross Section (cm^2)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

4.1.4. $Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{*}(n)$, n>4

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) 1s → n=5	1s → n=6	1s → n=7
1.00E+03	4.39E+07	7.18E−22	5.50E−22	3.46E−22
2.00E+03	6.21E+07	1.78E−20	1.00E−20	6.31E−21
5.00E+03	9.82E+07	1.77E−19	9.92E−20	6.25E−20
1.00E+04	1.39E+08	6.46E−19	3.61E−19	2.27E−19
2.00E+04	1.96E+08	1.70E−18	9.64E−19	6.07E−19
5.00E+04	3.11E+08	5.31E−18	2.96E−18	1.86E−18
1.00E+05	4.39E+08	1.02E−17	5.71E−18	3.59E−18
2.00E+05	6.21E+08	1.28E−17	7.34E−18	4.62E−18
5.00E+05	9.82E+08	1.02E−17	5.93E−18	3.74E−18
1.00E+06	1.39E+09	6.98E−18	4.04E−18	2.55E−18
2.00E+06	1.96E+09	4.36E−18	2.50E−18	1.58E−18
5.00E+06	3.11E+09	2.17E−18	1.23E−18	7.73E−19

Accuracy: $E \leq 10$ keV/amu : Indeterminate ; $10 < E$ (keV/amu) ≤ 80 : 30 - 60 % ; $80 < E$ (keV/amu) < 200 : 20 - 30 % ; $E \geq 200$ keV/amu : 15 - 20 %

Comments: (1) With the accuracies indicated above, the cross sections for the 1s → n (n ≥5) excitation of hydrogen atoms by Be^{4+} ion impact can be obtained by scaling the corresponding recommended excitation cross section by proton impact according to the relation

$$\sigma_n (Be^{4+} ; E) = 4\,\sigma_n (H^{+} ; E/4) \qquad \text{(a)}$$

(2) Within the same accuracy, the 1s → n (n ≥5) excitation cross sections in the energy region above 10 keV/amu can also be obtained by applying the above q-scaling to the proton-impact excitation data generated by the semi-empirical formula of Lodge et al [55].

(3) The excitation cross sections for n = 5 and n = 6 obtained by using the relation (a) and the the proton-impact excitation data (see reaction 2.16, p. 52) are given by

$$\sigma_{exc}(n{=}5\,,6) = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu and the values of parameters A_i are :

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
1s → n=5	19.918	129.16	5.2941E−02	2.7053E−06	7.7658E−02	−2.4161	5.9445	−6.3726
1s → n=6	10.203	148.70	9.8162E−02	3.4190E−06	6.4392E−02	−2.2950	4.9522	−5.5986

(4) The cross sections for the n ≥7 levels can be obtained by using the q-scaled formula of Lodge et al [55] via Eq. (a). Approximate estimates of σ_{exc} (n ≥ 7) can be obtained also from

$$\sigma_{exc}(1s \rightarrow n) = \left(\frac{6}{n}\right)^3 \sigma_{exc}(1s \rightarrow n{=}6), \qquad n \geq 7 .$$

ALADDIN evaluation function for cross section: HEXC3 for n = 5 - 6 and HEXC4 for n>6

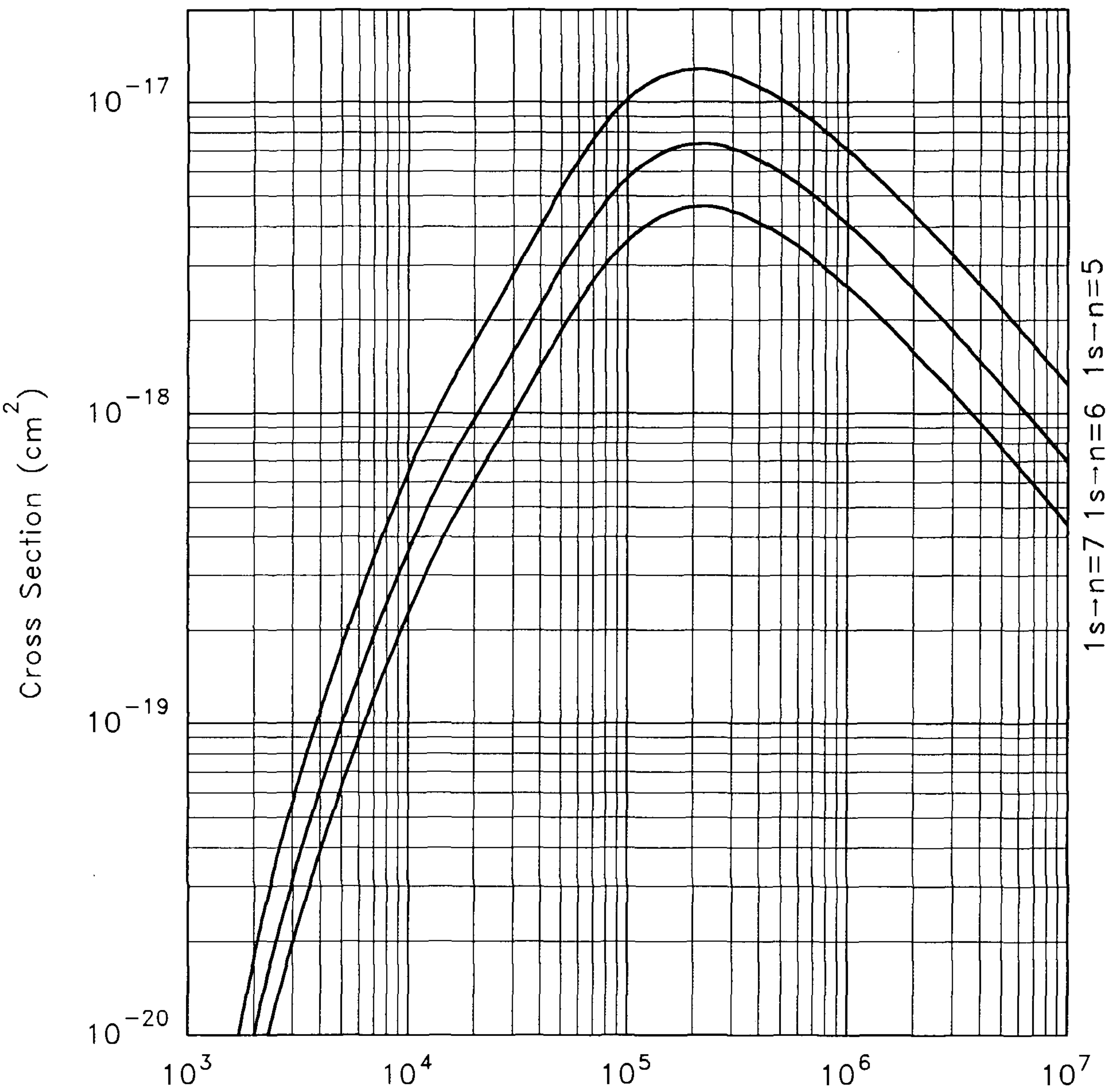
ALADDIN hierarchical labelling :

EXC Be [+4] H [+0] (1s) Be [+4] [+0] (n=5), for 1s→n=5

EXC Be [+4] H [+0] (1s) Be [+4] [+0] (n=6), for 1s→n=6

EXC Be [+4] H [+0] (1s) Be [+4] H [+0] (n>6), for 1s→n>6

$Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{*}(n),\ n>4$



Legend:

—— Recommended Cross Section

4.1.5. $A^{q+} + H(1s) \rightarrow A^{q+} + H^*(n=2)$, q>4

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross section / q χ(q) (cm^2)
5.00E+02	3.11E+07	3.87E−20
1.00E+03	4.39E+07	2.31E−19
2.00E+03	6.21E+07	1.19E−18
5.00E+03	9.82E+07	7.64E−18
1.00E+04	1.39E+08	2.75E−17
2.00E+04	1.96E+08	7.24E−17
5.00E+04	3.11E+08	1.15E−16
1.00E+05	4.39E+08	9.88E−17
2.00E+05	6.21E+08	6.87E−17
5.00E+05	9.82E+08	3.87E−17
1.00E+06	1.39E+09	2.31E−17
2.00E+06	1.96E+09	1.32E−17
5.00E+06	3.11E+09	6.17E−18

Accuracy: E/q < 1 keV/amu : Indeterminate ; 1 ≤ E/q (keV/amu) < 20 : 30 - 80 % ; 20 ≤ E/q (keV/amu) < 200 : 20 - 30 % ; E/q ≥ 200 keV/amu : 15 - 20 %

Comments: (1) Single-centre AO close-coupling cross section calculations for this reaction exist for fully stripped ions with q = 6, 8, 14 and 26 in the reduced energy range E/q = 15 - 250 keV/amu (Reinhold et al [54]), and for the C^{6+} + H system very extensive two-centre AO expansion close-coupling calculations are available [109] in the reduced energy range 1 - 70 keV/amu. In Ref. [54], CTMC cross sections for q = 6, 8 and 26, and symmeterized-eikonal (SE) cross sections for q = 26 are also provided in the reduced energy ranges 15 - 2000 keV/amu and 20 keV/amu - 10 MeV/amu, respectively. For q = 4, 5, cross section data are available from the adiabatic superpromotion model calculations of Krstic et al [108] in the reduced energy range below 20 keV/amu.

(2) The recommended reduced cross section σ_{exc}/q in the region E/q ≤ 70 keV/amu is based on the multi-state two-centre AO expansion coupled channel calculations for q = 6 [109] and on the adiabatic superpromotion model results for q = 5 [108]. In the reduced energy range 70 - 200 keV/amu the recommended cross section is based on the results of AO close-coupling calculations [54], and above 200 keV/amu it is based on the q-scaled (σ/q vs. E/q) recommended data for He^{2+} -impact excitation (reaction 3.1.1), and on the SE data of Reinhold et al [54] for q = 26. The scaled cross sections for q = 2 and q = 26 differ by about 30%, which is accounted for by the factor χ (q) in the analytic expression below.

Analytic fitting function

Cross section:

$$\frac{\sigma_{exc}(n)}{q} = 10^{-16}\chi(q)A_1\left[\frac{\exp(-A_2/\tilde{E})\ln(1+A_3\tilde{E})}{\tilde{E}} + \frac{A_4\exp(-A_5\tilde{E})}{\tilde{E}^{A_6}}\right]\ [cm^2]$$

where $\tilde{E} = \dfrac{E\ (keV/amu)}{q}$ and $\chi(q) = 2^{0.5238\,(1-\sqrt{2/q})}$

Fitting parameters

A_1	A_2	A_3	A_4	A_5	A_6
38.738	37.033	0.39862	7.7582E−05	0.25402	−2.7418

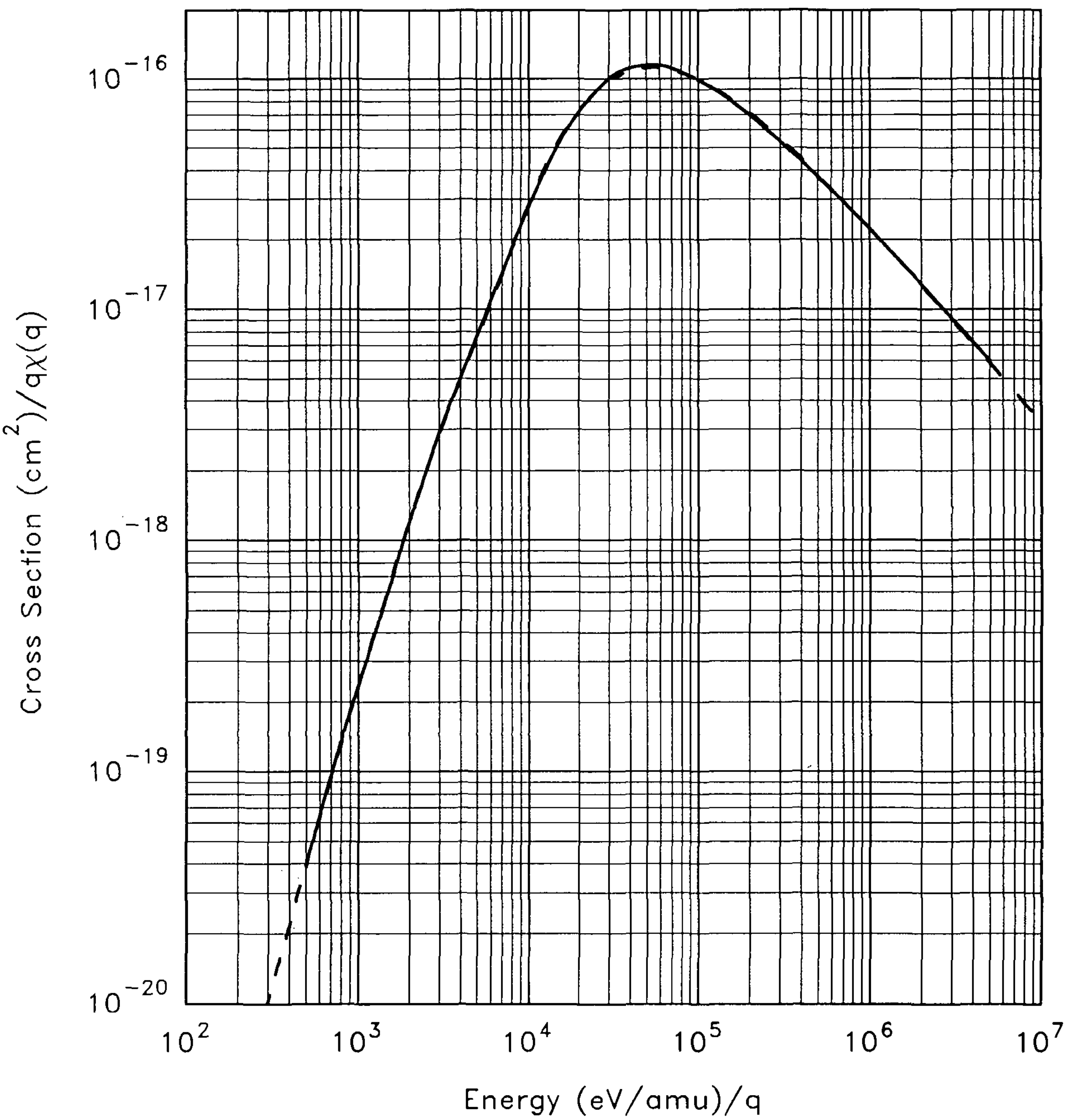
The rms deviation of the above fit to the recommended cross section is 2.1%, with a maximum deviation of 3.6% at 11.4 keV/amu.

ALADDIN evaluation function for cross section: AQEXC1

ALADDIN hierarchical labelling:

EXC A [+q>4] H [+0] (1s) A [+q>4] H [+0] (n=2)

$$A^{q+} + H(1s) \rightarrow A^{q+} + H^*(n=2),\ q>4$$



Legend:

—— Recommended Cross Section

- – Analytic Fit

4.1.6. $A^{q+} + H(1s) \rightarrow A^{q+} + H^{*}(n=3, n=4)$, $q>3$

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / $q\chi(q)$ (cm^2) 1s → n=3	1s → n=4
5.00E+02	3.11E+07	2.03E−20	5.41E−21
1.00E+03	4.39E+07	9.24E−20	2.50E−20
2.00E+03	6.21E+07	4.15E−19	1.20E−19
5.00E+03	9.82E+07	2.41E−18	7.39E−19
1.00E+04	1.39E+08	8.81E−18	2.71E−18
2.00E+04	1.96E+08	2.19E−17	7.18E−18
5.00E+04	3.11E+08	3.03E−17	9.94E−18
1.00E+05	4.39E+08	2.12E−17	6.94E−18
2.00E+05	6.21E+08	1.33E−17	4.41E−18
5.00E+05	9.82E+08	6.90E−18	2.29E−18
1.00E+06	1.39E+09	4.05E−18	1.34E−18
2.00E+06	1.96E+09	2.33E−18	7.63E−19
5.00E+06	3.11E+09	1.06E−18	3.52E−19

Accuracy: E/q < 1 keV/amu : Indeterminate ; 1 ≤ E/q (keV/amu) < 20 : 40 - 100 % ; 20 ≤ E/q (keV/amu) < 200 : 30 - 40 % ; E/q ≥ 200 keV/amu : 20 - 30 %

Comments : (1) Single-centre AO close-coupling cross section calculations for these transitions exist for fully stripped ions with q = 6, 8, 14 and 26 in the reduced energy range E/q = 15 - 250 keV/amu (Reinhold et al [54]). Very extensive multi-state AO-based close-coupling calculations for the n = 3 excitation of H by C^{6+} ions have been performed by Fritsch [109] in the reduced energy range 1 - 70 keV/amu. In Ref. [54], CTMC cross sections for q = 6, 8 and 26, and symmeterized-eikonal (SE) cross sections for q = 26 are also provided in the reduced energy ranges 15 - 2000 keV/amu and 20 keV/amu - 10 MeV/amu, respectively.

(2) The recommended reduced excitation cross sections in the reduced energy range 20 - 200 keV/amu are derived from the CTMC and AO close coupling data of Ref. [54], and in the case of n = 3 also from the data of Ref. [109] (for E/q ≤ 70 keV/amu). For E/q > 200 keV/amu the recommended cross sections are based on the q-scaled He^{2+} -impact excitation cross sections and the SE result for q = 26. In the energy region E/q < 20 keV/amu the σ (n=3)/q cross section is based on the data of Ref. [109], while the σ (n=4)/q cross section is constructed by keeping the ratio σ (n=2)/σ (n=4) from the region of cross section maximum unchanged.

Analytic fitting function

Cross section:

$$\frac{\sigma_{exc}(n)}{q} = 10^{-16}\chi(q)A_1\left[\frac{\exp(-A_2/\tilde{E})\ln(1+A_3\tilde{E})}{\tilde{E}} + \frac{A_4\exp(-A_5\tilde{E})}{\tilde{E}^{A_6}}\right] \ [\mathrm{cm}^2]$$

$$\text{where } \tilde{E} = \frac{E\,(\mathrm{keV/amu})}{q} \quad \text{and} \quad \chi(q) = 2^{0.5238(1-\sqrt{2/q})}$$

Fitting parameters

	A1	A2	A3	A4	A5	A6	Rms Deviation (%)	Maximum Deviation %	at E (keV/amu)
1s → 3	4.3619	57.451	21.001	2.3292E−04	0.083130	−2.2364	3.6	8.6	83.1
1s → 4	1.3730	60.710	31.797	2.0207E−04	0.082513	−2.3055	3.6	9.7	86.9

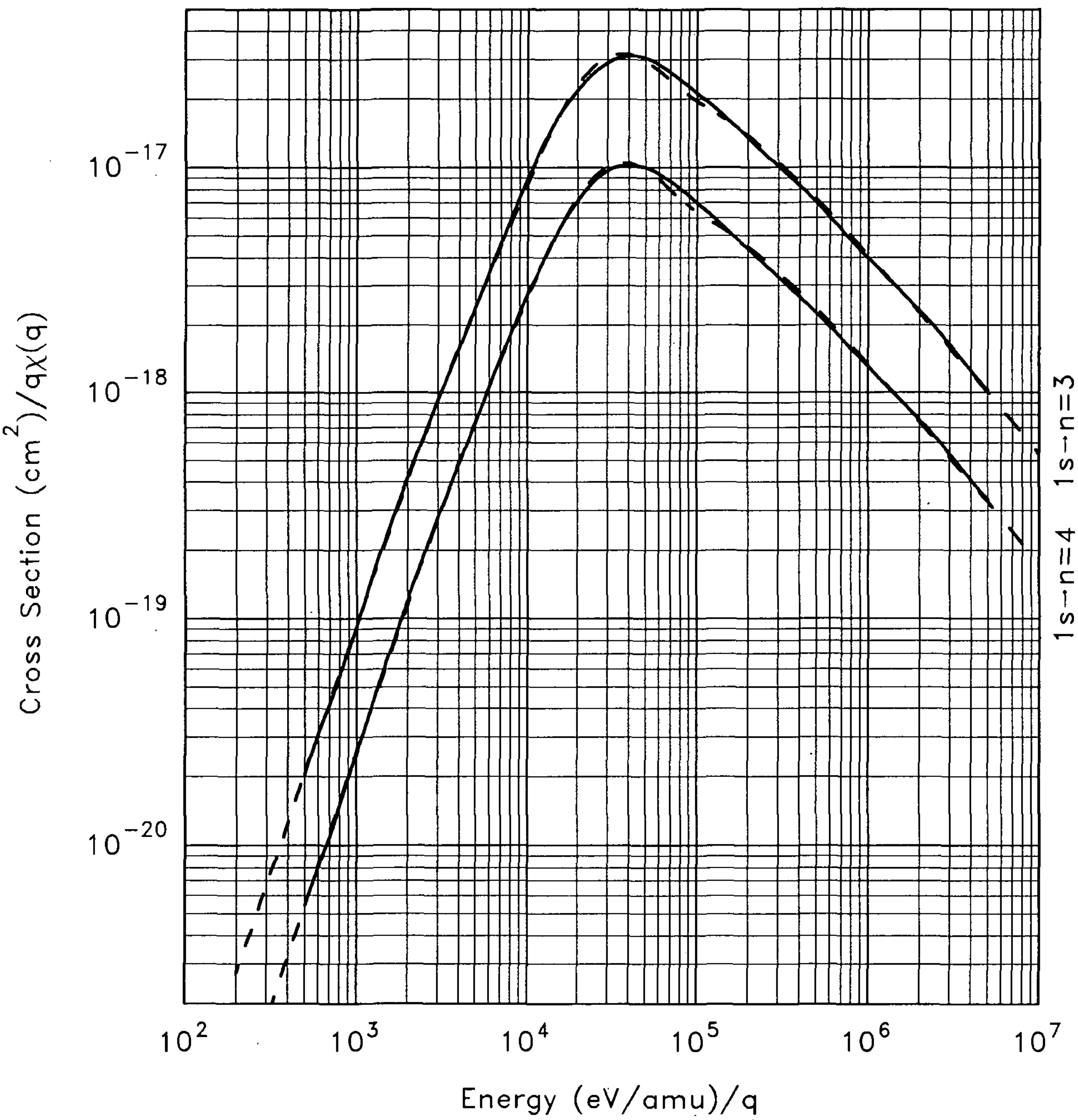
ALADDIN evaluation function for cross section: AQEXC1

ALADDIN hierarchical labelling :

EXC A [+q>4] H [+0] (1s) A [+q>4] [+0] (n=3), for 1s→n=3

EXC A [+q>4] H [+0] (1s) A [+q>4] [+0] (n=4), for 1s→n=4

$A^{q+} + H(1s) \rightarrow A^{q+} + H^*(n=3, n=4), q>4$



Legend:

—— Recommended Cross Section

- - Analytic Fit

4.1.7. $A^{q+} + H(1s) \rightarrow A^{q+} + H^*(n)$,n>4, q>4

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / q χ(q) (cm^2) 1s → n=5	1s → n=6	1s → n=7
5.00E+02	3.11E+07	2.41E−21	1.48E−21	9.32E−22
1.00E+03	4.39E+07	1.14E−20	6.51E−21	4.10E−21
2.00E+03	6.21E+07	4.81E−20	2.75E−20	1.73E−20
5.00E+03	9.82E+07	2.81E−19	1.61E−19	1.02E−19
1.00E+04	1.39E+08	8.94E−19	5.17E−19	3.25E−19
2.00E+04	1.96E+08	2.31E−18	1.39E−18	8.77E−19
5.00E+04	3.11E+08	3.56E−18	1.99E−18	1.26E−18
1.00E+05	4.39E+08	2.78E−18	1.49E−18	9.37E−19
2.00E+05	6.21E+08	1.86E−18	1.09E−18	6.85E−19
5.00E+05	9.82E+08	9.67E−19	5.85E−19	3.69E−19
1.00E+06	1.39E+09	5.62E−19	3.34E−19	2.10E−19
2.00E+06	1.96E+09	3.21E−19	1.84E−19	1.16E−19
5.00E+06	3.11E+09	1.47E−19	8.09E−20	5.10E−20

Accuracy: E/q < 1 keV/amu : Indeterminate ; 1 ≤ E/q (keV/amu) < 20 : 40 - 100 % ; 20 ≤ E/q (keV/amu) < 200 : 30 - 40 % ; E/q ≥ 200 keV/amu : 20 - 30 %

Comments : (1) In the energy range E/q > 20 keV/amu, the reduced excitation cross section σ/q vs. reduced collision energy E/q for the 1s → n=5 transition was constructed by q-scaling the corresponding recommended proton impact excitation cross section , and by introducing the correction factor χ (q) to account for the departure from the exact q-scaling, as observed in the SE calculations for 1s→n=2, 3, 4 excitation [54]. For reduced energies below 20 keV/amu, the σ (n=5) /q cross section was constructed by keeping the ratio σ (n=5)/σ (n=4) from the region E/q > 50 keV/amu unchanged.

(2) Within the above assigned accuracies, the cross sections for the 1s→n≥6 excitation can be obtained by using the n^{-3}−scaling,

$$\frac{\sigma_{exc}(n)}{q} = \left(\frac{5}{n}\right)^3 \frac{\sigma_{exc}(n=5)}{q}, \quad n \geq 6$$

Analytic expression for σ_{exc} (n=5)/q :

Cross section:

$$\frac{\sigma_{exc}(n=5)}{q} = 10^{-16}\chi(q)\,A_1 \left[\frac{\exp(-A_2/\tilde{E})\,\ln(1+A_3\tilde{E})}{\tilde{E}} + \frac{A_4\exp(-A_5\tilde{E})}{\tilde{E}^{A_6}}\right] \text{[cm}^2\text{]}$$

$$\text{where } \tilde{E} = \frac{E\,(\text{keV/amu})}{q} \quad \text{and} \quad \chi(q) = 2^{0.5238\,(1-\sqrt{2/q})}$$

Fitting parameters

A1	A2	A3	A4	A5	A6
0.56565	67.333	55.290	2.1595E−04	0.081624	−2.1971

The rms deviation of the above fit to the recommended cross section is 3.2%, with a maximum deviation of 8.3% at 89.0 keV/amu.

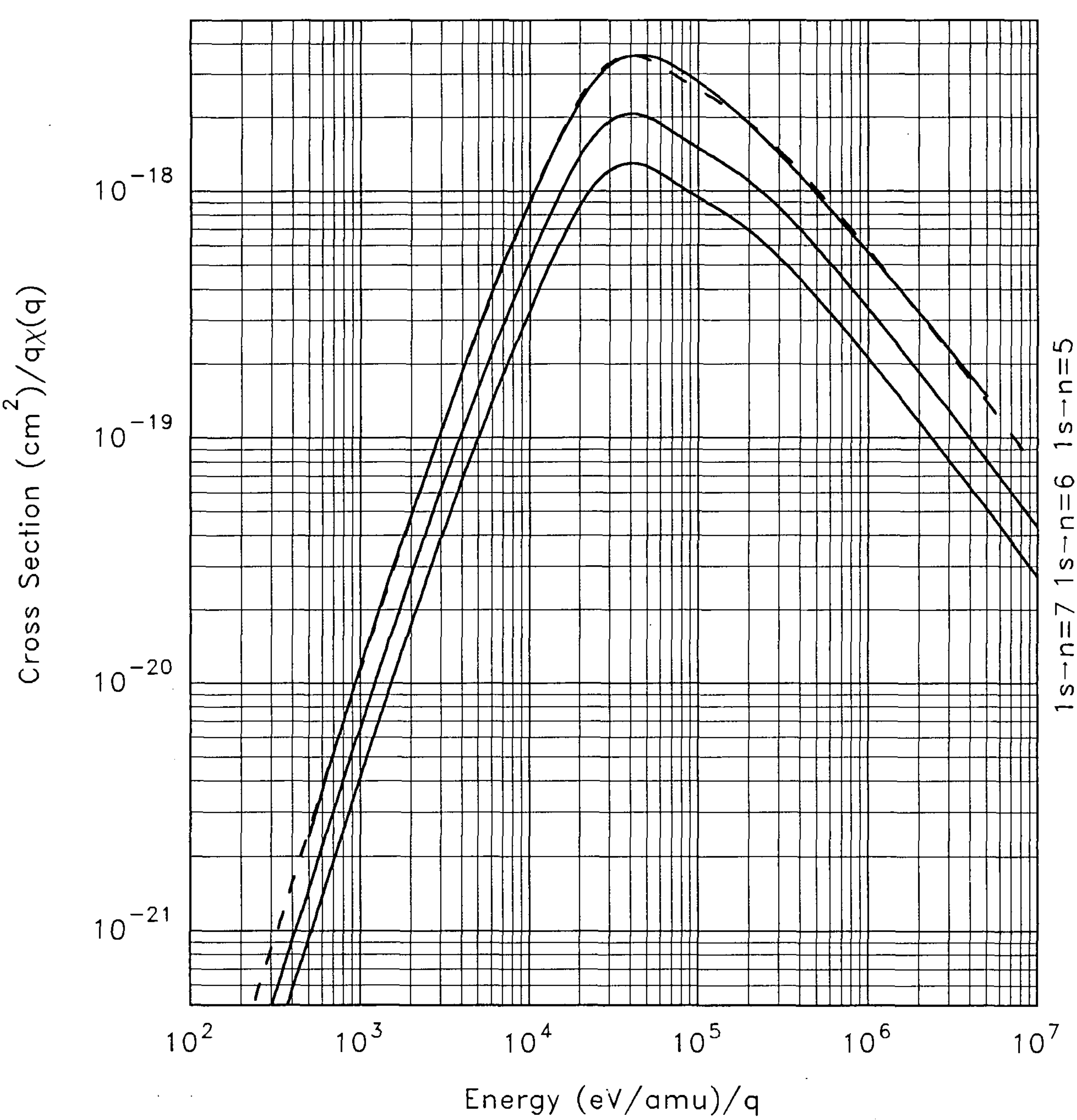
ALADDIN evaluation function for cross section: AQEXC1 for n = 5 and AQEXC2 for n>5

ALADDIN hierarchical labelling :

EXC A [+q] H [+0] (1s) A [+q] [+0] (n=5), for 1s → n=5

EXC A [+q] H [+0] (1s) A [+q] [+0] (n>5), for 1s → n>5

$A^{q+} + H(1s) \rightarrow A^{q+} + H^{*}(n),\ n>4,\ q>4$



Legend:

—— Recommended Cross Section

- — Analytic Fit

4.1.8. $A^{q+} + H^*(n=2) \rightarrow A^{q+} + H^*(m), m=3, 4, 5, q>3$

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) n=2 → m=3	n=2 → m=4	n=2 → m=5
5.00E+02	3.11E+07	2.44E−16	2.24E−17	7.67E−18
1.00E+03	4.39E+07	4.13E−16	5.33E−17	1.82E−17
2.00E+03	6.21E+07	6.65E−16	1.09E−16	3.71E−17
5.00E+03	9.82E+07	1.19E−15	2.27E−16	7.78E−17
1.00E+04	1.39E+08	1.78E−15	3.65E−16	1.25E−16
2.00E+04	1.96E+08	2.25E−15	4.34E−16	1.48E−16
5.00E+04	3.11E+08	1.96E−15	3.65E−16	1.25E−16
1.00E+05	4.39E+08	1.41E−15	2.51E−16	8.57E−17
2.00E+05	6.21E+08	8.90E−16	1.54E−16	5.29E−17
5.00E+05	9.82E+08	4.44E−16	7.43E−17	2.56E−17
1.00E+06	1.39E+09	2.54E−16	4.13E−17	1.43E−17
2.00E+06	1.96E+09	1.41E−16	2.26E−17	7.84E−18
5.00E+06	3.11E+09	6.39E−17	1.00E−17	3.49E−18

Accuracy: $E/q < 0.5$ keV/amu : Indeterminate ;
$0.5 \leq E/q$ (keV/amu) < 10 : 40 - 80 % for m = 3, 40 - 100 % for m = 4, 5;
$10 \leq E/q$ (keV/amu) < 100 : 30 - 40 % ; $E/q \geq 100$ keV/amu : 20 - 30 %

Comments: (1) For these reactions there exist CTMC cross section calculations for q = 6, 8 and 26, in the reduced energy range 4 keV/amu - 2 MeV/amu, and SE calculations for q = 26 in the range 5 keV/amu - 10 MeV/amu, performed in Ref. [54]. For m = 3 and m = 4, a single-centre AO close-coupling calculation for q = 6 at the reduced energy of 20 keV/amu is also available. All these data are mutually consistent, and within the accuracies assigned above, agree with the q-scaled recommended proton impact excitation data.

(2) The recommended reduced excitation cross sections $\sigma_{exc}(m)$ /q vs. the reduced collision energy E/q, are constructed by q-scaling the corresponding recommended proton impact excitation cross sections, and by introducing a multiplicative factor χ (q) to account for the departure of the q-scaling from the accurate SE calculations for q = 26 of Ref. [54] at high energies.

Analytic fitting function

Cross section:

$$\frac{\sigma_{exc}(m)}{q} = 10^{-16} \chi(q) A_1 \left[\frac{\exp(-A_2/\tilde{E}) \ln(1 + A_3\tilde{E})}{\tilde{E}} + \frac{A_4 \exp(-A_5\tilde{E})}{\tilde{E}^{A_6}} \right] \ [cm^2]$$

$$\text{where } \tilde{E} = \frac{E\,(keV/amu)}{q} \quad \text{and} \quad \chi(q) = 2^{0.5238\,(1 - \sqrt{2}/q)}$$

Fitting parameters

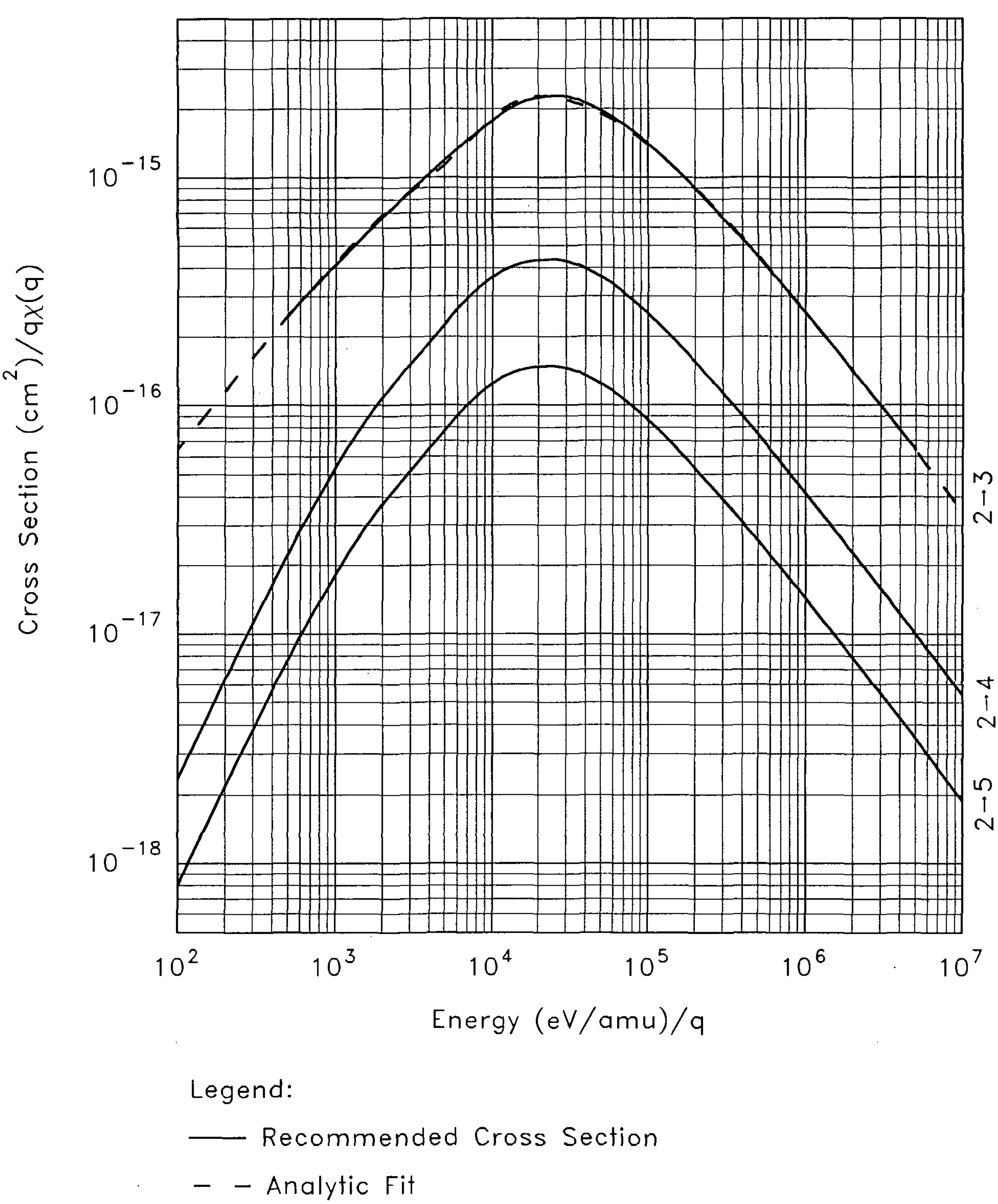
	A_1	A_2	A_3	A_4	A_5	A_6	Rms Deviation (%)	Maximum Deviation %	at E (keV/amu)
2 → 3	358.03	25.283	1.4726	0.014398	0.12207	−0.86210	1.70	4.7	3.3
2 → 4	50.744	19.416	4.0262	0.014398	0.31584	−1.4799			
2 → 5	18.264	18.973	2.9056	0.013701	0.31711	−1.4775			

ALADDIN evaluation function for cross section: AQEXC1

ALADDIN hierarchical labelling :

EXC A [+q] H [+0] (n=2) A [+1] [+0] (m=3), for n=2→m=3
EXC A [+1] H [+0] (n=2) A [+1] [+0] (m=4), for n=2→m=4
EXC A [+1] H [+0] (n=2) A [+1] [+0] (m=5), for n=2→m=5

$A^{q+} + H^*(n=2) \rightarrow A^{q+} + H^*(m),\ m=3,4,5,\ q>3$



4.1.9. $A^{q+} + H^*(n=2) \rightarrow A^{q+} + H^*(m)$,m>5, q>3

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / q χ(q) (cm^2) n=2 → m=6	n=2 → m=8	n=2 → m=10
5.00E+02	3.11E+07	3.63E−18	1.15E−18	4.77E−19
1.00E+03	4.39E+07	8.21E−18	2.61E−18	1.08E−18
2.00E+03	6.21E+07	1.64E−17	5.22E−18	2.15E−18
5.00E+03	9.82E+07	3.68E−17	1.17E−17	4.83E−18
1.00E+04	1.39E+08	5.62E−17	1.79E−17	7.38E−18
2.00E+04	1.96E+08	6.87E−17	2.18E−17	9.01E−18
5.00E+04	3.11E+08	5.81E−17	1.85E−17	7.62E−18
1.00E+05	4.39E+08	3.95E−17	1.25E−17	5.18E−18
2.00E+05	6.21E+08	2.41E−17	7.65E−18	3.16E−18
5.00E+05	9.82E+08	1.20E−17	3.81E−18	1.57E−18
1.00E+06	1.39E+09	6.68E−18	2.12E−18	8.77E−19
2.00E+06	1.96E+09	3.64E−18	1.16E−18	4.78E−19
5.00E+06	3.11E+09	1.56E−18	4.95E−19	2.04E−19

Accuracy: E/q < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E/q (keV/amu) < 10 : 40 - 100 % ;
10 ≤ E/q (keV/amu) < 100 : 30 - 40 % ; E/q ≥ 100 keV/amu : 20 - 30 %

Comments: (1) The excitation cross sections σ (2 → m)/q for m≥6 can be estimated (within the accuracies specified above) by scaling the corresponding proton-impact excitation cross sections according to the relation $\sigma_{exc}(A^{q+}; E) = q\,\sigma_{exc}(H^+; E/q)$, and introducing the correction factor χ (q) as in the case of 2 → m =3, 4, 5 transitions.

(2) The reduced excitation cross sections σ_{exc} (2 → m)/q for m = 6-10 is then given by

$$\frac{\sigma_{exc}(2 \rightarrow m)}{q} = \chi(q)\, A_{2-m} \frac{\sigma_{exc}(2 \rightarrow 5)}{q} \qquad \text{(a)}$$

where σ_{exc} (2 → 5)/q is the reduced cross section as a function of the reduced energy E/q for the 2 → m=5 transition (see preceding page), $\chi(q) = 2^{0.397\,(1 - \sqrt{2/q})}$, and the coefficients A_{2-m} are given in the table below.

(3) For the transitions σ_{exc} (2 → m), m>10, the cross sections can be estimated by using the m^{-3}–scaling,

$$\frac{\sigma_{exc}(2 \rightarrow m; \tilde{E})}{q} = \left(\frac{10}{m}\right)^3 \frac{\sigma_{exc}(2 \rightarrow 10; \tilde{E})}{q}, \quad m > 10 \qquad \text{(b)}$$

where $\tilde{E}$ = E(keV/amu)/q.

Values of the coefficients in equation (a)

A_{2-6}	A_{2-7}	A_{2-8}	A_{2-9}	A_{2-10}
0.4610	0.2475	0.1465	0.0920	0.0605

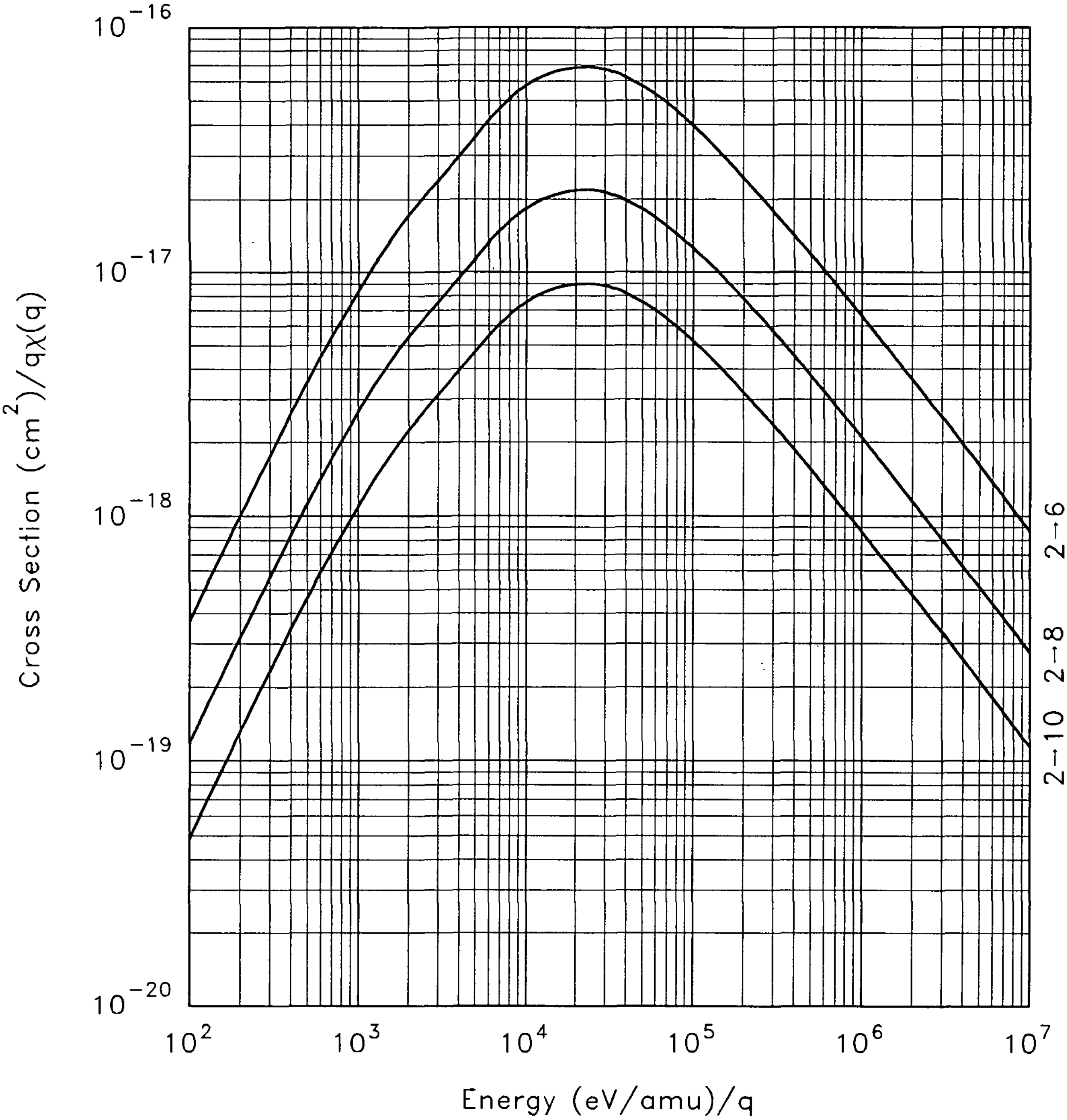
ALADDIN evaluation function for cross section: AQEXC2 for n = 6 - 10 and AQEXC3 for n>10

ALADDIN hierarchical labelling :

EXC A [+q>3] H [+0] (n=2) A [+q>3] [+0] (m), for n=2 → m=6−10

EXC A [+q>3] H [+0] (n=2) A [+q>3] [+0] (m>10), for n=2 → m>10

$A^{q+} + H^*(n=2) \rightarrow A^{q+} + H^*(m),\ m>5,\ q>3$



Legend:

—— Recommended Cross Section

4.1.10. $A^{q+} + H^*(n=3) \rightarrow A^{q+} + H^*(m)$, m=4, 5, 6, q>3

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / $q\chi(q)$ (cm^2) n=3 → m=4	n=3 → m=5	n=3 → m=6
5.00E+02	3.11E+07	2.81E−15	4.48E−16	1.60E−16
1.00E+03	4.39E+07	4.94E−15	7.87E−16	2.81E−16
2.00E+03	6.21E+07	7.78E−15	1.24E−15	4.42E−16
5.00E+03	9.82E+07	1.16E−14	1.85E−15	6.59E−16
1.00E+04	1.39E+08	1.41E−14	2.24E−15	7.99E−16
2.00E+04	1.96E+08	1.42E−14	2.27E−15	8.08E−16
5.00E+04	3.11E+08	9.95E−15	1.54E−15	5.58E−16
1.00E+05	4.39E+08	6.24E−15	9.69E−16	3.45E−16
2.00E+05	6.21E+08	3.70E−15	5.73E−16	2.01E−16
5.00E+05	9.82E+08	1.75E−15	2.70E−16	9.49E−17
1.00E+06	1.39E+09	9.66E−16	1.50E−16	5.21E−17
2.00E+06	1.96E+09	5.34E−16	8.27E−17	2.84E−17
5.00E+06	3.11E+09	2.42E−16	3.66E−17	1.30E−17

Accuracy: E/q < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E/q (keV/amu) < 5 : 40 - 80 % ; 5 ≤ E/q (keV/amu) < 100 : 30 - 40 % ; E/q ≥ 100 keV/amu : 20 - 30 %

Comments : (1) For the considered reactions, only CTMC cross section calculations are available for q = 6, 8 and 26 in the reduced energy range of E/q = 1 keV/amu - 2 MeV/amu, and a SE calculation for q = 26 in the reduced energy range 5 keV/amu - 10 MeV/amu, all calculations being performed in Ref. [54]. A single-centre AO close-coupling calculation at E/q ≈ 16 keV/amu for the n=3 → m=4 transition with q = 6 is also reported in Ref. [54]. In the reduced energy region below 30 keV/amu, the CTMC cross section data for the transitions to m = 4 and m = 5 agree to within 10 - 15 % with the q-scaled proton impact data, but for m = 6 the agreement is much worse (about 80 % at 5 keV/amu).

(2) The recommended cross sections for these transitions are constructed by q-scaling the corresponding recommended proton impact excitation cross sections $\sigma_{2\rightarrow m}(A^{q+}; E) = q\,\sigma_{2\rightarrow m}(H^+; E/q)$, and by introducing an overall correction factor $\chi(q)$ to account for the departure of the scaling from the accurate SE calculations for q = 26 at high energies.

Analytic fitting function

Cross section:

$$\frac{\sigma_{exc}(3\rightarrow m)}{q} = 10^{-16}\chi(q)\,A_1\left[\frac{\exp(-A_2/\tilde{E})\,\ln(1+A_3\tilde{E})}{\tilde{E}} + \frac{A_4\exp(-A_5\tilde{E})}{\tilde{E}^{A_6}}\right]\ [cm^2]$$

where $\tilde{E} = \frac{E\,(keV/amu)}{q}$ and $\chi(q) = 2^{0.397(1-\sqrt{2/q})}$, and the coefficients A_i are :

	A_1	A_2	A_3	A_4	A_5	A_6
3 → 4	1247.5	11.319	2.6235	0.068781	0.521176	−1.2722
3 → 5	190.59	11.096	2.9098	0.073307	0.54177	−1.2894
3 → 6	63.494	11.507	4.3417	0.077953	0.53461	−1.2881

ALADDIN evaluation function for cross section: AQEXC1

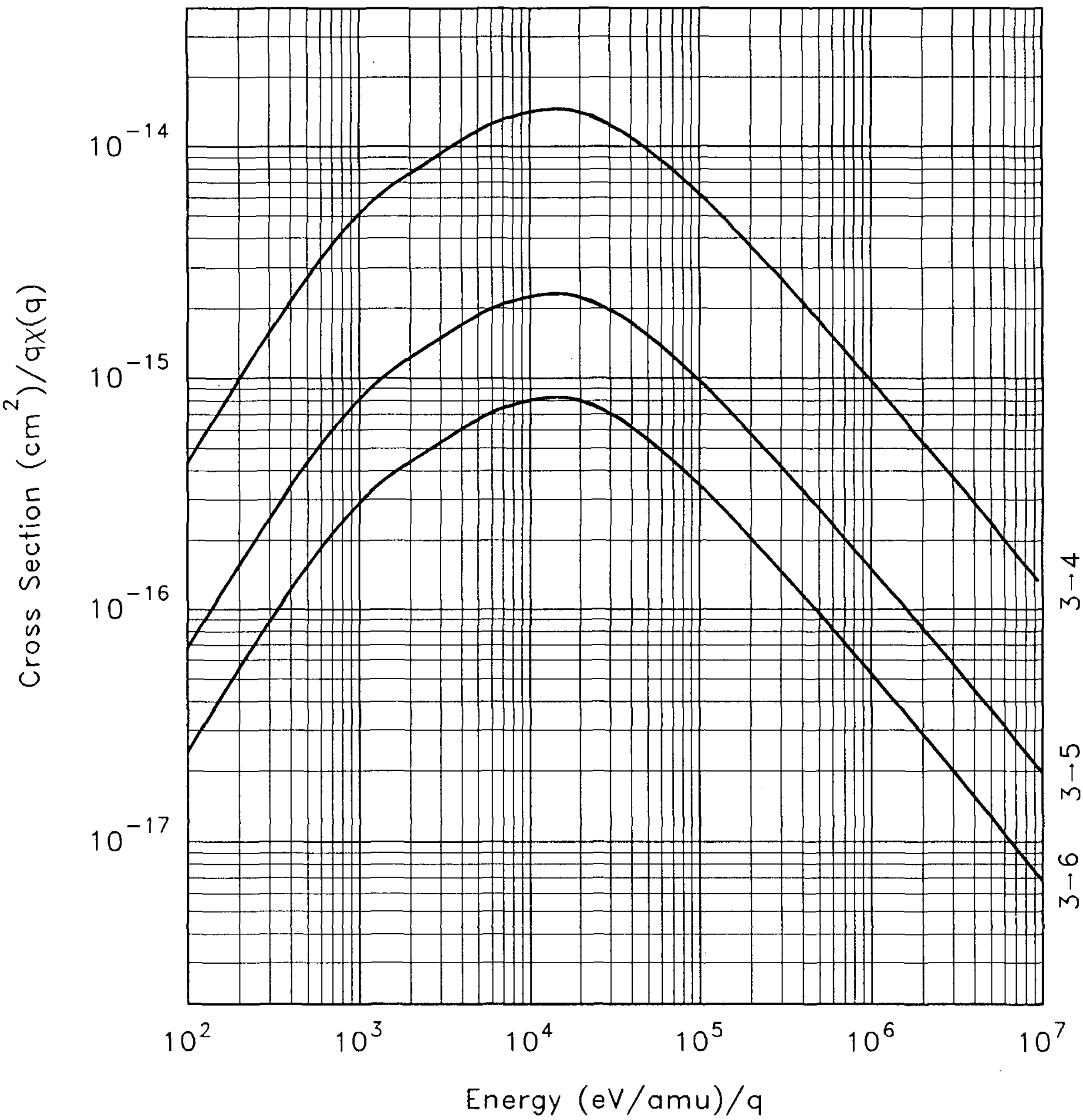
ALADDIN hierarchical labelling :

EXC A [+q>3] H [+0] (n=3) A [+q>3] [+0] (m=4), for n=3→m=4

EXC A [+q>3] H [+0] (n=3) A [+q>3] [+0] (m=5), for n=3→m=5

EXC A [+q>3] H [+0] (n=3) A [+q>3] [+0] (m=6), for n=3→m=6

$A^{q+} + H^*(n=3) \rightarrow A^{q+} + H^*(m),\ m=4,\ 5,\ 6,\ q>3$



Legend:

—— Recommended Cross Section

4.1.11. $A^{q+} + H^*(n=3) \rightarrow A^{q+} + H^*(m)$,m>6, q>3

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / q χ(q) (cm^2) n=3 → m=7	n=3 → m=8	n=3 → m=10
5.00E+02	3.11E+07	7.47E−17	4.07E−17	1.60E−17
1.00E+03	4.39E+07	1.31E−16	7.15E−17	2.81E−17
2.00E+03	6.21E+07	2.06E−16	1.12E−16	4.42E−17
5.00E+03	9.82E+07	3.08E−16	1.68E−16	6.59E−17
1.00E+04	1.39E+08	3.73E−16	2.03E−16	7.99E−17
2.00E+04	1.96E+08	3.78E−16	2.06E−16	8.09E−17
5.00E+04	3.11E+08	2.61E−16	1.42E−16	5.58E−17
1.00E+05	4.39E+08	1.61E−16	8.78E−17	3.45E−17
2.00E+05	6.21E+08	9.38E−17	5.11E−17	2.01E−17
5.00E+05	9.82E+08	4.43E−17	2.41E−17	9.49E−18
1.00E+06	1.39E+09	2.43E−17	1.32E−17	5.21E−18
2.00E+06	1.96E+09	1.33E−17	7.22E−18	2.84E−18
5.00E+06	3.11E+09	6.07E−18	3.31E−18	1.30E−18

Accuracy: E/q < 0.5 keV/amu : Indeterminate ; 0.5 ≤ E/q (keV/amu) < 5 : 40 - 100 % ; 5 ≤ E/q (keV/amu) < 100 : 30 - 40 % ; E/q ≥ 100 keV/amu : 20 - 30 %

Comments: (1) The excitation cross sections $\sigma(3 \rightarrow m)/q$ for m≥7 can be estimated (within the accuracies specified above) by scaling the corresponding proton-impact excitation cross sections according to the relation $\sigma_{exc}(A^{q+}; E) = q\,\sigma_{exc}(H^+; E/q)$, and introducing the correction factor χ (q) as in the case of 3 → m =4, 5, 6 transitions.

(2) The reduced excitation cross sections $\sigma_{exc}(3 \rightarrow m)/q$ for m = 7-10 is then given by

$$\frac{\sigma_{exc}(3 \rightarrow m)}{q} = \chi(q)\, A_{3-m} \frac{\sigma_{exc}(3 \rightarrow 6)}{q} \qquad \text{(a)}$$

where $\sigma_{exc}(3 \rightarrow 6)/q$ is the reduced cross section as a function of the reduced energy E/q for the 3 → m=6 transition (see preceding page), $\chi(q) = 2^{0.397(1-\sqrt{2/q})}$, and the coefficients A_{3-m} are given in the table below.

(3) For the transitions $\sigma_{exc}(3 \rightarrow m)$, m>10 , the cross sections can be estimated by using the m^{-3}−scaling,

$$\frac{\sigma_{exc}(3 \rightarrow m; \tilde{E})}{q} = \left(\frac{10}{m}\right)^3 \frac{\sigma_{exc}(3 \rightarrow 10; \tilde{E})}{q}, \quad m > 10 \qquad \text{(b)}$$

where $\tilde{E}$ = E(keV/amu)/q.

Values of the coefficients in equation (a)

A_{3-7}	A_{3-8}	A_{3-9}	A_{3-10}
0.4670	0.2545	0.1540	0.1000

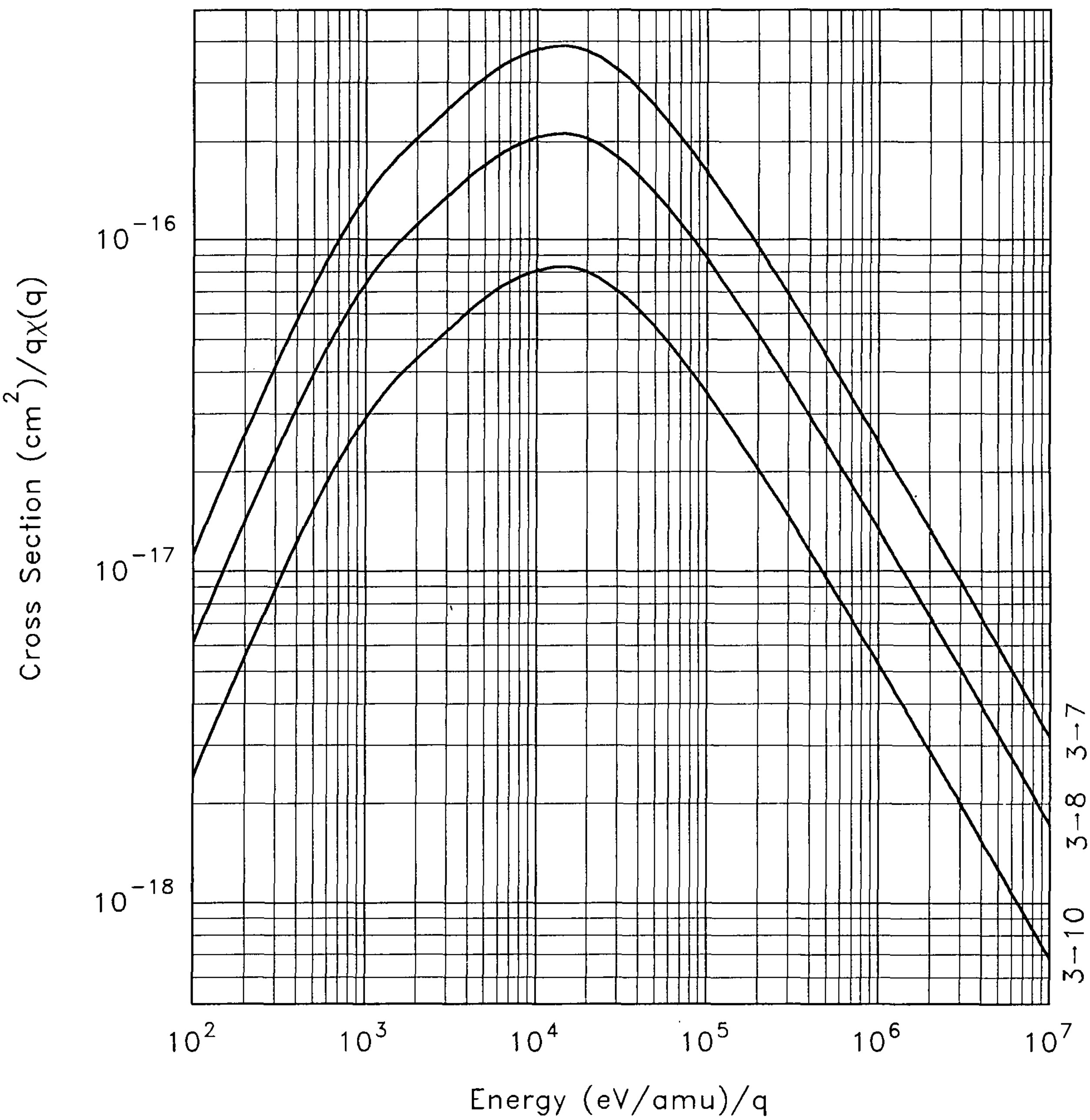
ALADDIN evaluation function for cross section: AQEXC2 for n = 7 - 10 and AQEXC3 for n>10

ALADDIN hierarchical labelling :

EXC A [+q>3] H [+0] (n=3) A [+q>3] [+0] (m), for n=3 → m=7−10

EXC A [+q>3] H [+0] (n=3) A [+q>3] [+0] (m>10), for n=3 → m>10

$A^{q+} + H^{*}(n=3) \rightarrow A^{q+} + H^{*}(m),\ m>6,\ q>3$



Legend:

—— Recommended Cross Section

4.1.12. $A^{q+} + H^*(n) \rightarrow A^{q+} + H^*(m)$, $n > 3$, $m > n$, $q>3$

Energy / q (eV/amu)	Velocity / $\sqrt{q}$ (cm/s)	Cross sections / $q\chi(q)$ (cm^2)		
		n=4 → m=5	n=4 → m=6	n=4 → m=7
1.00E+03	4.39E+07	2.01E−14	6.25E−15	2.95E−15
2.00E+03	6.21E+07	2.89E−14	8.46E−15	3.88E−15
5.00E+03	9.82E+07	4.17E−14	1.01E−14	4.20E−15
1.00E+04	1.39E+08	5.00E−14	9.93E−15	3.84E−15
2.00E+04	1.96E+08	4.71E−14	8.30E−15	3.06E−15
5.00E+04	3.11E+08	3.18E−14	5.08E−15	1.80E−15
1.00E+05	4.39E+08	2.03E−14	3.10E−15	1.08E−15
2.00E+05	6.21E+08	1.21E−14	1.79E−15	6.12E−16
5.00E+05	9.82E+08	5.75E−15	8.20E−16	2.77E−16
1.00E+06	1.39E+09	3.18E−15	4.46E−16	1.50E−16
2.00E+06	1.96E+09	1.74E−15	2.40E−16	8.00E−17
5.00E+06	3.11E+09	7.73E−16	1.05E−16	3.47E−17

Accuracy: For the $\Delta n = m - n \leq 6$ transitions : 25 - 30 % for energies above the cross section maximum, and 30 - 40 % below the energy at which the maximum occurs and above 100 n^2/q keV/amu. For the $\Delta n > 6$ transitions, the uncertainty progressively increases and may be larger than 100 %.

Comments: (1) In absence of any systematic data for the $n \rightarrow m$ $(m>n>3)$ transitions, the q-scaled proton-impact excitation semi-empirical formula of Lodge et al [55] can be used to estimate the cross sections with an accuracy as assessed above.

(2) In order to account for the deviation of the q-scaling at high energies and for high values of q (of the order of max 25 % when $q \rightarrow \infty$, as follows from the calculations of Reinhold et al [54] for the transitions between the lower n, m states and q = 26), an overall correction factor $\chi(q)$ can be introduced in the q-scaled Lodge et al [55] formula. For a 25 % deviation for $q \rightarrow \infty$, this factor is

$$\chi(q) = 2^{0.322\,(1 - \sqrt{2/q})} \qquad \text{(a)}$$

Analytic expression

Cross section:

$$\frac{\sigma_{exc}(n\rightarrow m)}{q} = \chi(q)\,\frac{8.86 \times 10^{-17}\, n^4}{\varepsilon}\left[ADL + FGH\right] \qquad [\mathrm{cm}^2], \qquad \text{(b)}$$

where, $\varepsilon = \dfrac{E\,(\mathrm{keV/amu})}{25\,q}$, $s = \Delta n = m - n$, $D = \exp\left[-1/(nm\varepsilon^2)\right]$

$$A = \frac{8}{3s}\left(\frac{m}{sn}\right)^3\left(0.184 - 0.04/s^{2/3}\right)\left(1 - \frac{0.2s}{nm}\right)^{1+2s}, \quad G = 0.5\left(\frac{\varepsilon\, n^2}{m - 1/m}\right)^3$$

$$L = \ln\left(\frac{1 + 0.53\,\varepsilon^2\, n\,(m - 2/m)}{1 + 0.4\varepsilon}\right), \quad F = \left[1 - 0.3sD/(nm)\right]^{1+2s}$$

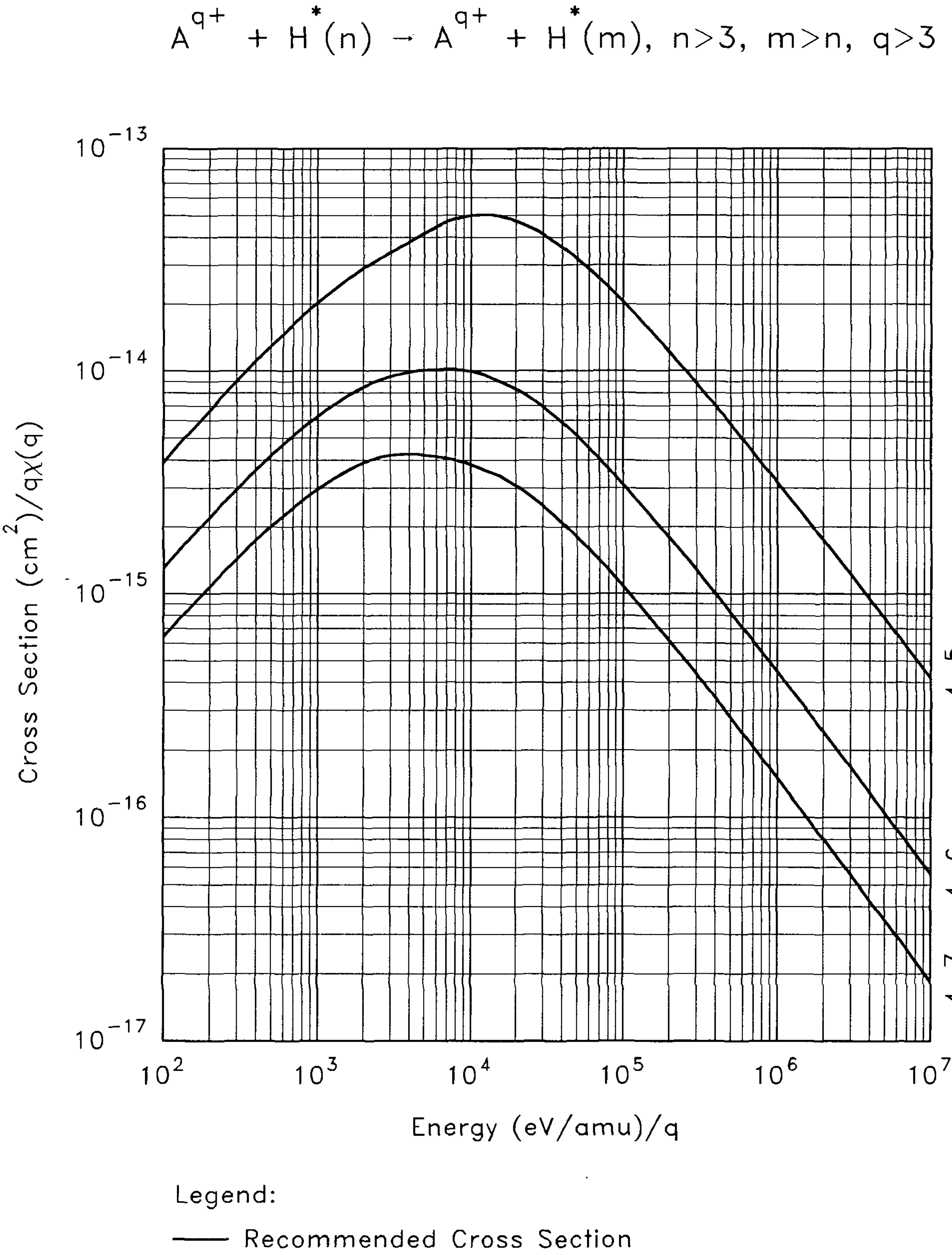
$$H = \left[C_2\left(z_-, y\right) - C_2\left(z_+, y\right)\right], \quad C_2(z, y) = \frac{z^2 \ln(1 + 2z/3)}{2y + 3z/2}$$

$$z_\pm = 2 \Big/ \left\{\varepsilon\, n^2\left[\left(2 - n^2/m^2\right)^{1/2} \pm 1\right]\right\}, \quad y = 1 \Big/ \left[1 - D\ln(18s)/(4s)\right]$$

ALADDIN evaluation function for cross section: HEXCLD

ALADDIN hierarchical labelling :

EXC A [+q>3] H [+0] (n>3) A [+q>3] H [+0] (m>n)


$A^{q+} + H^*(n) \rightarrow A^{q+} + H^*(m)$, n>3, m>n, q>3
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Cross Section $(cm^2)/q\chi(q)$
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV/amu)/q
4→5
4→6
4→7
Legend:
Recommended Cross Section

4. Collision Processes with Highly Charged Ions

4.2. Ionization

4.2.1. $Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{+} + e^{-}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+03	4.39E+07	1.61E−20
2.00E+03	6.21E+07	1.82E−19
5.00E+03	9.82E+07	3.30E−18
1.00E+04	1.39E+08	2.04E−17
2.00E+04	1.96E+08	9.08E−17
5.00E+04	3.11E+08	4.27E−16
1.00E+05	4.39E+08	9.10E−16
2.00E+05	6.21E+08	9.56E−16
5.00E+05	9.82E+08	5.10E−16
1.00E+06	1.39E+09	2.87E−16
2.00E+06	1.96E+09	1.59E−16
5.00E+06	3.11E+09	7.27E−17

Accuracy: $E < 2$ keV/amu : Indeterminate ; $2 \leq E$ (keV/amu) < 10 : 40 - 80 % ;
$10 \leq E$ (keV/amu) < 80 : 30 - 40 % ; $80 \leq E$ (keV/amu) < 300 : 15 - 30 % ;
$E \geq 300$ keV/amu : 10 - 15 %

Comments: (1) In the energy region below 100 keV/amu, the cross section data for this reaction are available from the adiabatic superpromotion model (Krstic et al [108]), and in the energy range 50 keV/amu - 10 MeV/amu cross section data are available from the symmeterized eikonal (SE) approximation (Rivarola et al [110]). In the energy range between 70 and 100 keV/amu the both sets of data agree within 2-5 %.

(2) The recommended cross section below 80 keV/amu follows the data of the adaibatic superpromotion model, while above this energy it follows the data of the SE calculations.

(3) In the energy range between 80 and 200 keV/amu, the recommended cross section agrees to within 10-20 % with the experimental data of Shah and Gilbody [111] for the C^{4+}, N^{4+}, O^{4+} + H collision systems, and with the CTMC calculations of Olson and Salop [112]. For energies below 80 keV/amu, the experimental data for the C^{4+}, N^{4+}, O^{4+} + H systems are by a factor of 1.3 - 1.5 higher than the recommended cross section.

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

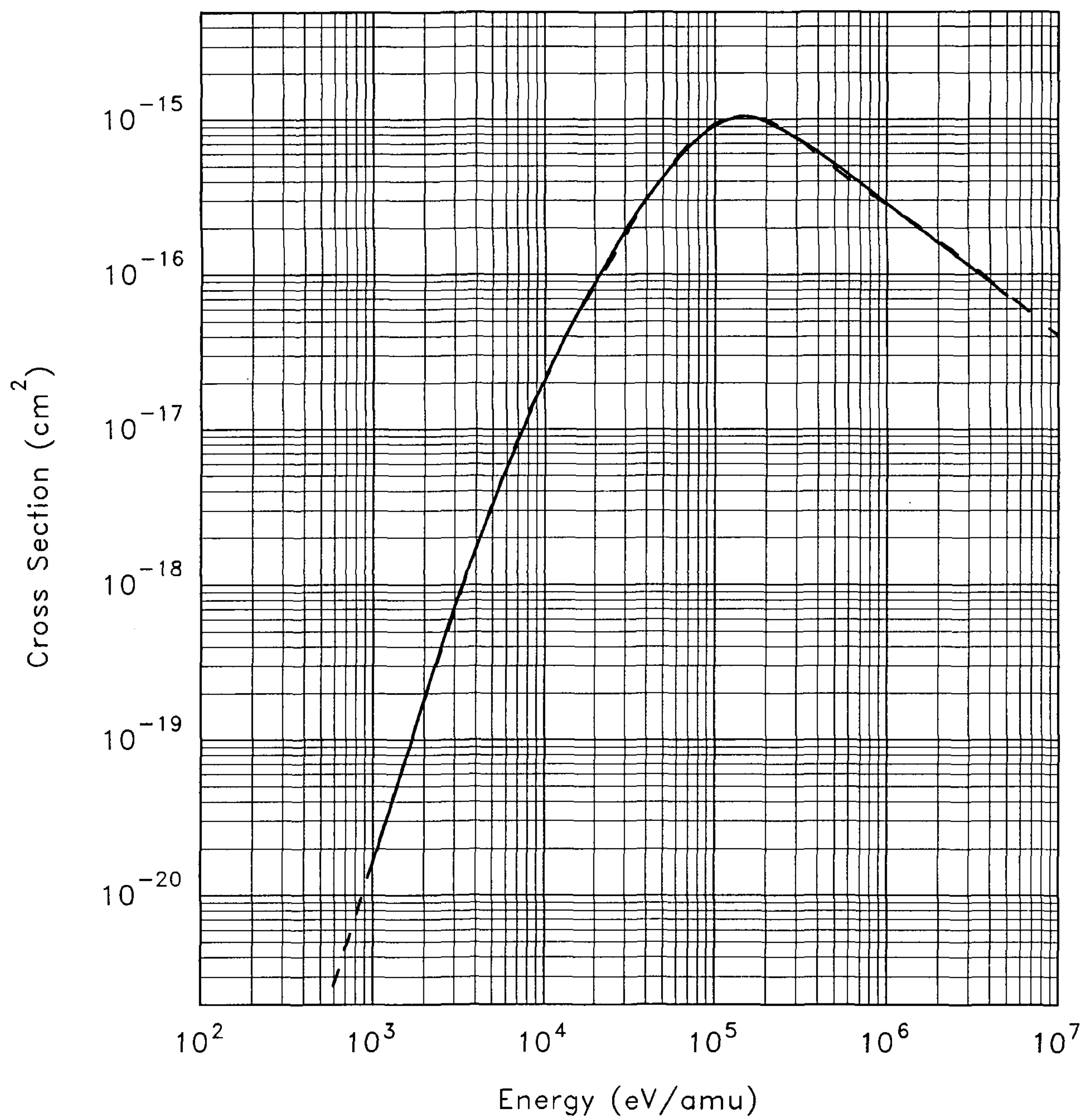
A_1 - A_4	306.63	178.22	62.033	3.1376E−05
A_5 - A_8	1.3455E−02	−1.6452	57.117	−3.53383

The rms deviation of the above fit to the recommended cross section is 3.4%, with a maximum deviation of 7.7% at 27.62 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION Be [+4] H [+0] (1s) Be [+4] H [+1] e

$Be^{4+} + H(1s) \rightarrow Be^{4+} + H^{+} + e^{-}$



Legend:

—— Recommended Cross Section

- - Analytic Fit

4.2.2. $B^{5+} + H(1s) \rightarrow B^{5+} + H^{+} + e^{-}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.00E+03	4.39E+07	2.33E−20
2.00E+03	6.21E+07	2.49E−19
1.00E+04	1.39E+08	2.08E−17
2.00E+04	1.96E+08	9.26E−17
5.00E+04	3.11E+08	4.82E−16
1.00E+05	4.39E+08	1.14E−15
2.00E+05	6.21E+08	1.22E−15
5.00E+05	9.82E+08	6.91E−16
1.00E+06	1.39E+09	4.13E−16
2.00E+06	1.96E+09	2.37E−16
5.00E+06	3.11E+09	1.08E−16

Accuracy: $E < 5$ keV/amu : Indeterminate ; $5 \le E$ (keV/amu) < 80 : 40 - 80 % ;
$80 \le E$ (keV/amu) < 200 : 30 - 40 % ; $200 \le E$ (keV/amu) < 400 : 15 - 30 % ;
$E \ge 400$ keV/amu : 10 - 15 %

Comments: (1) For energies below 50 keV/amu, ionization cross sections for this collision system are available from the adiabatic superpromotion model calculatiions (Krstic et al [108]), and for energies above 50 keV/amu (up to 10 MeV/amu) cross section data are available from the CTMC method [112] (up to 200 keV/amu) and the symmeterized eikonal (SE) approximation [110] (up to 10 MeV/amu). The data from the adiabatic superpromotion model for B^{5+} + H ionization lie above those for the Be^{4+} + H system, which is contrary to the experimentally observed trend for the q-dependance of ionization cross sections in the energy region well below the energy of the cross section maximum [111].

(2) The recommended cross section in the energy range 70 - 200 keV/amu is based on the CTMC results [112], and with an accuracy of 10-15 % it agrees with the experimental data for the N^{5+} ,O^{5+} + H systems [111]. For energies above 200 keV/amu, the recommended cross section is based on the SE calculations of Rivarola et al [110]. For energies below 80 keV/amu, the recommended cross section was constructed from the recommended cross section for the Be^{4+} + H reaction by using the approximate equality $\sigma(Be^{4+})/\sigma(B^{5+}) \sim \sigma(C^{4+})/\sigma(C^{5+})$, and the recommended values of Ref. [105] for $\sigma(C^{4+} + H)$ and $\sigma(C^{5+} + H)$.

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3 E)}{E} + \frac{A_4 \exp(-A_5 E)}{E^{A_6} + A_7 E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

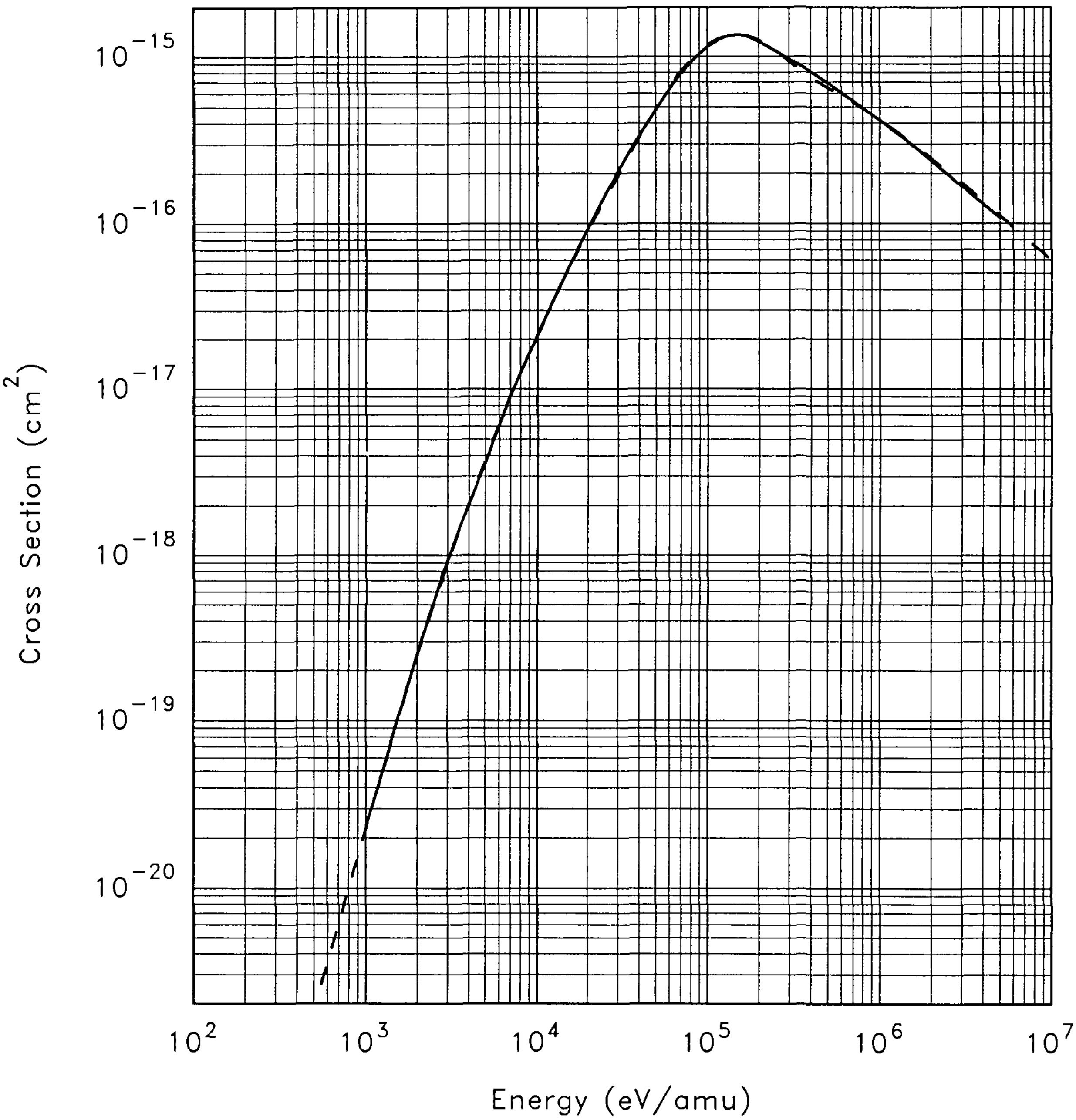
A_1 - A_4	351.52	233.63	3.2952E+03	5.3787E−06
A_5 - A_8	1.8834E−02	−2.2064	7.2074	−3.78664

The rms deviation of the above fit to the recommended cross section is 3.0%, with a maximum deviation of 7.6% at 444.2 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION B [+5] H [+0] (1s) B [+5] H [+1] e

$$B^{5+} + H(1s) \rightarrow B^{5+} + H^{+} + e^{-}$$



Legend:

—— Recommended Cross Section

- – Analytic Fit

4.2.3. $C^{6+} + H(1s) \rightarrow C^{6+} + H^+ + e^-$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
8.00E+03	1.24E+08	4.75E−18
1.00E+04	1.39E+08	9.16E−18
2.00E+04	1.96E+08	6.80E−17
5.00E+04	3.11E+08	5.65E−16
1.00E+05	4.39E+08	1.30E−15
2.00E+05	6.21E+08	1.55E−15
5.00E+05	9.82E+08	9.53E−16
1.00E+06	1.39E+09	5.99E−16
2.00E+06	1.96E+09	3.59E−16
5.00E+06	3.11E+09	1.67E−16
1.00E+07	4.39E+09	9.09E−17
2.00E+07	6.21E+09	4.76E−17
5.00E+07	9.82E+09	1.96E−17
1.00E+08	1.39E+10	1.02E−17

Accuracy: E < 10 keV/amu : Indeterminate ; 10 ≤ E (keV/amu) < 60 : 40 - 80 % ; 60 ≤ E (keV/amu) < 200 : 30 - 40 % ; 200 ≤ E (keV/amu) < 500 : 15 - 30 % ; E ≥ 500 keV/amu : 10 - 15 %

Comments:

(1) In the energy region above 200 keV/amu, the recommended cross section for this reaction is based on the continuum distorted wave (CDW) approximation results (Crothers and Mc Cann [85]), available up to 1 MeV/amu, and symmeterized eikonal calculations of Rivarola et al [110] available up to 10 Mev/amu. In the energy region above 500 keV/amu, the two sets of data agree with each other to within 2 - 3 %.

(2) In the energy region below 200 keV/amu, the recommended cross section is based on the semi-empirical scaling formula of Gillespie [87], and on the CTMC results of Hardie and Olson [113]. In the energy range 60 - 200 keV/amu the recommended cross section is about 20 - 30 % higher than the SE results of Ref. [110].

(3) The recommended cross section agrees with the single experimental point at E = 400 keV/amu (Shah and Gilbody [114]), and with the two experimental data values at 300 and 400 keV/amu for the O^{6+} + H system from the same reference with an accuracy of 5 - 10 %.

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

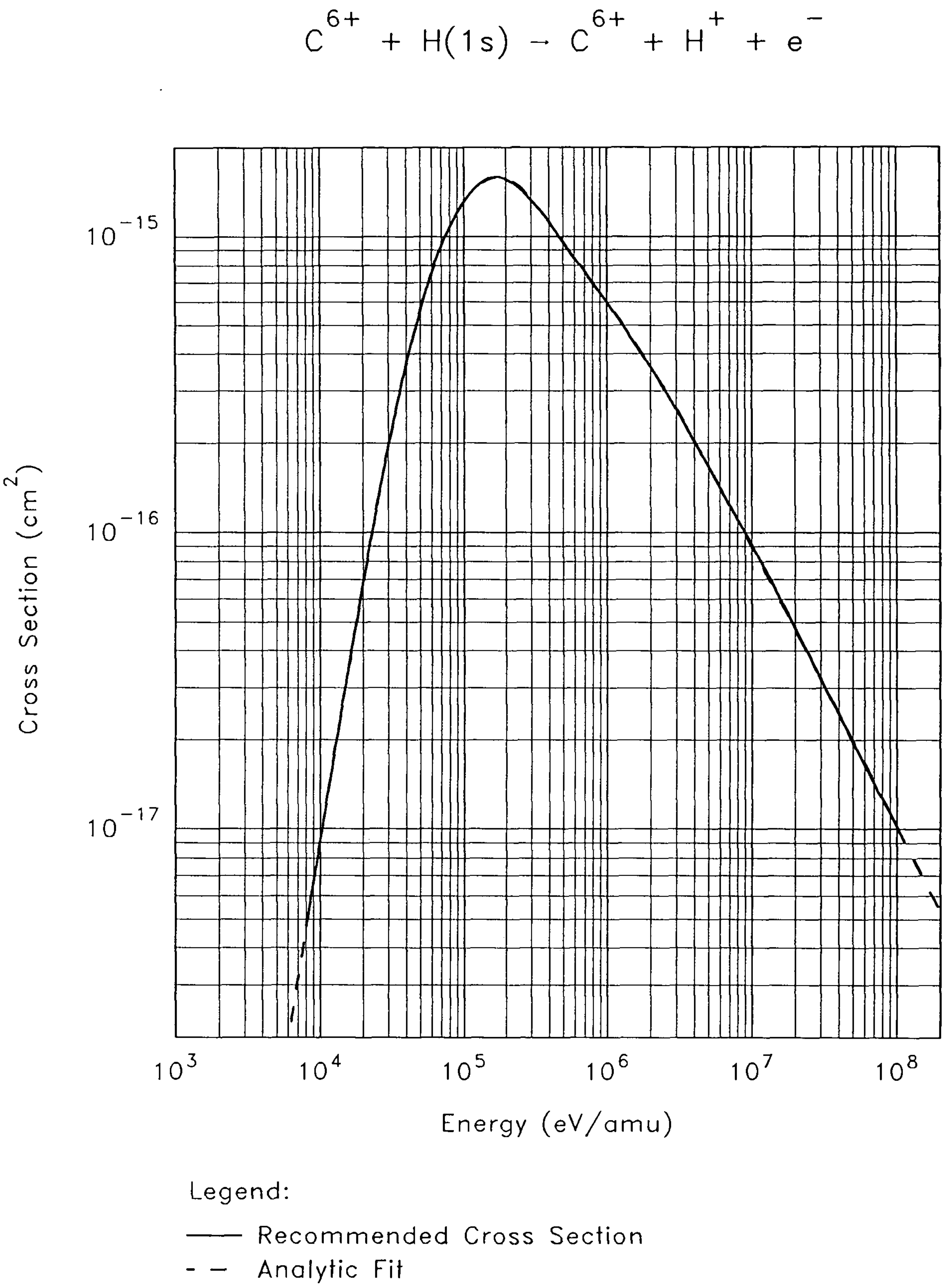
Fitting parameters

A_1 - A_4	438.36	327.10	1.4444E+05	3.5212E−03
A_5 - A_8	8.3031E−03	−0.63731	1.9116E+04	−3.1003

The rms deviation of the above fit to the recommended cross section is 0.8%, with a maximum deviation of 2.1% at 13.3 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION C [+6] H [+0] (1s) C [+6] H [+1] e



$C^{6+} + H(1s) \rightarrow C^{6+} + H^{+} + e^{-}$
Cross Section (cm^2)
10^{-15}
10^{-16}
10^{-17}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
Energy (eV/amu)
Legend:
—— Recommended Cross Section
- - Analytic Fit

4.2.4. $O^{8+} + H(1s) \rightarrow O^{8+} + H^{+} + e^{-}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
2.00E+04	1.96E+08	9.68E−17
5.00E+04	3.11E+08	7.09E−16
1.00E+05	4.39E+08	1.88E−15
2.00E+05	6.21E+08	2.53E−15
5.00E+05	9.82E+08	1.64E−15
1.00E+06	1.39E+09	1.02E−15
2.00E+06	1.96E+09	6.04E−16
5.00E+06	3.11E+09	2.82E−16
1.00E+07	4.39E+09	1.53E−16
2.00E+07	6.21E+09	8.37E−17

Accuracy: $E < 10$ keV/amu : Indeterminate ; $10 \leq E$ (keV/amu) < 60 : 40 - 80 % ; $60 \leq E$ (keV/amu) < 300 : 30 - 40 % ; $300 \leq E$ (keV/amu) < 800 : 20 - 30 % ; $E \geq 800$ keV/amu : 10 - 20 %

Comments: (1) In the energy region above 1 MeV/amu, the recommended cross section for this reaction is based on the symmetrized eikonal calculations of Rivarola et al [110]. In the energy range 100 - 800 keV/amu, the cross section is constructed on the basis of CTMC calculations of Hardie and Olson [113] for this collision system, and on the similar calculations for the $A^{8+} + H$ systems (A = Ti, Cr, Fe, Ni) of Katsonis et al [115]. All CTMC results agree with each other within a 5 - 10 % accuracy, irrespective of the chemical species of the ion.

(2) In the energy region below 200 keV/amu, the recommended cross section for this reaction is based on the semi-empirical scaling formula of Gillespie [87].

Analytic fitting function

Cross section:

$$\sigma_{ion} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E)\ \ln(1 + A_3E)}{E} + \frac{A_4 \exp(-A_5E)}{E^{A_6} + A_7E^{A_8}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

Fitting parameters

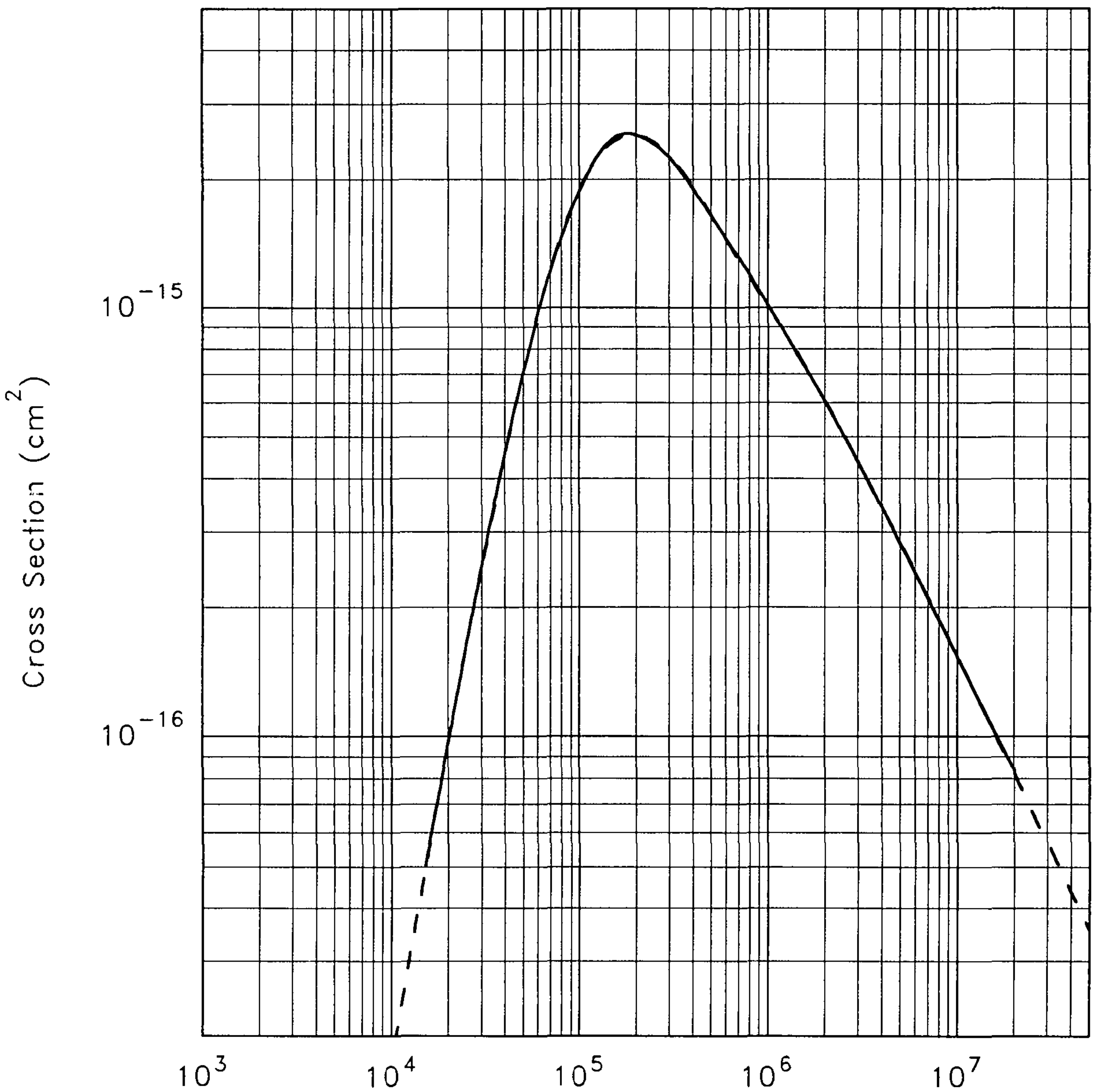
A_1 - A_4	1244.44	249.36	30.892	9.0159E−04
A_5 - A_8	7.7885E−03	−0.71309	3.2918E+03	−2.7541

The rms deviation of the above fit to the recommended cross section is 1.0%, with a maximum deviation of 3.1% at 15.1 keV/amu.

ALADDIN evaluation function for cross section: HEXC3

ALADDIN hierarchical labelling: ION O [+8] H [+0] (1s) O [+8] H [+1] e

$$O^{8+} + H(1s) \rightarrow O^{8+} + H^{+} + e^{-}$$



Legend:

—— Recommended Cross Section

- - Analytic Fit

4.2.5. $A^{q+} + H(1s) \rightarrow A^{q+} + H^+ + e^-$, q>8

Energy (eV/amu)	Velocity (cm/s)	Cross sections (cm^2) q=10	q=14	q=26
2.00E+04	1.96E+08	1.20E−18	5.27E−20	2.03E−24
5.00E+04	3.11E+08	4.41E−16	1.89E−16	6.82E−18
1.00E+05	4.39E+08	1.95E−15	1.79E−15	6.31E−16
2.00E+05	6.21E+08	3.00E−15	4.02E−15	4.43E−15
5.00E+05	9.82E+08	2.49E−15	4.19E−15	9.17E−15
1.00E+06	1.39E+09	1.66E−15	3.02E−15	8.29E−15
2.00E+06	1.96E+09	9.95E−16	1.88E−15	5.78E−15
5.00E+06	3.11E+09	4.66E−16	9.00E−16	2.97E−15
1.00E+07	4.39E+09	2.55E−16	4.95E−16	1.67E−15
2.00E+07	6.21E+09	1.37E−16	2.68E−16	9.13E−16
5.00E+07	9.82E+09	5.97E−17	1.17E−16	4.01E−16
1.00E+08	1.39E+10	3.17E−17	6.21E−17	2.14E−16

Accuracy: E/q < 1 keV/amu : Indeterminate ; 1 ≤ E/q (keV/amu) < 15 : 40 - 100 % ;
15 ≤ E/q (keV/amu) < 50 : 30 - 40 % ; 50 ≤ E/q (keV/amu) < 200 : 20 - 30 % ;
E/q ≥ 200 keV/amu : 15 - 20 %

Comments: (1) Within the above accuracies, the ionization cross section of H (1s) colliding with an arbitrary fully or partially stripped ion with charge > 8 can be obtained from the semi-empirical scaling formula of Gillespie [87]. This formula is qiven in Eq. (a) below.

(2) Within the assigned uncertainties, the Gillespie scaling formula is valid also for fully stripped ions with q < 8, and incompletely stripped ions in this charge range with q > Z/2, where Z is the nuclear charge.

(3) An alternative semi-empirical formula for ionization of H(1s) by multiply charged ions had been proposed by Tabata et al [116], and is given in Appendix A.2. This formula has somewhat better accuracy than (a) in the reduced energy range below 15 keV/amu.

Analytic expression

Cross section:

$$\sigma_{ion} = \exp(-\lambda q/v^2)\,\sigma_B \;,\; \lambda = 0.76 \qquad \text{(a)}$$

where σ_B is the Bethe cross section

$$\sigma_B = \frac{3.52 \times 10^{-16}\, q^2}{v^2} \left\{ M^2 \left[\ln\left(\frac{v^2}{c^2-v^2}\right) - \frac{v^2}{c^2} \right] + B - \frac{\gamma}{v^2} \right\} \quad [cm^2]$$

with $M^2 = 0.283$, $B = 4.04, \gamma = 0.662$, $c=137$ and

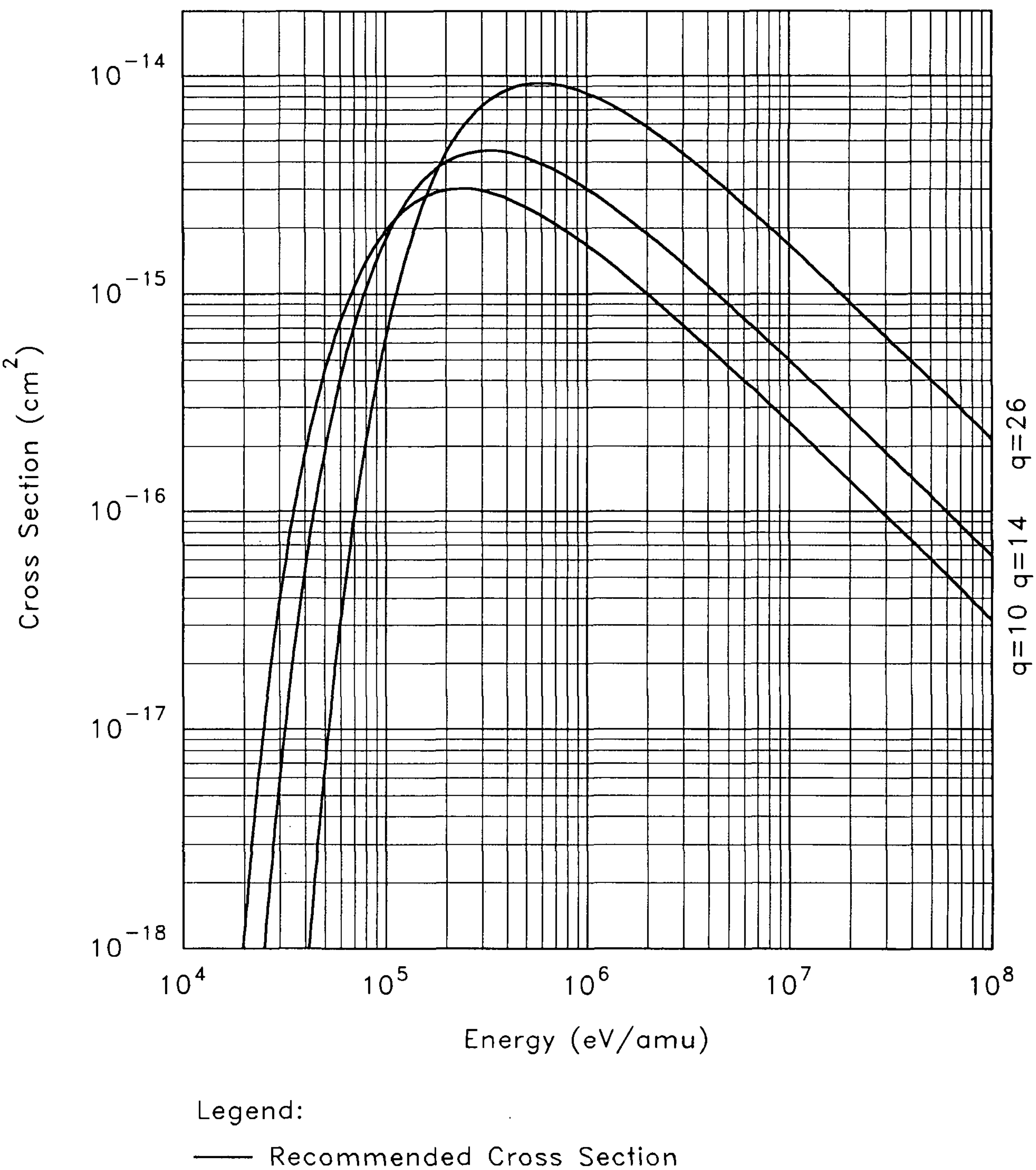
$v^2 = E$ (keV/amu)/25, v being the relative collision velocity in atomic units.

ALADDIN evaluation function for cross section: AIONGL

ALADDIN hierarchical labelling:

ION A [+q>8] H [+0] (1s) A [+q>8] H [+1] e

$$A^{q+} + H(1s) \rightarrow A^{q+} + H^{+} + e^{-}, \; q>8$$



4.2.6. $A^{q+} + H^*(n) \rightarrow A^{q+} + H^+ + e^-$,n>1 , q>3

Energy $\times n^2$ (eV/amu)	Velocity $\times$ n (cm/s)	Cross sections / n^4 (cm^2) q=4	q=6	q=8
2.00E+04	1.96E+08	5.74E−17	1.93E−17	5.14E−18
5.00E+04	3.11E+08	6.90E−16	7.26E−16	6.04E−16
1.00E+05	4.39E+08	9.76E−16	1.50E−15	1.83E−15
2.00E+05	6.21E+08	8.48E−16	1.58E−15	2.32E−15
5.00E+05	9.82E+08	5.01E−16	1.04E−15	1.72E−15
1.00E+06	1.39E+09	2.98E−16	6.45E−16	1.10E−15
2.00E+06	1.96E+09	1.69E−16	3.72E−16	6.49E−16
5.00E+06	3.11E+09	7.63E−17	1.70E−16	3.01E−16
1.00E+07	4.39E+09	4.12E−17	9.24E−17	1.64E−16
2.00E+07	6.21E+09	2.21E−17	4.96E−17	8.79E−17
5.00E+07	9.82E+09	9.58E−18	2.15E−17	3.83E−17
1.00E+08	1.39E+10	5.08E−18	1.14E−17	2.03E−17

Accuracy: $E\,n^2/q$ (keV/amu) < 1 : Indeterminate ; $1 \le E\,n^2/q$ (keV/amu) < 15 : 40 - 100 % ;
$15 \le E\,n^2/q$ (keV/amu) < 50 : 30 - 40 % ; $50 \le E\,n^2/q$ (keV/amu) < 200 : 20 - 30 % ;
$E\,n^2/q$ (keV/amu) $E \ge 200$: 20 %, or better

Comments: (1) Systematic CTMC cross section calculations for these reactions have been performed by Olson [101], for $En^2 > 25$ keV/amu , n = 2, 5, 10, 20 and q = 2, 5, 10. The CTMC calculations confirm the exact classical scaling relationships $\sigma_{ion} \sim n^4$, $E \sim n^{-2}$. The adiabatic superpromotion model predicts the $E \sim n^{-2}$ scaling also in the low energy region.

(2) Using these scalings in the semi-empirical ionization formula of Gillespie [87], the cross section can be constructed as given by Eq. (a) below.

Analytic expression

Cross section:

$$\sigma_{ion}(n) = \exp(-\lambda q / u^2)\, \sigma_B(n) \;,\; \lambda = 0.76 \tag{a}$$

where $\sigma_B(n)$ is the n-scaled Bethe cross section

$$\sigma_B(n) = \frac{3.52 \times 10^{-16}\, n^4 q^2}{u^2} \left\{ M^2 \left[\ln\left(\frac{u^2}{c^2 - u^2}\right) - \frac{u^2}{c^2} \right] + B - \frac{\gamma}{u^2} \right\} \quad [cm^2]$$

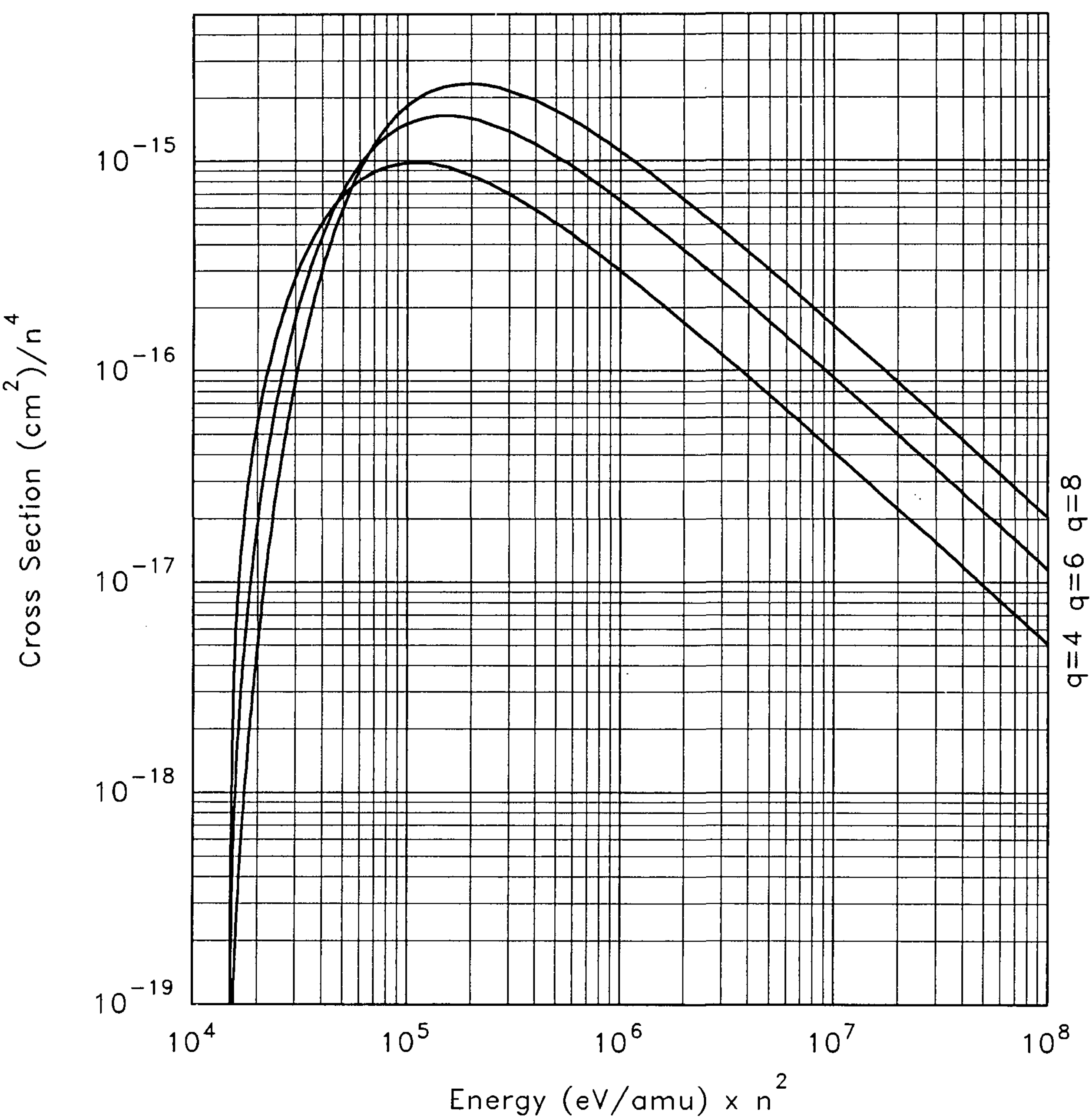
with $M^2 = 0.283$, $B = 4.04$, $\gamma = 0.662$, $c = 137$, $u = nv$,
and $v^2 = E$ (keV/amu)/25, v being the relative collision velocity in atomic units.

ALADDIN evaluation function for cross section: AIONGL

ALADDIN hierarchical labelling :

ION A [+q>3] H [+0] (n>1) A [+q>3] H [+1] e

$A^{q+} + H^*(n) \rightarrow A^{q+} + H^+ + e^-$, n>1 , q>3



Legend:

—— Recommended Cross Section

4.3. Electron capture

4.3.1. $Be^{4+} + H(1s) \rightarrow Be^{3+} + H^+$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E+01	9.82E+06	6.59E−16
1.00E+02	1.39E+07	1.09E−15
2.00E+02	1.96E+07	1.77E−15
5.00E+02	3.11E+07	2.74E−15
1.00E+03	4.39E+07	3.35E−15
2.00E+03	6.21E+07	3.61E−15
5.00E+03	9.82E+07	3.52E−15
1.00E+04	1.39E+08	3.09E−15
2.00E+04	1.96E+08	2.33E−15
5.00E+04	3.11E+08	1.16E−15
1.00E+05	4.39E+08	2.99E−16
2.00E+05	6.21E+08	2.45E−17
5.00E+05	9.82E+08	4.92E−19
1.00E+06	1.39E+09	2.37E−20
2.00E+06	1.96E+09	9.23E−22
4.00E+06	2.78E+09	2.85E−23

Accuracy: $E < 0.1$ keV/amu : Indeterminate ; $1 \leq E$ (keV/amu) < 20 : 10 - 20 % ; $20 \leq E$ (keV/amu) < 100 : 15 - 20 % ; $E \geq 100$ keV/amu : 10 - 15 %

Comments: (1) In the energy range 0.1 - 20 keV/amu, the recommended total electron capture cross section for this collision system is based on the extensive multi-state close-coupling calculations of Fritsch and Lin [117] (AO basis) and Kimura [118] (MO basis). In the overlapping region (0.1 - 10 keV/amu) these sets of data agree within 10 - 15 %.

(2) In the range 20 - 100 keV/amu, the recommended cross section is based on the UDWA calculations of Ryufuku [119], while for $E \geq 100$ keV/amu, the recommended cross section follows the results of the CDW approximation [120].

(3) The total CDW cross section was calculated by summing the partial cross sections up to the $n = 7$ shell, and by applying the n^{-3} -rule to include those for $n > 7$.

(4) No experimental data are available for this reaction.

Analytic fitting function

Cross section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E^{A_8})}{1 + A_3 E^2 + A_4 E^{A_5} + A_6 E^{A_7}} + \frac{A_9 \exp(-A_{10} E)}{E^{A_{11}}} \right] \ [cm^2]$$

where E is expressed in keV/amu.

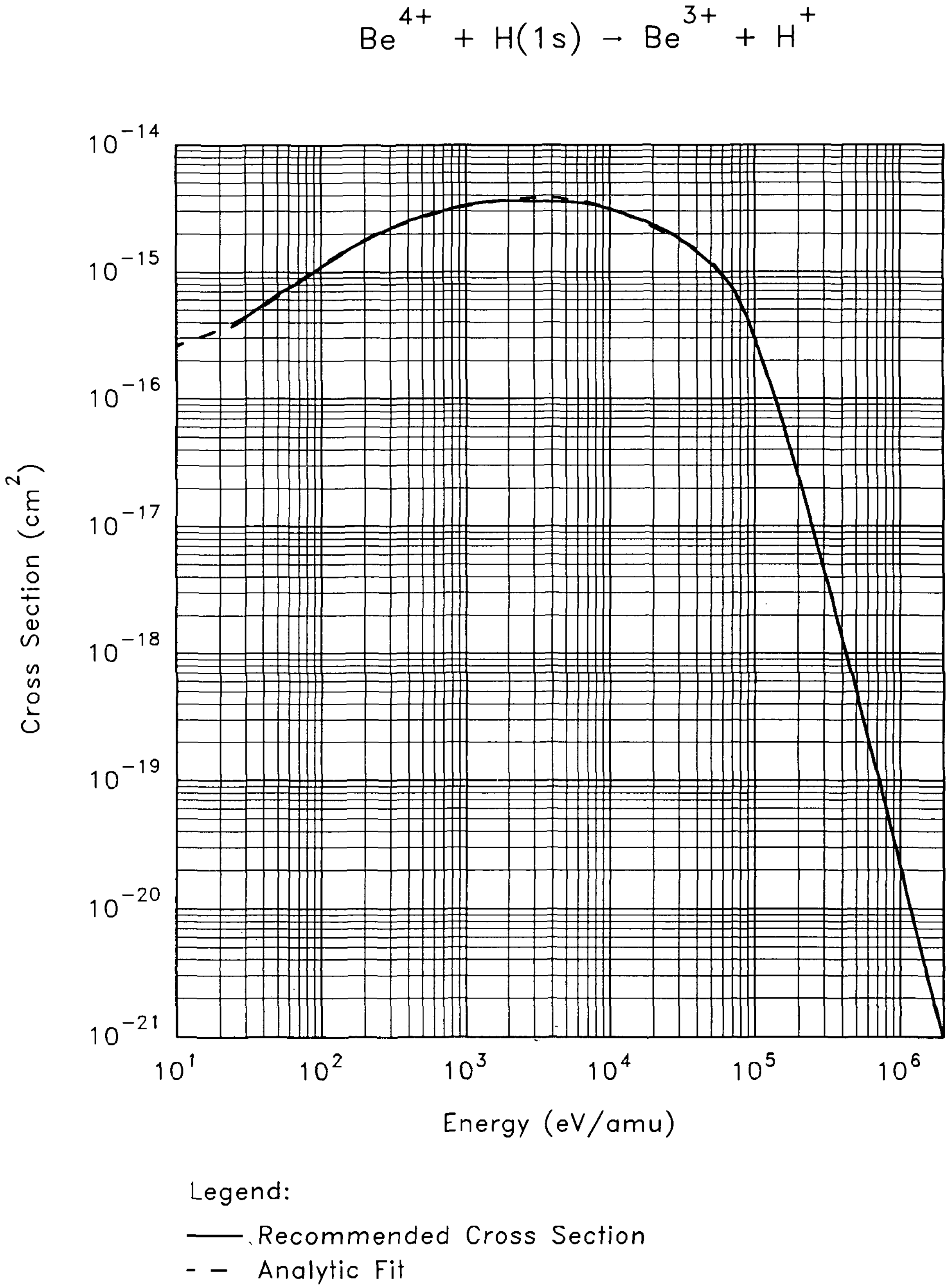
Fitting parameters

A_1 - A_6	19.952	0.20036	1.7295E−04	3.6844E−11	5.0411	2.4689E−08
A_7 - A_{11}	4.0761	0.88093	0.94361	0.14205	−0.42973	

The rms deviation of the above fit to the recommended cross section is 2.2%, with a maximum deviation of 7.1% at 3.65 keV/amu.

ALADDIN evaluation function for cross section: HCX4

ALADDIN hierarchical labelling: CX Be [+4] H [+0] (1s)


$Be^{4+} + H(1s) \rightarrow Be^{3+} + H^{+}$
Cross Section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

4.3.2. $B^{5+} + H(1s) \rightarrow B^{4+} + H^{+}$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
2.00E+01	6.21E+06	6.04E−16
5.00E+01	9.82E+06	7.29E−16
1.00E+02	1.39E+07	9.01E−16
2.00E+02	1.96E+07	1.11E−15
5.00E+02	3.11E+07	1.49E−15
1.00E+03	4.39E+07	1.93E−15
2.00E+03	6.21E+07	2.41E−15
5.00E+03	9.82E+07	2.98E−15
1.00E+04	1.39E+08	3.11E−15
2.00E+04	1.96E+08	2.91E−15
5.00E+04	3.11E+08	1.82E−15
1.00E+05	4.39E+08	5.70E−16
2.00E+05	6.21E+08	5.19E−17
5.00E+05	9.82E+08	9.35E−19
1.00E+06	1.39E+09	4.78E−20
2.00E+06	1.96E+09	1.75E−21
4.00E+06	2.78E+09	6.13E−23

Accuracy: $E < 0.1$ keV/amu : Indeterminate ; $0.1 \le E$ (keV/amu) < 10 : 10 - 20 % ;
$10 \le E$ (keV/amu) < 80 : 15 - 25 % ; $E \ge 80$ keV/amu : 15 %, or better

Comments: (1) In the energy range 0.1 - 10 keV/amu, the recommended total electron capture cross section is constructed on the basis of multi-state AO- [117] and MO- [118] coupled channel calculations, which agree to 10 - 15 % with each other. In the range 10 - 80 keV/amu, the recommended cross section is based on the UDWA calculations of Ryufuku [119].

(2) For energies above 80 keV/amu, the recommended cross section is based on the experimental data of Goffe et al [121] (available in the range 80 - 260 keV/amu), and on the results of CDW calculations [120]. In the energy range 100 - 200 keV/amu, the agreement of these two sets of data is within 10 %. (Above 200 keV/amu, the recommended cross section follows the CDW data.)

(3) The total CDW cross section was calculated from the partial ones given in Ref. [120] by direct summation of the shell capture cross sections up to $n = 7$, and by applying the Oppenheimer's n^{-3} -rule for the contribution of the $n > 7$ shells.

Analytic fitting function

Cross Section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E^{A_8})}{1 + A_3 E^2 + A_4 E^{A_5} + A_6 E^{A_7}} + \frac{A_9 \exp(-A_{10} E)}{E^{A_{11}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

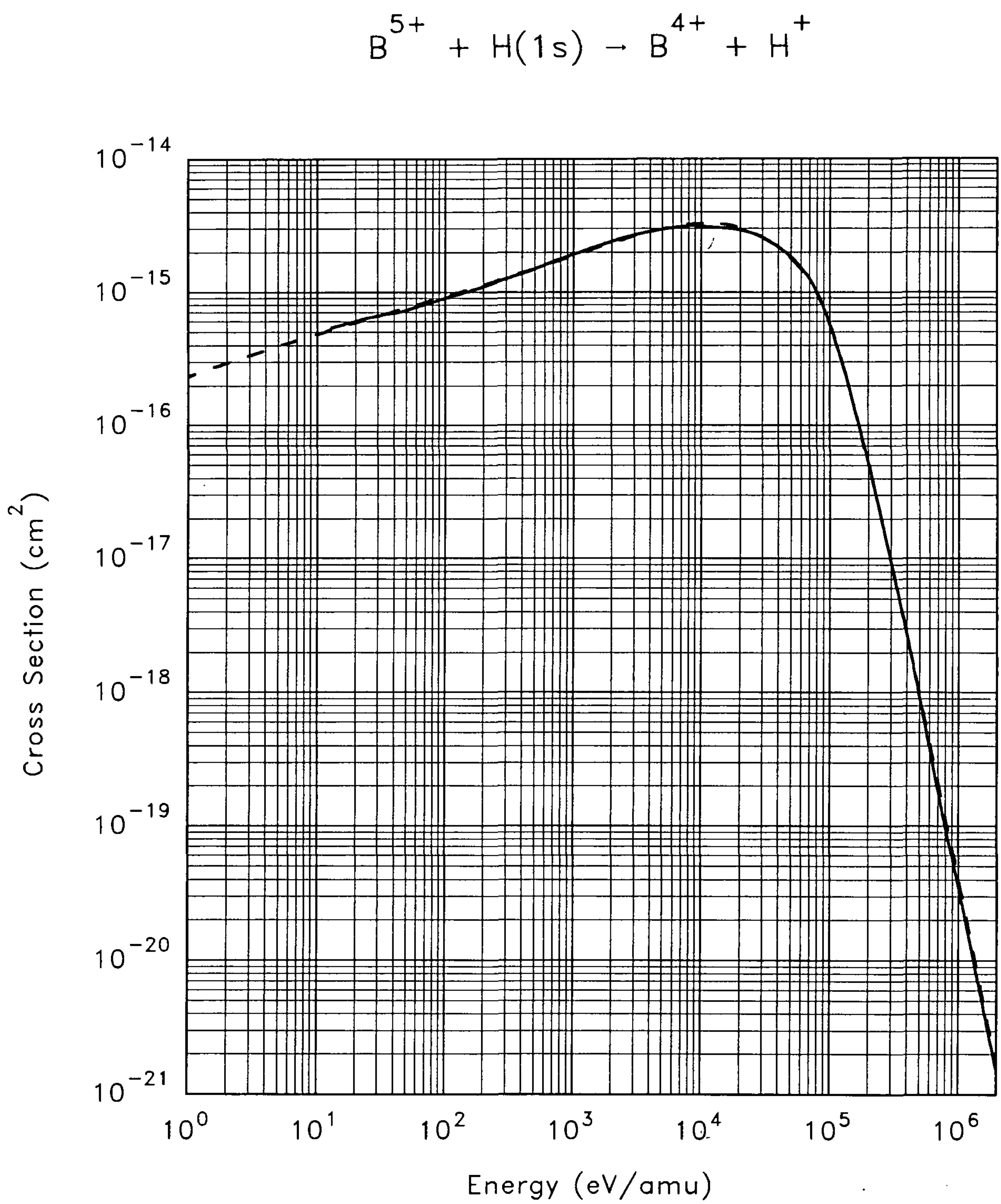
Fitting parameters

A_1 - A_6	31.226	1.1442	4.8372E−08	3.0961E−10	4.7205	6.2844E−07
A_7 - A_{11}	3.1297	0.12556	0.30098	5.9607E−02	−0.57923	

The rms deviation of the above fit to the recommended cross section is 2.2%, with a maximum deviation of 7.9% at 6.85 keV/amu.

ALADDIN evaluation function for cross section: HCX4

ALADDIN hierarchical labelling: CX B [+5] H [+0] (1s)



Legend:

—— Recommended Cross Section

- - Analytic Fit

4.3.3. $C^{6+} + H(1s) \rightarrow C^{5+} + H^+$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
5.00E−02	3.11E+05	1.47E−17
1.00E−01	4.39E+05	1.02E−17
2.00E−01	6.21E+05	7.01E−18
5.00E−01	9.82E+05	4.28E−18
1.00E+00	1.39E+06	2.89E−18
2.00E+00	1.96E+06	2.31E−18
5.00E+00	3.11E+06	4.56E−18
1.00E+01	4.39E+06	1.80E−17
2.00E+01	6.21E+06	6.28E−17
5.00E+01	9.82E+06	2.79E−16
1.00E+02	1.39E+07	6.73E−16
2.00E+02	1.96E+07	1.38E−15
5.00E+02	3.11E+07	2.68E−15
1.00E+03	4.39E+07	3.57E−15
2.00E+03	6.21E+07	4.13E−15
5.00E+03	9.82E+07	4.48E−15
1.00E+04	1.39E+08	4.17E−15
2.00E+04	1.96E+08	3.55E−15
5.00E+04	3.11E+08	2.04E−15
1.00E+05	4.39E+08	7.40E−16
2.00E+05	6.21E+08	8.16E−17
5.00E+05	9.82E+08	1.645−18
1.00E+06	1.39E+09	6.45E−20
2.00E+06	1.96E+09	2.44E−21
4.00E+06	2.78E+09	1.08E−22

Accuracy: $E < 0.05$ keV/amu : Indeterminate ; $0.05 \le E$ (keV/amu) < 1 : 25 - 30 % ;
$1 \le E$ (keV/amu) < 100 : 15 % ; $E \ge 100$ keV/amu : 15 - 20 %

Comments: (1) The cross section for this reaction up to 200 keV/amu has been taken from the critical assesment by Phaneuf et al [105]. The accuracies ascribed to the recommended cross section data are those given in that reference.

(2) For energies greater than 200 keV/amu, we have used the recent CDW results of Belkic et al [120]. The total cross section was obtained from the partial ones given in Ref. [120] by summing the individual n-shell capture cross sections up to $n = 8$, and by using the Oppenheimer's n^{-3} -rule to estimate the contribution from the electron capture to shells with $n > 8$.

Analytic fitting function data

Cross Section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E^{A_8})}{1 + A_3 E^2 + A_4 E^{A_5} + A_6 E^{A_7}} + \frac{A_9 \exp(-A_{10} E)}{E^{A_{11}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

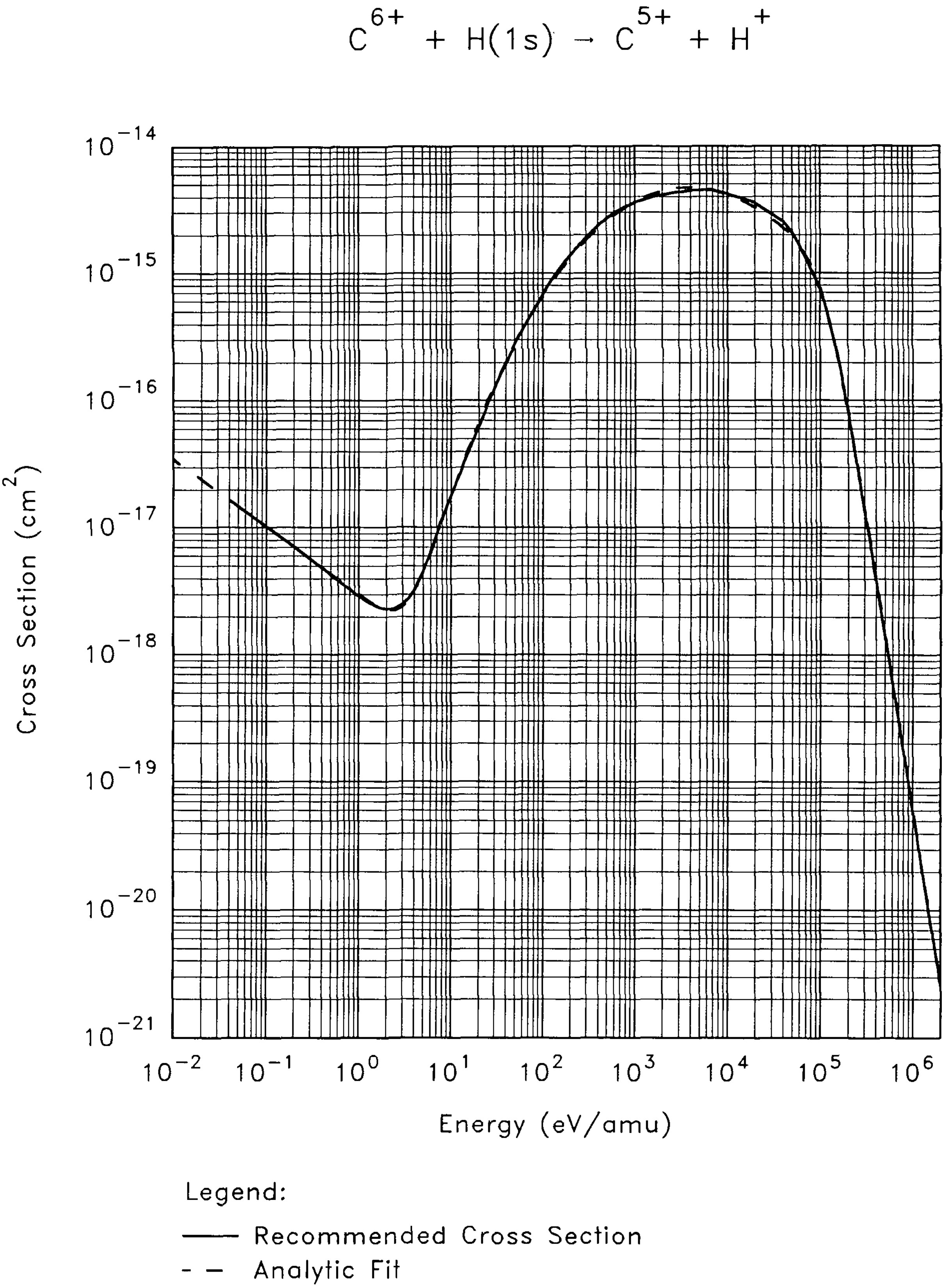
Fitting parameters

$A_1 - A_6$	418.18	2.1585	3.4808E−04	5.3333E−09	4.6556	0.33755
$A_7 - A_{11}$	0.81736	0.27874	1.8003E−06	7.1033E−02	0.53261	

The rms deviation of the above fit to the recommended cross section is 3.8%, with a maximum deviation of 12.1% at 701.2 keV/amu.

ALADDIN evaluation function for cross section: HCX4

ALADDIN hierarchical labelling: CX C [+6] H [+0] (1s)


$C^{6+} + H(1s) \rightarrow C^{5+} + H^{+}$
Cross Section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Energy (eV/amu)
Legend:
—— Recommended Cross Section
- - Analytic Fit

4.3.4. $O^{8+} + H(1s) \rightarrow O^{7+} + H^+$

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
6.00E−01	1.08E+06	1.15E−15
1.00E+00	1.39E+06	1.13E−15
2.00E+00	1.96E+06	1.10E−15
5.00E+00	3.11E+06	1.08E−15
1.00E+01	4.39E+06	1.06E−15
2.00E+01	6.21E+06	1.03E−15
5.00E+01	9.82E+06	9.74E−16
1.00E+02	1.39E+07	1.04E−15
2.00E+02	1.96E+07	1.86E−15
5.00E+02	3.11E+07	3.68E−15
1.00E+03	4.39E+07	4.83E−15
2.00E+03	6.21E+07	5.51E−15
5.00E+03	9.82E+07	5.85E−15
1.00E+04	1.39E+08	5.57E−15
2.00E+04	1.96E+08	4.84E−15
5.00E+04	3.11E+08	3.32E−15
1.00E+05	4.39E+08	1.42E−15
2.00E+05	6.21E+08	1.47E−16
5.00E+05	9.82E+08	3.42E−18
1.00E+06	1.39E+09	1.60E−19
2.00E+06	1.96E+09	5.58E−21
4.00E+06	2.78E+09	2.40E−22

Accuracy: $E < 0.05$ keV/amu : Indeterminate ; $0.05 \le E$ (keV/amu) < 100 : 25 - 30 % ; $1 \le E$ (keV/amu) < 100 : 15 % ; $E \ge 100$ keV/amu : 15 - 20 %

Comments: (1) The cross section for this reaction up to 150 keV/amu has been taken from the critical assesment by Phaneuf et al [105]. In the energy range 150 - 200 keV/amu it agrees with the recent CDW calcualtions of Belkic et al [120] to within 10 %.

(2) For energies greater than 200 keV/amu, we have used the recent CDW results of Belkic [120].

(3) The total cross section for $E \ge 200$ keV/amu has been obtained from the partial n-shell capture cross sections of Ref. [120] by summing the individual n-shell capture cross sections up to n = 9, and applying the Oppenheimer's n^{-3}-rule to estimate the contribution from the capture to higher n shells.

Analytic fitting function data

Cross Section:

$$\sigma_{cx} = 10^{-16} A_1 \left[\frac{\exp(-A_2/E^{A_8})}{1 + A_3 E^2 + A_4 E^{A_5} + A_6 E^{A_7}} + \frac{A_9 \exp(-A_{10} E)}{E^{A_{11}}} \right] \quad [cm^2]$$

where E is expressed in keV/amu.

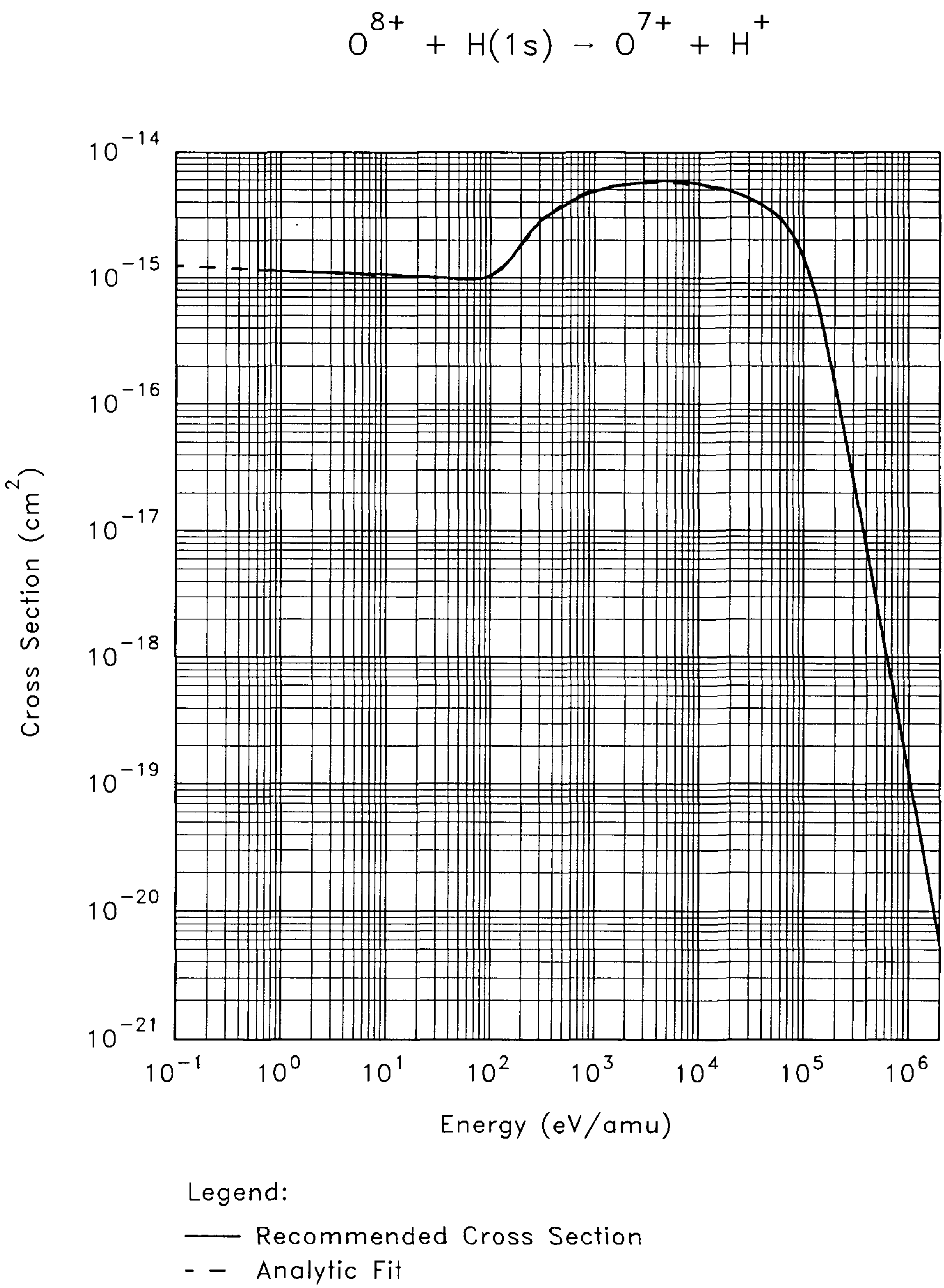
Fitting parameters

$A_1 - A_6$	54.535	0.27486	1.0104E−07	2.0745E−09	4.4416	7.6555E−03
$A_7 - A_{11}$	1.1134	1.1621	0.15826	3.6613E−02	3.9741E−02	

The rms deviation of the above fit to the recommended cross section is 3.7%, with a maximum deviation of 22.1% at 565 keV/amu.

ALADDIN evaluation function for cross section: HCX4

ALADDIN hierarchical labelling: CX O [+8] H [+0] (1s)


$O^{8+} + H(1s) \rightarrow O^{7+} + H^{+}$
Cross Section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Energy (eV/amu)
Legend:
Recommended Cross Section
Analytic Fit

4.3.5. $A^{q+} + H(1s) \rightarrow A^{(q-1)+} + H^+$, q>8

Scaled Energy, $E / q^{3/7}$ (eV/amu)	Scaled Velocity, $v / q^{3/14}$ (cm/s)	Scaled Cross section, σ_{cx} / q (cm^2)
1.00E+02	1.39E+07	9.23E−16
2.00E+02	1.96E+07	8.72E−16
5.00E+02	3.11E+07	8.03E−16
1.00E+03	4.39E+07	7.50E−16
2.00E+03	6.21E+07	6.94E−16
5.00E+03	9.82E+07	6.15E−16
1.00E+04	1.39E+08	5.42E−16
2.00E+04	1.96E+08	4.24E−16
5.00E+04	3.11E+08	1.03E−16
1.00E+05	4.39E+08	9.71E−18
2.00E+05	6.21E+08	5.41E−19
5.00E+05	9.82E+08	6.25E−21
1.00E+06	1.39E+09	1.58E−22
2.00E+06	1.96E+09	3.68E−24

Accuracy: a) For fully stripped ions: $E/q^{3/7}$(keV/amu) < 0.05 : Indeterminate
for q < 15, 40 - 50 %, for q ≥ 15; 0.05 ≤ $E/q^{3/7}$(keV/amu) < 1 : 30 - 60 %
for q < 15, 30 % for q > 15; 1 ≤ $E/q^{3/7}$(keV/amu) < 2 x 10^3 : 15 - 30 %;
$E/q^{3/7}$(MeV/amu) ≥ 2 : 20 - 40 %

b) For incompletely stripped ions: $E/q^{3/7}$(keV/amu) < 0.005 : Indeterminate;
0.005 ≤ $E/q^{3/7}$(keV/amu) < 0.1 : 30 - 60 %;
0.1 ≤ $E/q^{3/7}$(keV/amu) < 2 x 10^3 : 15 - 30 %; $E/q^{3/7}$(MeV/amu) ≥ 2 : 20 - 40 %

Comments: (1) The recommended reduced total electron capture cross section σ/q versus reduced energy $\tilde{E} = E/q^{3/7} \sim E/q^{0.43}$, described by Eq. (a) below, has been determined in the region below $\tilde{E}$ ~ 50 kev/amu on the basis of experimental data for incompletely stripped ions with q > 5 (see e.g. [122, 123, 124]), and for $\tilde{E}$ > 100 keV/amu on the basis of the scaled CDW calculations (q = 1 - 8) of Belkic et al [120] and 'H-reduced' experimental data for the $A^{q+} + H_2$ system (see e.g. Ref. [124]).

(2) The scaling relationship (a) below reproduces the recommended data of Ref. [124] for the Fe^{q+} + H (q > 5) systems, and with the above indicated accuracies, it also describes the recommended data from the present work for the H^+, He^{2+}, Be^{4+}, B^{5+}, C^{6+}, O^{8+} + H systems in the energy region above $\tilde{E}$ ~ 5 keV/amu.

(3) For reduced energies above $\tilde{E}$ ~ 5 MeV/amu, the accuracy of Eq. (a) should decrease progressively because it does not have the proper asymptotic behaviour $\sigma \sim E^{-5.5}$.

Analytic expression

Cross section:

$$\frac{\sigma_{cx}}{q} = \frac{10^{-16} A_1 \ln (A_2 / \tilde{E} + A_3)}{1 + A_4 \tilde{E} + A_5 \tilde{E}^{3.5} + A_6 \tilde{E}^{5.4}} \quad [cm^2] \qquad (a)$$

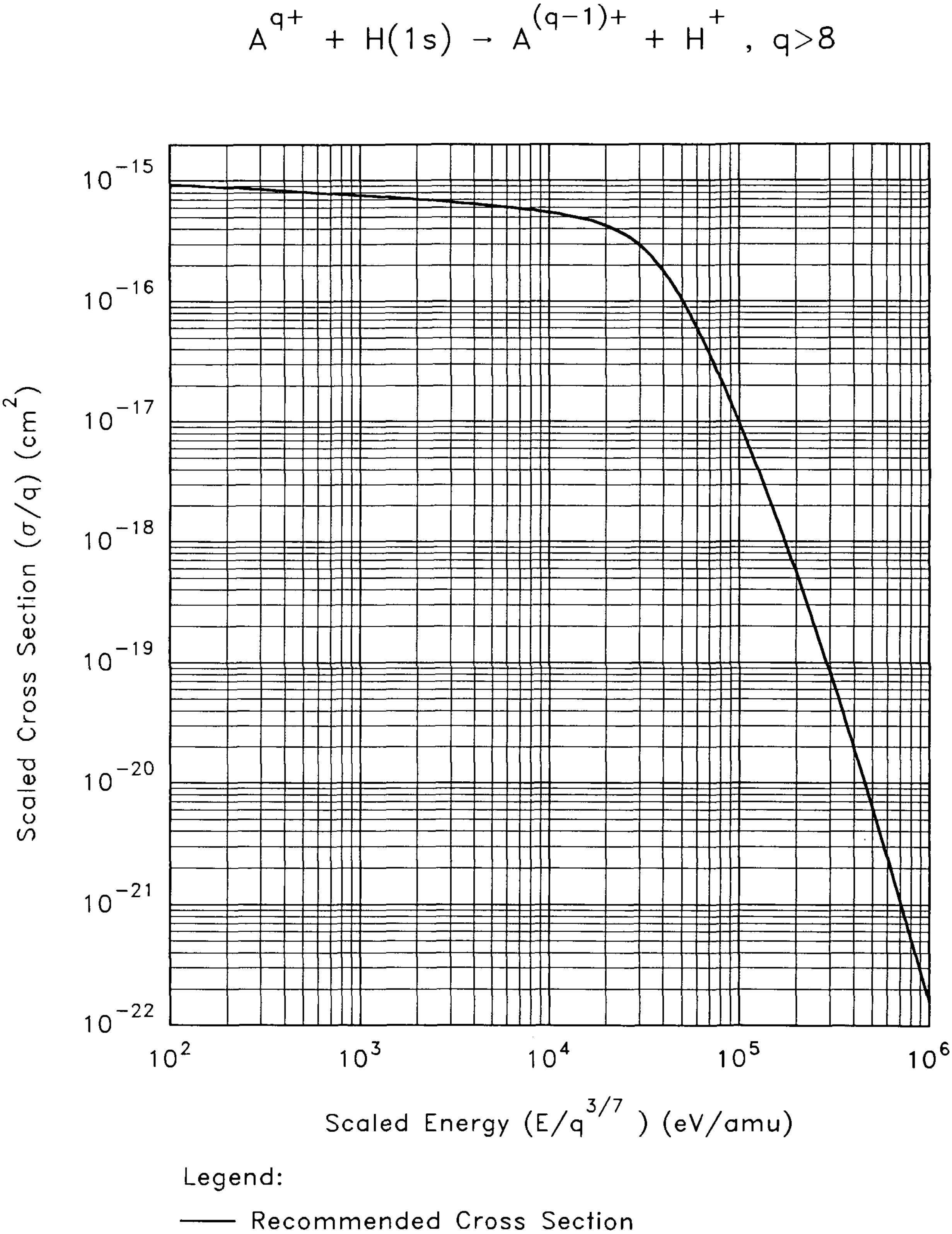
where $\tilde{E} = E/q^{3/7}$ keV/amu and the values of parameters A_i are:

A_1	A_2	A_3	A_4	A_5	A_6
0.73362	2.9391E+04	41.8648	7.1023E−03	3.4749E−06	1.1832E−10

ALADDIN evaluation function for cross section: ACXGL1

ALADDIN hierarchical labelling:

CX A [+q>8] H [+0] (1s) A [+(q-1)] H [+1]


$A^{q+} + H(1s) \rightarrow A^{(q-1)+} + H^{+}$, q>8
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
Scaled Cross Section (σ/q) (cm^2)
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Scaled Energy ($E/q^{3/7}$) (eV/amu)
Legend:
Recommended Cross Section

4.3.6. $A^{q+} + H^*(n) \rightarrow A^{(q-1)+} + H^+ \; , \; q>3$

Scaled Energy, $En^2 / q^{0.5}$ (eV/amu)	Scaled Velocity, $vn / q^{0.25}$ (cm/s)	Scaled Cross section, σ_{cx} / qn^4 (cm^2)
1.00E+02	1.39E+07	4.69E−16
2.00E+02	1.96E+07	4.69E−16
5.00E+02	3.11E+07	4.69E−16
1.00E+03	4.39E+07	4.69E−16
2.00E+03	6.21E+07	4.69E−16
5.00E+03	9.82E+07	4.69E−16
1.00E+04	1.39E+08	4.66E−16
2.00E+04	1.96E+08	4.34E−16
5.00E+04	3.11E+08	1.12E−16
1.00E+05	4.39E+08	8.86E−18
2.00E+05	6.21E+08	5.24E−19
5.00E+05	9.82E+08	6.40E−21
1.00E+06	1.39E+09	1.62E−22

Accuracy: $En^2/q^{0.5}$(keV/amu) < 0.01 : Indeterminate ; $0.01 \le En^2/q^{0.5}$(keV/amu) < 1 : 50 - 100 % ; $1 \le En^2/q^{0.5}$(keV/amu) < 100 : 30 - 50 % ; $En^2/q^{0.5}$(keV/amu) ≥ 100 : 20 - 40 %

Comments: (1) Systematic cross sections for these reactions with $A^{q+} = B^{5+}$, Ne^{10+} and n = 2, 5, 10, 20 are available from the CTMC calculations of Olson [101] in the reduced energy range $\tilde{E} = E\, n^2/q^{0.5}$ = 8 - 60 keV/amu. These data, as well as the similar ones for the He^{2+} + H(n) system from the same reference, satisfy the scaling relationship (a) given below [107] to an accuracy of 10 - 30 %.

(2) The uncertainties assigned to the reduced cross section reflect the uncertainties both in the q- and n- scalings.

(3) The recommended reduced cross section $\sigma/q\, n^4$ is taken from Ref. [107], and is shown in the figure on the next page as a function of reduced energy $\tilde{E}$.

Analytic expression

Cross section:

$$\frac{\sigma_{cx}}{q\, n^4} = 7.04 \times 10^{-16} \frac{A}{\tilde{E}^{3.5}\,(1 + B\,\tilde{E}^2)} \left[1 - \exp\left(\frac{-2\,\tilde{E}^{3.5}\,(1 + B\,\tilde{E}^2)}{3\,A} \right) \right] \; [cm^2] \qquad (a)$$

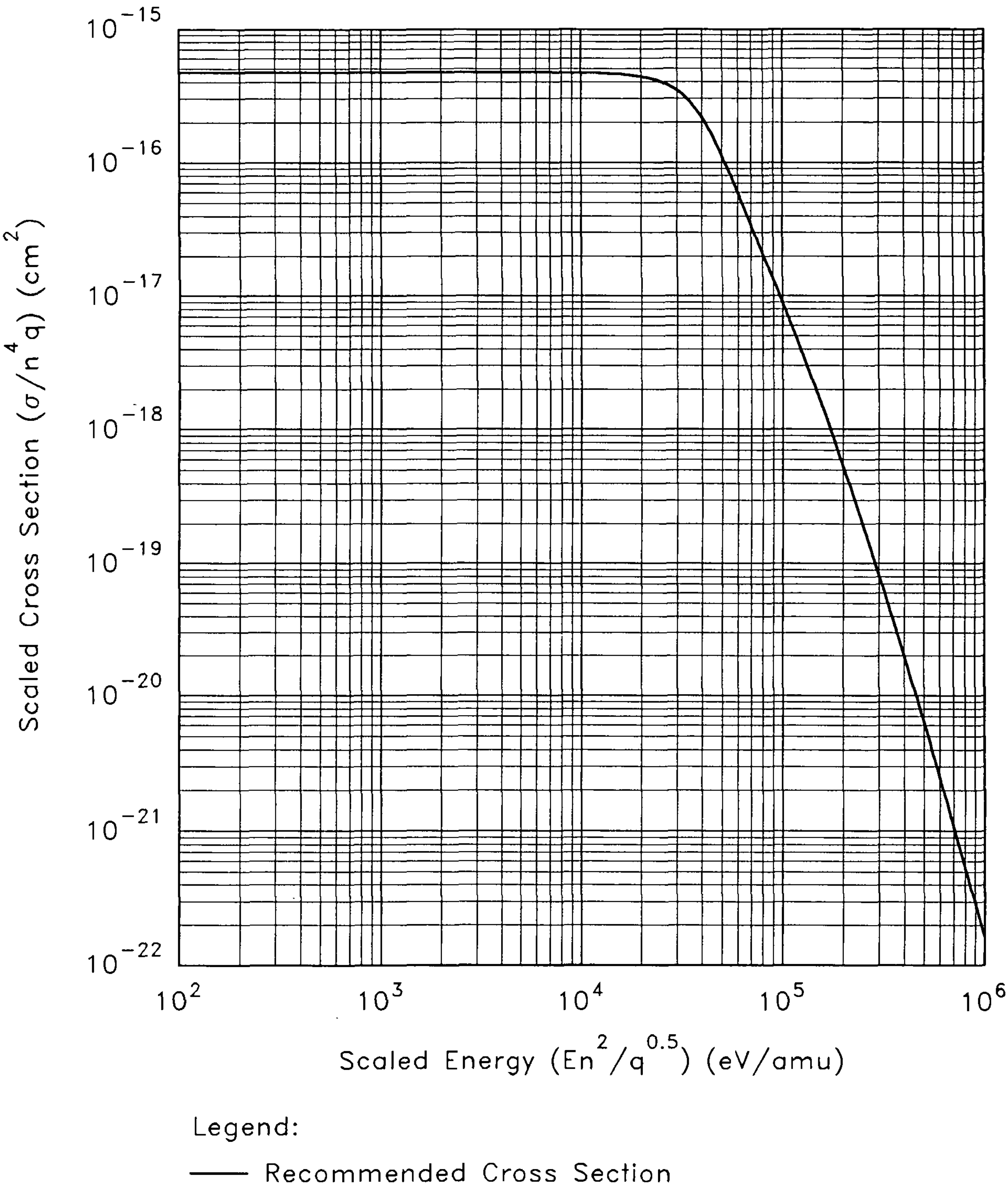
where $\tilde{E} = E\, n^2/q^{0.5}$ (keV/amu), $A = 1.507 \times 10^5$ and $B = 1.974 \times 10^{-5}$

ALADDIN evaluation function for cross section: ACXGL2

ALADDIN hierarchical labelling:

CX A [+q>3] H [+0] (n>1) A [+(q-1)] H [+1]

$$A^{q+} + H^{*}(n) \rightarrow A^{(q-1)+} + H^{+} \quad , \; q > 3$$



Appendices

A.1. Johnson's formula for the oscillator strengths in hydrogen [18]

$$f_{nm}(n>m) = \frac{32}{3\sqrt{3}\pi}\,\frac{n}{m^3}\,\frac{1}{x^3}\,g(n,x)\ ;\ x=1-\left(\frac{n}{m}\right)^2$$

$$g(n,x) = g_0(n) + g_1(n)\,\frac{1}{x} + g_2(n)\,\frac{1}{x^2}$$

where for n=1, 2 and n $\geq$ 3, the coefficients g_0, g_1 and g_2 have the values

	n=1	n=2	n≥3
g_0	1.1330	1.0785	$0.9935 + 0.2328\,n^{-1} - 0.1296\,n^{-2}$
g_1	- 0.4059	- 0.2319	$-\,n^{-1}\,(0.6282 - 0.5598\,n^{-1} + 0.5299\,n^{-2})$
g_2	0.0714	0.02947	$-\,n^{-2}\,(0.3887 - 1.181\,n^{-1} + 1.470\,n^{-2})$

A.2. Alternative scaling formula for ionization in A^{q+} + H(1s) collisions [116]

$$\sigma_{ion} = q^2\,F(q,v)\,\sigma_{MB}\,(v)$$

$$F(q,v) = \frac{(v^2)^{0.921}}{q^{1.587}}\left[\frac{2.188}{v^2} + \frac{(v^2)^{0.921}}{q^{1.587}}\right]^{-1}$$

$$\sigma_{MB}^{(v)} = \frac{3.52\ x\ 10^{-16}}{v^2}\left\{0.283\left[\ln\left(\frac{v^2}{c^2-v^2}+\delta\right)-\frac{v^2}{c^2}\right] + 4.04\right\}\ [cm^2]$$

$$v^2 = E(keV/amu)/25\ \ ,\ \ \delta = 1.35\ x\ 10^{-5}\ ,$$

where c=137 is the speed of light in atomic units.

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All figures should be on separate sheets and numbered consecutively with Arabic numerals, e.g. Fig. 1. A separate list of captions must be provided (see also *General* above).

Tables must carry a heading and be numbered consecutively with Roman numerals in the order in which they are mentioned in the text, e.g. Table II. Footnotes to tables should be indicated by raised letters (not numbers or asterisks) and set immediately below the table itself. Tables should be typed clearly for possible direct reproduction.

Footnotes to the text should be numbered consecutively with raised Arabic numerals; excessive use of footnotes should be avoided.

All *equations* should be typed as carefully as possible, with unavailable Greek letters and other symbols clearly inserted by hand. Specifically:

(1) To eliminate confusion between symbols with similar appearance (e.g. between ones, ells and primes), make them as distinct as possible, if necessary marking them clearly by hand. In manuscripts with handwritten formulas, all further sources of confusion (such as n's and u's, u's and v's, e's and l's, J's and I's) should also be marked.
(2) Indicate a vector by an arrow on top rather than by bold face lettering.
(3) Tensors of second rank should bear two arrows on top; if higher rank tensors are required, choose an appropriate symbol and explain it.
(4) Indicate the normal algebraic product by simple juxtaposition of symbols, i.e. without multiplication sign.
(5) Write scalar products of vectors with a raised point, e.g. $\vec{A}\cdot\vec{B}$.
(6) Use the multiplication sign (×) solely to designate: (i) a vector product, (ii) an algebraic (but not a scalar) product in the case where an equation has to be split over two lines, and (iii) in expressions like 3 cm × 3 cm or 2 × 10^6 cm.
(7) The nabla operator (∇) does not carry an arrow.
(8) When equations are split over two or more lines, place operational signs only at the beginning of each new line, not at the end of the preceding line. For direct reproduction of an equation, the length of the lines should not exceed 9 cm.
(9) Where it is impossible to split long fractions over two lines, use negative exponents: similarly, replace root signs by fractional exponents where appropriate.
(10) Do not use symbols, abbreviations and formulations that are recognizable only in a particular language.

Use *SI units* as far as possible; where this is not possible, please give the appropriate conversion factor.