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R. K. Janev W. D. Langer
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Elementary Processes in Hydrogen-Helium Plasmas

Cross Sections and Reaction Rate Coefficients

With 107 Figures

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Preface

Atomic and molecular processes play an important role in laboratory and astrophysical plasmas for a wide range of conditions, and determine, in part, their electrical, transport, thermal, and radiation properties. The study of these and other plasma properties requires a knowledge of the cross sections, reaction rate coefficients, and inelastic energy transfers for a variety of collisional reactions. In this review, we provide quantitative information about the most important collision processes occurring in hydrogen, helium, and hydrogen-helium plasmas in the temperature range from 0.1 eV to 20 keV. The material presented here is based on published atomic and molecular collision data, theoretical calculations, and appropriate extrapolation and interpolation procedures. This review gives the properties of each reaction, graphs of the cross sections and reaction rate coefficients, and the coefficients of analytical fits for these quantities. We present this information in a form that will enable researchers who are not experts in atomic physics to use the data easily.

The authors thank their colleagues at the Princeton Plasma Physics Laboratory and in the atomic physics community who have made many useful suggestions for the selection and presentation of the material. We gratefully acknowledge the excellent technical assistance of Elizabeth Carey for the typing, and Bernie Giehl for the drafting.

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Princeton, USA
September, 1987

R.K. Janev W.D. Langer
K. Evans, Jr., D.E. Post

Contents

List of Symbols and Abbreviations

$\langle A \rangle_\gamma$	Quantity A averaged over a finite interval of the parameter γ (γ can be continuous or discrete). For example, the index FC would denote the Franck-Condon interval, and v the vibrational levels.
E	Impact energy
E_{th}	Threshold energy
$\Delta E_i^{(-)}$	Kinetic energy *loss* of particle i in a reaction
$\Delta E_i^{(+)}$	Kinetic energy *gain* of particle i in a reaction
Ry	Rydberg, 13.58 eV
T	Maxwell temperature
v	Vibrational quantum number; collision velocity
$\alpha_j, \langle \sigma_j v \rangle$	Rate coefficient for reaction j
σ_j	Cross section of reaction j
σ_j^B	Cross section in the first Born approximation
$\sigma_{se}, \sigma_j^{se}$	Semiempirical cross section
σ_{exp}	Experimental cross section
σ_{se}^B	Cross section obtained by extrapolation of σ_{exp}, σ_{se}, or σ^B in the high-energy region by matching their high-energy parts to a Born-type analytic expression
$\sigma^{(N)CB}$	Cross section in the (normalized) Coulomb-Born approximation
$\sigma_{\mathrm{ion}}^{BEA}$	Ionization cross section in the classical impulse (binary encounter) approximation
$\sigma_{\mathrm{exc/ion}}^{DACC}$	Two-state close-coupling formula for excitation/ionization by heavy charged particles (Sect. 8.3)
$\sigma_{\mathrm{exc}}^{DWA}$	Distorted wave approximation cross section for excitation

σ^{BOR}	Cross section in the Born-Ochkur-Rudge approximation
σ^{LZ}	Cross section in the Landau-Zener approximation
σ^{RZD}	Cross section in the Rosen-Zener-Demkov approximation
σ_{det}	Detachment cross section
$AOCC$	Atomic orbital close-coupling method
$DACC$	Dipole-approximation close-coupling method
DWA	Distorted wave approximation

List of Reactions

Chapter 1

Introduction

Much of the behavior of low temperature plasmas, including ionization equilibrium, particle and energy transport, and radiation loss, is directly related to elementary collisional and radiative processes of atoms and molecules within the plasma. The sophisticated models currently used to address issues such as particle and energy transport and power loss in plasmas include a very large number of collisional processes, which need to be known over a wide range of plasma parameters. Due to the presence of molecules and negative ions, the requisite atomic physics information needed is often extensive, even if the plasma contains only hydrogen. Thus, a prerequisite for the study of such plasmas is a survey of the basic characteristics of these processes including cross sections (σ's), reaction rate coefficients ($\langle\sigma v\rangle$'s), radiative rates, and energy transfer.

1.1 Previous Surveys

It has long been recognized that systematic compilations and evaluations of atomic physics data research are useful to plasma physics research. Historically, this information has been used for astrophysical problems. More recently, however, research in controlled fusion, ion and neutral beams, process plasmas for semiconductor studies, and lasers has accentuated the need for such data. Accordingly, a number of data compilations have appeared, covering both radiative (Wiese et al. 1966) and collisional (cf. Freeman and Jones 1974; Jones 1977; Barnett et al. 1977; Takayanagi and Suzuki 1978) atomic and molecular processes. However, much of the data that is available in survey form is often neither complete nor convenient to use. Several of the published compilations (Freeman and Jones 1974; Jones 1977; Barnett et al. 1977; Takayanagi and Suzuki 1978; Bell et al. 1982; Janev et al. 1984a) contain data which have been critically evaluated, but only a few, such as those of Freeman and Jones (1974), Jones (1977), and Bell et al. (1982), provide analytic fits to the data, which enable one to make numerical calculations more easily. In most compilations the data are presented in a table or graph and are not amenable to use in computer codes for plasma applications. In practice, however, it is much more convenient to have simple algorithms for calculating the cross sections or reaction rate coefficients.

1.2 Scope of Present Survey

The goal of this survey is to provide as complete as possible collection of atomic and molecular collision data for hydrogen and helium plasmas with temperatures between 0.1 eV and 20 keV, and electron and ion densities less than ~ 5×10^{14} cm^{-3}. We present descriptions of the reactions, and graphs of the cross sections and reaction rate coefficients for all types of inelastic processes between the charged and neutral constituents of hydrogen-helium plasmas: e, H^+, H, H_2^+, H_2, H_3^+, He^{2+}, He^+, and He. We also include processes involving excited species such as H^*, He^*, H_2^* (electronic, vibrational, and rotational), and H^-, and processes involving important electron and proton rearrangement reactions. The survey also contains a brief description of the energetics of the reaction (energy loss or gain in the reaction, energy distribution of reaction products, etc.). Finally, we provide analytic fits to the cross sections and reaction rate coefficients. Their coefficients are tabulated in Chap. 8.

1.3 Organization of Information

We have arranged the material according to the charge and structural complexity of colliding particles. The units used for the more common quantities are

E: impact energy (in the laboratory reference system) in eV, unless otherwise stated;

σ: cross section in cm^2;

$\langle\sigma v\rangle$: reaction rate coefficient in cm^3/s, the average being taken over a Maxwellian distribution with temperature T in eV.

For each individual reaction we give the following information in order of presentation:

-- its symbolic notation,

-- the energy loss or gain,

-- the method (experimental, theoretical, or semiempirical), by which the cross section has been obtained in various energy regions with the reference to the corresponding data source,

-- the energetics of the reaction products (when applicable),

-- comments on the reaction and/or the procedures applied to determine the cross sections,

-- a graphic representation of the cross section σ as a function of energy

E (represented by a dashed curve with the scale on the right-hand side) and the corresponding reaction rate coefficient $<\sigma v>$ as a function of temperature T (given by a solid line with the scale on the left side),

-- in the case of reactions between heavy particles the target particle's energy (velocity) can be important, and the figures show the reaction rate coefficients as a function of plasma temperature for several energies of the target particle,

-- in the case of reactions between plasma electrons and heavier particles, the heavy particle's energy is taken to be zero and only the temperature dependence is plotted.

Nearly all the figures use the same scales for σ and $<\sigma v>$ so that these quantities can easily be compared. For groups of similar reactions, where energetics and cross sections are given by analytic formulas, the figures contain only a few representative examples. The Appendix gives information, such as energy levels, oscillator strengths, potential energy curves for H_2, H_2^+, and H_2^-, etc., common to several classes of reactions.

1.4 Sources and Criteria for Selection and Evaluation of Data

The main sources of information for the cross sections were previous compilations, such as those mentioned above, and the current journal literature. In selecting the data for a particular reaction, we gave priority to information with a stated accuracy. In cases where the original cross section data did not cover the entire energy range considered here, we have extended the range by employing appropriate interpolation or extrapolation procedures based either on reliable theoretical models or on a reasonable extension or scaling of the experimental data. In most cases, the extrapolations, which are necessary to calculate reaction rate coefficients, occur where the cross section is small. We calculated cross sections using existing theoretical methods (cf. Mott and Massey 1965; Smirnov 1973) for reactions for which no measurements could be found in the literature. We used simple two-state models (such as Landau-Zener and Rozen-Zener-Demkov models or the first Born approximation) to extend and generate new cross-section data. These theoretical methods provide results generally accurate to within a factor of two, or so. For the processes involving excited states (excitation, ionization, and charge transfer), we give generalized formulas for calculation of the cross sections. These formulas are, in most cases, based on a semiclassical or purely classical model of the processes in question, and in some cases are supplemented by appropriate semiempirical corrections. Their accuracy usually increases with the principal quantum number of the corresponding state. For processes involving heavy-particle collisions (excluding those induced by protons) for which no systematic experimental or theoretical data exist, we give appropriate scaling rules for cross sections and/or reaction rate coefficients based on the known data for the corresponding proton-induced processes. Our survey does not explicitly include collision processes that are related by the detailed balance principle to a corresponding "direct" process (for example, collisional de-excitation or collisional three-body electron-ion recombination). We include the radiative transition rates for hydrogen and helium atoms in the Appendix to complement the direct collisional processes.

1.5 Accuracy

In general, the accuracy for the cross section data for processes involving ground state species is ±50% or better, since, with few exceptions, we based the data presented here on experimental or evaluated theoretical results. For the processes involving excited species, the cross sections probably have an accuracy of a factor of two when they are based only on theoretical calculations or generalized formulas. A similar accuracy should apply to those molecular processes for which we determined the cross sections by averaging over vibrationally excited states (corresponding to a distribution of states typical for low-temperature plasmas), unless the cross section is known experimentally.

1.6 References

We used the following compilations as basic sources for the data whenever possible, after checking their consistency with more recent data: Freeman and Jones (1974), Jones (1977), Barnett et al. (1977), Takayanagi and Suzuki (1978), Fujimoto (1978), and Sataka et al. (1981). If no modifications were necessary, the reference we give is to these data sources (where the original references for the data can be found). In cases where other cross-section data are available for a given process, we have performed either a least-squares average of all the data or present the best results. In these latter cases, in order to avoid an excessive reference list, we include only the references used to construct the cross section in the figures.

1.7 Digitization of the Cross Sections

Most of the data available in either the original published sources or in the data surveys are presented in the form of a graph. We transformed these data to numbers using a Tektronix Graphics Tablet and combined digitized data from several sources in order to cover the required energy range (0.1 eV to 20 keV). For reactions with a nonzero threshold, a data point has been added at threshold.

1.8 Calculation of Reaction Rate Coefficients

The Maxwellian-averaged reaction rate coefficients for a particle of mass m and fixed energy $E = mV^2/2$ incident on a Maxwellian distribution of particles of mass M and temperature $T = Mu^2/2$ for the heavy-particle reactions is

$$\langle\sigma v\rangle = \frac{1}{\pi^{1/2}\,uV} \int_{v_{th}}^{\infty} v_r^2 dv_r \sigma(E_r) \left\{\exp\left[-(v_r-V)^2/u^2\right] - \exp\left[-(v_r+V)^2/u^2\right]\right\} ,$$

and for the electron reactions

$$\langle\sigma v\rangle = \frac{4}{\pi^{1/2}u^3} \int_{v_{th}}^{\infty} v_r^3 dv_r \sigma(E_r) \exp\left(-v_r^2/u^2\right) ,$$

where $v_r = |\vec{V}-\vec{u}|$ is the relative (collision) velocity related to E_r by $E_r = m_r v_r^2/2$, $m_r = mM/(m+M)$ being the reduced mass of colliding particles, and v_{th} is the value of v_r at threshold, $E_r = E_{th}$. We used a number of mathematical techniques to assure the reaction rate integrals were computed accurately for the nearly five orders of magnitude variation in E and T.

For the calculation of reaction rate coefficients, it is necessary to know the cross section from threshold to very large values of the energy. However, the digitized data necessarily represent the cross section for a finite energy range and for a finite number of points (less than 100). Our solution to this problem is: (1) to calculate values of σ within the digitized range by linear interpolation of $\ln \sigma$ in $\ln E$; and (2) to extrapolate σ outside the digitized range by a method depending on the type of reaction as discussed below.

Type 1. Reactions with a nonzero threshold and a zero cross section at threshold.

No low-energy extrapolation is necessary. We calculate the high-energy extrapolation from the formula $\sigma = a\ x^{-n}\ \ell n\ x$, where $x = E/E_{th}$, and obtain the quantities a and n by matching the function at the last data point and with the average slope for the last few data points.

Type 2. Reactions fit well by $\ell n\sigma = a+b\ell nE$.

We obtain both low- and high-energy extrapolations with the coefficients, a and b.

Type 3. Reactions with a zero threshold.

The form $\ell n\sigma = a+b\ell nE$ fits both the high- and low-energy extrapolations. The coefficients are obtained by matching the function at the first (last) point and the average slope at the first (last) few points, respectively.

Type 4. Reactions with a nonzero threshold and a nonzero cross section at threshold.

No low-energy extrapolation is necessary since there is a point at threshold, and σ is taken to be zero below threshold. The high-energy extrapolation is of the form $\ell n\ \sigma = a + b\ \ell n\ E$, with the coefficients calculated to match the function at the last point and the average slope at the last few points.

We calculated the cross sections used in the plots, in the numerical tables, and in the integrals for the reaction rate coefficients by the above procedures. There are sufficient data points for the interpolated values to be at least as accurate as the data. In most cases the extrapolations occur where the cross section is negligibly small. Where this is not the case, there is no better alternative to the above procedure.

1.9 Numerical Fits to σ and $\langle\sigma v\rangle$

We derived numerical fits for σ and $\langle\sigma v\rangle$ so that these processes can be evaluated easily in numerical codes and in other instances that demand simple and/or repeated evaluations. Since σ and $\langle\sigma v\rangle$ vary over many orders of magnitude, we made polynomial fits for $\ell n\ \sigma$ in terms of $\ell n\ E$ and for $\ell n\ \langle\sigma v\rangle$ in terms of $\ell n\ T$:

$$\ell n\sigma = \sum_{n=0}^{N} b_n\ (\ell n\ E)^n\ ,$$

$$\ell n\ \langle\sigma v\rangle = \sum_{n=0}^{N} b_n\ (\ell n\ T)^n.$$

For the electron reactions, $\langle\sigma v\rangle$ is essentially independent of E within the range of energies considered here. A more useful fit for the heavy-particle reactions is a double polynomial fit in both E and T:

$$\ln \langle\sigma v\rangle = \sum_{n=0}^{N} \sum_{m=0}^{M} \alpha_{mn} (\ln E)^n (\ln T)^m .$$

Such a fit requires a large number of coefficients in order to be accurate, but can be used for arbitrary E and T. We tabulate the coefficients for a 9 x 9 double fit of this form in Sect. 8.3.

An error is given for each fit as an indication of the quality of the fit. The error is defined as

$$\frac{1}{N} \sum_{i=1}^{N} (\ln x_i - \ln x_{fit,i})^2 ,$$

where N is the number of points fit, and x is σ or $\langle\sigma v\rangle$. An error of 10^{-4} is a good fit; that is, the fit is very close to the actual values, most likely well within the error in the data. Sections 8.1-3 contain examples of fits with several values of errors for each type of fit. It was hard to obtain the double fits with an error of 10^{-4} or better and Sect. 8.3 contains a more extensive discussion of their errors.

1.10 Example of Use of Fits

As an example of the use of the tables of fits for cross sections and reaction rate coefficients consider the calculation of $\langle\sigma v\rangle$ for reaction 2.1.5, $e + H(1s) \rightarrow e + H^+ + e$. We compute

$$\ln \langle\sigma v\rangle = \sum_{n=0}^{8} b_n (\ln T)^n$$

below for T = 10 eV using the coefficients for reaction 2.1.5 in Sect. 8.2. In the calculation below, only six digits need to be kept for these to be nearly perfect fits (see Sect. 8.2) and the coefficients have been truncated at six digits.

$$\begin{aligned}\ln \langle\sigma v\rangle = &(-3.27139e{+}01) + 1.35365e{+}01\ (2.30259) \\ &-5.73932e{+}00\ (2.30259)^2 + 1.56315e{+}00\ (2.30259)^3\end{aligned}$$

$$-2.87705e-01\ (2.30259)^4 + 3.48255e-02\ (2.30259)^5$$
$$-2.63197e-03\ (2.30259)^6 + 1.11954e-04\ (2.30259)^7$$
$$-2.03914e-06\ (2.30259)^8$$

$$\ell n <\sigma v> = -19.07995.$$

Thus,

$$<\sigma v> = 5.17228e-09 \text{ cm}^3/\text{s}.$$

Chapter 2

Electron Impact Collision Processes

2.1 Electron Collisions with H and H^+

2.1.1 $\boxed{e+H(1s) \rightarrow e+H^*(2p)}$

$$E_{th} = 10.2 \text{ eV}, \qquad \Delta E_e^{(-)} = E_{th}.$$

Cross Section:

$E = E_{th} - 10^3$ eV: $\sigma_{exc}(1s \rightarrow 2p) = \sigma_{exp}$,

$E = 10^3 - 10^6$ eV:

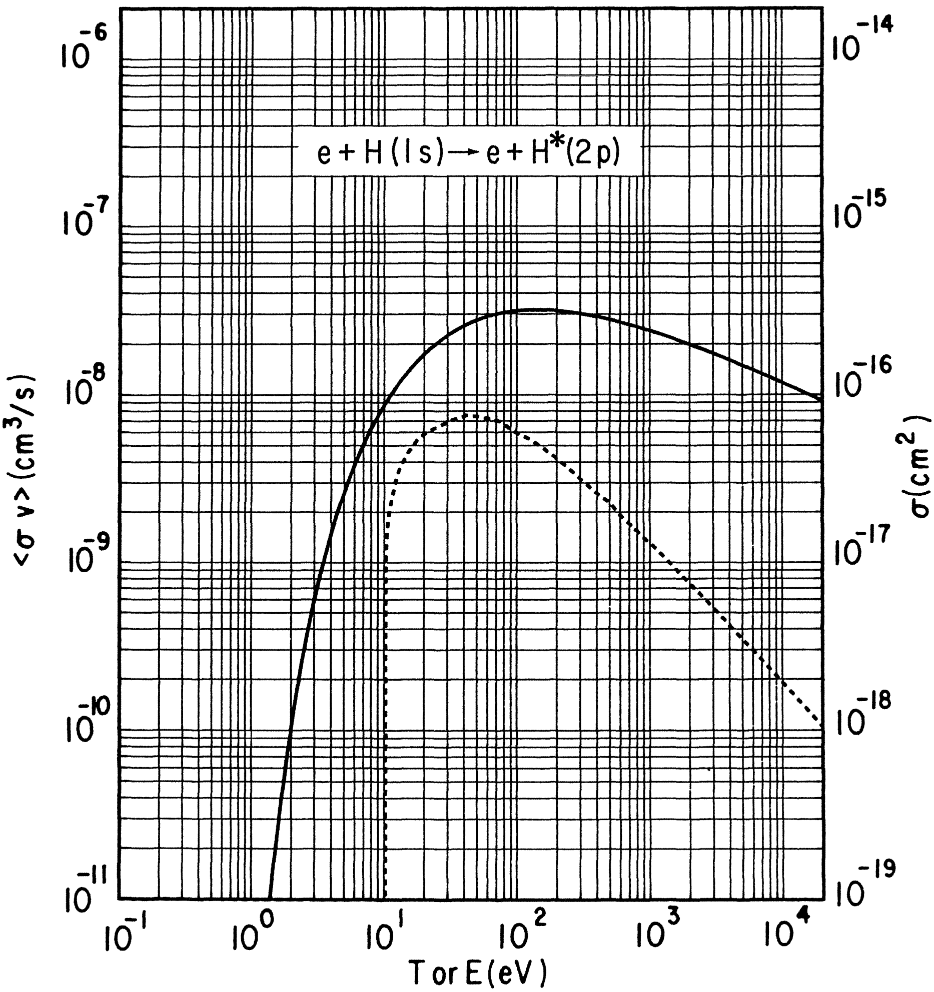
$$\sigma_{exc}(1s \rightarrow 2p) = \sigma_{exc}^B = \frac{6.115 \times 10^{-15}}{E} (\log_{10} E - 0.921) \; [cm^2].$$

Reference: Takayanagi and Suzuki (1978)

Comments:

(1) For $E > 10^5$ eV, relativistic corrections have to be included in σ_{exc}^B.

(2) Recent extensive multistate close-coupling calculations, with inclusion of pseudostates, full exchange and correlation effects agree well with experimental data (see the review by Callaway and McDowell, 1983).



e + H (1s) → e + H*(2p)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
<σ v> (cm³/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
σ(cm²)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

2.1.2 $\boxed{e+H(1s) \rightarrow e+H^*(2s)}$

$E_{th} = 10.2$ eV , $\Delta E_e^{(-)} = E_{th}$.

Cross Section:

$E = E_{th} - 10^3$ eV: $\sigma_{exc}(1s \rightarrow 2s) = \sigma_{exp}$.

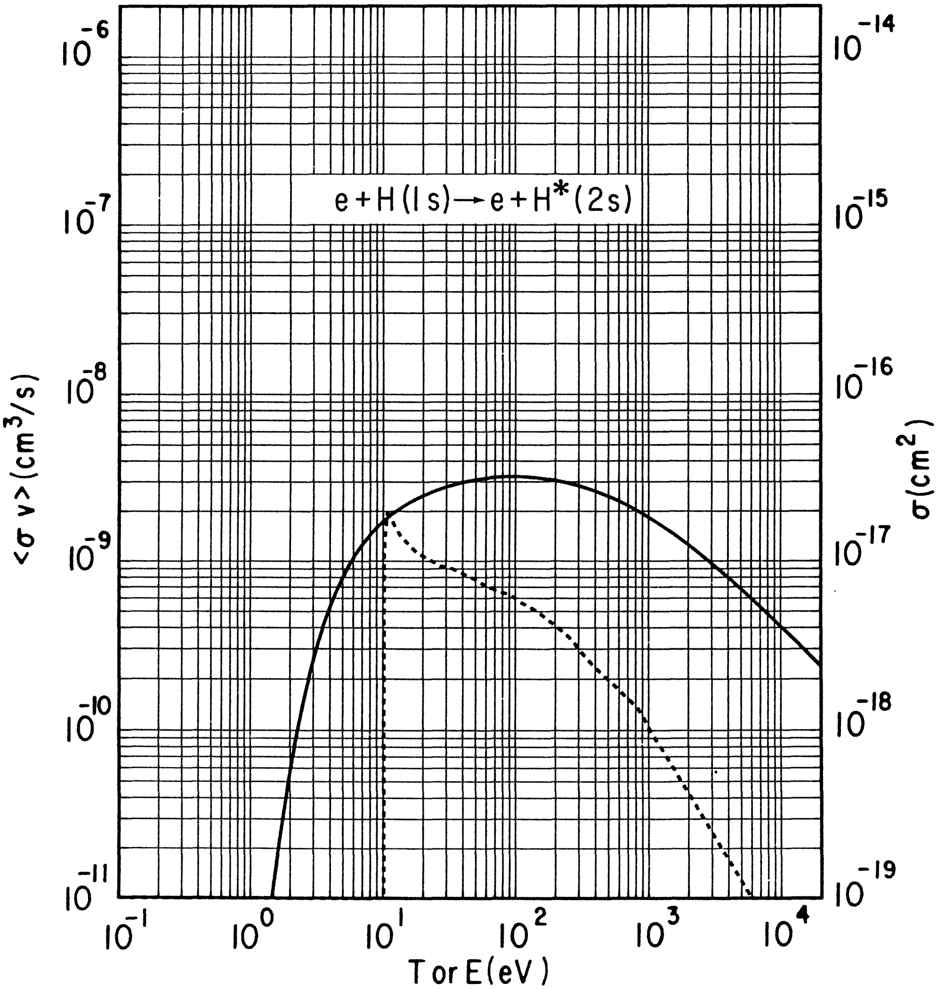
Reference: Takayanagi and Suzuki (1978)

$$E = 10^3 - 10^6 \text{ eV: } \sigma_{exc}(1s \rightarrow 2s) = \sigma_{exc}^B = \frac{5.312 \times 10^{-16}}{E} \left[cm^2\right] .$$

Comments:

(1) For $E > 10^5$ eV, relativistic corrections need to be included in σ_{exc}^B.

(2) Recent multistate close-coupling calculations with inclusion of pseudostates, full exchange and correlation effects agree well with experimental data (see Callaway and McDowell 1983).



e + H(1s) → e + H*(2s)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
<σ v> (cm³/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
σ(cm²)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)

2.1.3 $\boxed{e + H^*(2s) \rightarrow e + H^*(2p)}$

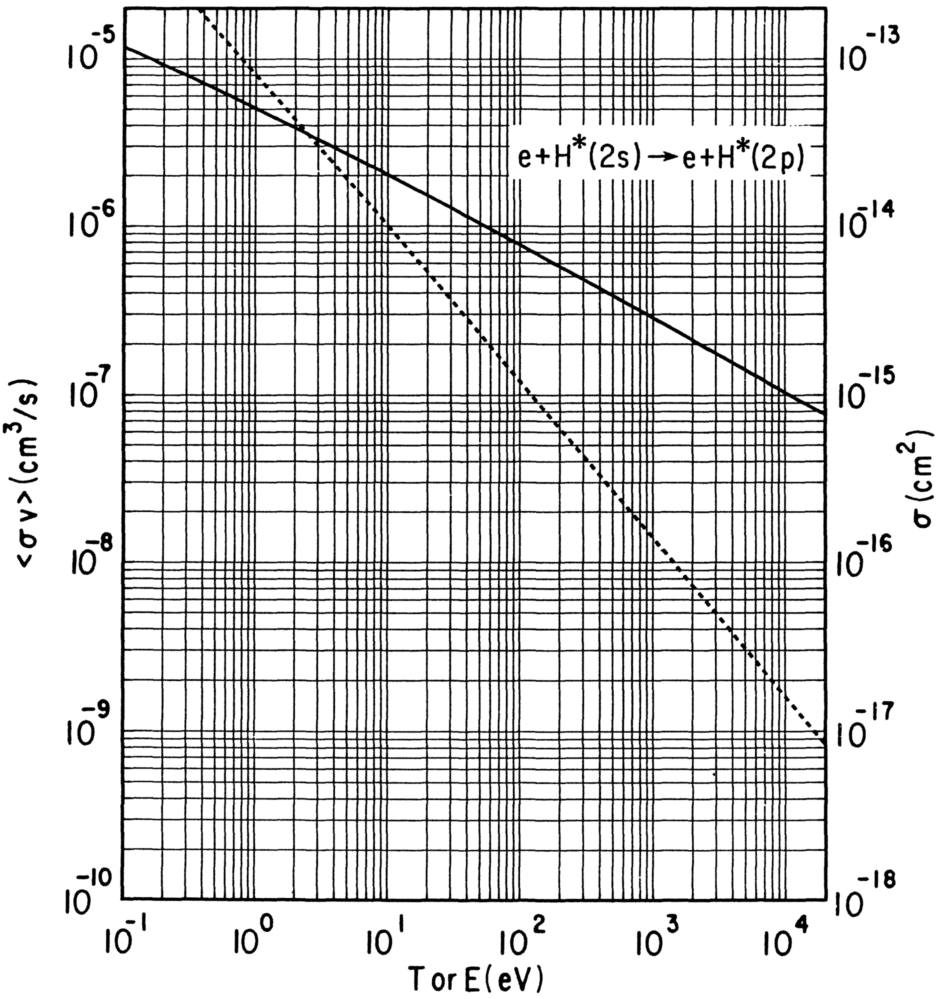
$E_{th} = 1.934 \times 10^{-5}$ eV, $\Delta E_e^{(-)} = E_{th}$.

Cross Section:

$$\sigma_{(2s \rightarrow 2p)} = \frac{8.617 \times 10^{-15}}{E} \ln \left(1.14 \times 10^4 E\right)\left[cm^2\right].$$

Reference: Chibisov (1969)

Comment: The analytic formula for $\sigma(2s \rightarrow 2p)$ is obtained by perturbation theory and is valid for $E >> E_{th}$.



e+H*(2s)→e+H*(2p)
<σv> (cm³/s)
σ (cm²)
T or E (eV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.1.4 $\boxed{e+H^*(n) \rightarrow e+H^*(m), \quad (m>n, \; m\neq 2)}$

$$E_{th} = \Delta E_{nm} = Ry \left(\frac{1}{n^2} - \frac{1}{m^2}\right), \qquad \Delta E_e^{(-)} = \Delta E_{nm} .$$

Cross Section:

$$\sigma_{exc}^{se}(n\rightarrow m) = \frac{2.394\times 10^{-15}}{E + \gamma_{nm}} \left[A_{nm} \ln\left(\frac{E}{2Ry} + \delta_{nm}\right) + B_{nm}\right] \; [cm^2] ,$$

$$A_{nm} = \frac{2Ry}{\Delta E_{nm}} f_{nm} \; ; \; \left(f_{nm}\text{: oscillator strength; see Appendix A.2}\right) ,$$

$$B_{nm} = \frac{4Ry^2}{m^3} \left(\frac{1}{\Delta E_{nm}^2} + \frac{4}{3}\frac{E_{n,ion}}{\Delta E_{nm}^3} + b_n \frac{E_{n,ion}^2}{\Delta E_{nm}^4}\right); \; E_{n,ion} = \frac{Ry}{n^2} ;$$

$$b_n = \frac{1.4 \ln n}{n} - \frac{0.7}{n} - \frac{0.51}{n^2} + \frac{1.16}{n^3} - \frac{0.55}{n^4} ;$$

$$\delta_{nm} = \exp\left(-B_{nm}/A_{nm}\right) - 0.4\, \Delta E_{nm}/Ry \; ; \; s = |m-n| ;$$

$$\gamma_{nm} = Ry\left[8 + 23\left(\frac{s}{n}\right)^2\right]\left[8 + 1.1ms + \frac{0.8}{s^2} + 0.4\, m\left(\frac{m}{s}\right)^{1/2}|s-1|\right]^{-1} .$$

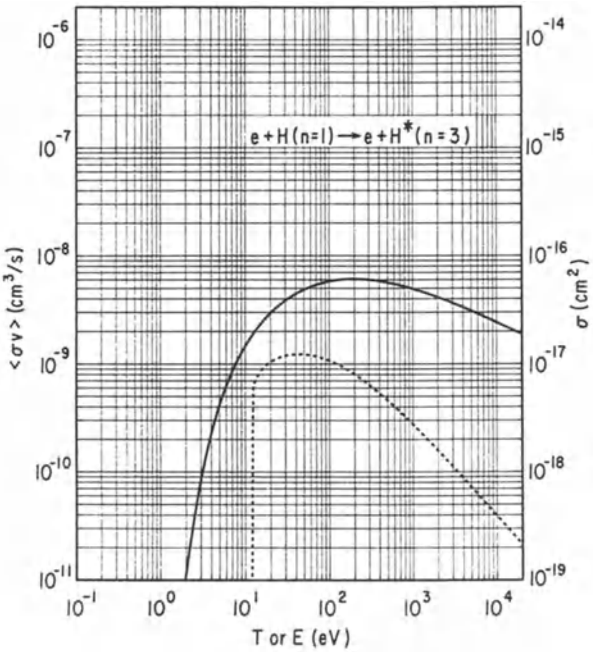
Reference: Vriens and Smeets (1980)

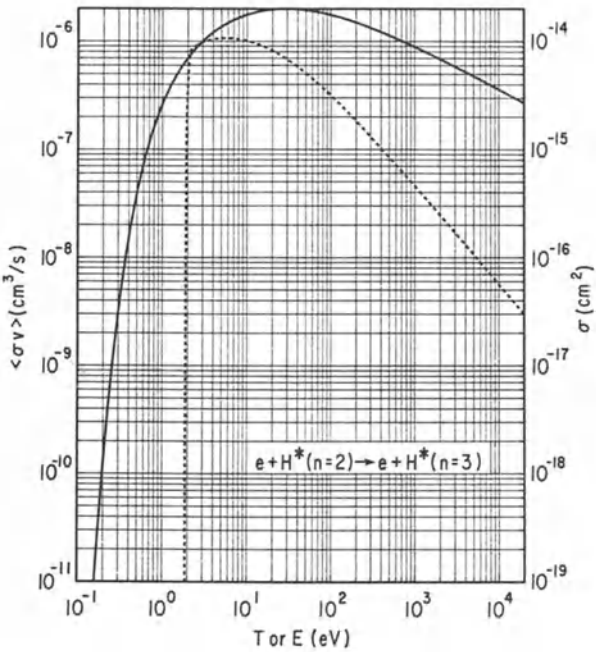
The figures show two examples: (a) $e + H(1) \rightarrow e + H^*(3)$, and (b) $e + H^*(2) \rightarrow e + H^*(3)$; their fitting coefficients for $\langle\sigma v\rangle$ are given in Sect. 8.2.

Comments:

(1) The formula for $\sigma_{exc}^{se}(n\rightarrow m)$ has been derived semiempirically and its accuracy is claimed to be within ± 30%. It can also be applied for dipole- allowed transitions, $(n,\ell) \rightarrow (m,\ell\pm 1)$. An analytic expression for the reaction rate coefficient $\alpha_{exc}^{se}(n\rightarrow m)$ has been also derived by Vriens and Smeets (1980).

(2) The cross section for $e + H(1) \rightarrow e + H^*(3)$ excitation agrees to within 20% with recent quantal calculations (see Callaway and McDowell 1983).


e + H (n=1) → e + H* (n = 3)
⟨σv⟩ (cm³/s)
σ (cm²)
T or E (eV)


e + H* (n=2) → e + H* (n=3)
⟨σv⟩ (cm³/s)
σ (cm²)
T or E (eV)

2.1.5 $\boxed{e_1 + H(1s) \rightarrow \bar{e}_1 + H^+ + \bar{e}_2}$

$E_{th} = 13.6$ eV, $\quad \Delta E_{e_1}^{(-)} (\equiv E - E_{\bar{e}_1}) = E_{th} - E_{\bar{e}_2}$.

<u>Cross Section</u>:

$E = E_{th} - 10^3$ eV: $\sigma_{ion}(1s) = \sigma_{exp}$.

$E = 10^3 - 10^6$ eV:

$$\sigma_{ion}(1s) = \sigma_{ion}^{B} = \frac{3.123 \times 10^{-15}}{E} \left(\log_{10} E + 0.792\right) \left[cm^2\right].$$

Reference: Takayanagi and Suzuki (1978)

<u>Mean Energy of Ejected Electrons</u>:

$$\langle E_{\bar{e}_2} \rangle = \frac{1}{2} \left(E - E_{th}\right), \qquad E \le \frac{3}{2} E_{th}$$

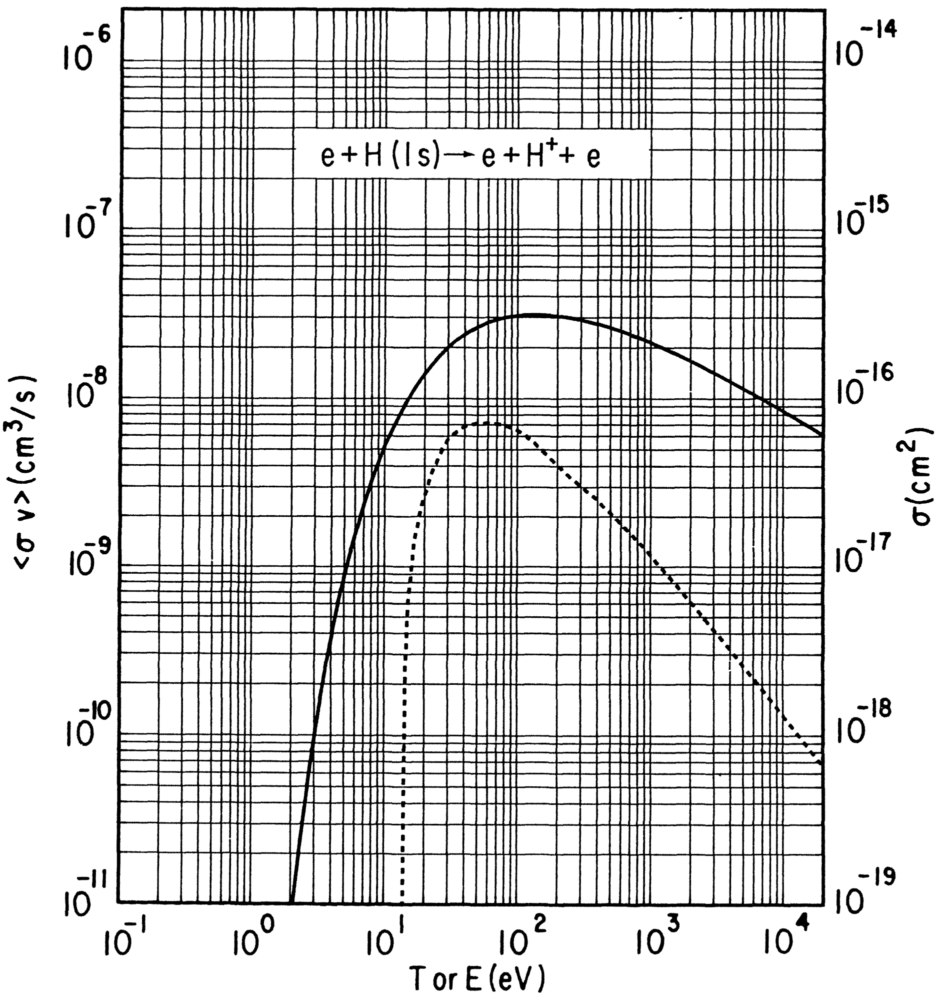
$$= \frac{1}{4} E_{th} = E \ge \frac{3}{2} E_{th}.$$

Reference: Omidvar (1965)

<u>Comments</u>:

(1) Relativistic corrections are needed in σ_{ion}^{B} for $E > 10^5$ eV.

(2) For $E \ge (3/2)\, E_{th}$, $E_{\bar{e}_2}$ is distributed between 0 and E with a sharp peak at $(1/4)\, E_{th}$.


e + H (1s) → e + H⁺ + e
<σ v> (cm³/s)
σ (cm²)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.1.6 $\boxed{e_1 + H^*(2s) \rightarrow \bar{e}_1 + H^+ + \bar{e}_2}$

$E_{th} = 3.4$ eV, $\qquad \Delta E^{(-)}_{e_1} = E_{th} + E_{\bar{e}_2}$.

Cross Section:

$E = E_{th} - 300$ eV: $\sigma_{ion}(2s) = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

$E = 300 - 10^6$ eV:

$$\sigma_{ion}(2s) = \sigma^B_{se} = \frac{1.887 \times 10^{-14}}{E} \left(\log_{10}E + 1.155\right) \left[cm^2\right] .$$

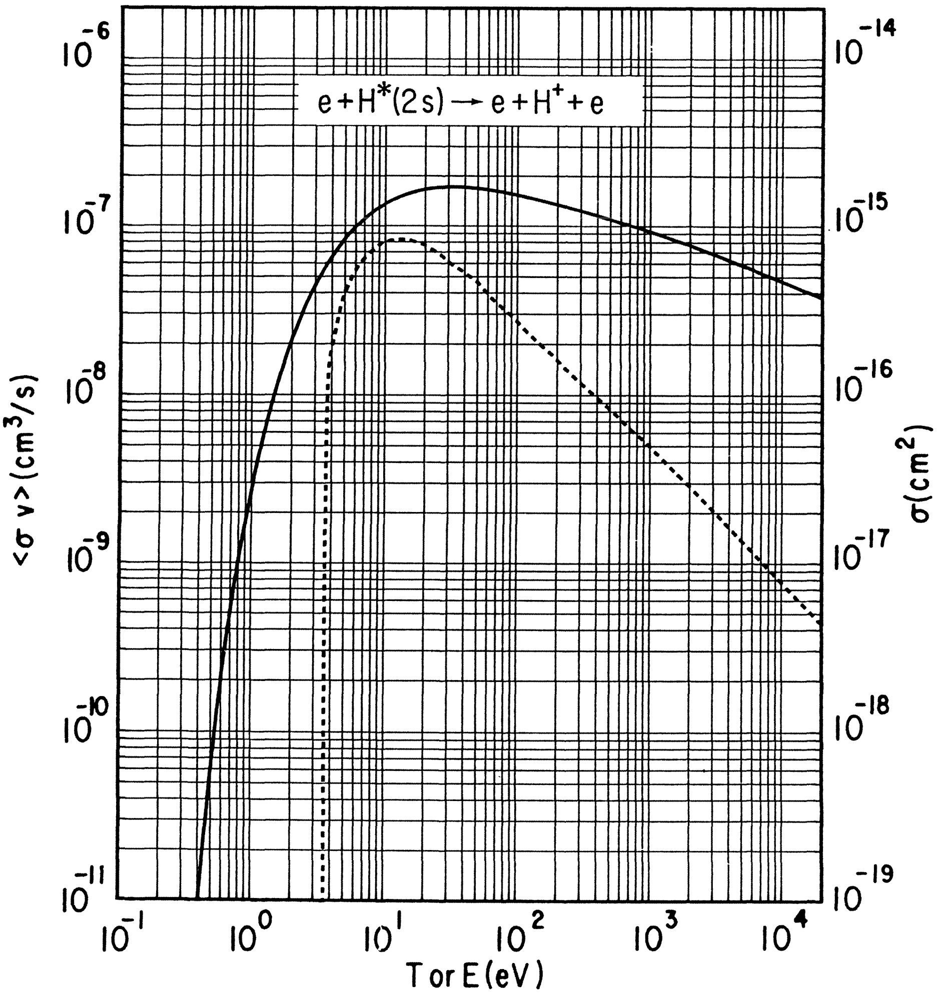
Mean Energy of Ejected Electrons:

$$<E_{\bar{e}_2}> = \frac{1}{2}\left(E - E_{th}\right) \text{ eV}, \quad E \leq \frac{3}{2} E_{th}$$

$$= \frac{1}{4} E_{th}, \quad E \geq \frac{3}{2} E_{th} .$$

Reference: Omidvar (1965)

Comment: For the energy distributions $E_{\bar{e}_1}$ and $E_{\bar{e}_2}$, the same remarks hold as in the case of reaction 2.1.5.



$e + H^*(2s) \rightarrow e + H^+ + e$
$\langle\sigma v\rangle\ (cm^3/s)$
$\sigma\ (cm^2)$
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
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10^{2}
10^{3}
10^{4}

2.1.7 $\boxed{e_1 + H^*(n) \rightarrow \bar{e}_1 + H^+ + \bar{e}_2, \quad (n>2)}$

$$E_{th} = E_n^{ion} = Ry/n^2; \ \Delta E_{e_1}^{(-)} = E_{th} + E_{\bar{e}_2} \ .$$

Cross Section and Rate Coefficient:

$$\sigma_{ion}(n) = \sigma_{se}^{BEA} = \frac{6.51 \times 10^{-14}}{E + 3.25\, E_n^{ion}} \left(\frac{5}{3E_n^{ion}} - \frac{1}{E} - \frac{2}{3} \frac{E_n^{ion}}{E^2} \right) [\mathrm{cm}^2] \ .$$

$$\alpha_{ion}(n) = \frac{9.56 \times 10^{-6}\, T^{-1.5} \exp(-\beta_n)}{\beta_n^{2.33} + 4.38\, \beta_n^{1.72} + 1.32\, \beta_n}$$

$$\beta_n = E_n^{ion}/T$$

Reference: Vriens and Smeets (1980)

Mean Energy of Ejected Electrons:

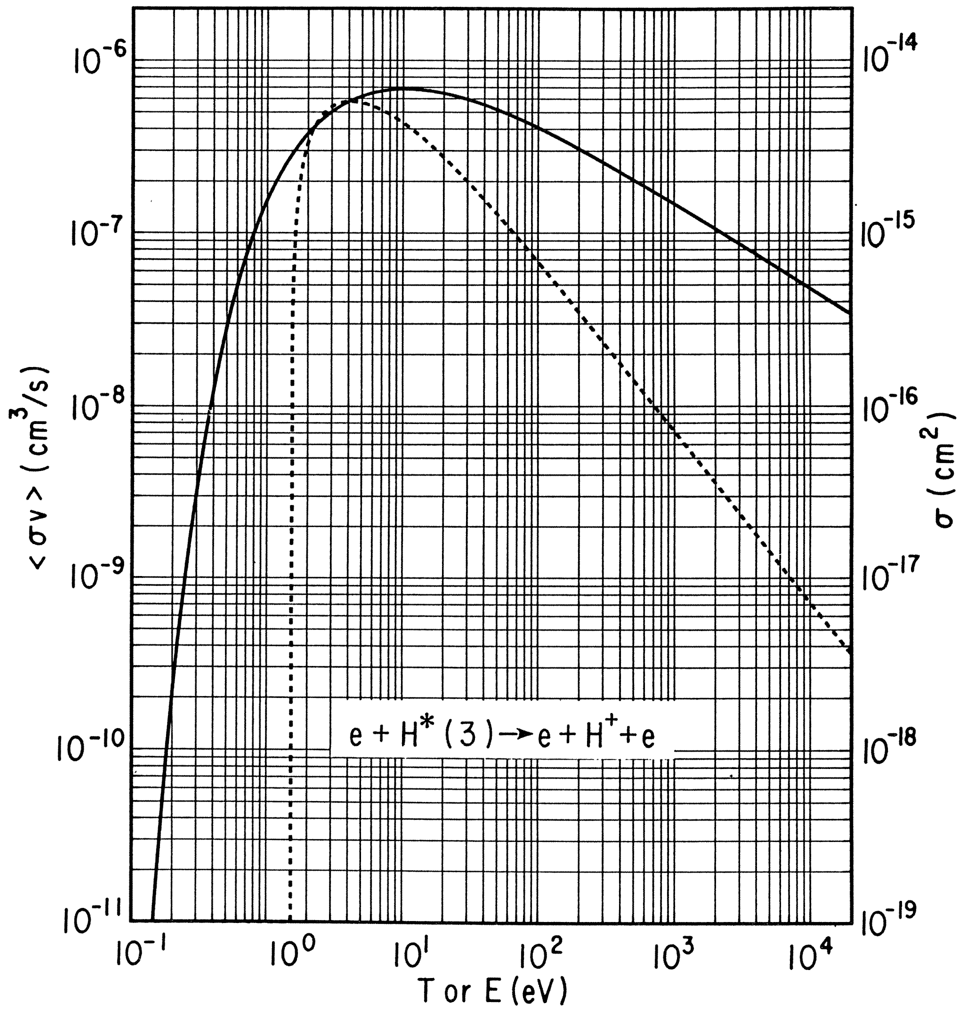
$$\langle E_{\bar{e}_2} \rangle = \frac{1}{2} (E - E_{th}), \quad E \le \frac{3}{2} E_{th}$$

$$= \frac{1}{4} E_{th} = \frac{Ry}{4n^2}, \quad E \ge \frac{3}{2} E_{th}.$$

Reference: Omidvar (1965)

Comment: The cross section $\sigma_{se}^{BEA}(n)$ is derived semiempirically and is based on a modified binary encounter approximation. The accuracy of $\sigma_{se}^{BEA}(n)$ is expected to be high for $n \gg 1$. (See also Percival and Richards 1979).

Note: For $n = 3$, σ_{ion} and a numerical integration of $\langle\sigma_{ion}v\rangle$ are given in the figure.


$<\sigma v>$ (cm^3/s)
σ (cm^2)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)
$e + H^*(3) \rightarrow e + H^+ + e$

2.1.8 $\boxed{e + H^+ \rightarrow H(n) + h\nu}$

$$E_{th} = E_n^{ion} = Ry/n^2, \quad \Delta E_e^{(-)} = E, \quad E_{h\nu} = E - Ry/n^2$$

Reaction Rate Coefficients:

For $n \equiv n\ell$ = 1s; 2s; 2p:

$$\alpha_{rec}^{rad}(n\ell) = A_{n\ell} \times 10^{-14} \left(E_n^{ion}/Ry\right)^{1/2} \frac{\beta_n^{3/2}}{\beta_n + \chi_{n\ell}} \quad \left[cm^3/s\right],$$

$$\beta_n = \frac{E_n^{ion}}{T} .$$

$n\ell$	1s	2s	2p
$A_{n\ell}$	3.92	2.47	6.22
$\chi_{n\ell}$	0.35	0.12	0.61

For $n \geq 3$: $\alpha_{rec}^{rad}(n) = 5.201 \times 10^{-14} \beta_n^{3/2} E_1(\beta_n) \exp(\beta_n) \quad \left[cm^3/s\right],$

$E_1(\beta_n)$: exponential integral .

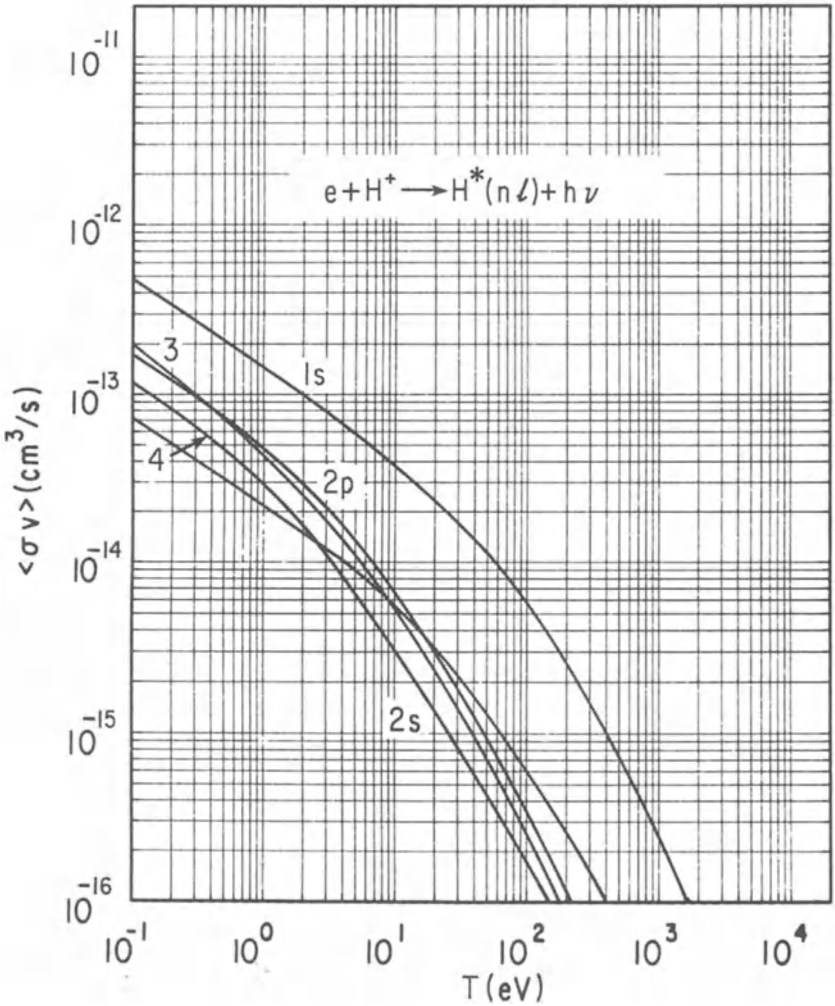
Reference: Sobelman et al. (1981)

Comments:

(1) The expression $\alpha_{rec}(n \leq 2)$ uses an analytical fit to $\sigma_{rec}^{B,rad}$. Values of $\alpha_{rec}^{rad}(n \geq 3)$ are given in the semiclassical (Kramers) approximation.

(2) Useful expansions of $\exp(\beta)E_1(\beta)$ can be found in Abramowitz and Stegun (1972). Another good approximation is

$$\exp(\beta)\, E_1(\beta) = \ell n\left[1 + (1/\gamma\beta)(1 + 1.4\gamma\beta)/(1 + 1.4\beta)\right], \quad \gamma = 1.78$$



$e + H^+ \longrightarrow H^*(n\ell) + h\nu$
1s
2p
2s
3
4
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$<\sigma v>$ (cm^3/s)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T (eV)

2.2 Electron Collisions with H_2 H_2^+, and H_3^+

2.2.1a $\boxed{e+H_2(v=0) \rightarrow e+H_2(v=1)}$

$E_{th} = 0.5$ eV, $\Delta E_e^{(-)} = E_{th}$.

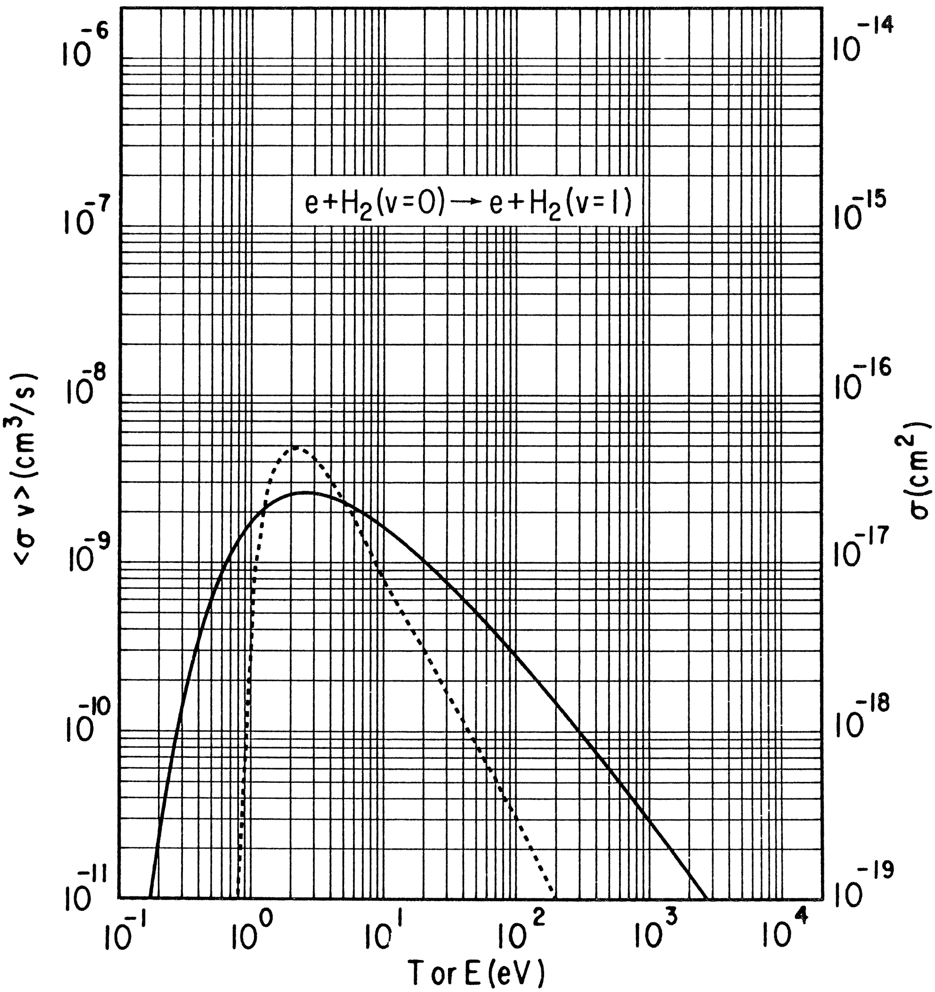
Cross Section:

$E = E_{th} - 10$ eV: $\sigma_{exc}^{vib}(0 \rightarrow 1) = \sigma_{exp}$.

Reference: Miles et al. (1972)

$E > 10$ eV: $\sigma_{exc}^{vib}(0\rightarrow 1) = \sigma_{se}^{B}$

Comment: σ_{se}^{B} is a Born-type extrapolation of σ_{exp} in the region above 10 eV.



$e + H_2(v=0) \rightarrow e + H_2(v=1)$
$\langle \sigma v \rangle$ (cm^3/s)
σ(cm^2)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.1b $\boxed{e+H_2(v=0) \rightarrow e+H_2(v=2)}$

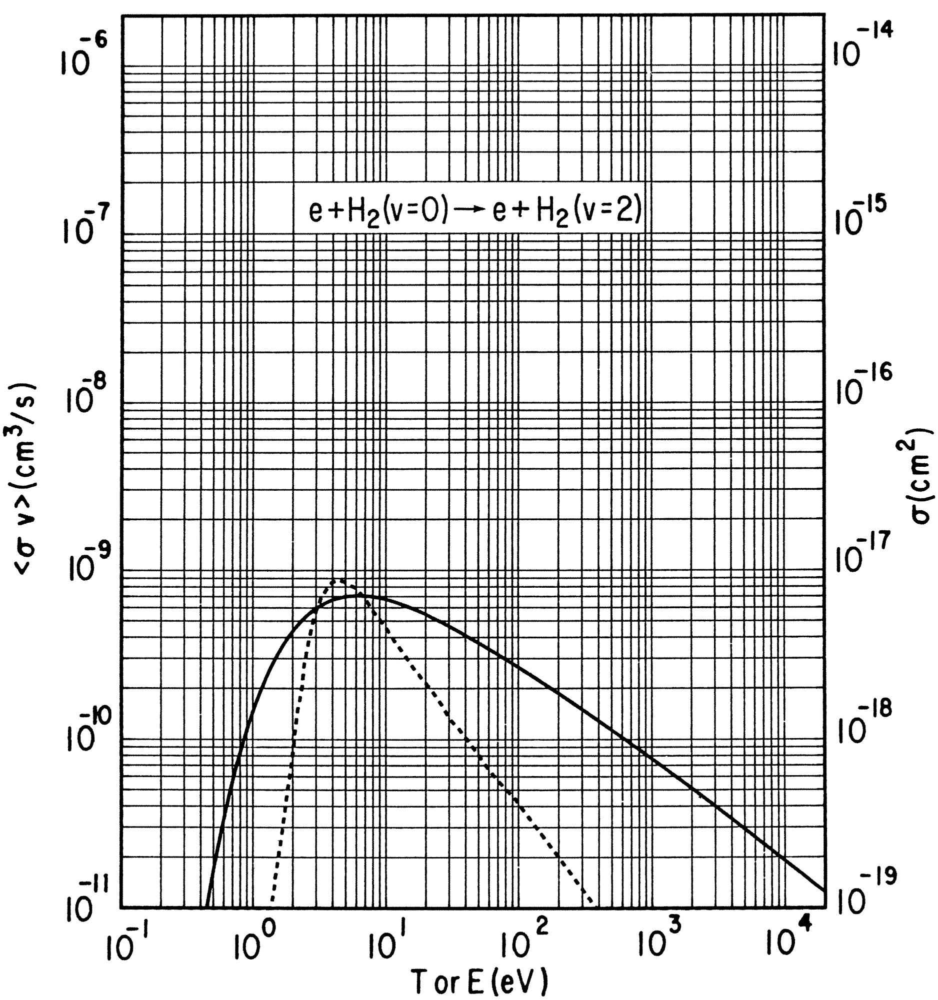
$E_{th} = 1$ eV, $\Delta E_e^{(-)} = E_{th}$.

Cross Section:

$E = E_{th} - 10$ eV: $\sigma_{exc}^{vib}(0\rightarrow 2) = \sigma_{exp}$.

Reference: Miles et al. (1972)

$E = 10 - 400$ eV: $\sigma_{exc}^{vib}(0\rightarrow 2) = \sigma_{se}^{B}$.



$e + H_2(v=0) \rightarrow e + H_2(v=2)$
$\langle \sigma v \rangle$ (cm^3/s)
σ(cm^2)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
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10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.2 $\boxed{e+H_2\ (X^1\Sigma_g^+) \rightarrow e+H_2^*(B\ ^1\Sigma_u^+ 2p\ \sigma)}$

$E_{th} = 11.37$ eV, $<\Delta E_e^{(-)}>_{FC} = 12.1$ eV.

Cross Section:

$E = E_{th} - 10^3$ eV; $\sigma_{exc}(B^1\Sigma_u^+) = \sigma_{se}$.

Reference: Miles et al. (1972)

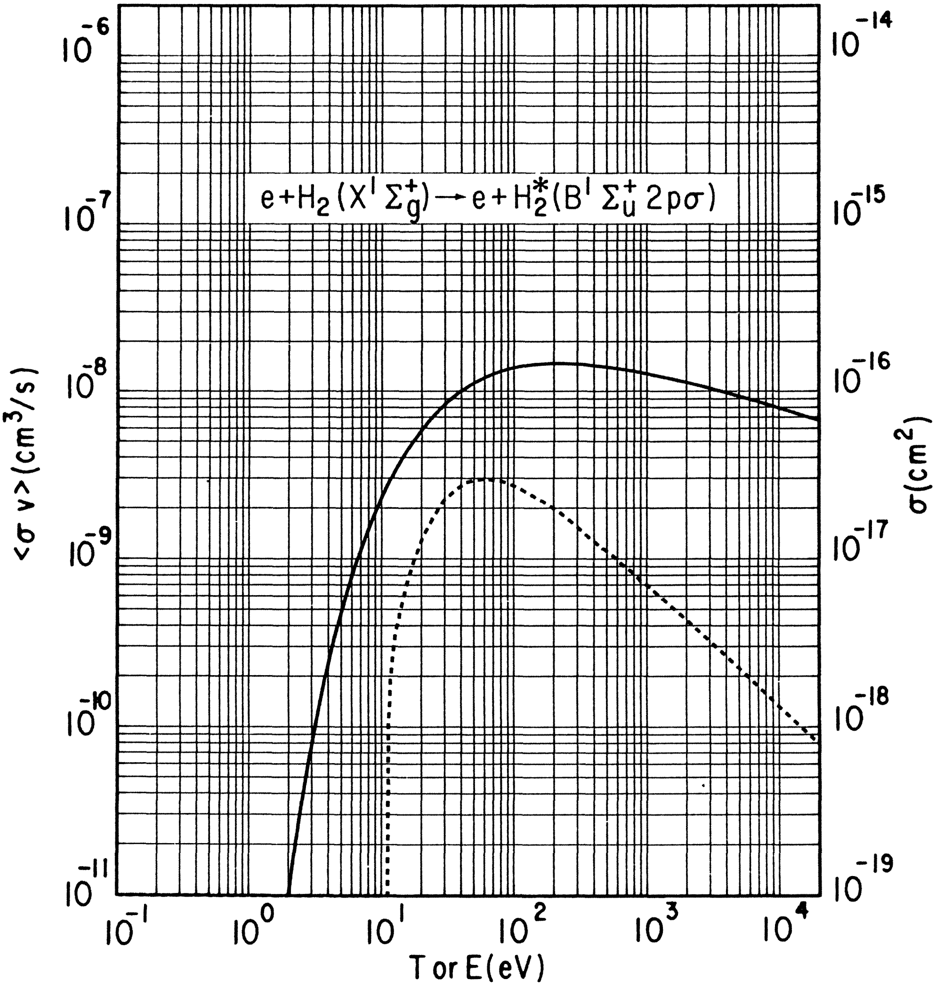
$E = 10^3 - 2 \times 10^4$ eV: $\sigma_{exc}(B^1\Sigma_u^+) = \sigma_{se}^B$.

Comments:

(1) The semiempirical cross section in the energy range below 100 eV is consistent with recent experimental data of Trajmar et al. (1983), Shemansky et al. (1985), and Khakoo and Trajmar (1986).

(2) $<\Delta E_e^{(-)}>_{FC}$ is the mean electron energy loss, averaged over the Franck-Condon region.

(3) The $B^1\Sigma_u^+$ state decays radiatively to the ground state (Lyman band emission), and the emission cross section has been measured (Ajello et al. 1982).


$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(B^1\Sigma_u^+ 2p\sigma)$
$\langle\sigma v\rangle$ (cm^3/s)
σ(cm^2)
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.3 $\boxed{e+H_2\ (X^1\Sigma_g^+) \rightarrow e+H_2^*(C^1\Pi_u 2p\pi)}$

$E_{th} = 11.7$ eV, $<\Delta E_e^{(-)}>_{FC} = 12.4$ eV.

Cross Section:

$E = E_{th} - 200$ eV: $\sigma_{exc}(C^1\Pi_u) = \sigma_{exc}^{DWA}$.

Reference: Mu-Tao et al. (1982)

$E = 200 - 2 \times 10^4$ eV: $\sigma_{exc}(C^1\Pi_u) = \sigma_{se}^{B}$.

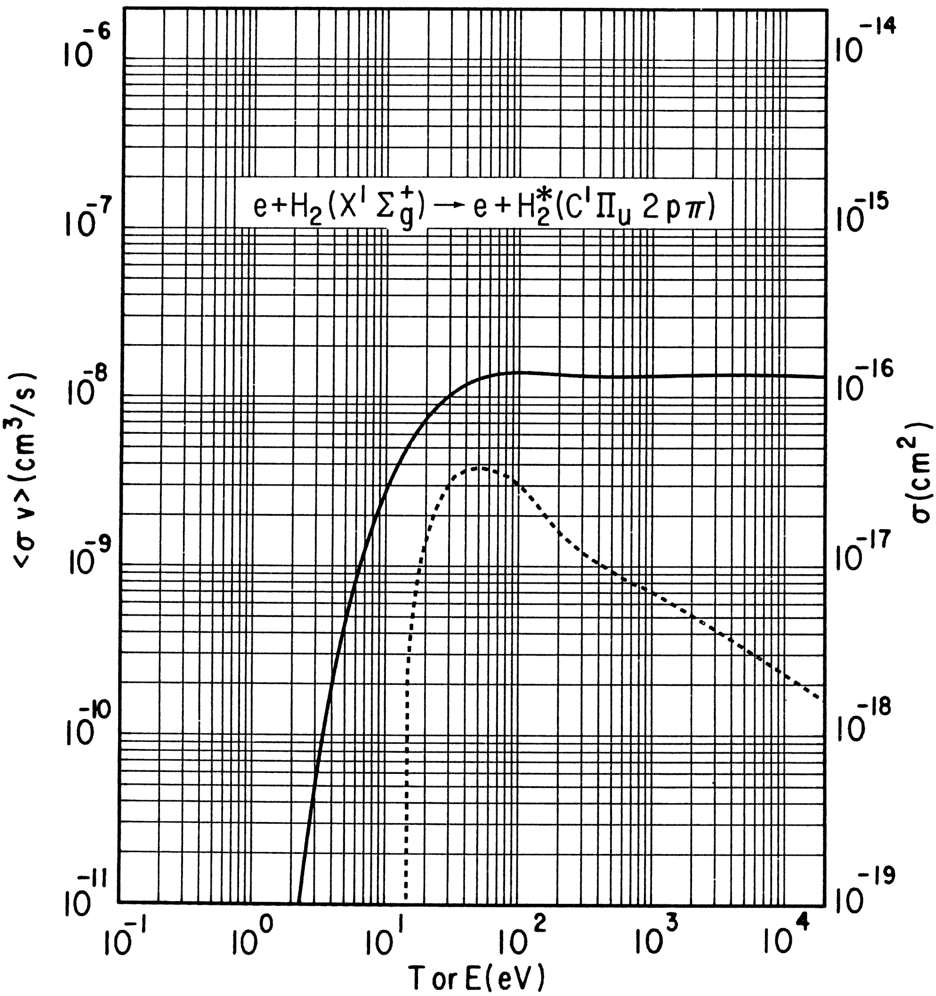
Comments:

(1) The distorted wave approximation cross section σ_{exc}^{DWA} in the region below 100 eV is consistent with the recent experimental data of Shemansky et al. (1985), and Khakoo and Trajmar (1986) to within 25%.

(2) σ_{se}^{B} is obtained by fitting the high-energy part of σ_{exc}^{DWA} to a Born-type analytic expression.

(3) $<\Delta E_e^{(-)}>_{FC}$ is the electron energy loss, averaged over the Franck-Condon region.

(4) The $C^1\Pi_u$ state decays radiatively to the ground state (Werner band emission), and the corresponding emission cross section has been measured (Ajello et al. 1982).



$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(C^1\Pi_u\, 2p\pi)$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.4 $e+H_2\ (X^1\Sigma_g^+) \rightarrow e+H_2^*(E,F^1\Sigma_g^+)$

$E_{th} = 12.2$ eV, $\langle\Delta E_e^{(-)}\rangle_{FC} = 12.7$ eV.

Cross Section:

$E = E_{th} - 60$ eV: $\sigma_{exc}(E,F^1\Sigma_g^+) = \sigma_{exc}^{DWA}$.

Reference: Mu-Tao et al. (1982)

$E = 60 - 10^3$ eV: $\sigma_{exc}(E,F^1\Sigma_g^+) = \sigma_{se}$,

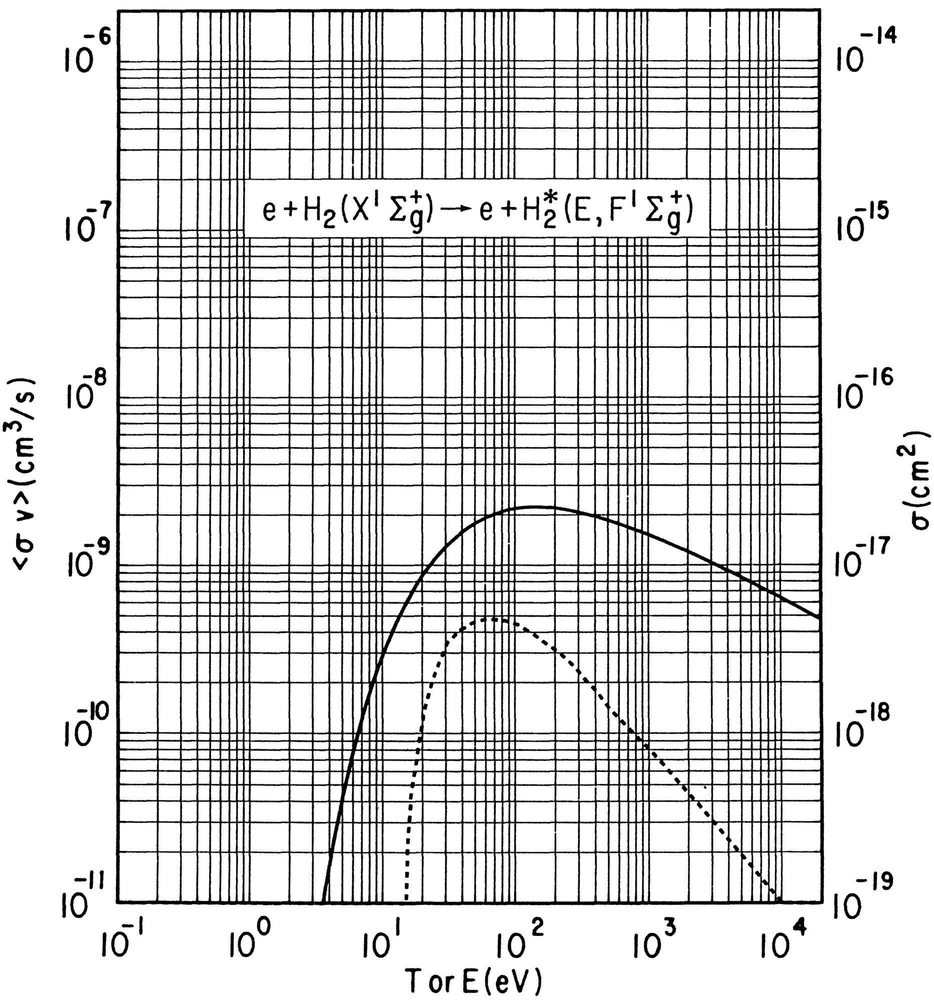
$E = 10^3 - 10^4$ eV: $\sigma_{exc}(E,F^1\Sigma_g^+) = \sigma_{se}^B$.

Comments:

(1) σ_{se} is obtained by matching the semiempirical cross section of Miles et al. (1972) with σ^{DWA}.

(2) $\langle\Delta E_e^{(-)}\rangle_{FC}$ is the mean electron energy loss averaged over the Franck-Condon region.

(3) The state $E,F^1\Sigma_g^+$ decays radiatively to the ground state.



e + H2(X1 Σg+) → e + H2*(E, F1 Σg+)
<σ v> (cm3/s)
σ (cm2)
T or E (eV)
10-6
10-7
10-8
10-9
10-10
10-11
10-14
10-15
10-16
10-17
10-18
10-19
10-1
100
101
102
103
104

2.2.5 $e+H_2\,(X^1\Sigma_g^+) \rightarrow e_1+H_2^* \begin{pmatrix} b^3\Sigma_u^+ \\ a^3\Sigma_g^+ \\ c^3\Pi_u \end{pmatrix} \rightarrow e_1+H(1s)+H(1s)$

$E_{th}^{(b)} \simeq 8.5$ eV, $E_{th}^{(a)} \simeq 11.7$ eV, $E_{th}^{(c)} \simeq 11.7$ eV; $\langle E_{th}\rangle_{a,b,c} \simeq 10$ eV.

Cross Section:

$E = \langle E_{th}\rangle - 60$ eV: $\sigma_{exc}^{diss}(H_2^*) = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

$E = 60 - 200$ eV: $\sigma_{exc}^{diss}(H_2^*) = \sigma_{se}^{BOR}$.

Mean Energy of Reaction Products:

$\langle \Delta E_{e_1}^{(-)}\rangle_{FC}^{a,b,c} = 10.5$ eV; $\langle \Delta E_{H^o}^{(+)}\rangle_{\Delta\varepsilon} \simeq 3$ eV.

Comments:

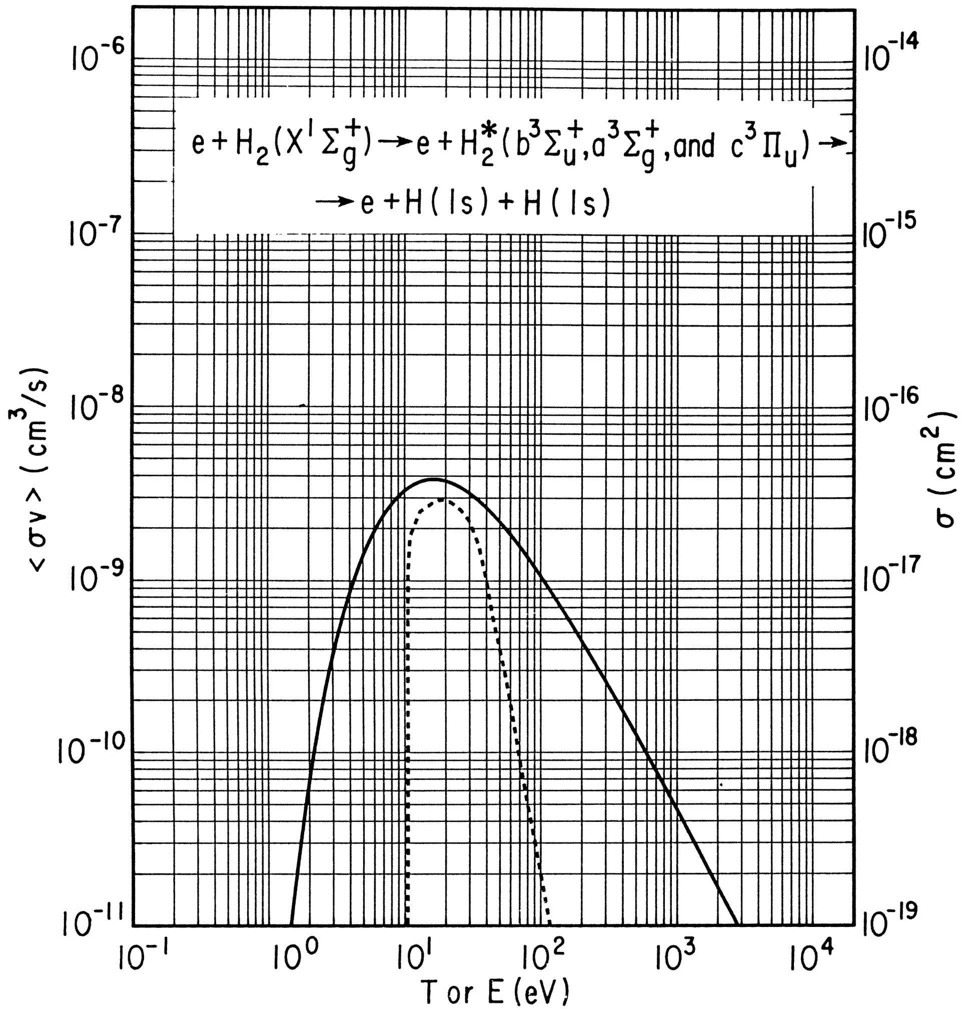
(1) σ_{exp} is corrected from the values in Corrigan (1965) (see Takayanagi and Suzuki 1978). Below 50 eV it is consistent with the two-state close-coupling calculations of Chung and Lin (1978), but the sum of $\sigma(a^3\Sigma_g^+)$ and $\sigma(c^3\Pi_u)$ is a factor of 3 too large compared to the recent measurements by Khakoo and Trajmar (1986).

(2) σ_{se}^{BOR} is a Born-Ochkur-Rudge extrapolation of σ_{exp}.

(3) $\langle E_{th}\rangle_{a,b,c}$ and $\langle \Delta E_e\rangle_{FC}^{a,b,c}$ are weighted mean values, the latter is averaged over the Franck-Condon region.

(4) $\langle \Delta E_{H^o}^{(+)}\rangle_{\Delta\varepsilon}$ is averaged over a distribution $\Delta\varepsilon$ between 2 and 4.25 eV, and assumes that H atoms share the dissociation energy.

(5) The states $a^3\Sigma_g^+$ and $c^3\Pi_u$ decay radiatively to $b^3\Sigma_u^+$, producing the H_2 continuum emission.



$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(b^3\Sigma_u^+, a^3\Sigma_g^+, \text{and } c^3\Pi_u) \rightarrow$
$\rightarrow e + H(1s) + H(1s)$
$\langle \sigma v \rangle$ (cm^3/s)
σ (cm^2)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
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10^{4}

2.2.6 $\boxed{e + H_2\ (X^1\Sigma_g^+) \rightarrow e + H_2^*(1s\sigma_g, nl\lambda|^1\Lambda) \rightarrow e + H(1s) + H^*(2s)}$

$\langle E_{th} \rangle_{^1\Lambda} = 14.9$ eV, $\langle \Delta E_e^{(-)} \rangle_{FC} \simeq 15.3$ eV.

Cross Section:

$E = \langle E_{th} \rangle - 250$ eV: $\sigma_{exc}^{diss} = \sigma_{exp}$,

$E = 250 - 360$ eV: $\sigma_{exc}^{diss} = \sigma_{se}$.

Reference: Gerhart (1975)

$E = 360 - 2 \times 10^4$ eV: $\sigma_{exc}^{diss} = \sigma_{se}^B$.

Mean Energy of Dissociation Products:

$\langle \Delta E_H^{(+)} \rangle_{^1\Lambda} \simeq \langle \Delta E_{H^*}^{(+)} \rangle_{^1\Lambda} \simeq 0.3$ eV.

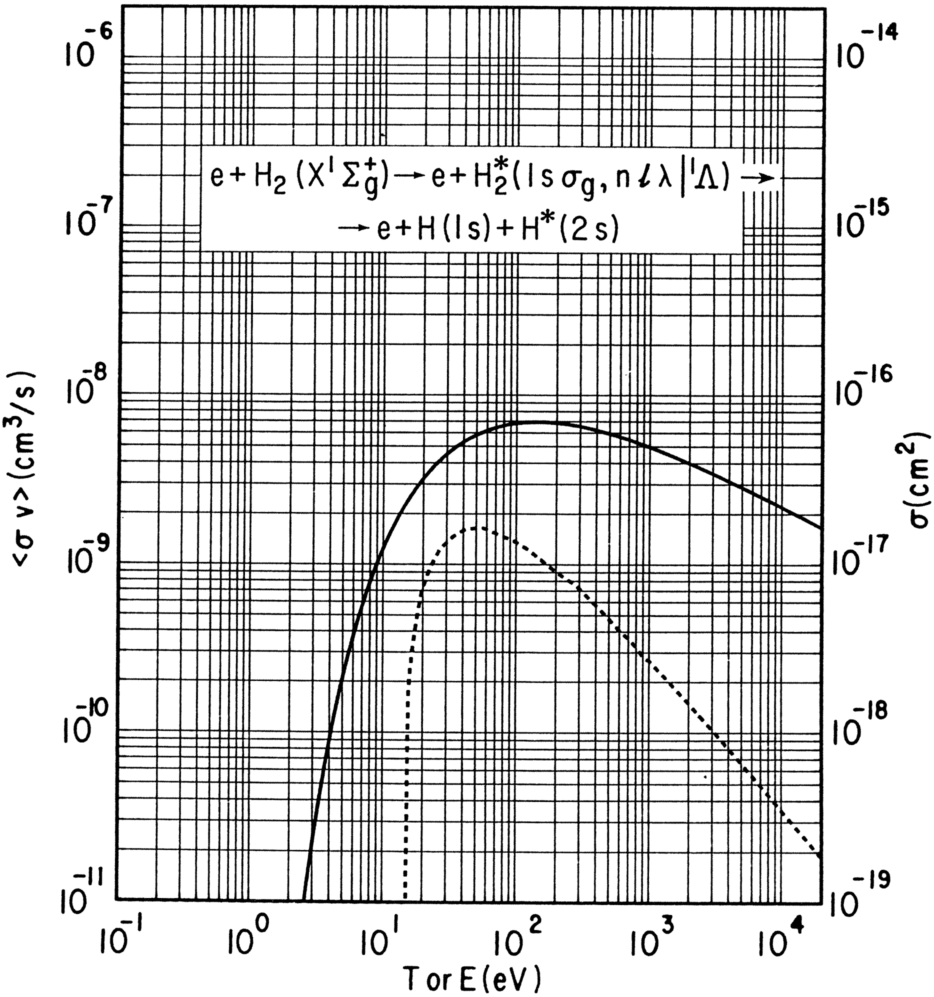
Comments:

(1) $\Delta E_e^{(-)}$ is distributed between 14.9 and 16.0 eV and sharply peaked at 15.3 eV (the center of the Franck-Condon region).

(2) The energy gain distribution per product atom (assuming equal sharing) ranges between 0.0 and 0.55 eV, with a broad maximum at $\simeq 0.3$ eV.

(3) σ_{se} is the semiempirical cross section of Gerhart (1975), matched with σ_{exp}. The cross section σ_{se}^B is a Born-type extrapolation of σ_{se}.

(4) $(n\ell\lambda|^1\Lambda)$ is a group of one-electron Rydberg states with $n \geq 3$, over which an average is performed.



$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(1s\sigma_g, n\ell\lambda\,|\,^1\Lambda) \rightarrow$
$\rightarrow e + H(1s) + H^*(2s)$
$<\sigma v>$ (cm^3/s)
σ(cm^2)
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
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10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.7 $e + H_2\ (X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u; nl\lambda|Q_2^1\Pi_u) \rightarrow e + H^*(2p) + H^*(2s)$

$E_{th} \simeq 23$ eV, $\langle \Delta E_e^{(-)} \rangle_{FC} \simeq 34.6$ eV.

Cross Section:

$E = E_{th} - 360$ eV: $\sigma_{exc}^{diss} = \sigma_{se}$.

Reference: Gerhart (1975)

$E = 360 - 5 \times 10^3$ eV: $\sigma_{exc}^{diss} = \sigma_{se}^{B}$.

Mean Energy of Dissociation Products:

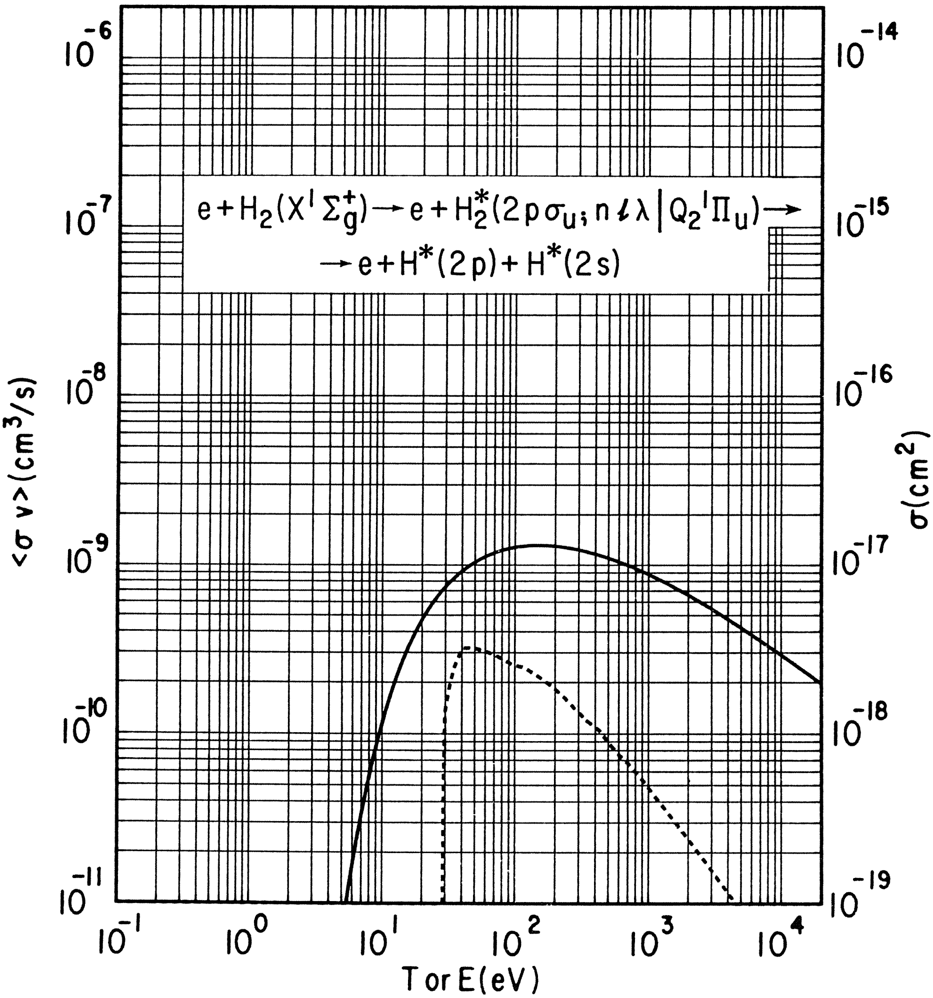
$\langle \Delta E_{H^*(2s)}^{(+)} \rangle \simeq \langle \Delta E_{H^*(2p)}^{(*)} \rangle \simeq 4.85$ eV.

Comments:

(1) $\Delta E_e^{(-)}$ is distributed between ~ 31 and ~ 37 eV, with a sharp maximum at ~ 34.6 eV.

(2) $\Delta E_{H^*}^{(+)}$ for each of the excited products is distributed between 2.85 and 5.85 eV, with a maximum at 4.85 eV. Equipartition of dissociation energy is assumed.

(3) The state $(2p\sigma_u;\ n\ell\lambda|Q_2{}^1\Pi_u)$ is an autodissociating state.


$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u; n\ell\lambda \mid Q_2{}^1\Pi_u) \rightarrow$
$\rightarrow e + H^*(2p) + H^*(2s)$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
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10^{-15}
10^{-16}
10^{-17}
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2.2.8 $\boxed{e+H_2(X^1\Sigma_g^+) \rightarrow e+H_2^*(2p\sigma_u; n=3) \rightarrow e+H(1s)+H^*(n=3)}$

$E_{th} \simeq 19.0$ eV, $\langle\Delta E_{FC}^{(-)}\rangle \simeq 21.5$ eV.

Cross Section:

$E = E_{th} - 360$ eV: $\sigma_{exc}^{diss} = \sigma_{se}$.

Reference: Gerhart (1975)

$E = 360 - 3 \times 10^3$ eV: $\sigma_{exc}^{diss} = \sigma_{se}^B$.

Mean Energy of Dissociation Products:

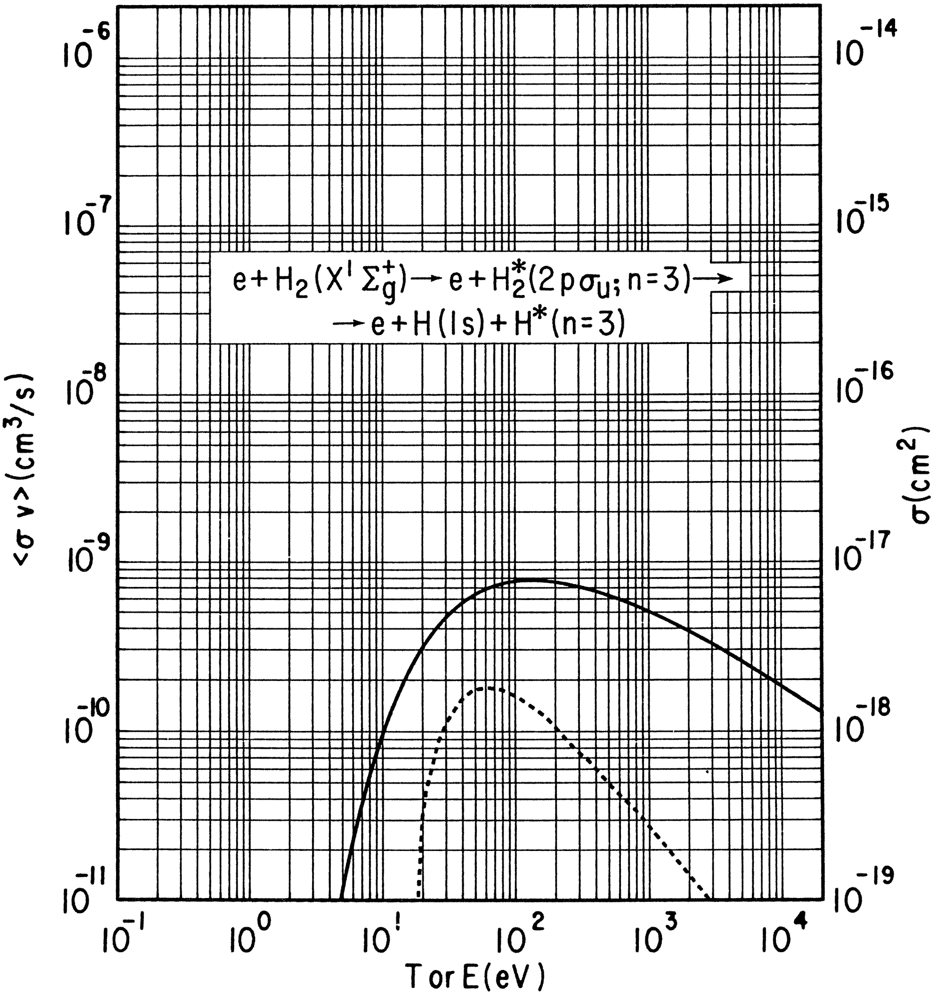
$\langle\Delta E_{H^o}^{(+)}\rangle \simeq \langle\Delta E_{H^*}^{(+)}\rangle \simeq 2.5$ eV.

Comments:

(1) $\Delta E_e^{(-)}$ is distributed between 19 and 24 eV with a maximum at 21.5 eV.

(2) $\Delta E_{H^o}^{(+)} = \Delta E_{H^*}^{(+)}$ is distributed between 1.25 and 3.75 eV with a maximum at 2.5 eV.

(3) $(2p\sigma_u$; n=3) is a group of autodissociating states over which an average is performed.



$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u; n=3) \rightarrow$
$\rightarrow e + H(1s) + H^*(n=3)$
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.9 $\boxed{e_1 + H_2(X^1\Sigma_g^+) \rightarrow \bar{e}_1 + H_2^+(v) + \bar{e}_2}$

$E_{th} = 15.4$ eV, $\Delta E_{e_1}^{(-)} \equiv E_{e_1} - E_{\bar{e}_1} = E_{th} + E_{\bar{e}_2}$.

Cross Section:

$E = E_{th} - 2 \times 10^4$ eV: $\sigma_{ion}(H_2) = \sigma_{exp}^{fit}$.

Reference: Freeman and Jones (1974)

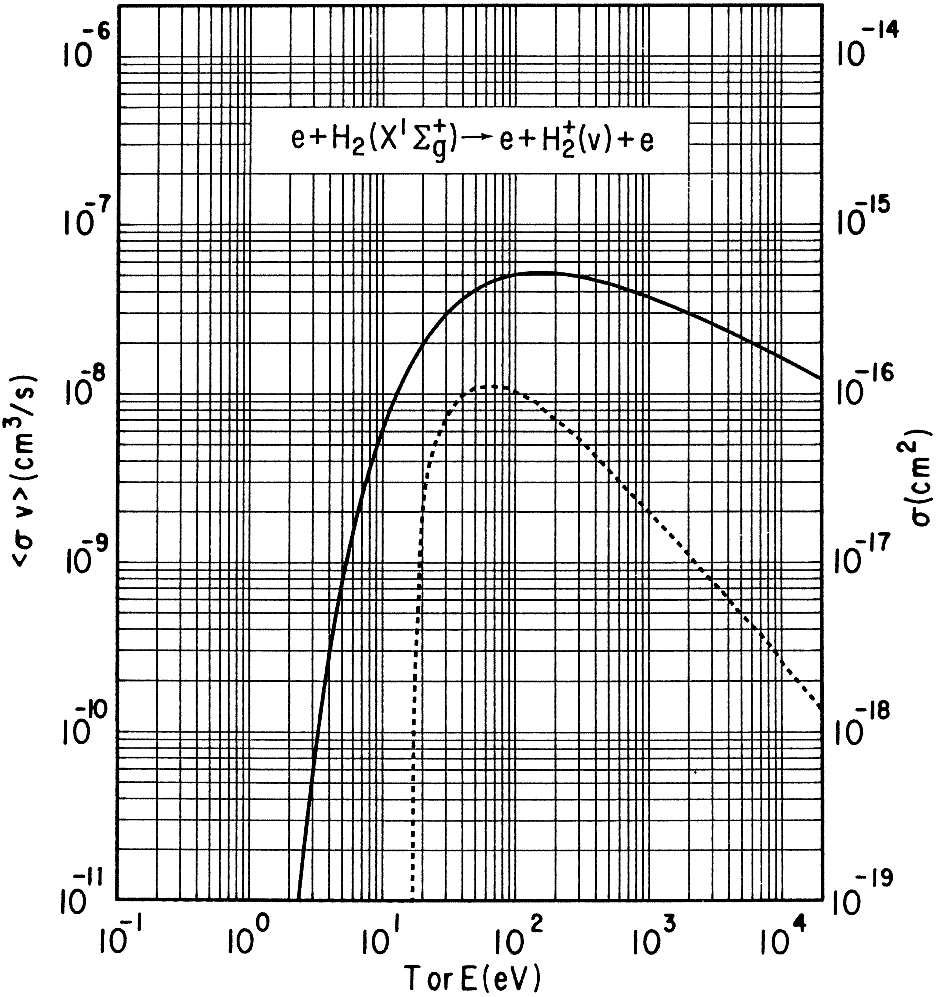
Comments:

(1) The distribution of $H_2^+(v)$ over the vibrational quantum numbers is known (Busch and Dunn 1972):

v	0	1	2	3	4	5	6	7	8	9	Σ(v≥10)
%	11.9	19.0	18.8	15.2	12.5	7.5	5.2	3.7	2.4	1.6	2.2

(2) σ_{exp}^{fit} represents a least squares fit to the experimental data.

(3) For the mean energy distribution of ejected electrons $\langle E_{\bar{e}_2} \rangle$, see Sect. 2.1.5.


$e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^+(v) + e$
$\langle\sigma v\rangle(cm^3/s)$
$\sigma(cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.10 $e_1+H_2\ (X^1\Sigma_g^+) \rightarrow \bar{e}_1+[H_2^+\ (\Sigma_g \text{ and } \Sigma_u)+\bar{e}_2] \rightarrow \bar{e}_1+H^+ + H(1s)+\bar{e}_2$

$E_{th} = E_{th}(\Sigma_g) = 18.0$ eV, $[E_{th}(\Sigma_u) = 26.0$ eV$]$.

Cross Section:

$E = E_{th} - 40$ eV: $\sigma_{ion}^{diss}(\Sigma_g,\Sigma_u) = \sigma_{ion}^{diss}(\Sigma_g) + \sigma_{ion}^{diss}(\Sigma_u)$.

Reference: Crowe and McConkey (1973)

$E = 40\text{-}10^3$ eV: $\sigma_{ion}^{diss} = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

$E = 10^3 - 6 \times 10^3$ eV: $\sigma_{ion}^{diss} = \sigma_{se}^{B}$.

Mean Energy of Ejected Particles:

$E_{e_1} = 18.0\text{-}18.5$ eV: $\Delta E_{e_1}^{(-)} = E_{e_1}$; $E_{\bar{e}_1} = E_{\bar{e}_2} = 0$; $E_{H^o} = E_{H^+} = \frac{1}{2}(E - E_{th})$,

$E_{e_1} = 18.5\text{-}26$ eV: $<\Delta E_{e_1}^{(-)}>_{FC} = 18.25 + E_{\bar{e}_2}$; $E_{\bar{e}_1} \simeq E_{\bar{e}_2}$; $E_{H^o} = E_{H^+} \simeq 0.25$ eV,

$E_{e_1} = 26\text{-}38$ eV: $\Delta E_{e_1}^{(-)} = E_{e_1}$; $E_{\bar{e}_1} = E_{\bar{e}_2} = 0$; $E_{H^o} = E_{H^+} = \frac{1}{2}(E_{e_1} - E_{th})$,

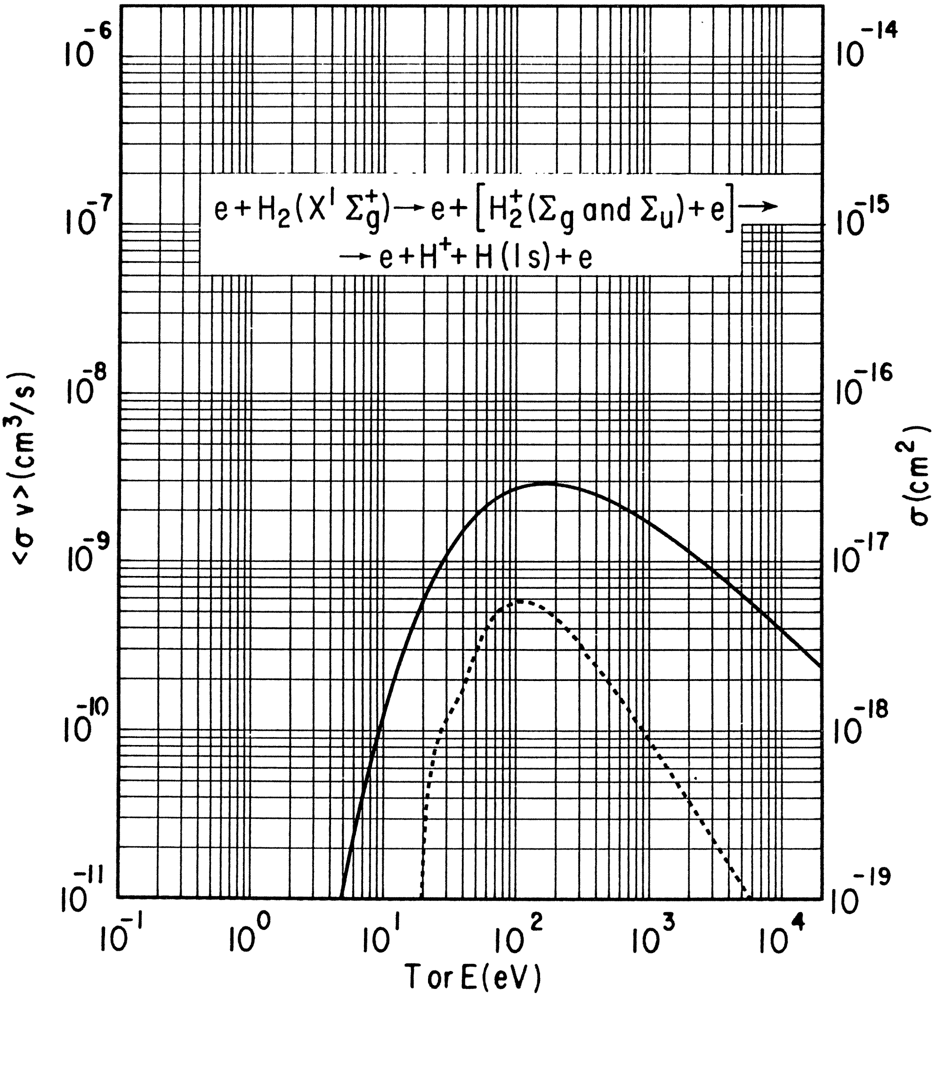
$E_{e_1} = 38\text{-}40$ eV: $\Delta E_{e_1}^{(-)} = 33.6$ eV $+ E_{\bar{e}_2}$; $E_{\bar{e}_1} \simeq E_{\bar{e}_2}$; $E_{H^o} = E_{H^+} = 7.8$ eV,

$E_{e_1} > 40$ eV: $\Delta E_{e_1}^{(-)} = 33.6$ eV $+ E_{\bar{e}_2}$; $<E_{\bar{e}_2}> = 3.7$ eV; $E_{H^o} = E_{H^+} = 7.8$ eV.

Comments:

(1) $\sigma_{ion}^{diss}(\Sigma_g,\Sigma_u)$ in the region E_{th} to 40 eV have been calculated within the first Born approximation.

(2) The electron energy loss and mean energies of the products are calculated on the basis of potential energy diagrams (Sect. 8.2). Equipartition of the dissociation energy is assumed.



$e + H_2(X^1\,\Sigma_g^+) \rightarrow e + [H_2^+(\Sigma_g \text{ and } \Sigma_u) + e] \rightarrow$
$\rightarrow e + H^+ + H(1s) + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle\sigma v\rangle\,(cm^3/s)$
$\sigma\,(cm^2)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

2.2.11 $\boxed{e_1 + H_2^+(v) \rightarrow \bar{e}_1 + H^+ + H^+ + \bar{e}_2, \quad (v = 0-9)}$

$E_{th} = 14.7$ eV, $\langle \Delta E_{e_1}^{(-)} \rangle = 15.5$ eV $+ E_{\bar{e}_2}$.

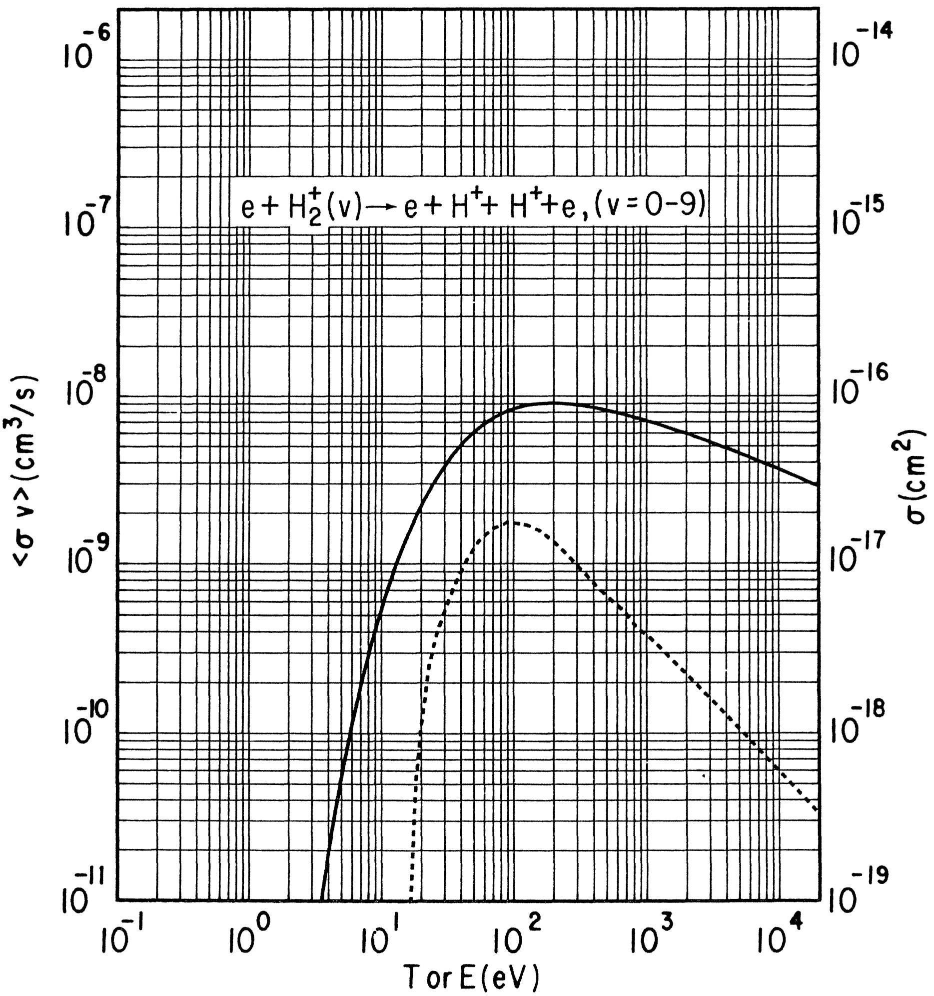
Cross section:

$E_{e_1} = E_{th} - 10^3$ eV: $\sigma_{ion}^{diss} = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

$E_{e_1} = 10^3 - 2 \times 10^4$ eV: $\sigma_{ion}^{diss} = \sigma_{se}^{B}$.

Comment: $\langle \Delta E_{H^+}^{(+)} \rangle_{\bar{v},FC}$ for each H^+ is equal to $\simeq 0.4$ eV and is obtained from the average vibrational energy of H_2^+ (which approximately coincides with that for the state $\bar{v} \simeq v \simeq 3$), and then averaged over the Franck-Condon region. For $E_{\bar{e}_2}$, see Sect. 2.1.5.



$e + H_2^+(v) \rightarrow e + H^+ + H^+ + e, (v = 0-9)$
$<\sigma v> (cm^3/s)$
$\sigma (cm^2)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)

2.2.12 $\boxed{e_1+H_2^+(v) \rightarrow e+H_2^{+*}(2p\sigma_u) \rightarrow e+H^+ + H(1s), \quad (v'=0-9)}$

$\langle E_{th}\rangle = 2.4$ eV, $\langle \Delta E_e^{(-)}\rangle_{\bar{v},FC} = 10.5$ eV.

Cross Section:

$E = \langle E_{th}\rangle_{\bar{v}} - 10^3$ eV: $\sigma_{exc}^{diss} = \sigma_{exp}^{e}$.

Reference: Takayanagi and Suzuki (1978)

$E = 10^3 - 2 \times 10^4$: $\sigma_{exc}^{diss} = \sigma_{se}^{B}$.

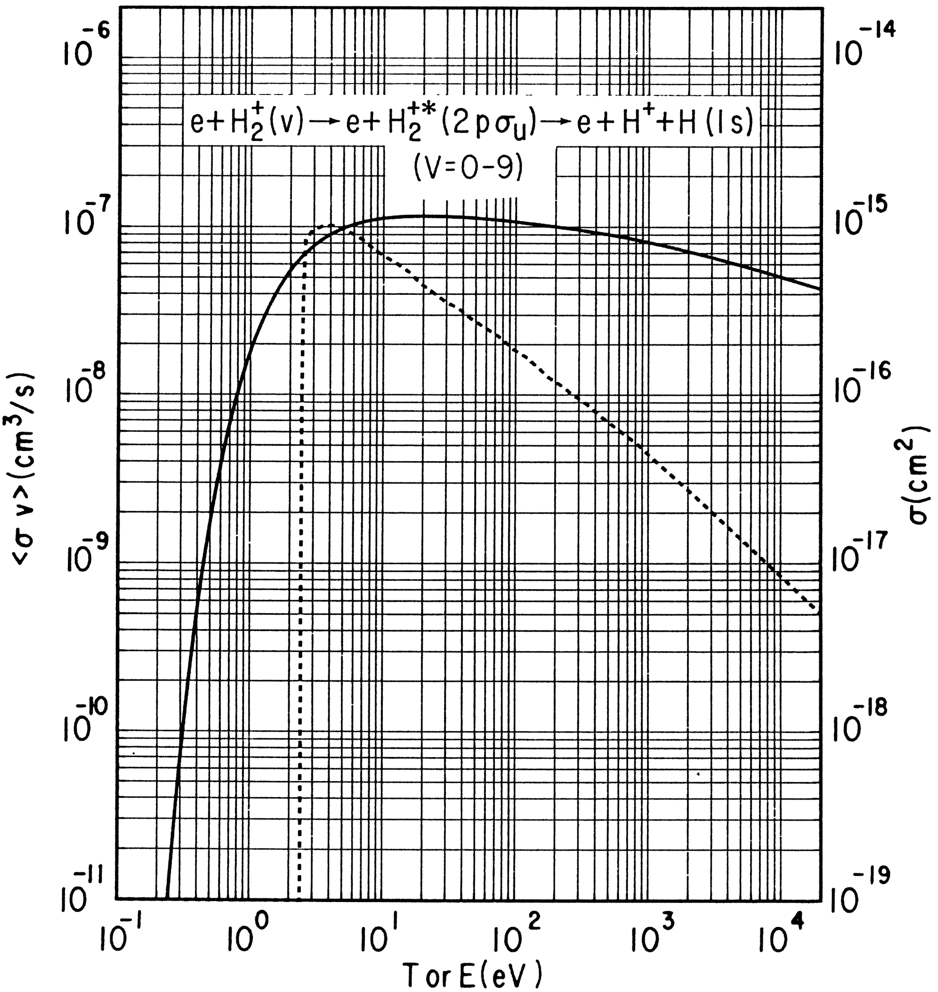
Mean Energy of Reaction Products:

$\langle \Delta E_{H^+}^{(+)}\rangle_{\bar{v},FC} \simeq \langle \Delta E_{H^o}^{(+)}\rangle_{\bar{v},FC} = 4.3$ eV.

Comments:

(1) $\langle ...\rangle_{\bar{v},FC}$ is an average over the Franck-Condon region corresponding to $\bar{v} \simeq v = 3$.

(2) σ_{exp}^{e} is an experimental cross section, extrapolated from E = 3.2 eV down to the threshold.



$e + H_2^+(v) \rightarrow e + H_2^{+*}(2p\sigma_u) \rightarrow e + H^+ + H(1s)$
(V=0-9)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

2.2.13 $\boxed{e+H_2^+(v) \rightarrow e+H_2^{+*}(2p\pi_u) \rightarrow e+H^++H^*(n=2), \quad (v=0-9)}$

$<E_{th}>_{\bar{v}} \approx 14.0$ eV, $<\Delta E_e^{(-)}>_{\bar{v},FC} \approx 17.5$ eV $\left[<E_{th}(v=0)>_{FC} \approx 25 \text{ eV}\right]$.

Cross Section:

$E = <E_{th}>_{\bar{v}} - 400$ eV: $\sigma_{exc}^{diss} = \sigma^B$

Reference: Takayanagi and Suzuki (1978)

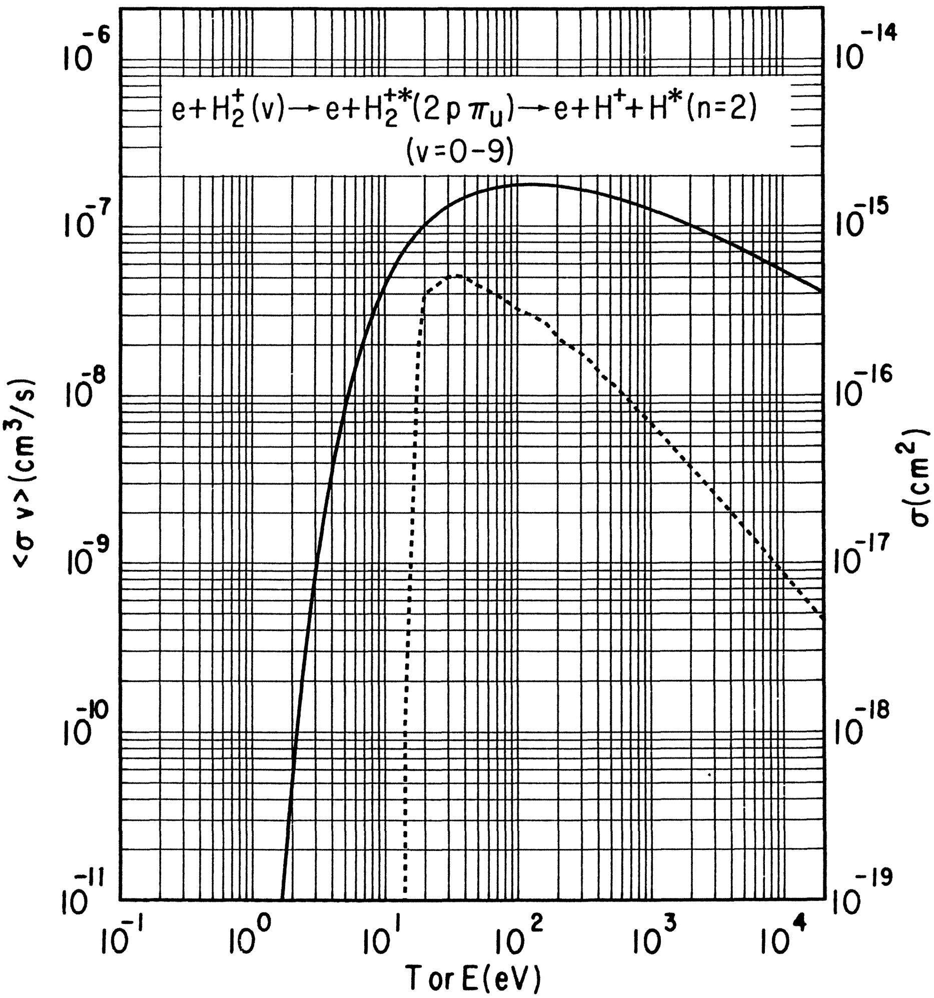
$E = 400 - 2 \times 10^4$ eV: $\sigma_{exc}^{diss} = \sigma_{ext}^B$.

Mean Energy of Dissociation Products:

$<\Delta E_{H^+}^{(+)}>_{\bar{v},FC} \approx <\Delta E_{H^*}^{(+)}>_{\bar{v},FC} \approx 1.5$ eV.

Comments:

(1) $<...>_{\bar{v},FC}$ is an average over the Franck-Condon region for $\bar{v} \approx v = 3$.
(2) σ_{ext}^B is a Born-type extrapolation of σ^B.
(3) Within n=2, the 2s and 2p states are populated according to their statistical weights.



$e + H_2^+(v) \rightarrow e + H_2^{+*}(2p\pi_u) \rightarrow e + H^+ + H^*(n=2)$
$(v = 0-9)$
$\langle\sigma v\rangle\ (cm^3/s)$
$\sigma\ (cm^2)$
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.14 $\boxed{e+H_2^+(v) \rightarrow H(1s)+H^*(n), \quad (v=0-9,\ n\geq 2)}$

$E_{th} = 0$ eV, $\Delta E_e^{(-)} = E$.

Cross Section:

$$\sigma_{tot} = \sum_{n\geq 2} \sigma(n) = \sigma_{exp} .$$

Reference: Jones (1977)

$\sigma(n=2) = 0.10\ \sigma_{exp}$; $\sigma(n=3) = 0.45\ \sigma_{exp}$;

$\sigma(n=4) = 0.22\ \sigma_{exp}$; $\sigma(n=5) = 0.12\ \sigma_{exp}$;

$\sigma(n=6) = 0.069\ \sigma_{exp}$; $\sigma(n\geq 7) = 10/n^3\ \sigma_{exp}$.

Mean Energy of Reaction Products:

$$<\Delta E^{(+)}_{H^o}> \simeq <\Delta E^{(+)}_{H^*(n)}> \simeq \frac{1}{2}\left(E - \frac{Ry}{n^2}\right) .$$

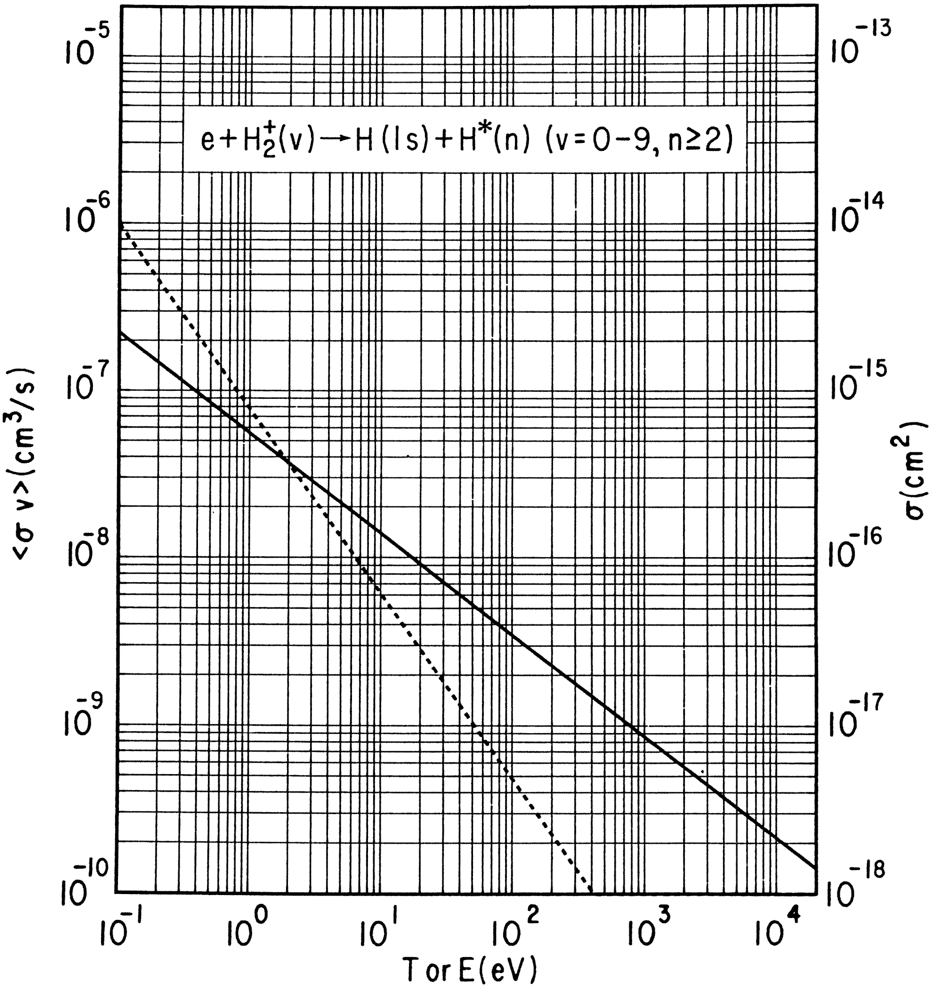
Comments:

(1) $\sigma(n)$ is averaged over the vibrational levels v.

(2) For very low energies, < 0.1 eV, $\sigma(v=0-2)$ is considerably smaller than σ(all v) (McGowan et al. 1979).

(3) The $\sigma(n)$ have been determined on the basis of theoretical calculations (Zhdanov and Chibisov 1978), and experimental data (Vogler and Dunn 1975; Phaneuf et al. 1975) on $\sigma(n)$ and all normalized to the experimental data on σ_{tot} (Peart and Dolder 1973).

(4) Within a given n, the population of sublevels $n\ell$ may be assumed statistical: $\sigma_{n\ell} = (2\ell+1/n^2)\sigma_n$.


$e + H_2^+(v) \rightarrow H(1s) + H^*(n)$ $(v = 0-9, n \geq 2)$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

2.2.15a $\boxed{e+H_3^+ \rightarrow H+H+H}$

2.2.15b $\boxed{e+H_3^+ \rightarrow H_2(v>5)+H^*(n=2)}$

$E_{th} = 0.0, \quad \Delta E_e^{(-)} = E$

Cross Section:

$E = 0.1 - 6$ eV : $\sigma_{tot}^{diss} = \sigma_{exp}$ (total)

References: Auerbach et al. (1977), Mitchell et al. (1983), Peart and Dolder (1974)

$E = 6 - 300$ eV : $\sigma \propto E^{-1}$.

Mean Energy of Reaction Products:

Channel (a): $<\Delta E_H^{(+)}> \simeq (1/3)$ E.

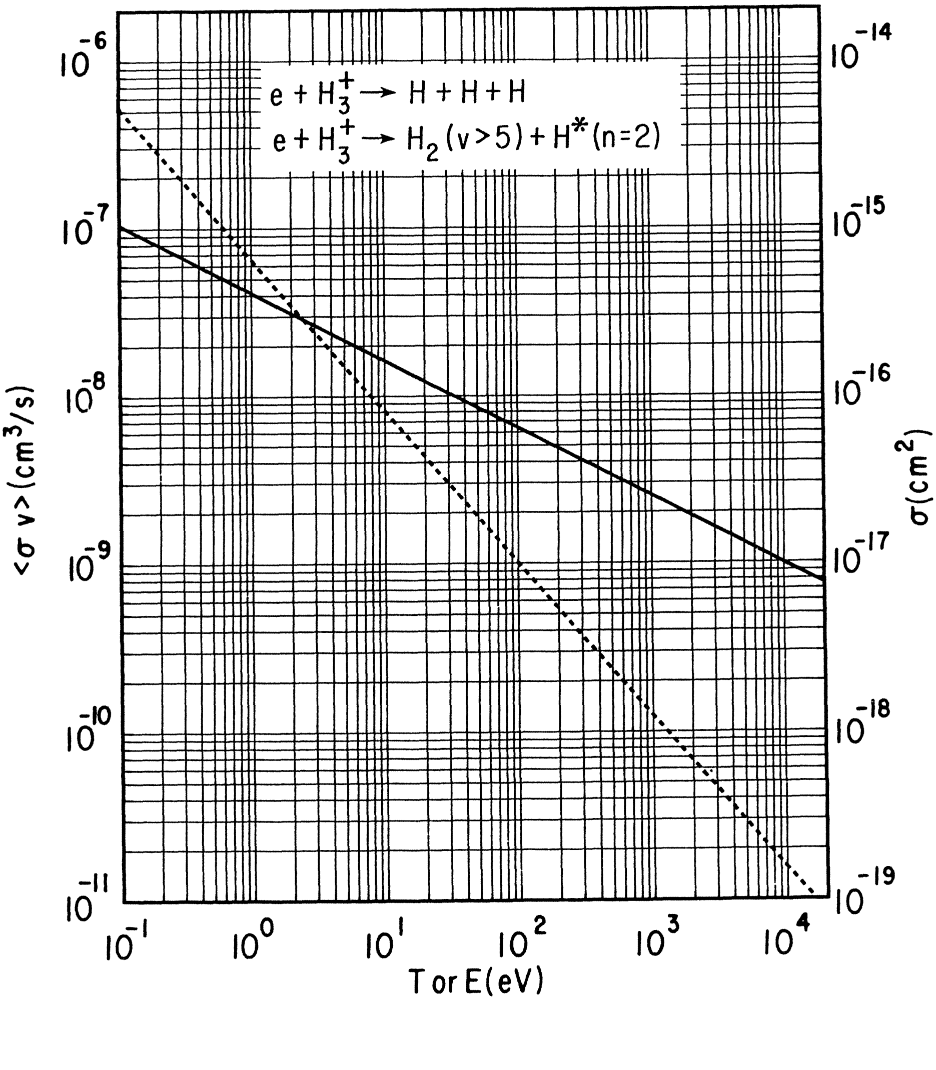
Channel (b): $<\Delta E_{H_2}^{(+)}> \simeq (2/3)$ E, $<\Delta E_{H^*}> \simeq (1/3)$ E.

Comments:

(1) The cross section up to 6 eV is a smoothed average of data (including resonances) from Peart and Dolder (1974) and Auerbach et al. (1977) as corrected in Mitchell et al. (1983), and is valid only for a plasma with a distribution of vibrationally excited states. For $H_3^+(v=0)$, $<\sigma v>$ is too small to be measured (Adams et al. 1984).

(2) The branching to channels (a) and (b) has been measured by Mitchell et al. (1983). Over the range 0.1 to 1.0 eV the formation of H + H + H is favored by about 2.5:1, though there is considerable variation with energy (perhaps due to resonance effects). Above 1 eV, theoretical calculations by Kulander and Guest (1979) indicate that the reverse is true and the dominant channel is predicted to be $H_2(^1\Sigma_g^+)$ + H(2s or 2p).

(3) The cross section presented in the figure has the fit, $\sigma_{tot}^{diss} = 6.47 \times 10^{-16} E^{-0.905}$ cm^2, close to the theoretical E^{-1} prediction.



$e + H_3^+ \rightarrow H + H + H$
$e + H_3^+ \rightarrow H_2(v>5) + H^*(n=2)$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

2.2.16 $\boxed{e+H_3^+ \rightarrow e+H^++2H}$

$E_{th} = 14$ eV, $\Delta E_e^{(-)} = E_{th}$.

<u>Cross Section</u>:

$E = E_{th} - 600$ eV: $\sigma_{diss} = \sigma_{exp}$.

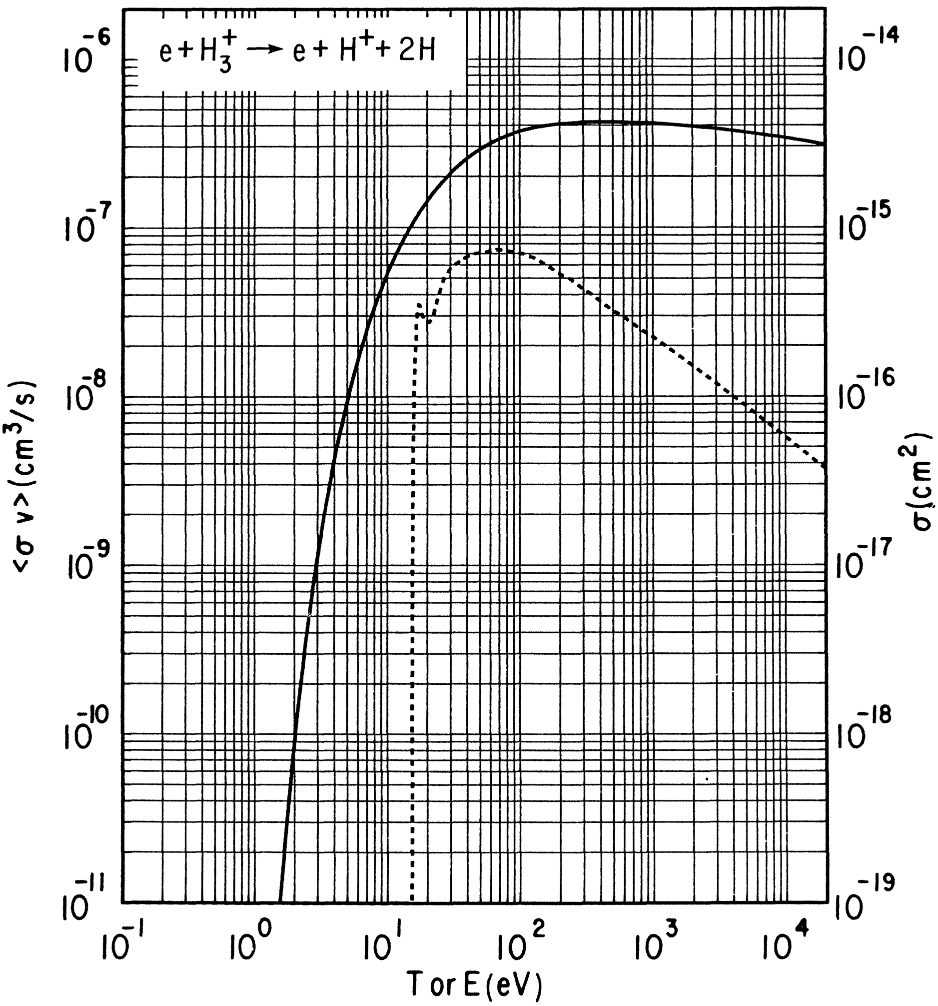
Reference: Jones (1977)

$E = 600 - 2 \times 10^4$ eV: $\sigma_{diss} = \sigma_{se}^B$.

<u>Mean Energy of Reaction Products</u>:

$<\Delta E_{H^+}^{(+)}> \simeq <\Delta E_H^{(+)}> \simeq 4.33$ eV .

<u>Comment</u>: In determining $<\Delta E^{(+)}>$ of the reaction products, it is assumed that the dissociation energy of H_3^+ is ≈ 1 eV and all three products share equally the available excitation energy.



$e + H_3^+ \rightarrow e + H^+ + 2H$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v>(cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma(cm^2)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

2.2.17 $\boxed{e+H_2(v\geq4) \rightarrow (H_2^-)^* \rightarrow H^-+H}$

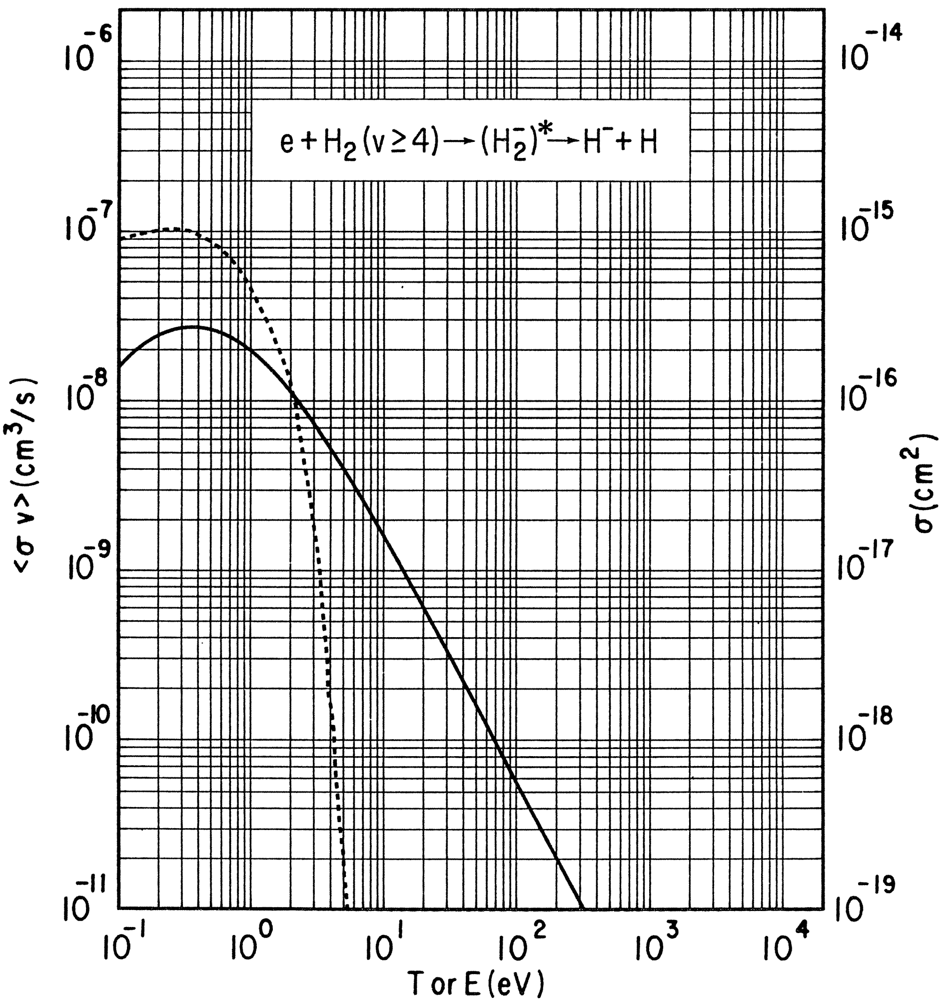
$$E_{th} \simeq 0.1 \text{ eV}; \quad \Delta E_e^{(-)} = E, \quad E \leq 0.745$$
$$= 0.745 \text{ eV}, \quad E \geq 0.745 \text{ eV}.$$

Cross Section:

$$\sigma_{cap}^{diss} = \sum_{v=4}^{9} \sigma_{cap}(v) .$$

References: $\sigma(v=4)$, Wadehra and Bardsley (1978); $\sigma(v=5-9)$, Wadehra (1980)

Comment: The contributions of $\sigma(v=0)$ to $\sigma(v=3)$ to the total dissociative capture cross section σ_{cap}^{diss} are negligible (see Wadehra and Bardsley 1978).



e + H2(v≥4) → (H2−)* → H− + H
<σ v> (cm3/s)
σ(cm2)
10-6
10-7
10-8
10-9
10-10
10-11
10-14
10-15
10-16
10-17
10-18
10-19
10-1
100
101
102
103
104
T or E (eV)

2.3 Electron Collisions with He, He^+, and He^{2+}

2.3.1 $\boxed{e+He(1s^2|^1S) \rightarrow e+He^*(1snp|^1P), \quad (n\geq 2)}$

$$E_{th} = E^{exc}_{np}, \quad \Delta E^{(-)}_{e} = E^{exc}_{np} \ .$$

<u>Cross Section:</u>

$$\sigma^{se}(1s\rightarrow np) = 3.52 \times 10^{-16} \left(Ry/E^{exc}_{np}\right)^2 f_{1s\rightarrow np} Y(u) \quad \left[cm^2\right],$$

$$Y(u) = \frac{1}{u} \left\{1 - \exp\left[-\xi(u + 1)\right]\right\} \ell nu \ ,$$

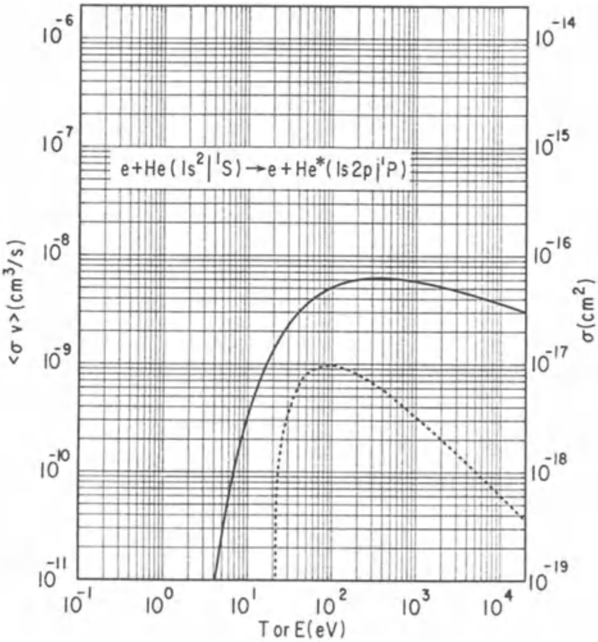
$$u = \frac{E}{E^{exc}_{np}} \ ; \ \xi = \beta \left(\frac{Ry\ f_{1s\rightarrow np}}{E^{exc}_{np}}\right)^{-\gamma} \ ,$$

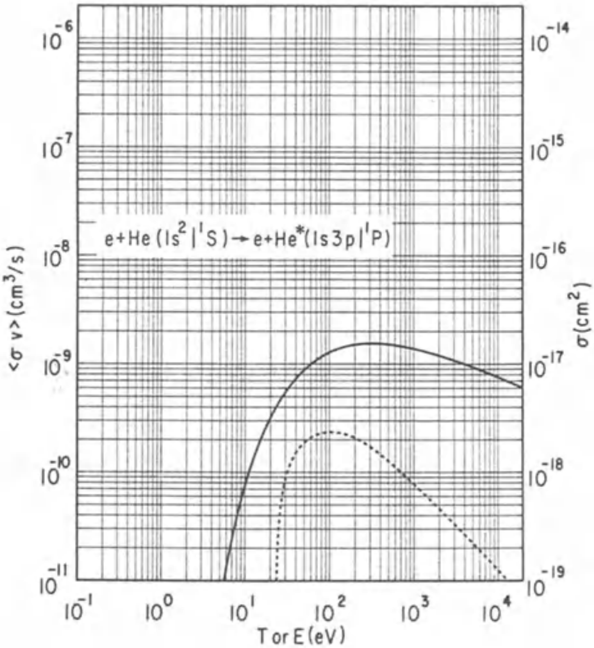
$f_{1s\rightarrow np}$: oscillator strength (see Appendix A.4).

n	2	3	≥ 4
β	0.1	0.15	0.2
γ	0.3	0.2	0.1

Reference: Fujimoto (1978)

<u>Comment</u>: For n=2, σ_{se} does not reproduce adequately the experimental data in the region 35-300 eV. In the figure, only the experimental data are used for n=2. For other transitions σ_{se} can be used in the entire energy range.


e+He (1s^2|^{1}S) → e+He*(1s2p|^{1}P)
<σ v> (cm^3/s)
σ(cm^2)
T or E(eV)


e+He (1s^2|^{1}S) → e+He*(1s3p|^{1}P)
<σ v> (cm^3/s)
σ(cm^2)
T or E(eV)

2.3.2 $\boxed{e+He(1s^2|^1S) \rightarrow e+He^*(1snl|^1L), \quad (n\geq 2,\ l\neq 1}$

$E_{th} = E^{exc}_{n\ell}, \quad \Delta E^{(-)}_{e} = E^{exc}_{n\ell}$ (see Appendix A.4).

Cross Section:

$$\sigma^{se}_{exc}(1s\rightarrow n\ell) = 3.52 \times 10^{-16}\ B\left(Ry/E^{exc}_{ne}\right)Y(u) \quad \left[cm^2\right],$$

$$Y(u) = \frac{1}{u^2}\left[1 - \exp(-tu)\right]\left(u - 1 + \delta\right),$$

$$t = 1.6\ \beta B^{-\gamma}\left(\frac{Ry}{4E^{He}_{ion}}\ \frac{E^{exc}_{n\ell}}{E^{ion}_{n\ell}}\right)^{1-\gamma},$$

$$u = E/E^{exc}_{n\ell},\ E^{He}_{ion} = 24.5876\ .$$

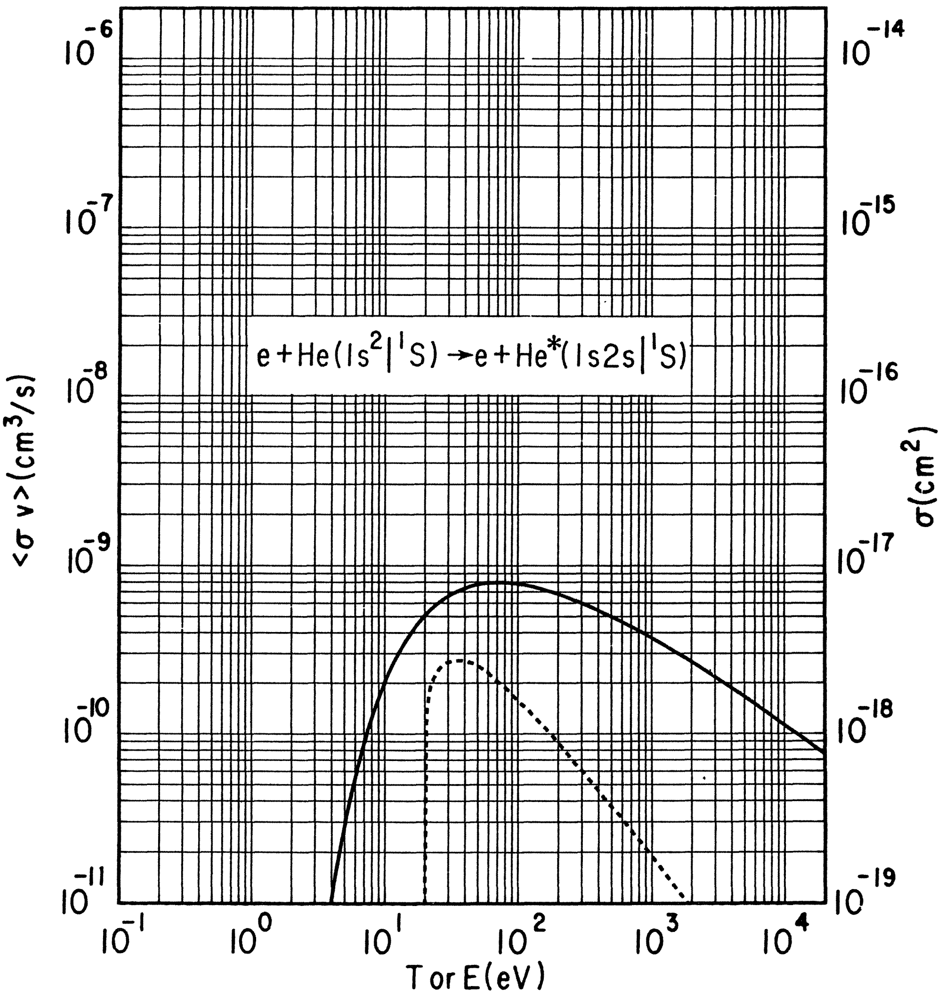
$n\ell$	2s	3s	3d	≥ 4s	4d	4f	≥ 5ℓ
β	1	0.1	0.5	0.3	0.5	0.5	0.5
γ	0.7	0.2	0.7	0.5	0.7	0.7	0.7
δ	0.15	7.0(-2)	0.2	2.0(-2)	0.2	0.2	0.2

Reference: Fujimoto (1978)

Comments:

(1) The values of B for 2s, 2p, and 3d for the e-H case are tabulated by Kingston and Lauer (1966) and in application to reaction 3.2, they have to be divided by two in order to account for the two electrons in He.

(2) The cross section in the figure for $n\ell|^1L = 2s|^1S$ is taken from Fujimoto (1978).



$e + He(1s^2 \mid {}^1S) \rightarrow e + He^*(1s2s \mid {}^1S)$
$<\sigma v> (cm^3/s)$
$\sigma (cm^2)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)

2.3.3 $\boxed{e+He(1s^2|^1S) \rightarrow e+He^*(1snl|^3L), \quad (n\geq 2,\ l\geq 0)}$

$$E_{th} = E_{n\ell}^{exc}, \qquad \Delta E_e^{(-)} = E_{n\ell}^{exc}.$$

Cross Section:

$$\sigma_{exc}^{se}(1s\rightarrow n\ell|^1S\rightarrow {}^3L) = 3.52 \times 10^{-16}\left[a\left(\frac{1}{u^3} - \frac{1}{u^5}\right) + \frac{b}{u^9}\right] \ [cm^2],$$

$$u = \frac{E}{E_{n\ell}^{exc}},$$

$n\ell$	2s	3s	≥4s	2p	3p	≥4p	3p	4d	≥4f
a	3.13×10^{-2}	1.3×10^{-2}	$\frac{0.275}{(n^*)^3}$	4.5×10^{-2}	2.5×10^{-2}	$\frac{0.75}{(n^*)^3}$	3.5×10^{-3}	$\frac{0.088}{(n^*)^3}$	$\frac{0.045}{(n^*)^3}$

$b = 1.07 \times 10^{-2}$, for $n\ell = 2s$

$= 0.00$, in all other cases

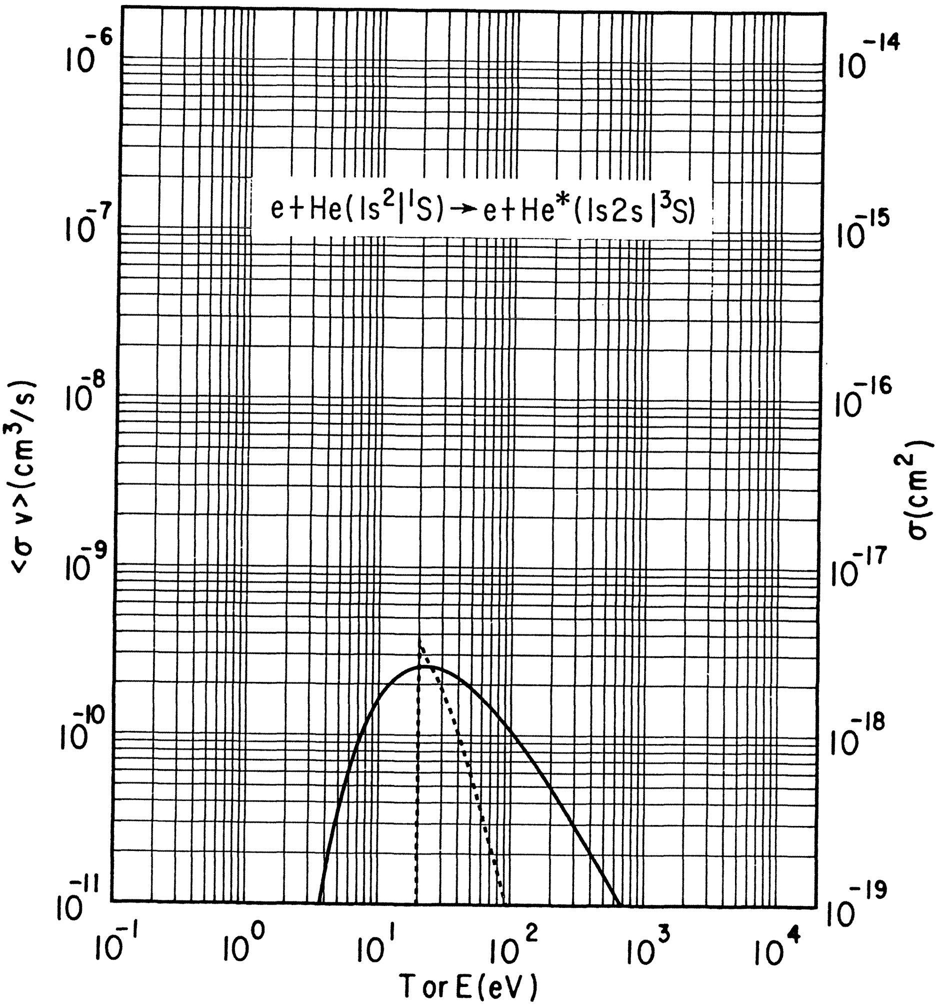
$n^* = (Ry/E_{n\ell}^{ion})^{1/2}$.

Reference: Fujimoto (1978)

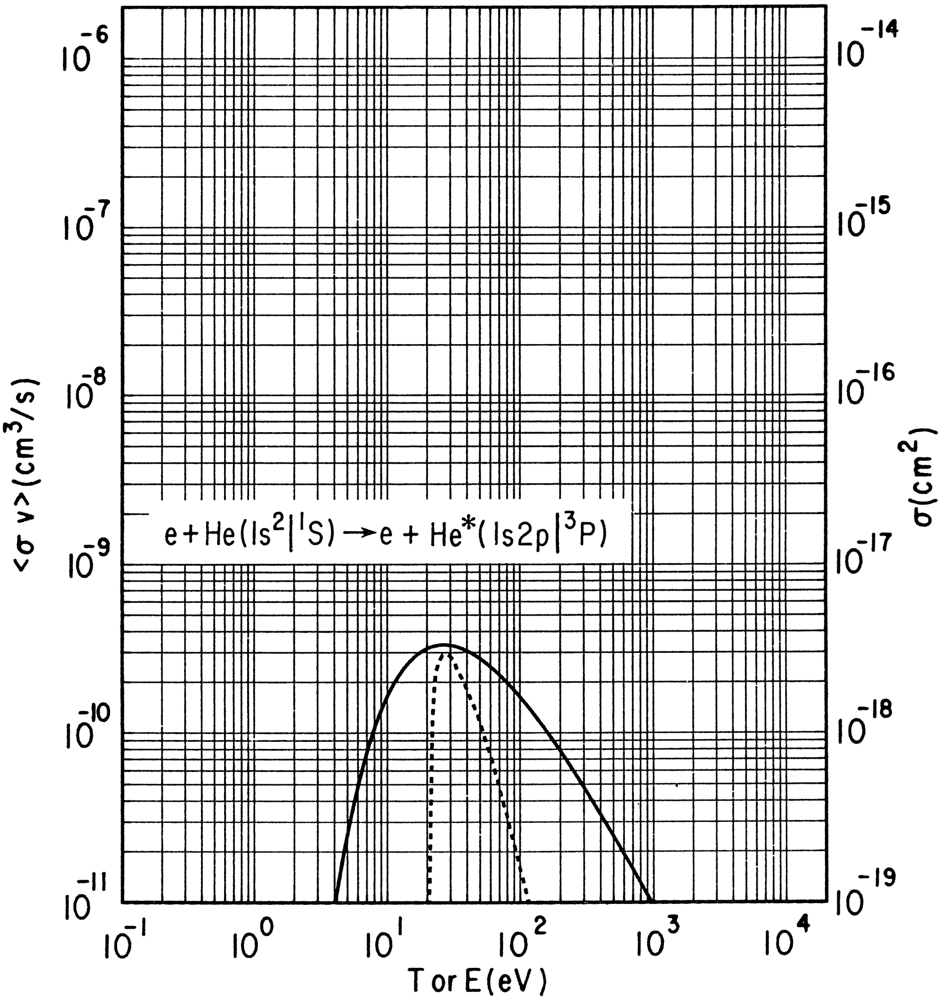
Comments:

(1) For the $1s^2|^1S) \rightarrow 1s2p|^3P)$ transition, σ_{exc}^{se} does not represent the experimental data in the range 40-100 eV sufficiently well, therefore in the figure the experimental data are plotted (see Fujimoto 1978).

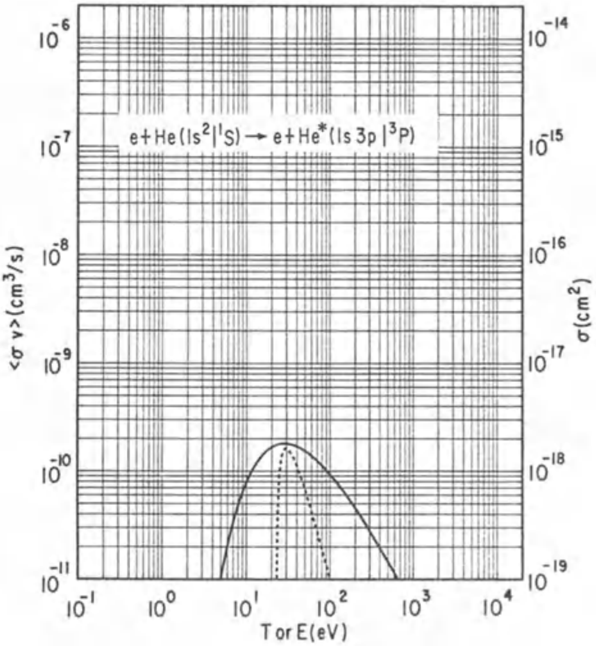
(2) The cross section for the $1s^2|^1S) \rightarrow 1s2s|^3S)$ transition agrees to within 20-30% with the recent measurements Johnston and Burrows (1983) and with the 11-state R-matrix calculations of Freitas et al. (1984)



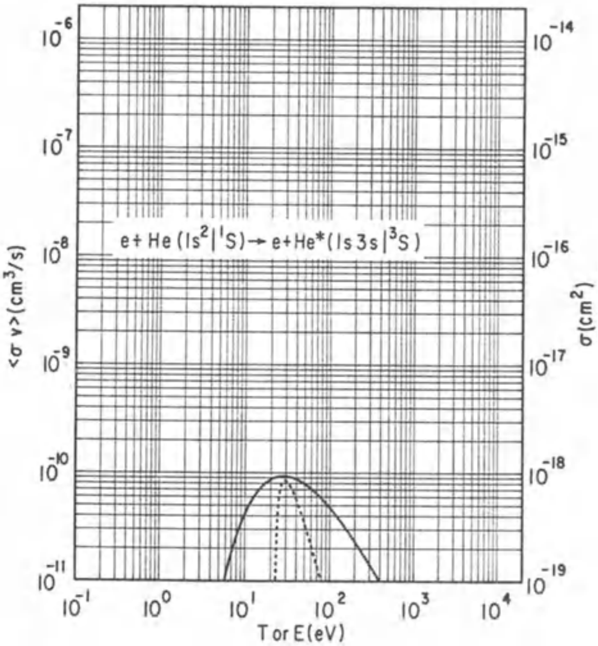
$e + He(1s^2\,|^1S) \rightarrow e + He^*(1s2s\,|^3S)$
$\langle \sigma v \rangle (cm^3/s)$
$\sigma (cm^2)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle \sigma v \rangle (cm^3/s)$
$\sigma (cm^2)$
$e + He(1s^2|^1S) \rightarrow e + He^*(1s2p|^3P)$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E (eV)



e + He (1s^2 | ^{1}S) → e + He*(1s 3p | ^{3}P)
$\langle\sigma v\rangle$ (cm^3/s)
σ (cm^2)
T or E (eV)



e + He (1s^2 | ^{1}S) → e + He*(1s 3s | ^{3}S)
$\langle\sigma v\rangle$ (cm^3/s)
σ (cm^2)
T or E (eV)

2.3.4 $e + He^*(1s2l|^3L) \rightarrow e + He^*(1s2l'|^1L')$

$E_{th} = \Delta E(^3L, ^1L')$, $\Delta E_e^{(-)} = E_{th}$, $\Delta E(^3L, ^1L') = |E_{exc}(^1L') - E_{exc}(^3L)|$.

Cross Section:

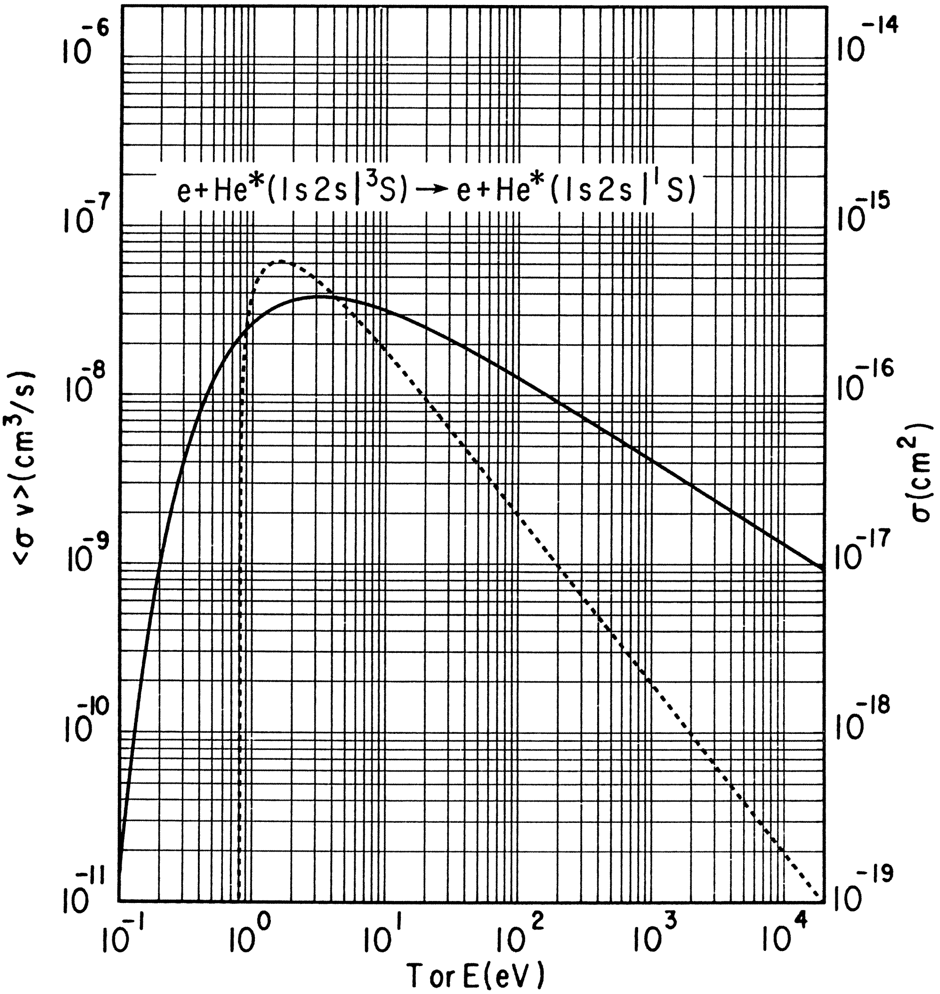
$$\sigma_{exc}^{se}(^3L \rightarrow ^1L') = 3.52 \times 10^{-16} Q \frac{(u-1)}{u^2} \ [cm^2],$$

$$u = \frac{E}{\Delta E(^3L, ^1L')} \ .$$

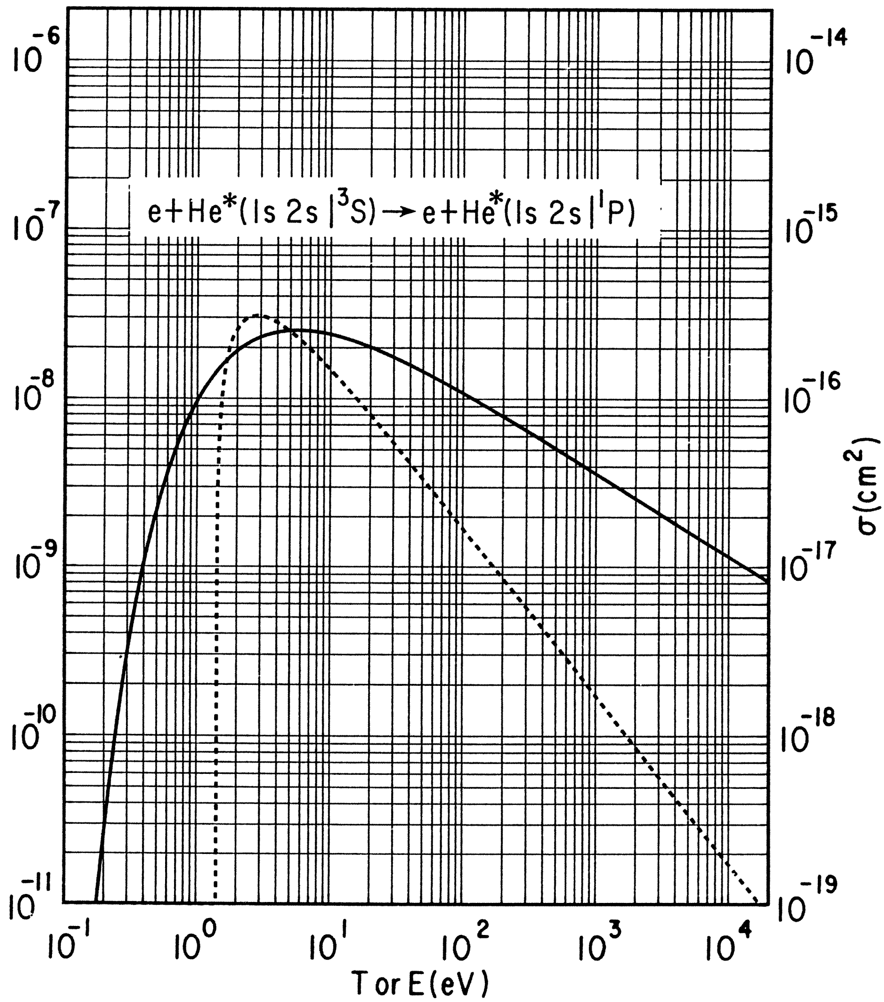
$2\ell^3L \rightarrow 2\ell^1L'$	$2s^3S \rightarrow 2s^1S$	$2s^3S \rightarrow 2p^1P$	$2p^3P \rightarrow 2s^1S$	$2p^3P \rightarrow 2p^1P$
Q	7.0	3.5	27.5	5.0

Reference: Fujimoto (1978)

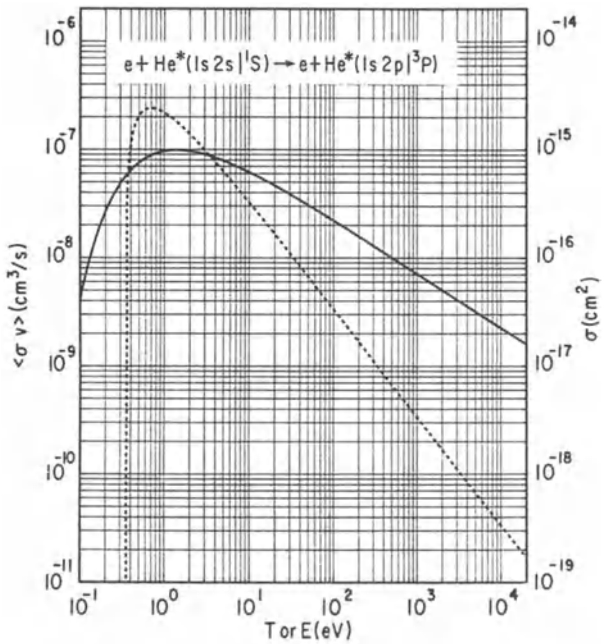
Comment: $E_{exc}(^{1,3}L)$ are given in Appendix A.3. For the $2p^3P$ and $2s^1S$ states the excitation transition is $2s^1S \rightarrow 2p^3P$ $[E_{exc}(^1S) < E_{exc}(^3P)]$ and the arrow in reaction 2.3.4 has to be reversed.



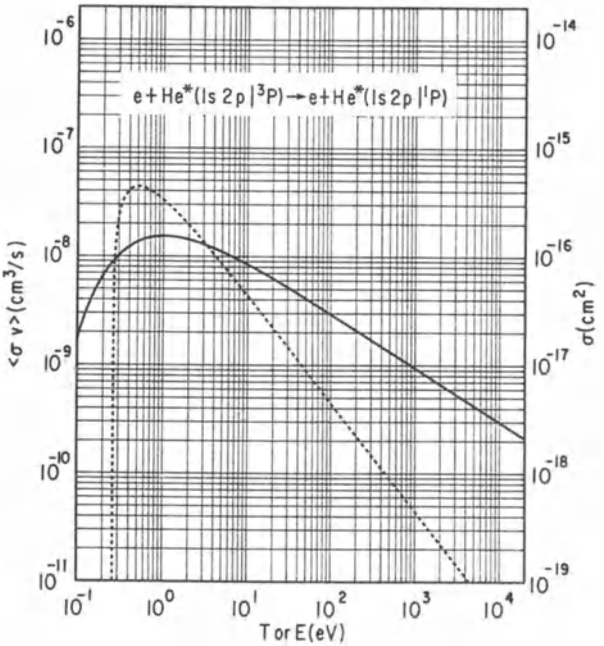
e + He*(1s2s | ^{3}S) → e + He*(1s2s | ^{1}S)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
<σ v>(cm^3/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
σ(cm^2)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)



e+He*(1s 2s |³S) → e+He*(1s 2s |¹P)
<σ v> (cm³/s)
σ (cm²)
T or E (eV)



e + He*(1s 2s | ¹S) → e + He*(1s 2p | ³P)
<σ v> (cm³/s)
σ (cm²)
T or E (eV)



e + He*(1s 2p | ³P) → e + He*(1s 2p | ¹P)
<σ v> (cm³/s)
σ (cm²)
T or E (eV)

2.3.5a $\boxed{e+He^*(1s2s|^1S) \rightarrow e+He^*(1s2p|^1P)}$

2.3.5b $\boxed{e+He^*(1s2s|^3S) \rightarrow e+He^*(1s2p|^3P)}$

$E_{th}(^1S \rightarrow {}^1P) = 0.602$ eV; $E_{th}(^3S \rightarrow {}^3P) = 1.145$ eV; $\Delta E_e^{(-)} = E_{th}$.

Cross Section:

$$\sigma_{exc}^{se}(2^{1,3}S \rightarrow 2^{1,3}P) = 3.52 \times 10^{-16}\ (Ry/\Delta E_{sp})^2\ f_{s\rightarrow p} Y(u)\quad [cm^2],$$

$$u = \frac{E}{\Delta E_{sp}}\ ;\quad \Delta E_{sp} = E_{th}\ ,$$

$$Y(u) = \frac{1}{u}\ \{1 - \exp[-\ \xi(u + 1)]\}\ \ell nu,$$

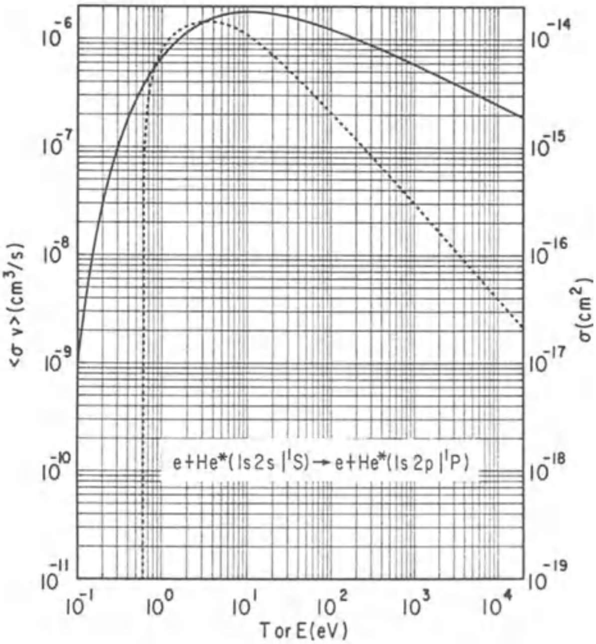
$$\xi = \beta\ \left(f_{s\rightarrow p}\ \frac{Ry}{\Delta E_{sp}}\right)^{-\gamma}\ ,$$

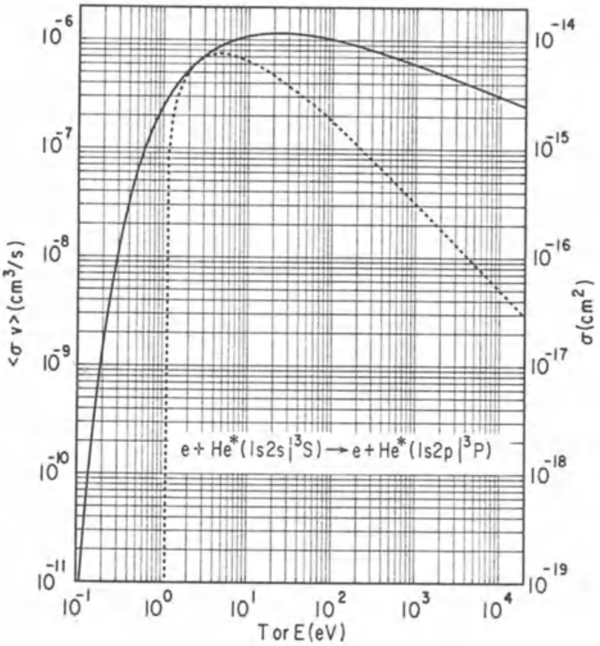
$f_{s\rightarrow p}$: oscillator strength.

Transition	β	γ	ΔE_{sp}	$f_{s\rightarrow p}$
$2s^1S \rightarrow 2p^1P$	0.8	0.7	0.602	0.376
$2s^3S \rightarrow 2p^3P$	0.5	0.2	1.145	0.539

Reference: Fujimoto (1978)

Comment: The cross section for $2s^3S \rightarrow 2p^3P$ is an average of different theoretical calculations with the proper Bethe-Born limit at high energy.


e + He*(1s2s | ¹S) → e + He*(1s 2p | ¹P)
<σ v>(cm³/s)
σ(cm²)
T or E(eV)


e + He*(1s2s | ³S) → e + He*(1s2p | ³P)
<σ v>(cm³/s)
σ(cm²)
T or E(eV)

2.3.6a $\boxed{e+He^*(1s2s|^1S) \rightarrow e+He^*(1snp|^1P), \quad (n\geq 3)}$

2.3.6b $\boxed{e+He^*(1s2s|^3S) \rightarrow e+He^*(1snp|^3P), \quad (n\geq 3)}$

$E_{th} = \Delta E_{2s,np}$, $\Delta E_e^{(-)} = E_{th}$; $\Delta E_{2s,np} = E_{exc}(np) - E_{exc}(2s)$

(see Appendix A.4)

Cross Section:

$$\sigma_{exc}^{se}\left(2s|^{1,3}S \rightarrow 2p|^{1,3}P\right) = 3.52 \times 10^{-16} \left(Ry/\Delta E_{2s,np}\right)^2 f_{2s\rightarrow np} Y(u) \ [cm^2],$$

$f_{2s\rightarrow np}$: oscillator strength, (see Appendix A.4).

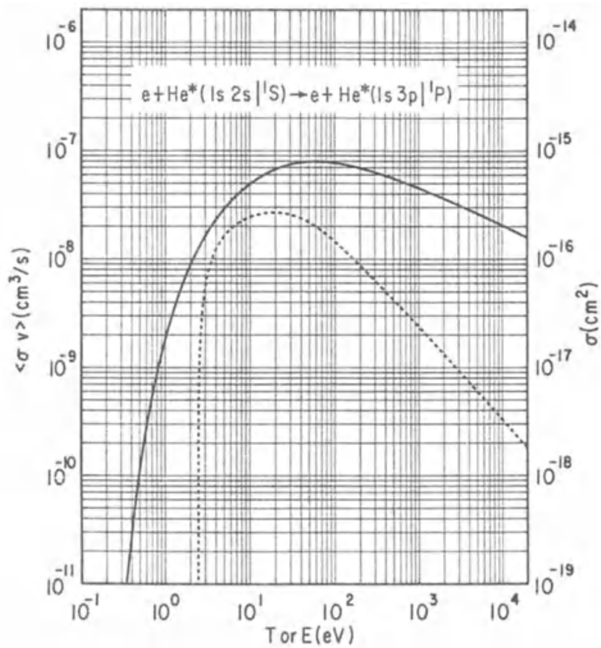
$$Y(u) = \frac{1}{u}\left\{1 - \exp\left[-\xi(u+1)\right]\right\} \ell nu,$$

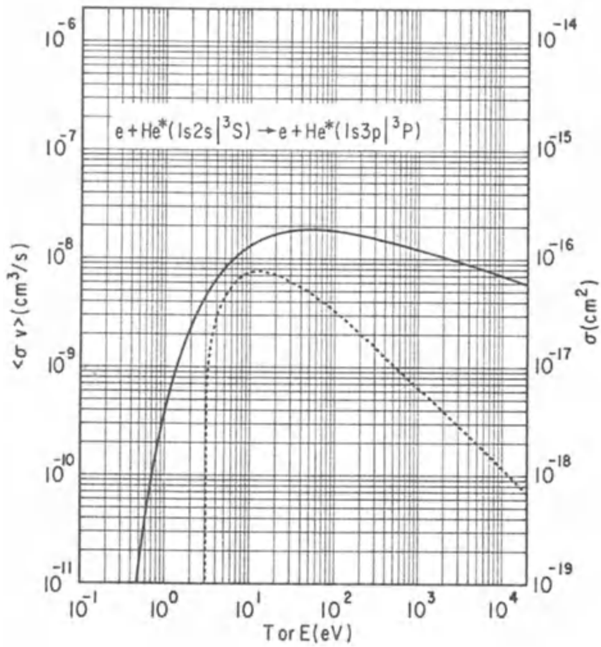
$$u = \frac{E}{\Delta E_{2s,np}}, \qquad \xi = \beta\left(f_{2s\rightarrow np} Ry/\Delta E_{2s,np}\right)^{-\gamma}.$$

Transition	β	γ
$1s2s|^1S \rightarrow 1snp|^1P$	0.1	0.7
$1s2s|^3S \rightarrow 1snp|^3P$	0.1	0.1

Reference: Fujimoto (1978)

Comment: For the $2s|^3S) \rightarrow 3p|^3P)$ excitation cross section in the figure, we have used an average of theoretical results (see Fujimoto, 1978) having the proper high-energy behavior, instead of using the formula given above.


e + He*(1s 2s | ¹S) → e + He*(1s 3p | ¹P)
<σ v> (cm³/s)
σ (cm²)
T or E (eV)


e + He*(1s2s | ³S) → e + He*(1s3p | ³P)
<σ v> (cm³/s)
σ (cm²)
T or E (eV)

2.3.7 $\boxed{e+He^*(1s2p|^{1,3}P) \rightarrow e+He^*(1snl|^{1,3}L)}$

($n \geq 3$, $\Delta S = 0$, ℓ = s or d; L = P or D)

$E_{th} = \Delta E_{2p,n\ell} = \Delta E_e^{(-)}$ (see Appendix A.3)

Cross Section:

$$\sigma_{exc}^{se}(2s\rightarrow n\ell) = 3.52 \times 10^{-16}(Ry/\Delta E_{2p,n\ell})^2\ f_{2p\rightarrow n\ell}Y(u) \quad [cm^2],$$

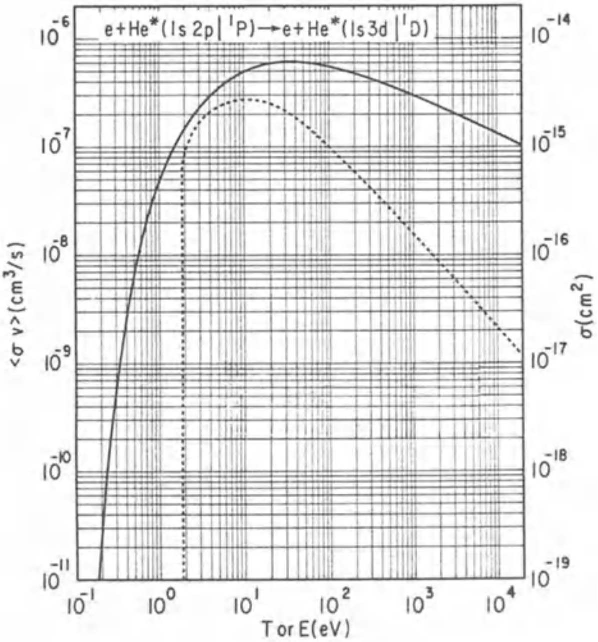
$$Y(u) = \frac{1}{u}\{1 - \exp[-\ \xi(u+1)]\}\ \ell n(u + \delta),$$

$$u = \frac{E}{\Delta E_{2p,n\ell}} \quad , \ \xi = \beta(f_{2p\rightarrow n\ell}Ry/\Delta E_{2p,n\ell})^{-\gamma} \ .$$

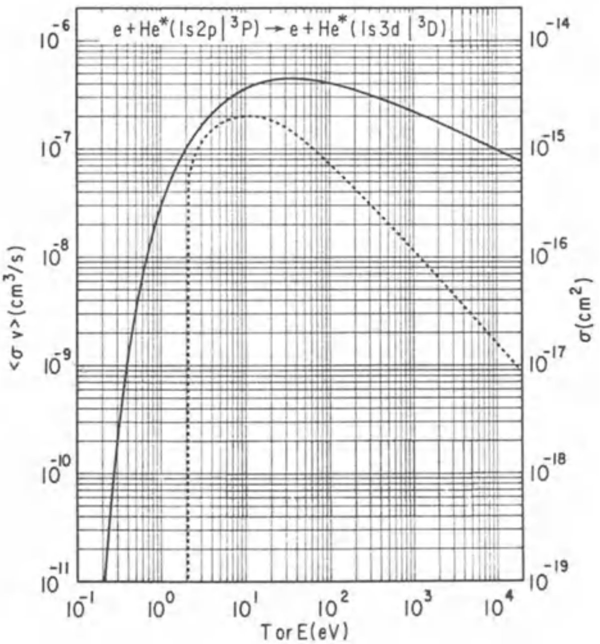
$\beta = 0.5$; $\gamma = 0.7$; $\delta = 0.2$, for all transitions,

$f_{2p\rightarrow n\ell}$: oscillator strength (see Appendix A.4)

Reference: Fujimoto (1978)



e + He*(1s 2p | ¹P) → e + He*(1s 3d | ¹D)
<σ v> (cm³/s)
σ(cm²)
T or E(eV)



e + He*(1s 2p | ³P) → e + He*(1s 3d | ³D)
<σ v> (cm³/s)
σ(cm²)
T or E(eV)

2.3.8 $\boxed{e+He^*(n) \rightarrow e+He^*(m), \quad (n\geq 3, \; m>n)}$

$E_{th} = \Delta E_{nm} = \Delta E_e^{(-)}$.

Cross Section:

$$\sigma_{exc}(n \rightarrow m) = 3.52 \times 10^{-16} \left(Ry/\Delta E_{nm}\right)^2 f_{n\rightarrow m} Y(u) \quad \left[cm^2\right],$$

$$Y(u) = \frac{1}{u} \left\{1 - \exp\left[-\xi\left(u + 1\right)\right]\right\} \ln(u + \delta) \; ,$$

$$u = \frac{E}{\Delta E_{nm}} \; , \; \xi = \beta\left(f_{n\rightarrow m} Ry/\Delta E_{nm}\right)^{-\gamma} \; ,$$

$$\beta = 0.5; \; \gamma = 0.7; \; \delta = 0.2,$$

$f_{n\rightarrow m}$: oscillator strength for hydrogenic transitions (see Appendix A.2).

Reference: Fujimoto (1978)

Comment: In calculating $\Delta E_{nm} = E_n^{ion} - E_m^{ion}$, an average value of the levels within a given n(m) is used. For instance, $E_3^{ion} \simeq 1.507$ eV, $E_4^{ion} \simeq 0.848$ eV, and for $n \geq 5$, E_n^{ion} are given in Appendix A.3.

2.3.9 $\boxed{e_1 + He(1s^2|^1S) \rightarrow \bar{e}_1 + He^+ + \bar{e}_2}$

$E_{th} = 24.588$ eV, $\Delta E_e^{(-)} = E_{th} + E_{\bar{e}_2}$.

Cross Section:

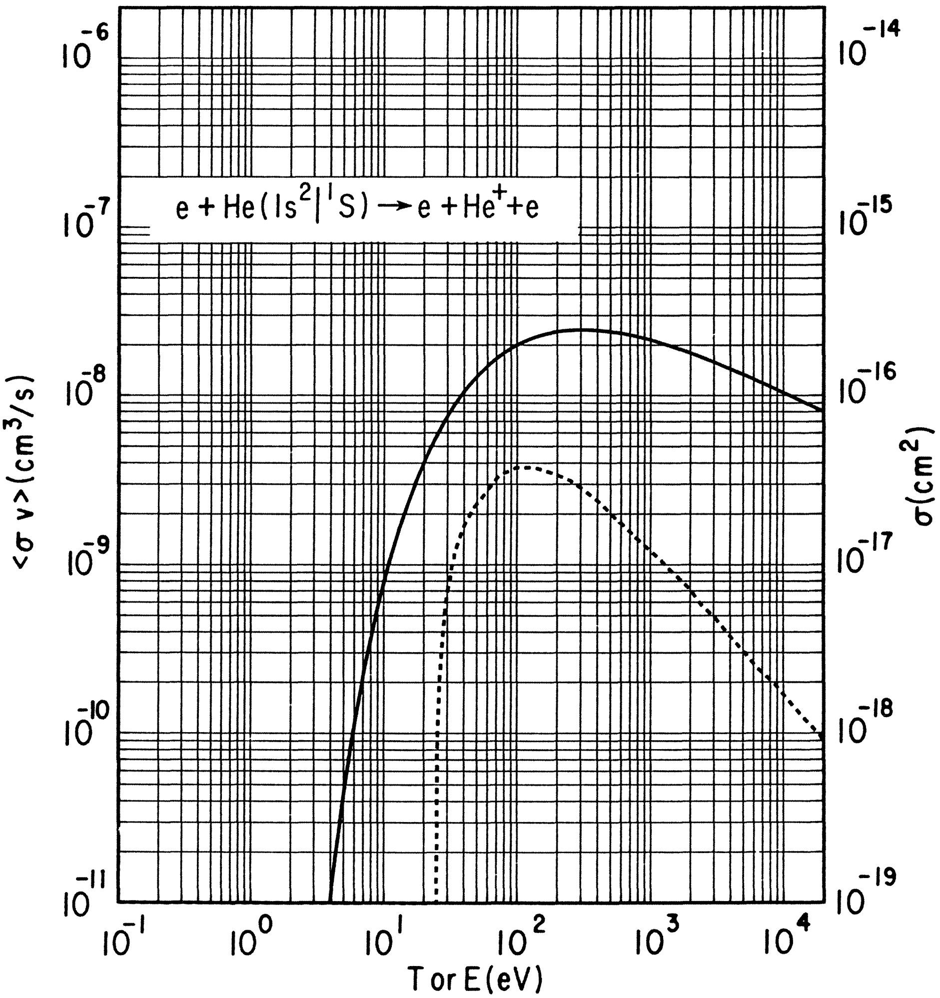
$E = E_{th} - 2 \times 10^4$ eV: $\sigma_{ion} = \sigma_{exp}$.

Reference: Freeman and Jones (1974)

Comments:

(1) For E = 30 to 400 eV, the data from Kieffer (1966) are plotted in the figure.

(2) For the mean energy of ejected electrons see Sect. 2.1.5.


e + He(1s²|¹S) → e + He⁺+e
<σ v> (cm³/s)
σ(cm²)
T or E(eV)
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴

2.3.10 $\boxed{e+He^*(1s2l|^{2S+1}L) \rightarrow \bar{e}_1+He^+(1s)+\bar{e}_2}$

$E_{th} = E^{ion}_{2\ell}$; $\Delta E^{(-)}_{e} = E_{th} + E_{\bar{e}_2}$.

Cross Section:

$$\sigma^{se}_{ion}(1s2\ell|^{2S+1}L) = 3.52 \times 10^{-16}(Ry/E^{ion}_{2\ell})^2 \; A \; \frac{(u-1)}{u^2} \; \ell n(1.25 \; \beta \; u) \quad [cm^2],$$

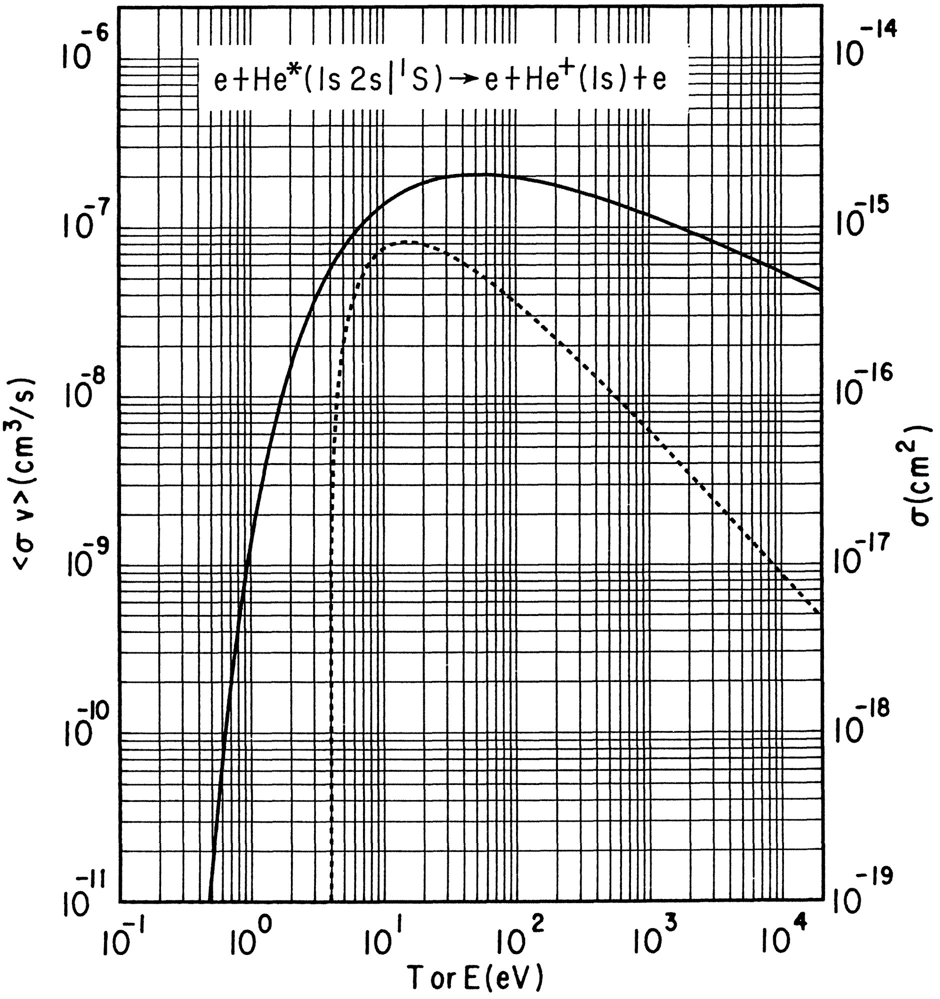
$u = E/E^{ion}_{2\ell}$,

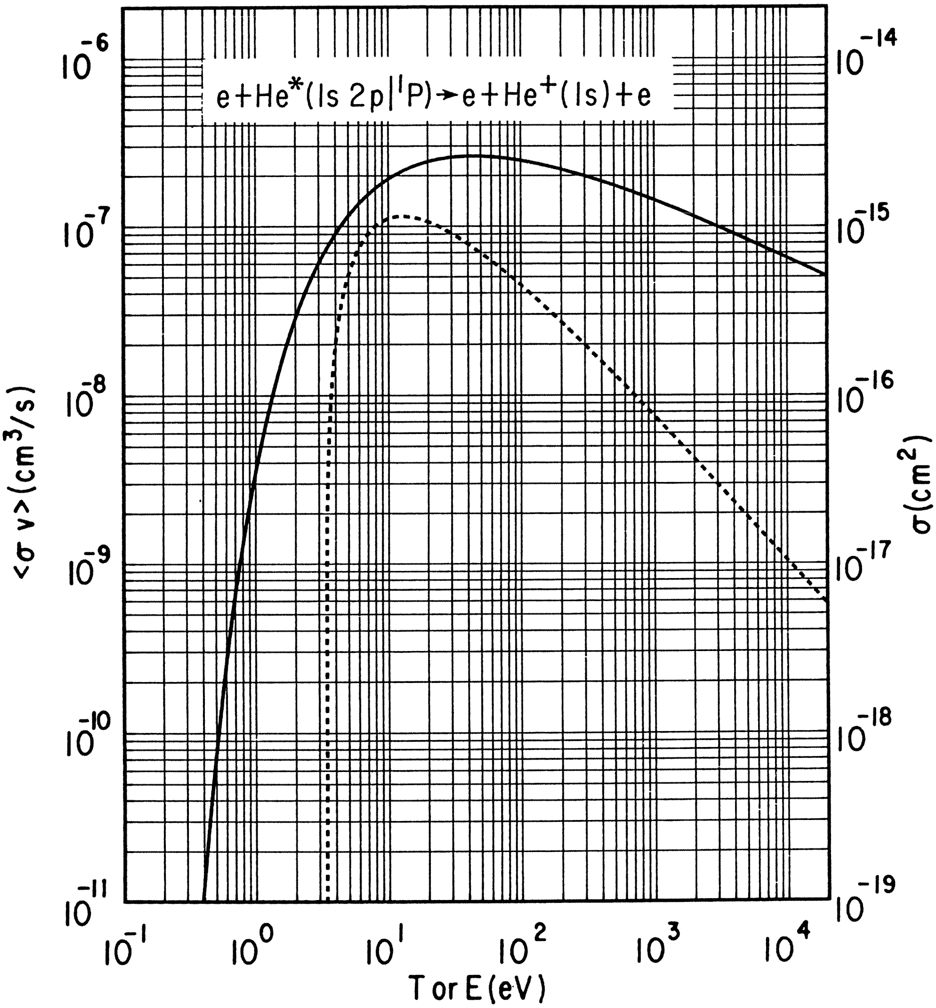
$A = 0.66$; $\beta = 2.5$ for $He^*(1s2s|^3S)$,

$A = 0.66$; $\beta = 1.0$, for all other transitions.

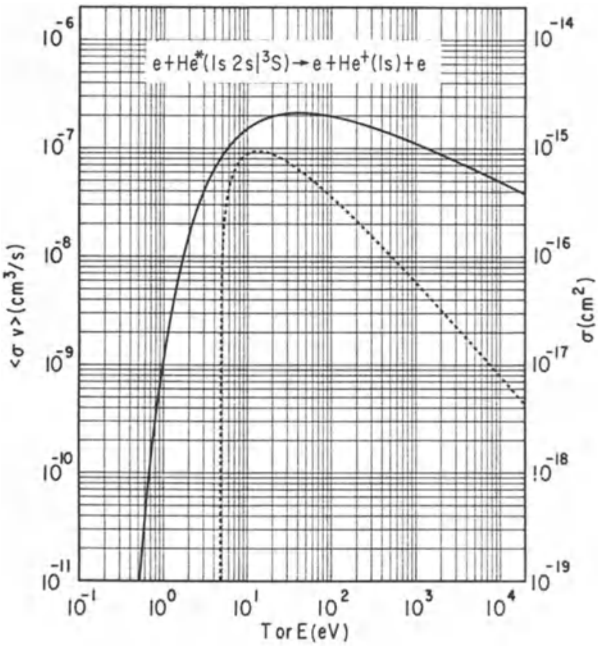
Reference: Fujimoto (1978)

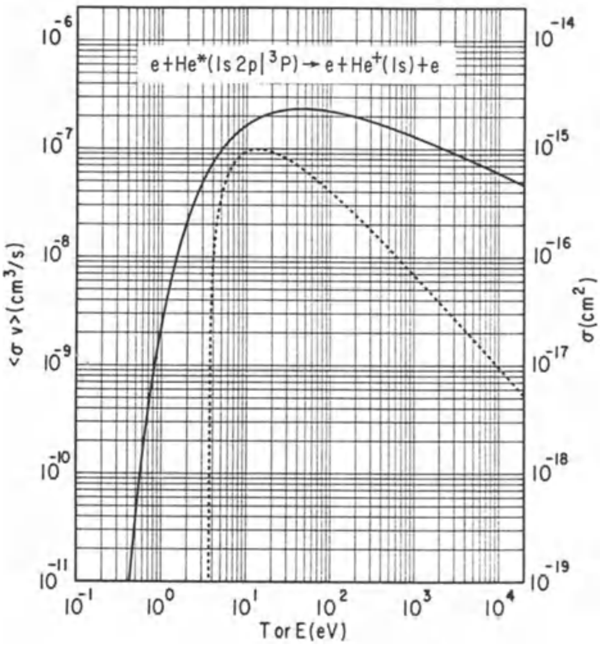
Comment: For the mean energy of the ejected electrons see Sect. 2.1.5.


e + He*(1s 2s | ¹S) → e + He⁺(1s) + e
<σ v> (cm³/s)
σ (cm²)
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴
T or E (eV)



e+He*(1s 2p|¹P)→e+He⁺(1s)+e
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
<σ v> (cm³/s)
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
σ (cm²)
10⁻¹
10⁰
10¹
10²
10³
10⁴
T or E (eV)


e + He*(1s 2s | ³S) → e + He⁺(1s) + e
<σ v> (cm³/s)
σ (cm²)
T or E (eV)
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴


e + He*(1s 2p | ³P) → e + He⁺(1s) + e
<σ v> (cm³/s)
σ (cm²)
T or E (eV)
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴

2.3.11 $\boxed{e+He^*(1s,n) \rightarrow \bar{e}_1+He^+(1s)+\bar{e}_2,\ (n\geq 3)}$

$$E_{th} = E_n^{ion}\ ,\ \Delta E_e^{(-)} = E_{th} + E_{\bar{e}_2}\ .$$

Cross Section:

$$\sigma_{ion}^{se} = 2.32 \times 10^{-16}(Ry/E_n^{ion})^2 (u-1)/u^2\ \ell n(1.25\ u)\quad [cm^2],$$

$$u = E/E_{th}\ .$$

Reference: Fujimoto (1978)

Comments: E_n^{ion} is the mean ionization energy of the levels with the same value of n (see Appendix A.3). For the mean energy $\langle E_{\bar{e}_2} \rangle$ of ejected electrons see Sect. 2.1.5.

2.3.12 $\boxed{e+He^*(1snl|^{2S+1}L) \rightarrow \bar{e}_1+He^{+*}(nl)+\bar{e}_2}$

$$E_{th} \approx 54.4 \text{ eV}, \quad \Delta E_e^{(-)} = E_{th} + E_{\bar{e}_2} \quad .$$

Cross Section:

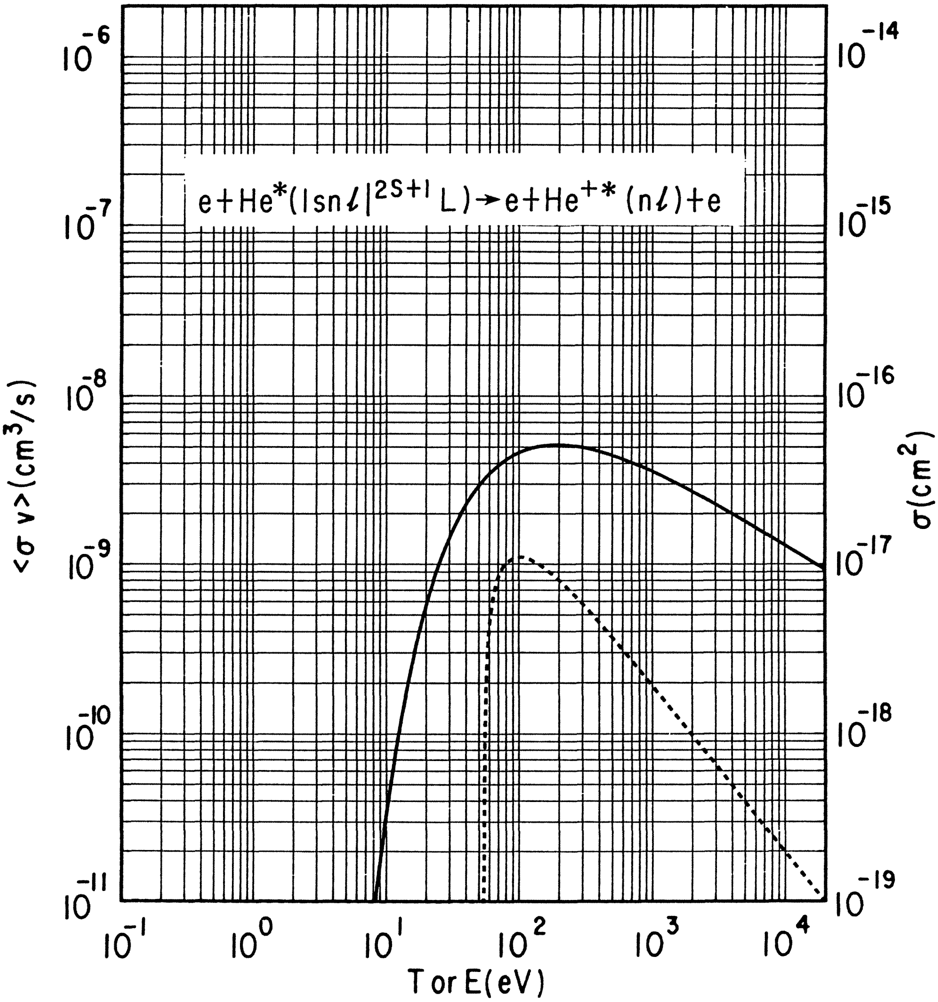
$$\sigma_{ion}^{BEA} = 7.33 \times 10^{-18} \frac{(u-1)(2+5u)}{u^3} \; [cm^2],$$

$$u = E/E_{th} \; .$$

Comments:

(1) $(1sn\ell|^{2S+1}L)$ in reaction 2.3.12 may be any one electron excited state of He.

(2) For the mean energy of the ejected electrons see Sect. 2.1.5.



$e + He^*(1sn\ell\,|^{2S+1}L) \rightarrow e + He^{+*}(n\ell) + e$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

2.3.13 $\boxed{e+He^+(1s) \rightarrow He^*(1snl|^{2S+1}L) + h\nu}$

$$E_{th} = E_{n\ell}^{ion},\ \Delta E_e^{(-)} = E,\ E_\nu = E - E_{n\ell}^{ion}\ .$$

Reaction Rate Coefficients:

n=1: $\alpha_{rec}^{rad}(1s^2|^1S) = 1.96 \times 10^{-14}(E_{1s}^{ion}/Ry)^{1/2}\ \dfrac{\beta_{1s}^{3/2}}{\beta_{1s} + 0.35}\ [cm^3/s]$,

$E_{1s}^{ion} = 24.5876$ eV, $\beta_{1s} = E_{1s}^{ion}/T$.

n=2: $\alpha_{rec}^{rad}(1s2\ell|^{2S+1}L) = A_{n\ell} \times 10^{-14}\ \beta_{n\ell}^{3/2}\ \exp(\beta_{n\ell})\ E_1(\beta_{n\ell})\ (cm^3/s)$,

$n\ell\ ^{2S+1}L$	$2s\ ^1S$	$2s\vert^3S$	$2p\vert^1P$	$2p\vert^3P$
$A_{n\ell}$	0.254	0.401	0.827	1.381

$\beta_{n\ell} = E_{n\ell}^{ion}/T$

n ≥ 3: (summed over ℓ)

$\alpha_{rec}^{rad}(n \geq 3) = 5.201 \times 10^{-14}\beta_n^{3/2}\ \exp(\beta_n)\ E_1(\beta_n)\ [cm^3/s]$,

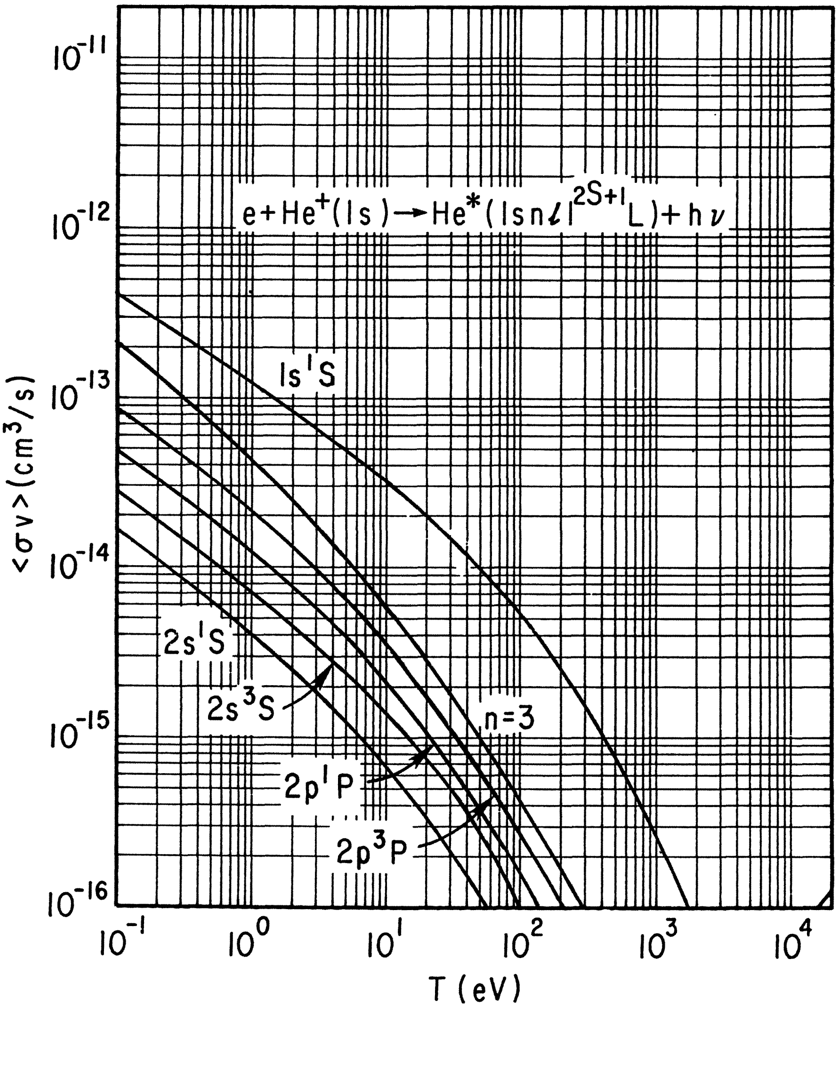
$\beta_n = E_n^{ion}/T$, $E_1(\beta)$ = exponential integral.

Comments:

(1) The values of $E_{n\ell}^{ion}$ and E_n^{ion} are given in Appendix A.3.

(2) α_{rec}^{rad} for $1s|^1S$ is obtained within the Coulomb-Born approximation (Sobelman 1979), α_{rec}^{rad} for n = 2 states is a semiempirical formula which in the low temperature limit reproduces the data from (Fujimoto 1978). For n≥3 the expression for α_{rec}^{rad} is given in the Kramers approximation (Sobelman 1979).

(3) Useful expansions for the function $\exp(\beta)\ E_1(\beta)$ can be found in Abramowitz and Stegun (1972); a simple approximate expression is also given in comment (2) of Sect. 2.1.8.



$e + He^+(1s) \rightarrow He^*(1sn\ell\,{}^{2S+1}L) + h\nu$
1s 1S
2s 1S
2s 3S
n=3
2p 1P
2p 3P
$\langle\sigma v\rangle$ (cm³/s)
T (eV)

2.3.14 $\boxed{e + He^{+}(1s) \rightarrow e + He^{+*}(2p)}$

$E_{th} = \Delta E_{12} = 40.8$ eV , $\Delta E_e^{(-)} = E_{th}$,

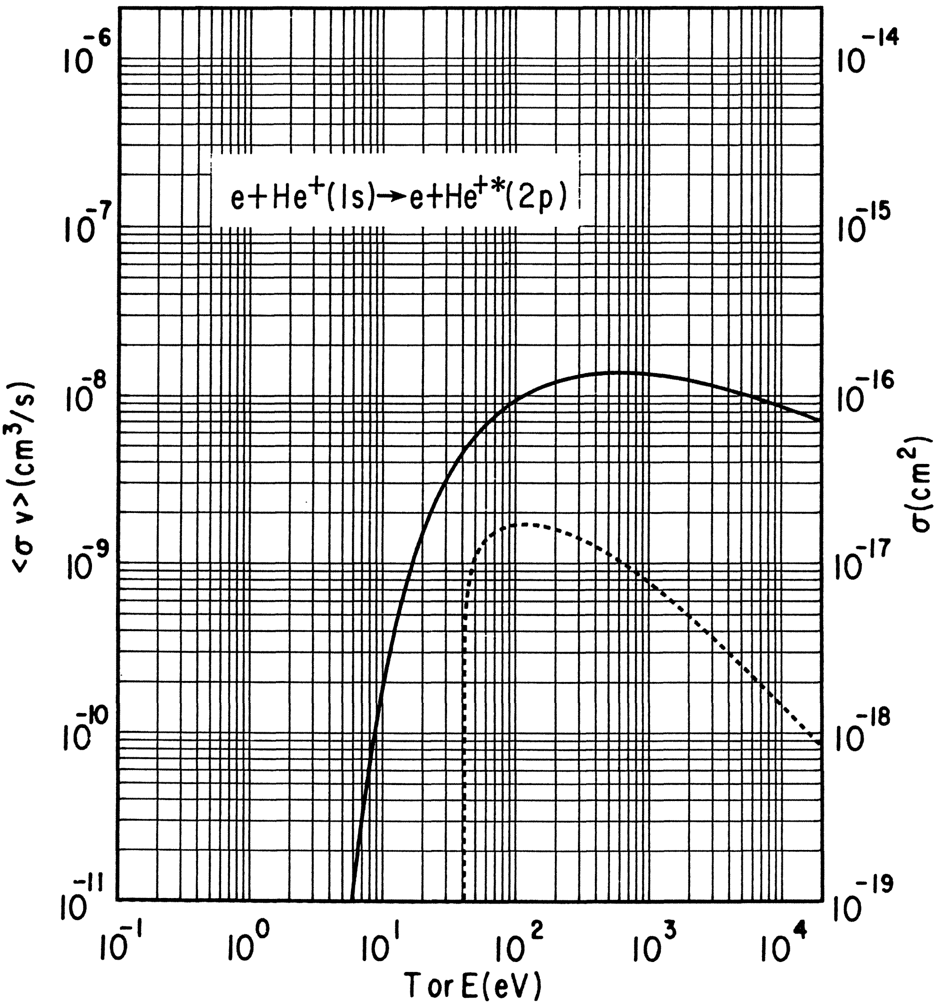
Cross Section:

$$\sigma_{exc}^{NCB}(1s \rightarrow 2p) = 6.61 \times 10^{-17} \left(\frac{u}{u+1}\right)^{1/2} \frac{\ell n(u+16)}{u+7.15} \; [cm^2] \; ,$$

$$u = (E - \Delta E_{12})/\Delta E_{12}.$$

Reference: Sobelman et al. (1981)

Comments: σ_{exc}^{NCB} is an analytic fit to the results of a normalized Coulomb-Born approximation calculation. The σ_{exc}^{NCB} data are consistent with those produced by the Callaway (1983) fit to the multi-state close-coupling results (averaged over the resonances).



e + He+(1s) → e + He+*(2p)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
<σ v> (cm3/s)
σ(cm2)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

2.3.15 $\boxed{e + He^{+}(1s) \rightarrow e + He^{+*}(2s)}$

$E_{th} = 40.8$ eV, $\Delta E_{12} = E_{th}$, $\Delta E_e^{(-)} = \Delta E_{12}$.

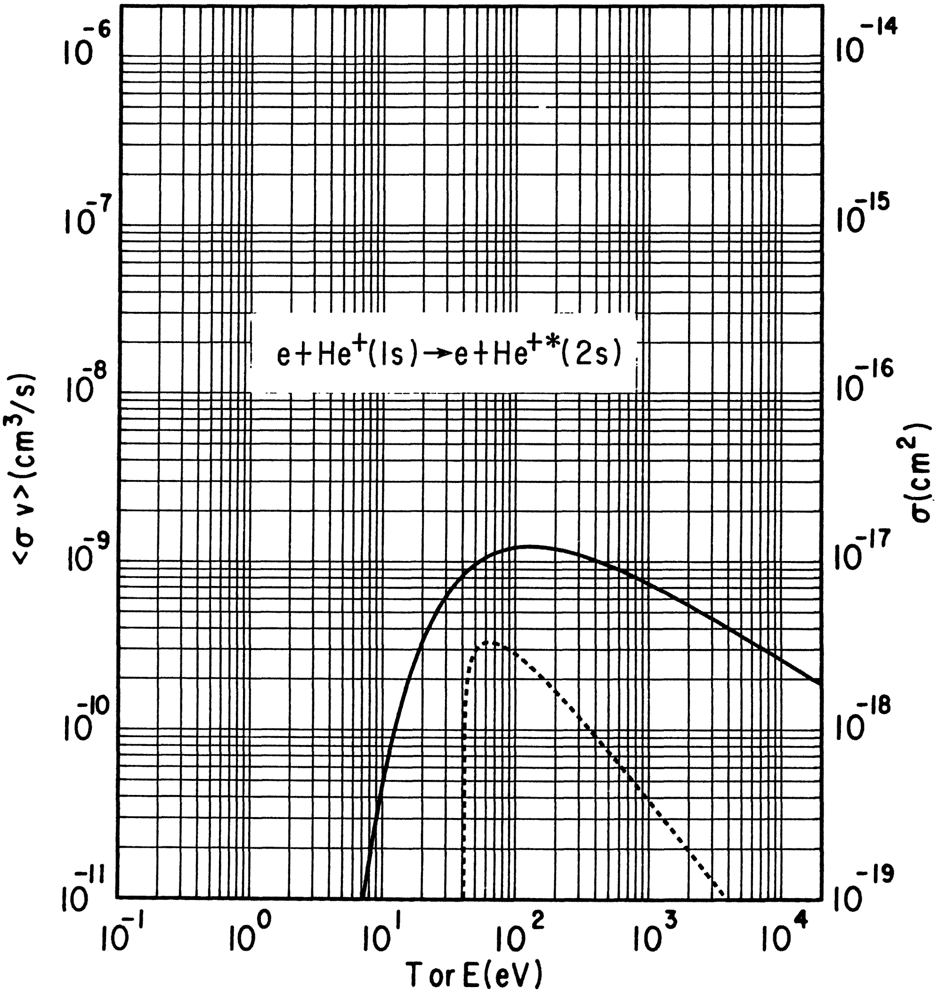
Cross Section:

$$\sigma_{exc}^{NCB}(1s \rightarrow 2s) = 3.21 \times 10^{-18}\left(\frac{u}{u+1}\right)^{1/2} \frac{1}{u + 1.19} \; [cm^2],$$

$$u = (E - \Delta E_{12})/\Delta E_{12}.$$

Reference: Sobelman et al. (1981)

Comments: σ_{exc}^{NCB} is an analytic fit to properly normalized Coulomb-Born calculations. The σ_{exc}^{NCB} data are consistent with the Callaway (1983) fit to the multi-state close-coupling calculations (averaged over the resonances).


e + He+(1s) → e + He+*(2s)
<σ v> (cm3/s)
σ (cm2)
T or E (eV)
10-6
10-7
10-8
10-9
10-10
10-11
10-14
10-15
10-16
10-17
10-18
10-19
10-1
100
101
102
103
104

2.3.16 $e + He^{+}(1s) \rightarrow e + He^{+*}(n), \quad (n = 3, 4, 5)$

$$E_{th} = 4Ry\left(1 - \frac{1}{n^2}\right), \quad \Delta E_n = E_{th}, \quad \Delta E_e^{(-)} = \Delta E_n .$$

Cross Section:

$$\sigma_{exc}^{NCB}(1\rightarrow n) = 0.88 \times 10^{-16} \frac{C}{n^3} (Ry/\Delta E_n)^2 [u/(u+1)]^{1/2} \frac{\ln(u + 16)}{u + \phi} \quad [cm^2],$$

$$u = \frac{E - \Delta E_n}{\Delta E_n} .$$

n	3	4	5
C	36.3	32.1	28.0*
ϕ	5.87	5.54	5.21*

*Extrapolated

Reference: Sobelman et al. (1981)

Comment: The $\sigma_{exc}^{NCB}(1s\rightarrow n)$ formula above refers to $1s\rightarrow$ np transitions. For the $1s\rightarrow$ns, nd transitions with $n \leq 6$, cross section data in the Coulomb-Born approximation are also available (Tully 1973).

2.3.17a $e + He^{+*}(2p) \rightarrow e + He^{+*}(n), \quad (n = 3,4,5)$

$$E_{th} = 4Ry\left(\frac{1}{4} - \frac{1}{n^2}\right)eV, \quad \Delta E_n = E_{th}, \quad \Delta E_e^{(-)} = \Delta E_n .$$

Cross Section:

$$\sigma_{exc}^{NCB}(2p \rightarrow n) = 2.347 \times 10^{-16} \frac{C}{n^3} \left(Ry/\Delta E_n\right)^2 \left[u/(u+1)\right]^{1/2} \frac{\ell n(u + 16)}{u + \phi} \quad [cm^2] ,$$

$$u = \frac{E - \Delta E_n}{\Delta E_n} .$$

n	3	4	5
C	104	46	15*
ϕ	6.69	3.99	2.0*

*Extrapolation

Reference: Sobelman et al. (1981)

Comments:

(1) σ_{exc}^{NCB} above contains only the contribution from $2p \rightarrow nd$ transitions.

(2) For $n \rightarrow m$ transitions ($n=2$, $m=3,4,5$), scaled Coulomb-Born cross sections are available (Clark et al. 1982).

2.3.17b $e+He^{+*}(2s) \rightarrow e+He^{+*}(n), \quad (n = 3,4,5)$

$$E_{th} = 4Ry\left(\frac{1}{4} - \frac{1}{n^2}\right), \quad \Delta E_n = E_{th}, \quad \Delta E_e^{(-)} = \Delta E_n.$$

Cross Section:

$$\sigma_{exc}^{NCB} = 7.04 \times 10^{-16} \frac{C}{n^3} (Ry/\Delta E_n)^2 \left(\frac{u}{u+1}\right)^{1/2} \frac{\ln (u + 16)}{u + \phi} \; [cm^2],$$

$$u = \frac{(E - \Delta E_n)}{\Delta E_n} .$$

n	3	4	5
C	20.9	13.1	6.6
ϕ	14.8	24.4	32.0

Reference: Sobelman et al. (1981)

Comments:

(1) The formula given above for σ_{exc}^{NCB} refers to the 2s→np transitions.

(2) For n→m transitions (n=2, m=3,4,5), scaled Coulomb-Born cross sections are available (Clark et al. 1982).

2.3.18 $\boxed{e+He^{+*}(n) \rightarrow e+He^{+*}(m), \quad (n\geq 3, \; m>n)}$

$$E_{th} = 4Ry\left(\frac{1}{n^2} - \frac{1}{m^2}\right), \quad \Delta E_{nm} = E_{th}, \quad \Delta E_e^{(-)} = \Delta E_{nm} .$$

Reaction Rate Coefficient:

$$\alpha_{exc}^{CB}(n\rightarrow m) = 1.16 \times 10^{-6}(Ry/\Delta E_{nm}) \frac{f_{nm}}{T^{1/2}} \exp(-\Delta E_{nm}/T)[cm^3/s].$$

Reference: Bhala (1969)

Comments:

(1) $\alpha_{exc}^{CB}(n\rightarrow m)$ has been derived by parametrizing the Coulomb-Born results. The oscillator strength f_{nm} can be calculated from Johnson's (1972) formula (see Appendix A.2).

(2) For $n\rightarrow m$ excitations with $n,m \geq 5$, one can also use the semiclassical results of Percival and Richards (1978).

2.3.19 $\boxed{e_1 + He^+(1s) \rightarrow \bar{e}_1 + He^{2+} + \bar{e}_2}$

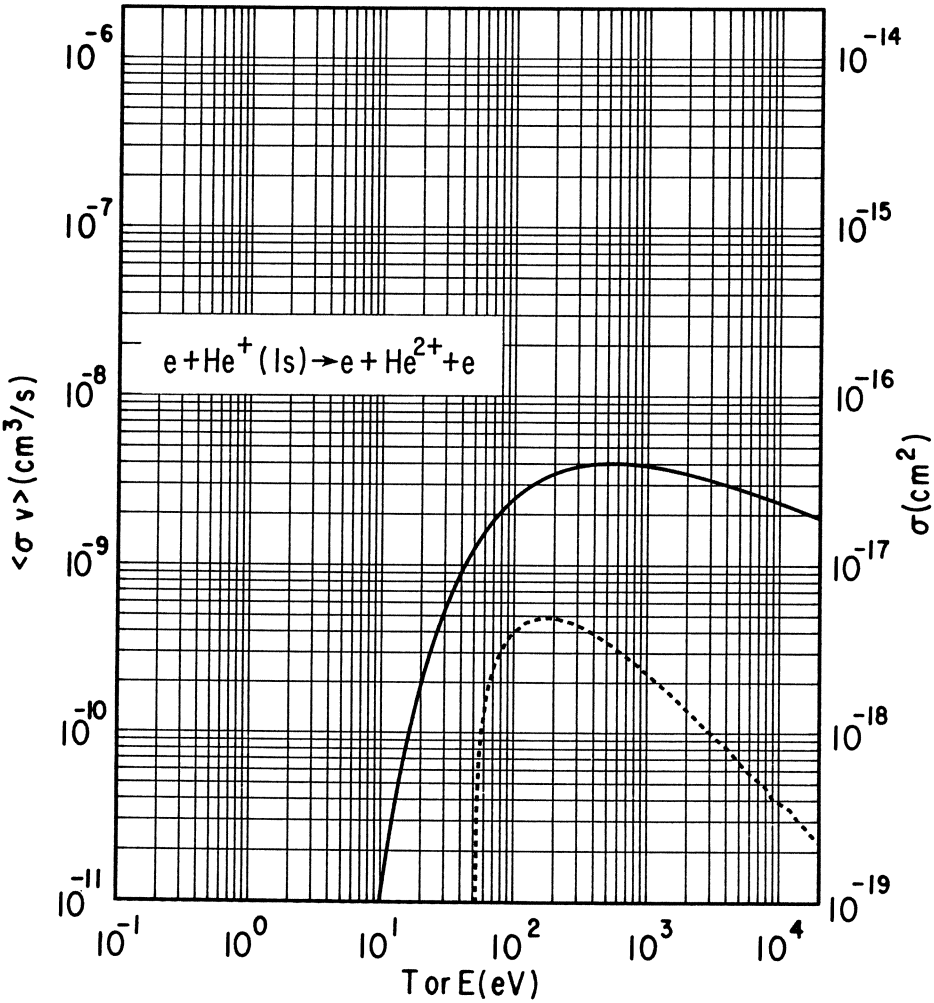
$E_{th} = 54.4$ eV, $\Delta E^{(-)}_{e_1} = E_{th} + E_{\bar{e}_2}$.

Cross Section:

$\sigma_{ion}(1s) = \sigma_{exp}$

Reference: Itikawa and Kato (1981)

Comment: For the mean energy of ejected electrons see Sect. 2.1.5.



e + He+ (1s) → e + He2+ + e
<σ v> (cm3/s)
σ (cm2)
T or E (eV)
10-6
10-7
10-8
10-9
10-10
10-11
10-14
10-15
10-16
10-17
10-18
10-19
10-1
100
101
102
103
104

2.3.20 $e_1 + He^{+*}(n) \rightarrow \bar{e}_1 + He^{2+} + \bar{e}_2, \quad (n \geq 2)$

$$E_{th} = \frac{4Ry}{n^2} = E_n^{ion} \ , \ \Delta E_{e_1}^{(-)} = E_{th} + E_{\bar{e}_2} \ .$$

Cross Section:

$$\sigma_{ion}^{BEA}(n) = 1.173 \times 10^{-16} \left(Ry/E_n^{ion}\right)^2 \frac{(u - 1)(2 + 5u)}{u^3} \quad \left[cm^2\right],$$

$$u = \frac{E}{E_n^{ion}} \ .$$

Comment: For the mean energy of the ejected electrons see Sect. 2.1.5.

2.3.21 $\boxed{e+He^{2+} \rightarrow He^{+(*)}(n) + h\nu}$

$$E_{th} = E_n^{ion} = \frac{4Ry}{n^2}, \quad \Delta E_e^{(-)} = E, \quad E_{h\nu} = E - E_n^{ion} .$$

Reaction Rate Coefficient:

n = 1s, 2s, 2p:

$$\alpha_{rec}^{rad}(n) = 10^{-14}\left(E_n^{ion}/Ry\right)^{1/2} \frac{A_n\beta_n^{3/2}}{\beta_n + \chi_n} \left[cm^3/s\right] ,$$

$$\beta_n = \frac{E_n^{ion}}{T} .$$

n	1s	2s	2p
A_n	3.92	2.42	6.22
χ_n	0.35	0.12	0.61

n ≥ 3:

$$\alpha_{rec}^{rad}(n) = 5.201 \times 10^{-14} \beta_n^{3/2} \exp(\beta_n)E_1(\beta_n) \left[cm^3/s\right] ,$$

$E_1(\beta_n)$: exponential integral.

Reference: Sobelman et al. (1981)

Comments:

(1) α_{rec}^{rad} for 1s,2s,2p is based on a normalized Coulomb-Born calculation of σ_{rec}^{rad}.

(2) α_{rec}^{rad} for n≥3 is given in the Kramers approximation. For calculation of $\exp(\beta)E_1(\beta)$ see comment (2) of Sect. 2.1.8.

2.3.22 $\boxed{e + He^{+(*)}(n_0) \rightarrow He^{**}(n_1 n) \rightarrow He^{*}(n_0 n) + h\nu, \quad (n_0 \geq 1, \; n_1 > n_0)}$

$$\Delta E_e^{(-)} = E, \; E_{h\nu} = \Delta E_{n_o n_1} \approx 4 \; Ry \left(\frac{1}{n_o^2} - \frac{1}{n_1^2} \right) .$$

Reaction Rate Coefficient:

$$\alpha_{rec}^{diel}(n_o, n_1) = 10^{-13} B_d \beta_o^{3/2} \exp(- \beta_o \chi_d) \; [cm^3/s] \; ,$$

$$\beta_o = \frac{4Ry}{T} \; ,$$

$$B_d = 480 \; f_{n_o n_1} \left(\frac{\gamma}{14.4}\right)^{1/2} \left(1 + 0.21 \; \gamma + 0.60 \; \gamma^2\right)^{-1} \; ,$$

$f_{n_o n_1}$: oscillator strength,

$$\chi_d = 0.99638 \; \gamma \; , \quad \gamma = \left(\frac{1}{n_o^2} - \frac{1}{n_1^2} \right) .$$

Reference: Sobelman et al. (1981)

Comments:

(1) The above expression for α_{rec}^{diel} is the Burgess (1964) formula for dielectronic recombination. It usually overestimates α_{rec}^{diel} by a factor of ~ 1.5.

(2) The values of $f_{n_o n_1}$ can be calculated from the Johnson formula (Appendix A.2).

Chapter 3

Proton Impact Collision Processes

3.1 Proton Collisions with H

3.1.1 $\boxed{p+H(1s) \rightarrow p+H^*(2p)}$

$E_{th} = 10.2$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

$E = E_{th} - 10^3$ eV: $\sigma_{exc}(2p) = \sigma_{se}^{DACC}$,

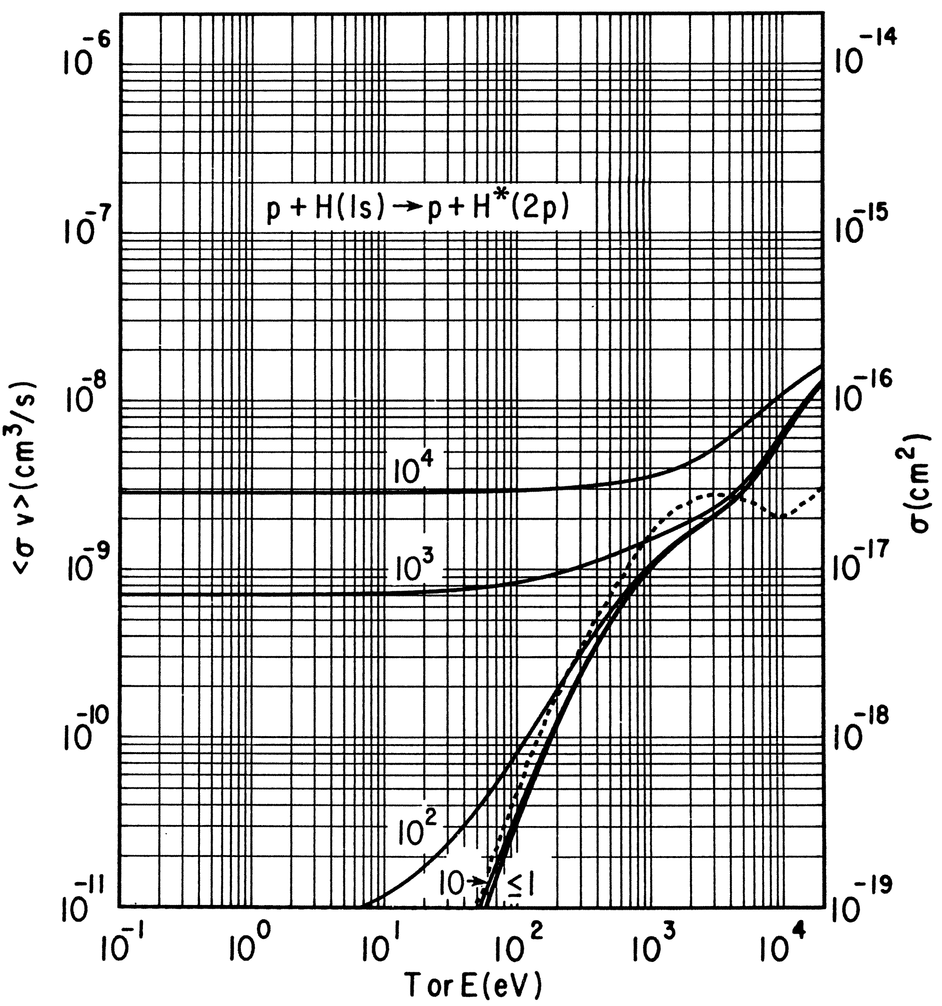
$E \geq 10^3$ eV: $\sigma_{exc}(2p) = \sigma_{exc}^{AO}(2p)$.

Comments:

(1) $\sigma_{exc}^{AO}(2p)$ is the result of 40 atomic states close-coupling (AOCC) calculations (Fritsch and Lin 1983). These calculations agree well with the experimental data of several groups.

(2) σ_{se}^{DACC} is $\sigma_{exc}^{DACC}(2p)$ (see Appendix C), smoothly matched with $\sigma_{exc}^{AO}(2p)$ in the region 600 - 10^3 eV.

(3) For the calculation of $\sigma_{exc}^{DACC}(2p)$ the formula given with reaction 3.1.4., can be used where n is taken to be 2p (see Janev and Presnyakov 1980).


p + H(1s) → p + H*(2p)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{4}
10^{3}
10^{2}
10
≤1
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
T or E(eV)
<σ v> (cm³/s)
σ (cm²)

3.1.2 $\boxed{p+H(1s) \rightarrow p+H^*(2s)}$

$E_{th} = 10.2$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

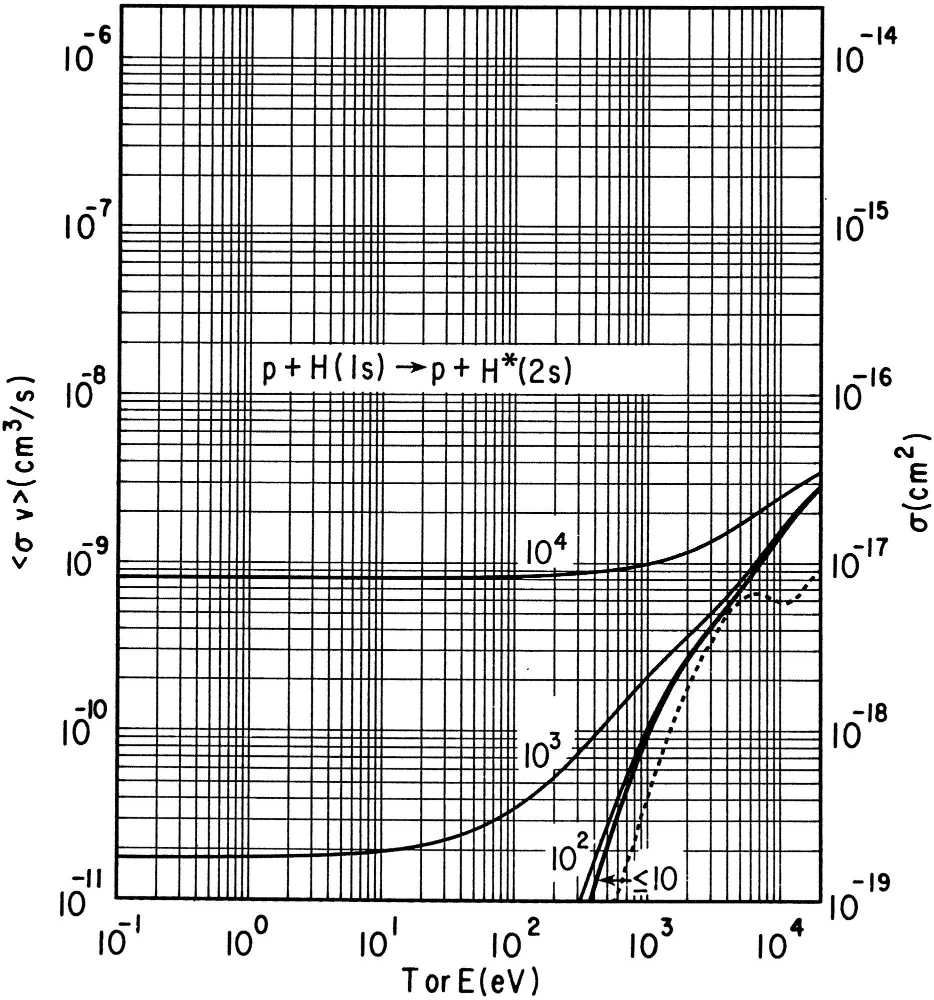
$E = 1.5 \times 10^3 - 2 \times 10^4$ eV: $\sigma_{exc}(2s) = \sigma_{exc}^{AO}(2s)$,

$E < 1.5 \times 10^3$ eV: $\sigma_{exc}(2s) = \sigma_{se}^{ext}$.

Comments:

(1) The $\sigma_{exc}^{AO}(2s)$ results from a 40 atomic states close-coupling (AOCC) calculation for $E > 4 \times 10^3$ eV (Fritsch and Lin 1983) and 22 AOCC calculation for $E < 4 \times 10^3$ eV (Fritsch and Lin 1982). For $E > 5 \times 10^3$ eV, these results agree well with the experimental data.

(2) σ_{se}^{ext} is an extension of $\sigma_{exc}^{AO}(2s)$ in the region $E < 1.5 \times 10^3$ eV, keeping the ratio $\sigma_{exc}(2s)/\sigma_{exc}(2p)$ constant at the point 1.5×10^3 eV.



p + H(1s) → p + H*(2s)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
<σ v>(cm³/s)
σ(cm²)
10^4
10^3
10^2
≤10
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

3.1.3 $\boxed{p+H^*(2s) \rightarrow p+H^*(2p)}$

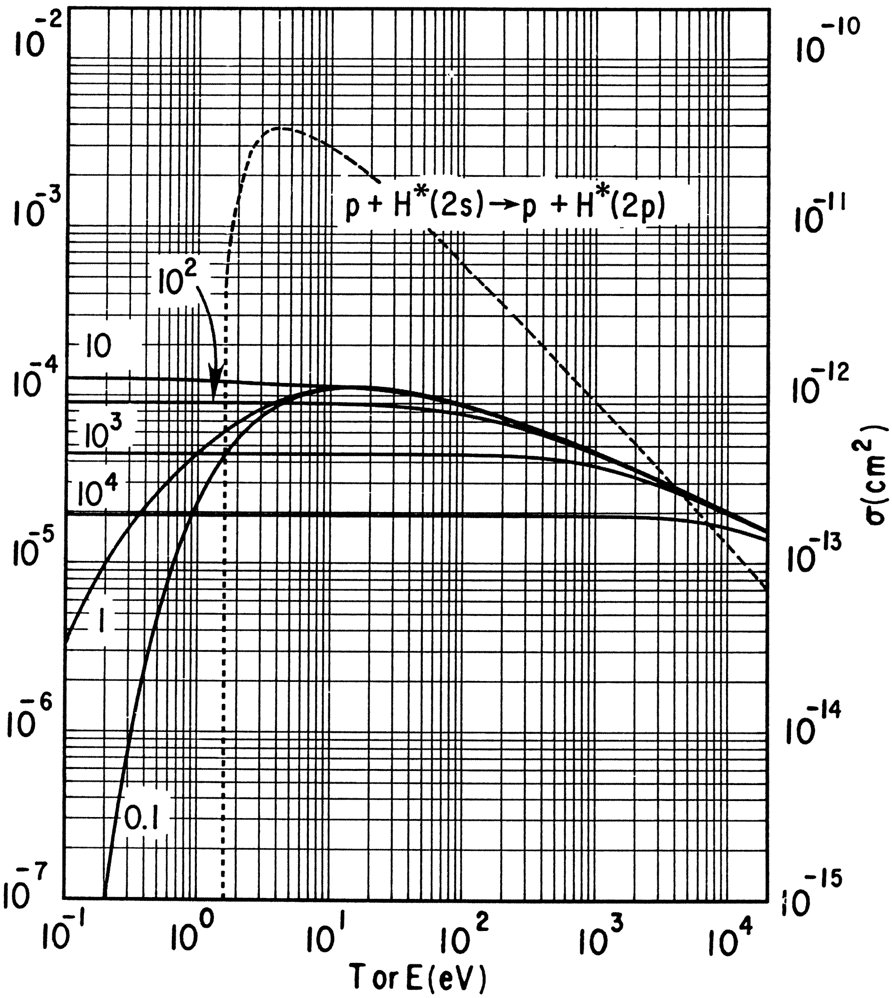
$E_{th} = \Delta E^{(-)} \simeq 0.$

Cross Section:

$$\sigma(2s\rightarrow 2p) = \frac{1.584 \times 10^{-10}}{E} \ell n(0.62E) \left[cm^2\right].$$

Reference: Chibisov (1969)

Comment: The above expression for $\sigma(2s\rightarrow 2p)$ has been derived on the basis of perturbation theory and is valid for $E > 1.6$ eV.



p + H*(2s) → p + H*(2p)
10²
10
10³
10⁴
1
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹
10⁰
10¹
10²
10³
10⁴
T or E (eV)
<σ v> (cm³/s)
σ (cm²)

3.1.4 $\boxed{p+H(1s) \rightarrow p+H^*(n), \quad (n\geq 3)}$

$E_{th} = Ry\ (1 - 1/n^2), \quad \Delta E^{(-)} = E_{th}.$

Cross Section:

$$\sigma_{exc}(n) = \sigma_{exc}^{DACC}(n) = 1.76 \times 10^{-16} \frac{\lambda_{1n}}{\omega_{1n}} D(\beta_{1n})[cm^2] ,$$

$$\lambda_{1n} = (f_{1n}/2\omega_{1n})^{1/2} , \quad \beta_{1n} = \lambda_{1n}\omega_{1n}/v^2 ,$$

$$v = 6.3246 \times 10^{-3} (E[eV])^{1/2},$$

f_{1n}: oscillator strength (see Appendix A.2).

$D(\beta)$ is given in Appendix C.

E is the proton energy in the laboratory frame.

Reference: Janev and Presnyakov (1980)

Comment: σ_{exc}^{DACC} may overestimate the cross section for $\beta > 0.3$ by about 80% or so due to the neglect of ns - np coupling.

3.1.5 $\boxed{p+H^*(n) \rightarrow p+H^*(m), \quad (n \geq 2,\ m > n)}$

$$E_{th} = Ry\left(\frac{1}{n^2} - \frac{1}{m^2}\right), \quad \Delta E^{(-)} = E_{th} .$$

Cross Section:

$$\sigma_{exc}^{DACC}(n \rightarrow m) = 1.76 \times 10^{-16} \frac{\lambda_{nm}}{\omega_{nm}} D(\beta_{nm}) \ [cm^2],$$

$$\lambda_{nm} = (f_{nm}/2\omega_{nm})^{1/2} ,$$

$$\beta_{nm} = \frac{\lambda_{nm}\omega_{nm}}{v^2} ,$$

$$\omega_{nm} = \frac{1}{2}\left(\frac{1}{n^2} - \frac{1}{m^2}\right),$$

f_{nm}: oscillator strength (see Appendix A.2).

$$v = 6.3246 \times 10^{-3} \ (E[eV])^{1/2} .$$

$D(\beta)$ is given in Appendix C.

E is the proton energy in the laboratory frame.

Comment: In the region $\beta > 0.3$, the formula alone is accurate to within a factor of two or so.

3.1.6 $\boxed{p+H(1s) \rightarrow p+H^{+}+e}$

$E_{th} = 13.6$ eV, $\Delta E^{(-)} = E_{th} + E_e$.

Cross Section:

$$\sigma_{ion}^{DACC}(1s) = 1.76 \times 10^{-16} \left(\frac{\lambda_{eff}}{\omega_i} D(\beta_i) + \frac{1}{8} \frac{\lambda_{o1}}{\omega_{o1}} D(\beta_{o1}) \right) \quad [cm^2],$$

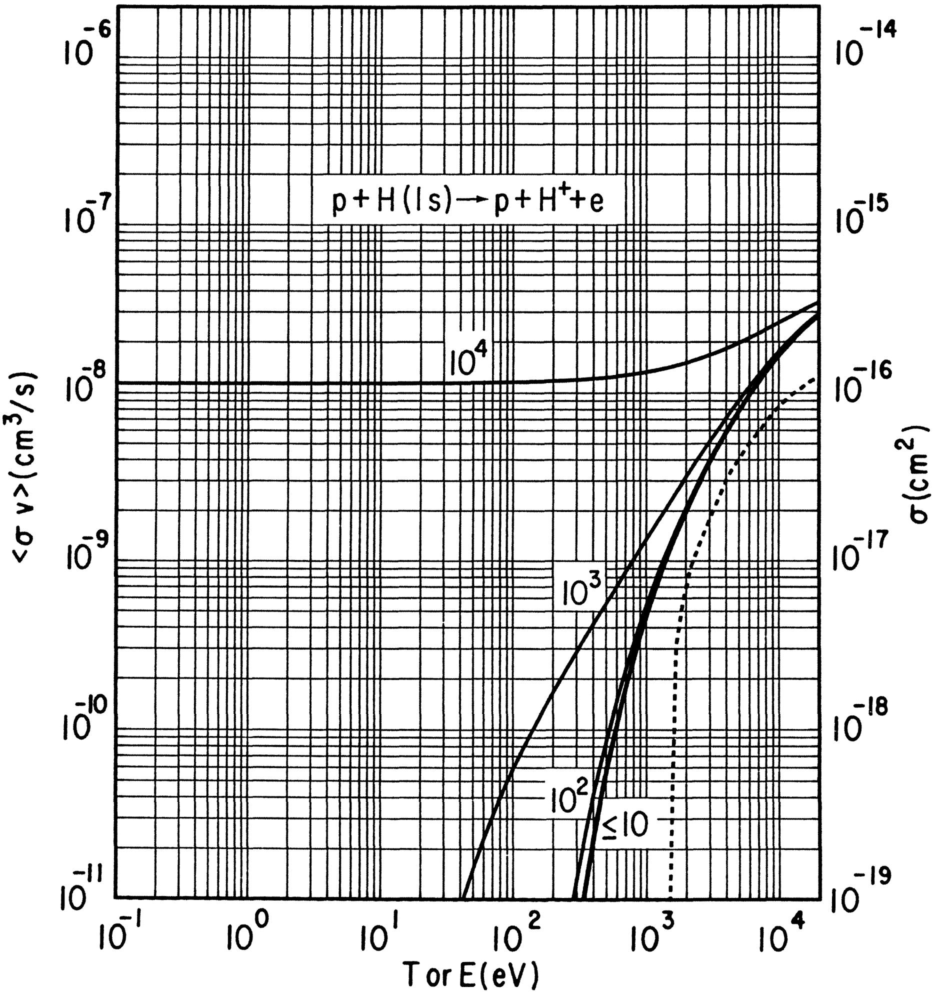
$\lambda_{eff} = 0.808$, $\lambda_{01} = 0.7448$, $\omega_i = 0.5$, $\omega_{01} = 0.375$,

$$\beta_i = \frac{\lambda_{eff}\omega_i}{v^2}, \quad \beta_{o1} = \frac{\lambda_{o1}\omega_{o1}}{v^2},$$

$v = 6.3246 \times 10^{-3}(E[eV])^{1/2}$.

$D(\beta)$ is given in Appedix C.

Comment: $\sigma_{ion}^{DACC}(1s)$ also includes the contribution to ionization from the transitions that proceed via the 2p resonant level. It reproduces the existing experimental data for the region above 8×10^3 eV (Fite et al. 1960; Shah and Gilbody 1981) within their given uncertainties.



p + H(1s) → p + H⁺ + e
10^4
10^3
10^2
≤10
$\langle\sigma v\rangle$ (cm³/s)
σ (cm²)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

3.1.7 $\boxed{p+H^*(n) \rightarrow p+H^+ + e,\ (n \geq 2}$

$E_{th} = Ry/n^2$, $\Delta E^{(-)} = E_{th} + E_e$.

Cross Section:

$$\sigma_{ion}^{BEA}(n) = 0, \text{ for } \alpha < 0.207,$$

$$= 5.867 \times 10^{-17}\ n^4 \left(\alpha - \frac{0.164}{\alpha^2} + \frac{0.1875}{\alpha^2(\alpha+1)}\right) \quad [cm^2]$$

for $0.207 < \alpha < 1.207$,

$$= 1.467 \times 10^{-16}\ n^4\ \frac{1}{\alpha^2} \left(1 - \frac{0.15}{\alpha^2 - 1}\right) \quad [cm^2]$$

for $\alpha > 1.207$.

$$\alpha = nv_{au} = 6.3246 \times 10^{-3}\ n\left(E[eV]\right)^{1/2} .$$

3.1.8 $\boxed{p+H(1s) \rightarrow H(1s)+p}$

$E_{th} = 0.$

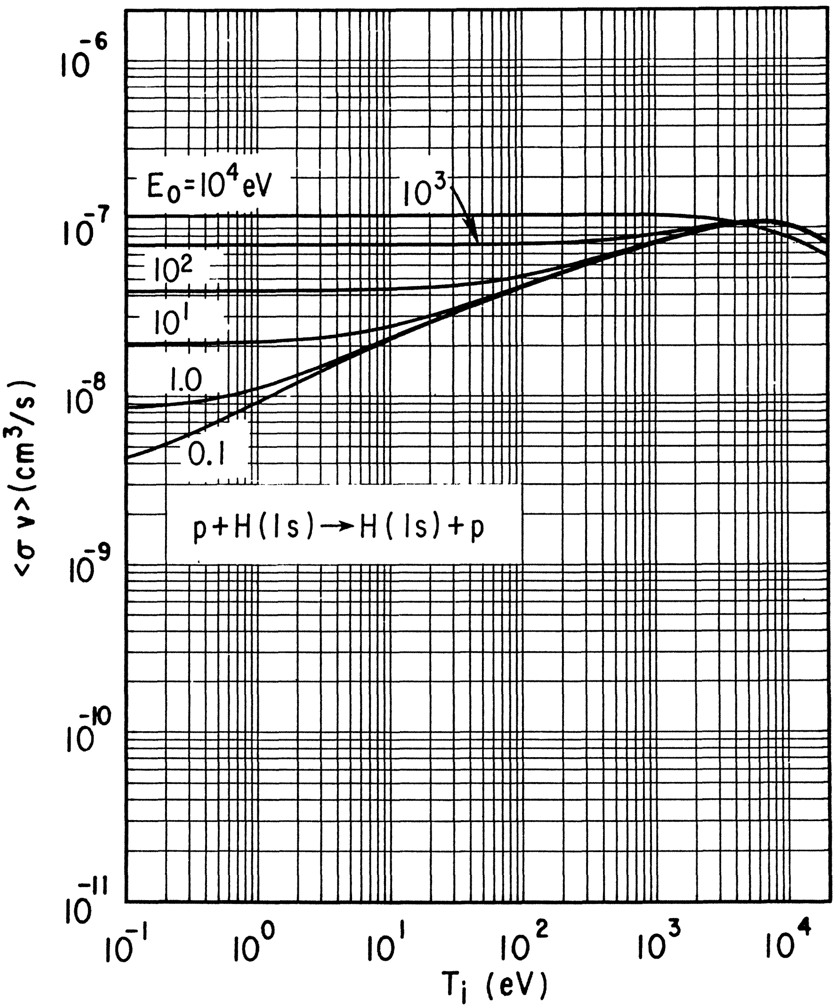
Cross Section:

$E = 0.1\text{-}5 \times 10^5$ eV: $\sigma_{cx} = \sigma_{exp}$

Reference: Takayanagi and Suzuki (1978)

Comment: The cross section σ_{cx} can be represented by the following analytic fit (see Freeman and Jones 1974):

$$\sigma_{cx} = \frac{0.6937 \times 10^{-14}(1 - 0.155 \log_{10}E)^2}{1 + 0.1112 \times 10^{-14}E^{3.3}} \; [\mathrm{cm}^2].$$



$E_0 = 10^4$ eV
10^3
10^2
10^1
1.0
0.1
p + H(1s) → H(1s) + p
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
<σ v> (cm³/s)
10^{-1}
10^0
10^1
10^2
10^3
10^4
T_i (eV)

3.1.9 $p + H(1s) \rightarrow H^{*}(2p) + p$

$E_{th} = 10.2$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

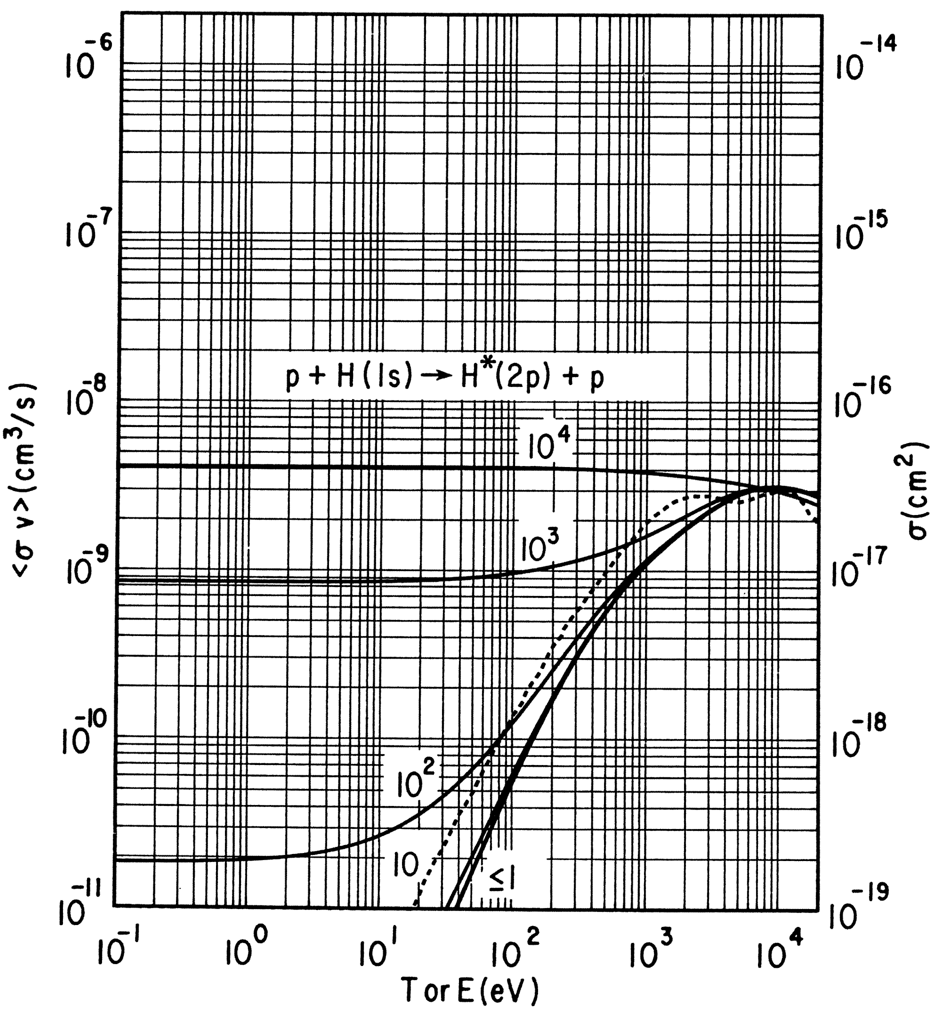
$E = E_{th} - 2 \times 10^3$ eV: $\sigma_{cx}(2p) = \sigma_{se}^{RZD}$.

$E \geq 2 \times 10^3$ eV: $\sigma_{cx}(2p) = \langle\sigma_{cx}\rangle_{exp,th}$.

Comments:

(1) $\langle\sigma_{cx}\rangle_{exp,th}$ is an average over the experimental and theoretical data (see Fritsch and Lin 1983).

(2) σ_{se}^{RZD} is an extrapolation of $\langle\sigma_{cx}\rangle$ using the Rosen-Zener-Demkov model (Smirnov 1973).



$p + H(1s) \rightarrow H^*(2p) + p$
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
T or E (eV)
10^4
10^3
10^2
10
≤1
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^0
10^1
10^2
10^3
10^4

3.1.10 $\boxed{p+H(1s) \rightarrow H^*(2s)+p}$

$E_{th} = 10.2$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

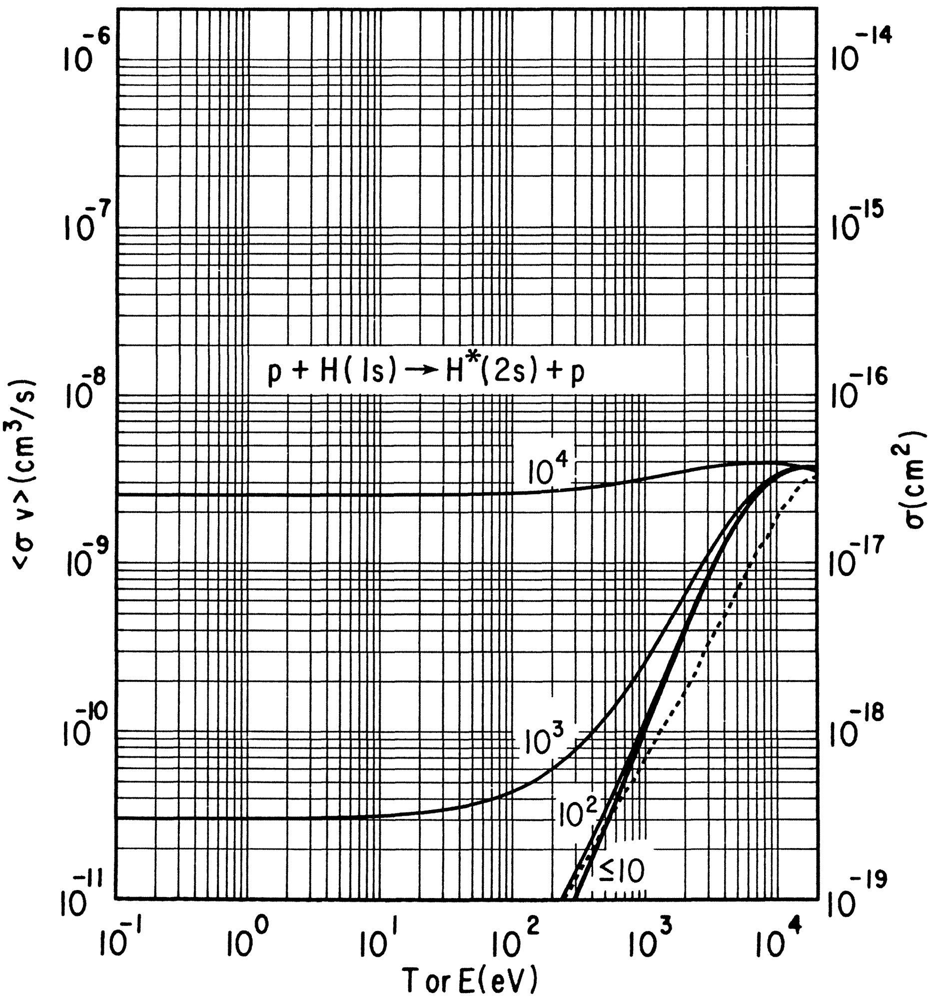
$E = E_{th} - 2 \times 10^3$ eV: $\sigma_{cx}(2s) = \sigma_{se}^{RZD}$,

$E \geq 2 \times 10^3$: $\sigma_{cx}(2s) = \langle\sigma_{cx}\rangle_{exp,th}$.

Comments:

(1) $\langle\sigma_{cx}\rangle_{exp,th}$ is an average over the experimental and theoretical data (see Fritsch and Lin 1983).

(2) σ_{se}^{RZD} is an extrapolation of $\langle\sigma_{cx}\rangle_{exp,th}$ according to the Rosen-Zener-Demkov model (Smirnov 1973).


p + H(1s) → H*(2s) + p
<σ v> (cm³/s)
σ(cm²)
T or E(eV)
10⁴
10³
10²
≤10
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴

3.1.11 $p+H^*(n) \rightarrow H^*(n)+p, \quad (n = 2,3)$

Cross Section:

$$\sigma_{cx}^{res}(n) = 4.4 \times 10^{-17}\, R_o^2(v)\ [cm^2] ,$$

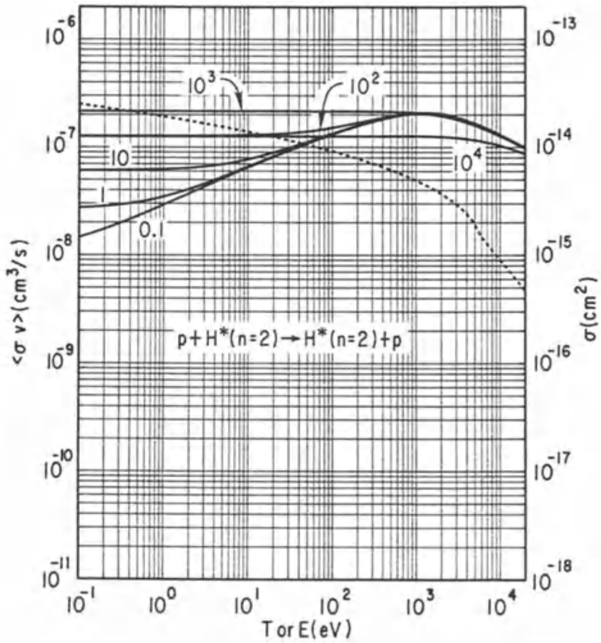
$R_o(v)$ is determined from:

$$n = 2: \quad R_o^{2.5} \exp(-\, R_o/2) = 9.2752\ v ,$$

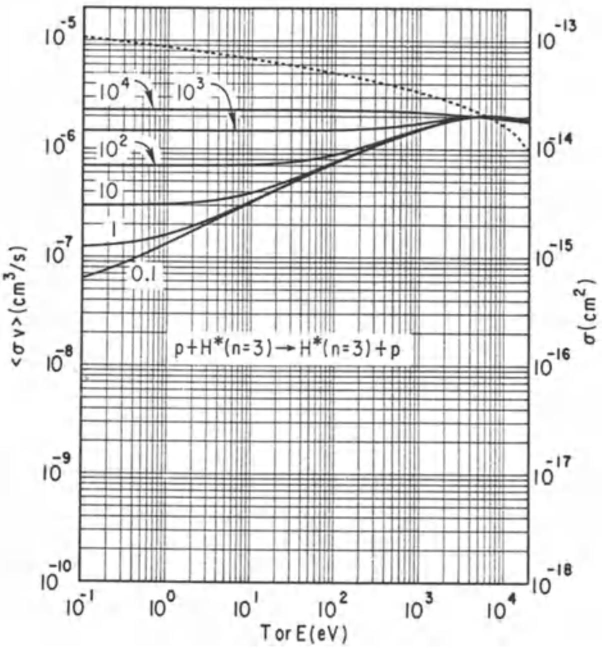
$$n = 3: \quad R_o^{4.5} \exp(-\, R_o/3) = 1.5515 \times 10^3\ v,$$

$$v = 6.3246 \times 10^{-3}\ [E(eV)]^{1/2}.$$

Comment: The formula above for $\sigma_{cx}^{res}(n)$ comes from the asymptotic theory of resonant charge transfer reactions (see Smirnov 1973).



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^3
10^2
10
10^4
1
0.1
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
$p + H^*(n=2) \rightarrow H^*(n=2) + p$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E (eV)



10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^4
10^3
10^2
10
1
0.1
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
$p + H^*(n=3) \rightarrow H^*(n=3) + p$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E (eV)

3.1.12 $\boxed{p+H^*(n) \rightarrow H^*(n)+p, \quad (n \geq 4)}$

$E_{th} = 0.$

Cross Section:

$$\sigma_{cx}^{cl}(n) = 1.584 \times 10^{-15} \frac{n^4}{1+0.8(nv)^{2/5} + 2.6(nv)} \left[cm^2\right] ,$$

$$v = 6.3246 \times 10^{-3} E^{1/2}.$$

Comment: $\sigma_{cx}^{cl}(n)$ is the classical cross section for resonant charge transfer (Smirnov 1973; Janev et al. 1984b). It is valid for $v \lesssim v_o/n$, where $v_o = 2.19 \times 10^8$ cm/sec.

3.2 Proton Collisions with H_2 and H_2^+

3.2.1a $\boxed{p+H_2(j=0) \rightarrow p+H_2(j'), \quad (j' \geq 2)}$

3.2.1b $\boxed{p+H_2(j=1) \rightarrow p+H_2(j'), \quad (j' \geq 3)}$

E_{th} [3.2.1(a)] $\simeq$ 0.05 eV, $\langle \Delta E^{(-)} \rangle_j \simeq$ 0.1 eV.

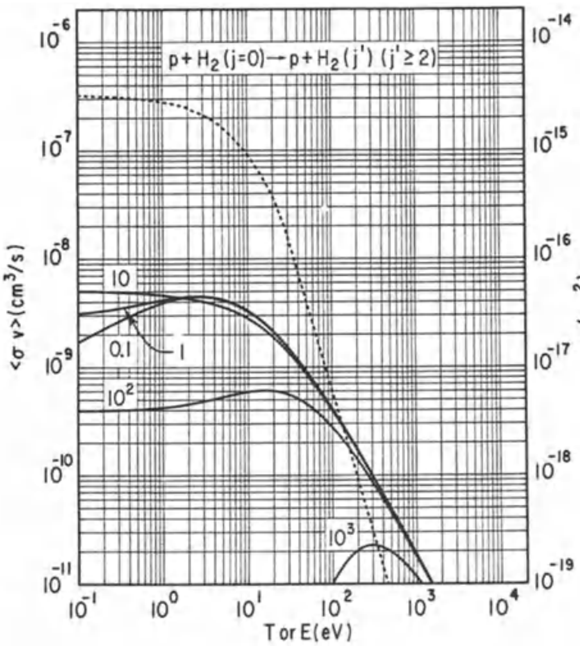
Cross Section:

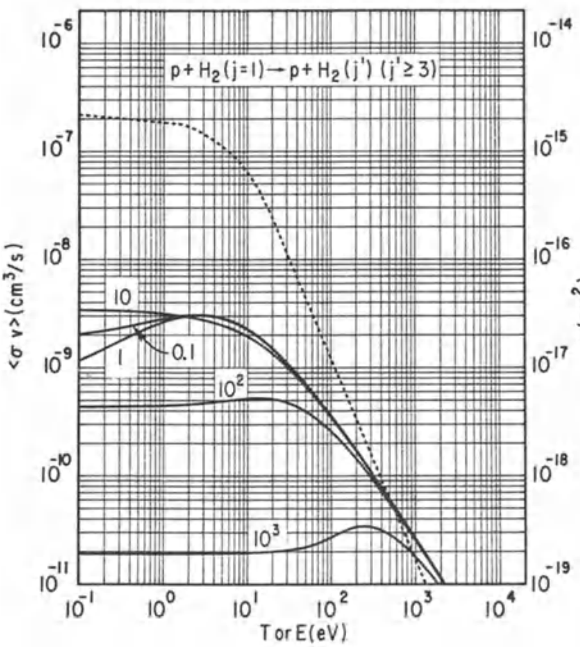
E = 1 - 18 eV: $\sigma_{exc}^{rot}(v=0, \sum_{j'=2} j') = \sigma_{exp}$.

Reference: Linder (1980)

E = 0.1 - 1.0 eV and 18-400 eV; $\sigma_{exc}^{rot} = \sigma_{se}^{ext}$.

Comment: The rotational states j=0 and j=1 correspond to para- and ortho-hydrogen, respectively. The cross section σ_{se}^{ext} is an extrapolation of σ_{exp}.


p + H2 (j=0) → p + H2 (j') (j' ≥ 2)
<σ v> (cm3/s)
σ (cm2)
T or E (eV)
10
0.1
1
10^2
10^3


p + H2 (j=1) → p + H2 (j') (j' ≥ 3)
<σ v> (cm3/s)
σ (cm2)
T or E (eV)
10
1
0.1
10^2
10^3

3.2.2 $\boxed{p+H_2(v=0) \rightarrow p+H_2(v>0)}$

$E_{th} = 0.5$ eV, $<\Delta E^{(-)}>_v \simeq 1$ eV,

Cross Section:

$E = 4-18$ eV: $\sigma^{vib}_{exc}(v=0 \rightarrow \text{all } v \leq 4)$.

Reference: Linder (1980)

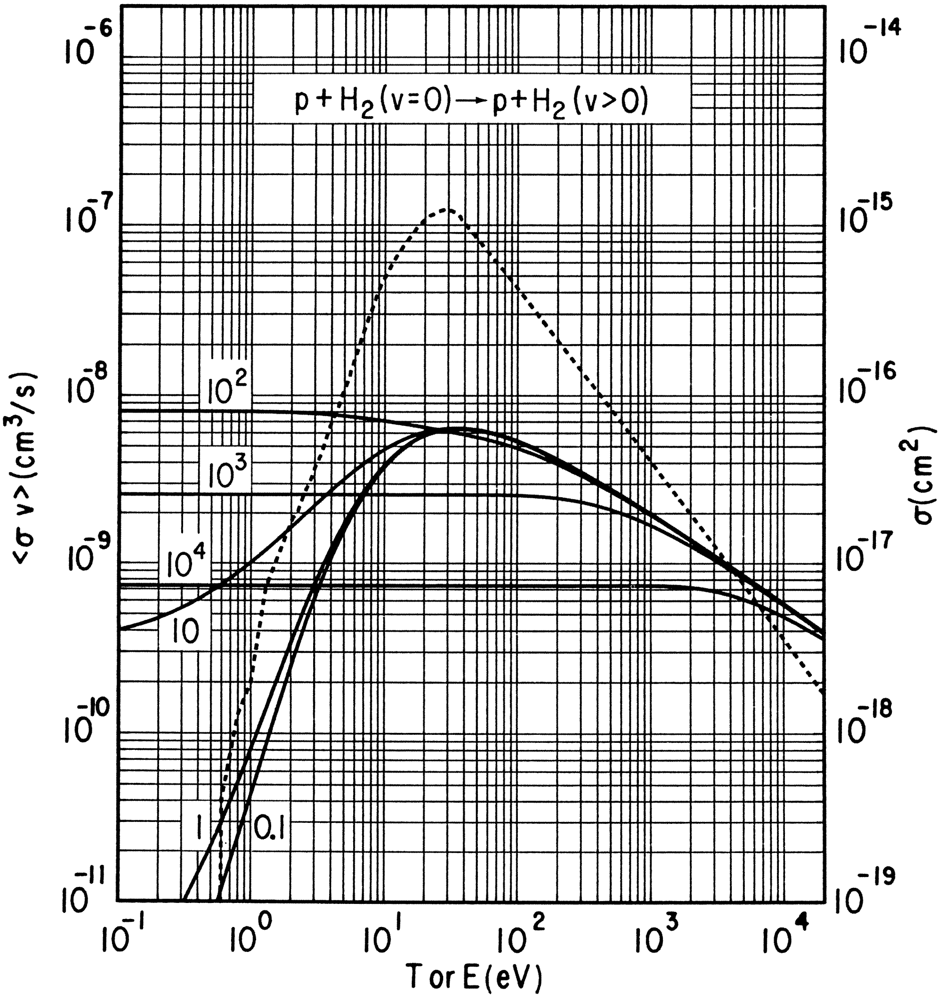
$E = E_{th} - 4$ eV: $\sigma^{vib}_{exc} = \sigma^{ext}_{se}$.

$E = 18 - 2 \times 10^4$ eV: $\sigma^{vib}_{exc} = \sigma^{B}_{se}$.

Comments:

(1) σ^{ext}_{se} is an extrapolation of σ_{exp} down to the threshold.

(2) σ^{B}_{se} represents a Born-type extrapolation of σ_{exp}.


$p + H_2(v=0) \rightarrow p + H_2(v>0)$
$\langle\sigma v\rangle$ (cm^3/s)
σ(cm^2)
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^2
10^3
10^4
10
1
0.1

3.2.3 $\boxed{p+H_2 \rightarrow H(1s)+H_2^+}$

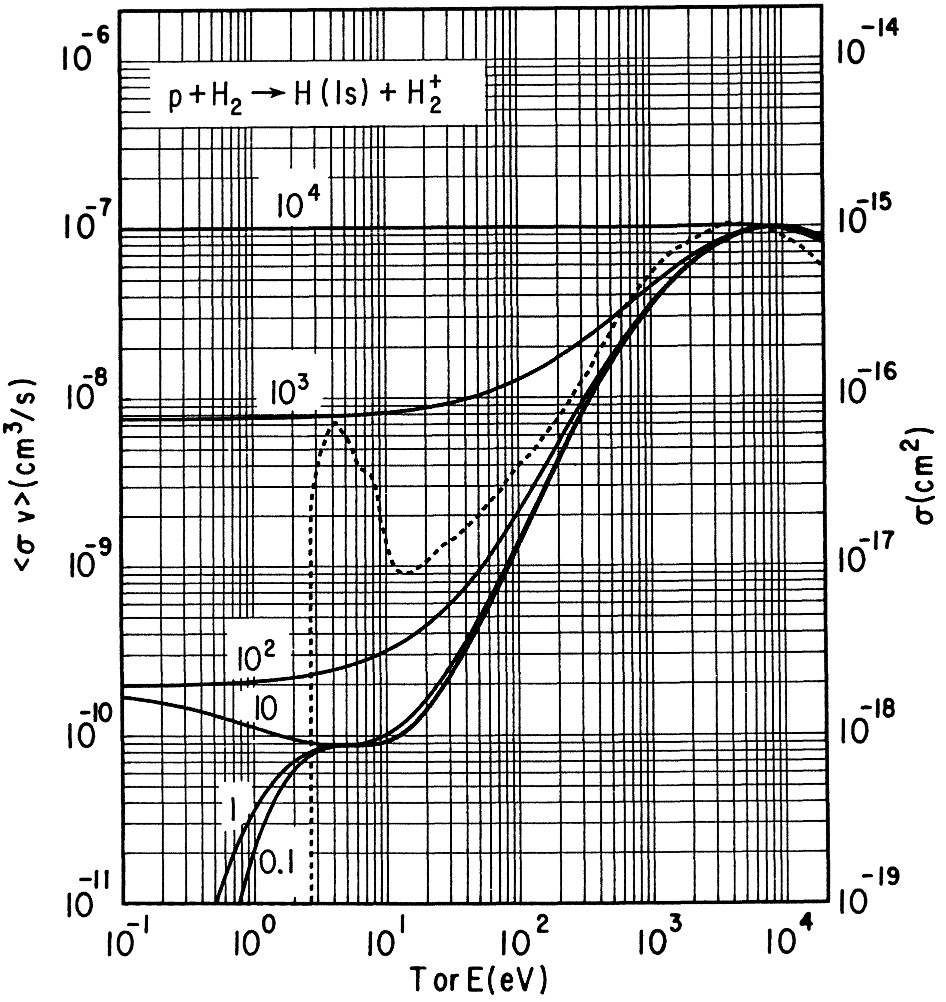
$E_{th} = 1.83$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

$\sigma_{cx} = \sigma_{exp}$

References: E > 400 eV, Freeman and Jones (1974); 50 < E < 400 eV, Barnett et al. (1977); E < 15 eV, Holliday et al. (1971).

Comment: σ_{cx} is extrapolated between 15 and 50 eV. In this reaction, the vibrational levels up to v = 7 are populated in H_2^+.



$p + H_2 \rightarrow H(1s) + H_2^+$
10^4
10^3
10^2
10
1
0.1
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
T or E(eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^0
10^1
10^2
10^3
10^4

3.2.4a $\boxed{p+D_2 \rightarrow D^+ + HD \text{ (or H+D)}}$

$E_{th} = 0.04$ eV, $\Delta E^{(-)} = E_{th}$.

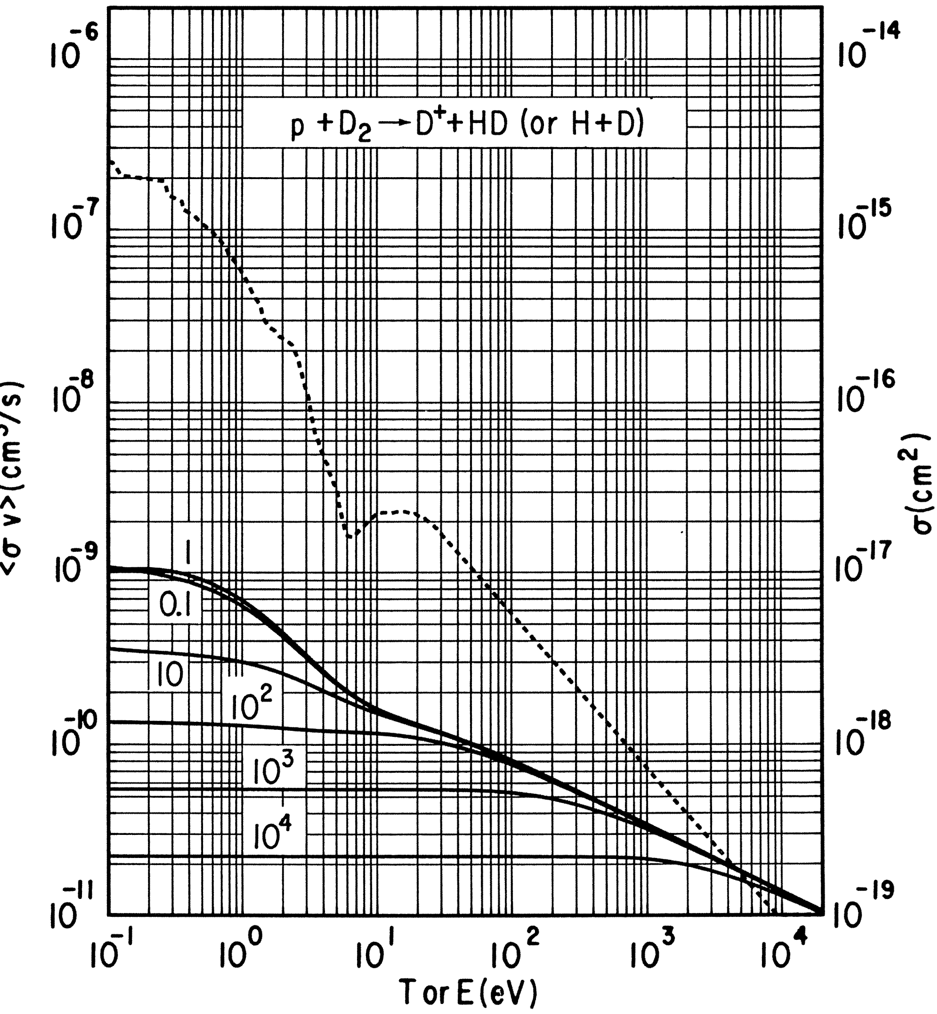
Cross Section:

$E < 15$ eV, $\sigma_p^{exch} = \sigma_{exp}$.

Reference: Ochs and Teloy (1974); see also Teloy (1978) and Linder (1980).

$E > 15$ eV: $\sigma_p^{exch} = \sigma_{se}^{ext}$.

Comment: The extrapolation of σ_p^{exch} in the region $E > 15$ eV is made assuming an approximate E^{-1} behavior.



p + D2 → D+ + HD (or H + D)
1
0.1
10
10^2
10^3
10^4
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-1
10^0
10^1
10^2
10^3
10^4
<σ v> (cm^3/s)
σ (cm^2)
T or E (eV)

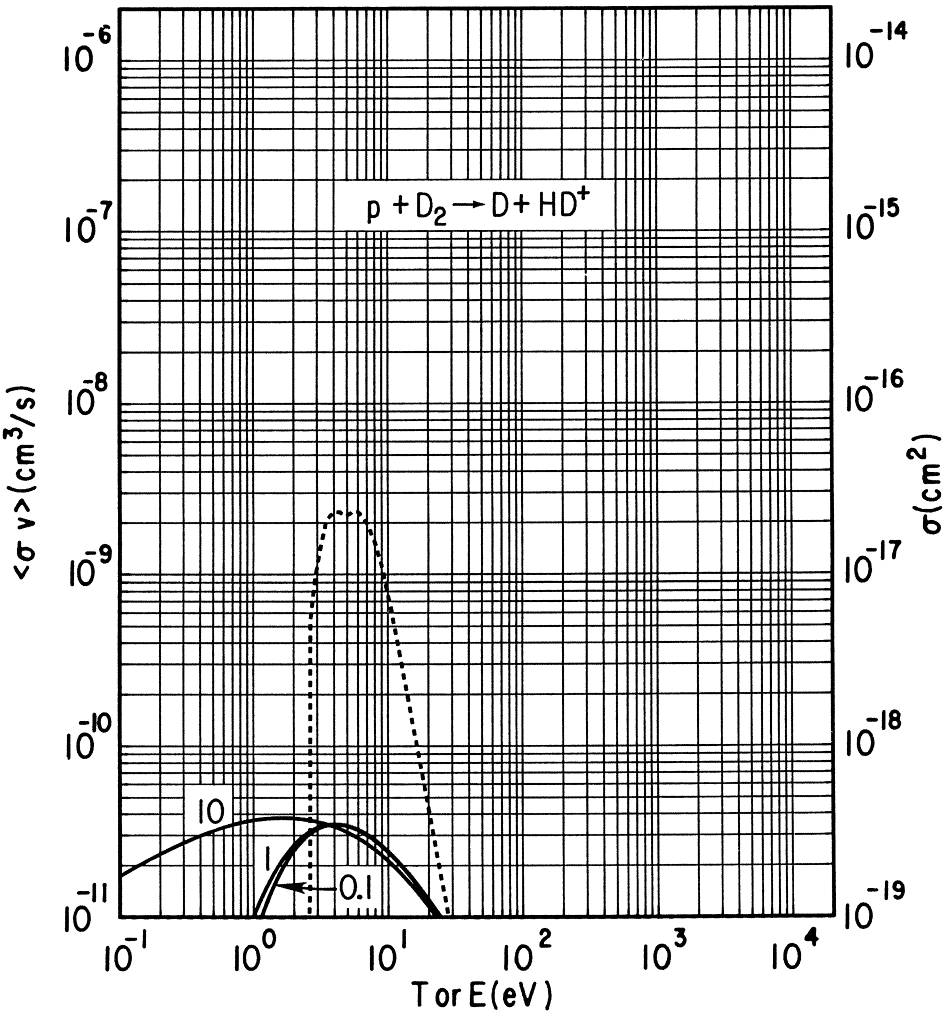
3.2.4b $\boxed{p + D_2 \rightarrow D + HD^+}$

$E_{th} = 1.87$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

$\sigma = \sigma_{exp}$

Reference: Ochs and Teloy (1974); see also Holliday et al. (1971).



$p + D_2 \rightarrow D + HD^+$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10
1
0.1
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

3.2.5 $\boxed{p+H_2 \rightarrow p+H_2^+(v\leq 9)+e}$

$E_{th} = 15.4$ eV, $\Delta E^{(-)} = E_{th} + E_e$.

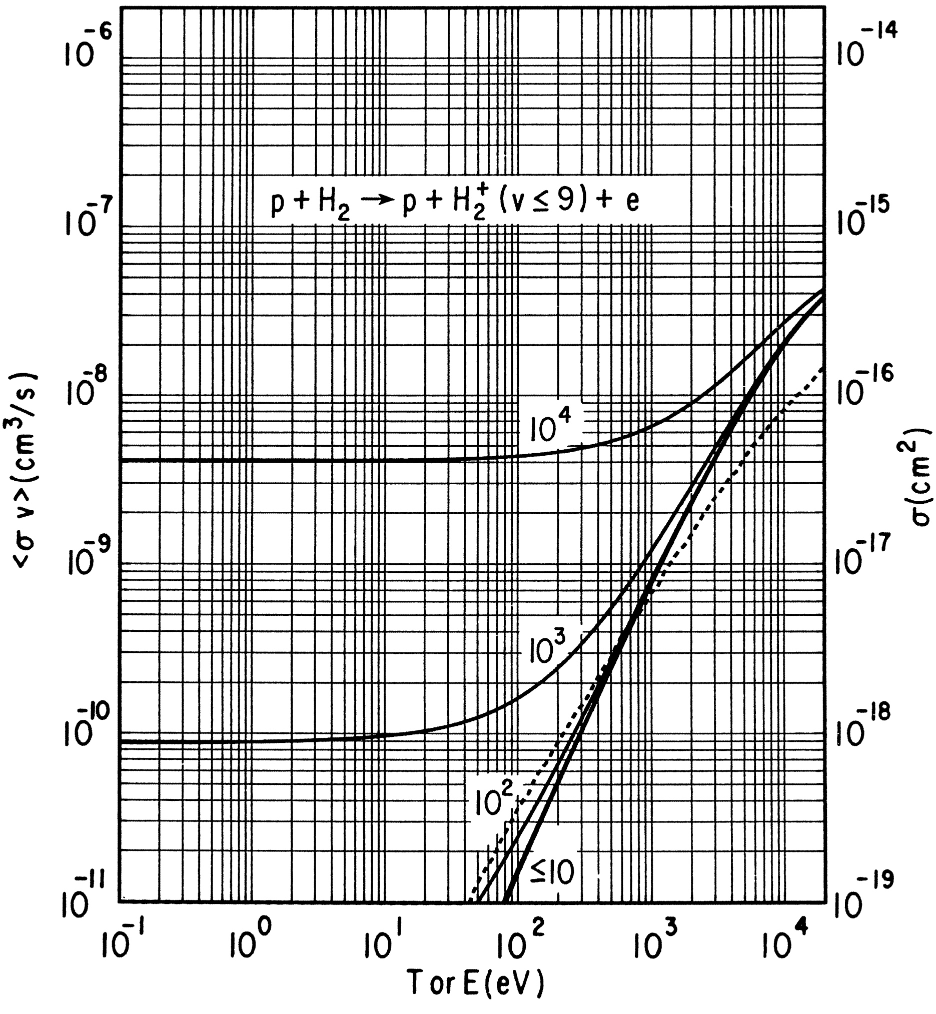
Cross Section:

$E = E_{th} - 300$ eV, $\sigma_{ion} = \sigma_{se}$.

$E \geq 300$ eV, $\sigma_{ion} = \langle\sigma_{ion}\rangle_{exp}$.

References: Freeman and Jones (1974); Sataka et al. (1981)

Comment: σ_{se} is an extrapolation of $\langle\sigma_{ion}\rangle_{exp}$, which preserves the slope of the experimental data over the energy range $300 - 2 \times 10^3$ eV.



$p + H_2 \rightarrow p + H_2^+ (v \leq 9) + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v> (cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma (cm^2)$
10^4
10^3
10^2
≤ 10
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

3.2.6 $\boxed{p + H_2^+(v) \rightarrow p + H(1s) + H^+, \quad (v = 0-9)}$

$\bar{E}_{th} \simeq 6$ eV, $\langle \Delta E^{(-)} \rangle_{v,FC} \simeq 11.0$ eV.

Average Cross Section:

$$\langle \sigma_{diss}^{exc} \rangle_v = \kappa \sum_{v=0}^{9} g(v)\, \sigma_{exc}^{diss}(v) , \qquad \kappa = 0.75,$$

g(v) = relative population of the state $H_2^+(v)$ [see comment (1) in Sect. 2.2.9].

E ≥ 700 eV: $\sigma_{exc}^{diss}(v) = \sigma_{exc}^{diss,B}(v)$.

Reference: Takayanagi and Suzuki (1978)

E = 20-700 eV: $\sigma_{exc}^{diss}(v) = \sigma_{ext}^{B}(v)$.

Mean Energy of Dissociated Products:

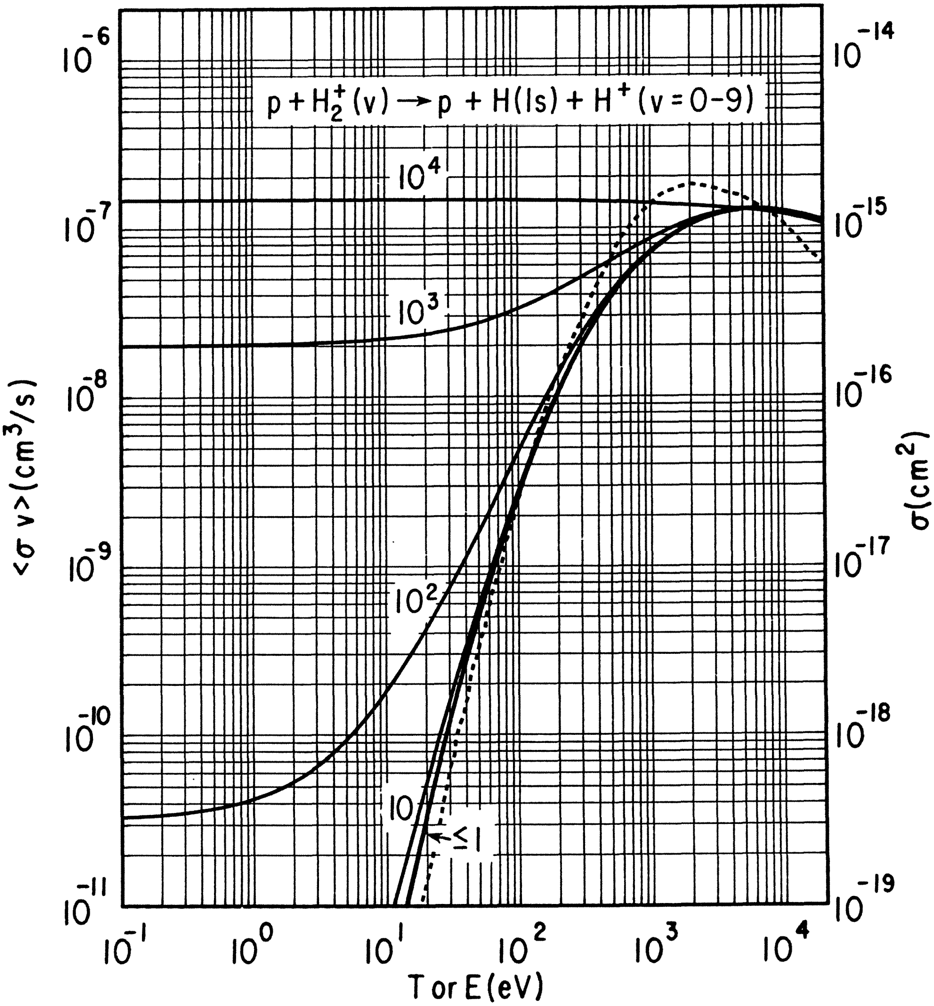
$$\langle E_{H^o}^{(+)} \rangle_{v,FC} \simeq \langle E_{H^+}^{(+)} \rangle_{v,FC} \simeq 4.5 \text{ eV}.$$

Comments:

(1) $\sigma_{ext}^{B}(v)$ is a Born-type extension of $\sigma_{exc}^{diss,B}(v)$.

(2) The reduction factor κ has been introduced to account for the fact that the Born approximation overestimates $\sigma_{exc}^{B}(v)$ in the energy region about and below the cross section maximum.

(3) The overall accuracy of $\langle \sigma_{exc}^{diss} \rangle_v$ is expected to be within a factor of 2.



$p + H_2^+(v) \rightarrow p + H(1s) + H^+ (v=0-9)$
10^4
10^3
10^2
10
≤ 1
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$

3.3 Proton Collisions with He and He*

3.3.1 $\boxed{p+He \rightarrow H+He^{+}}$

$E_{th} = 11.2$ eV

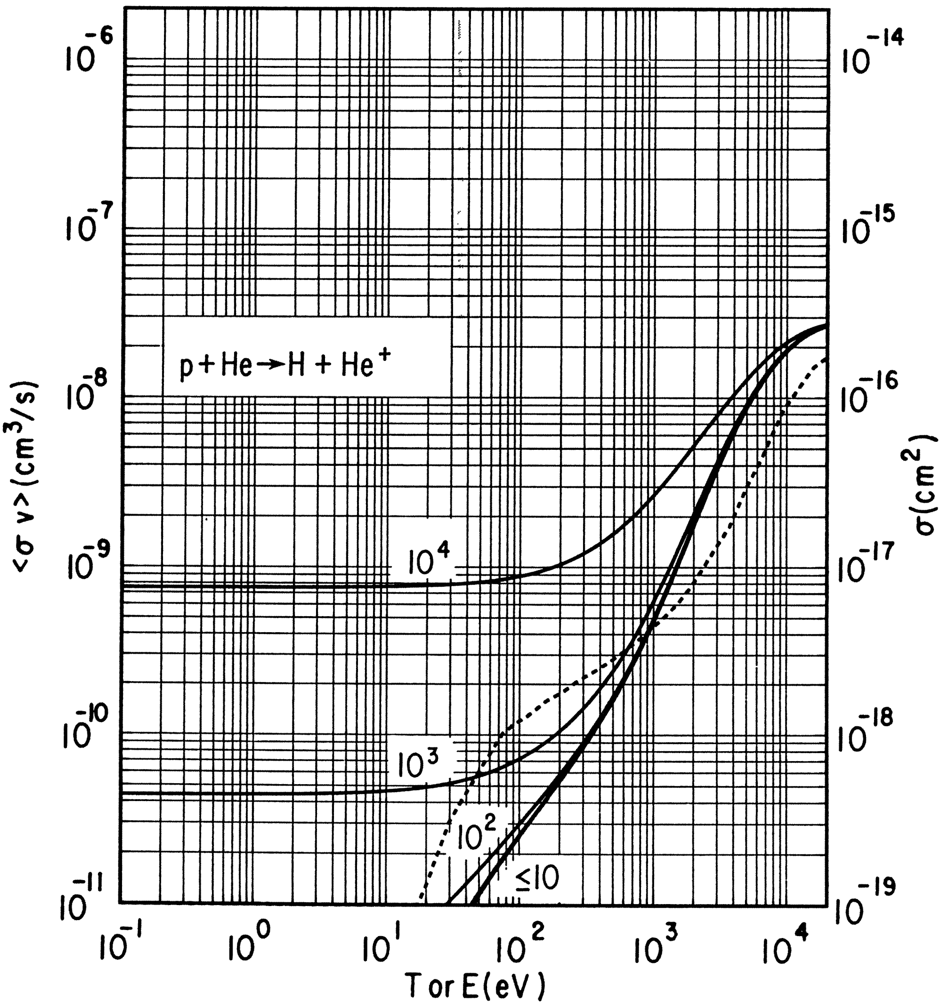
<u>Cross Section</u>:

$E = E_{th} - 10^2$ eV: $\sigma_{cx} = \sigma_{ext}^{fit}$,

$E = 10^2 - 2 \times 10^4$ eV: $\sigma_{cx} = \sigma_{exp}^{fit}$.

Reference: Jones (1977)

<u>Comment</u>: For the region $E = E_{th} - 10^2$ eV, we have used an extrapolation of σ_{exp}^{fit}, where σ_{exp}^{fit} is a least squares fit to experimental data (Jones 1977).


p + He → H + He$^+$
10^4
10^3
10^2
≤10
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)
$\langle\sigma v\rangle$ (cm^3/s)
σ(cm^2)

3.3.2 $\boxed{p+He \rightarrow p+He^{+}+e}$

$E_{th} = 24.58$ eV , $\Delta E^{(-)} = E_{th} + E_{e}$.

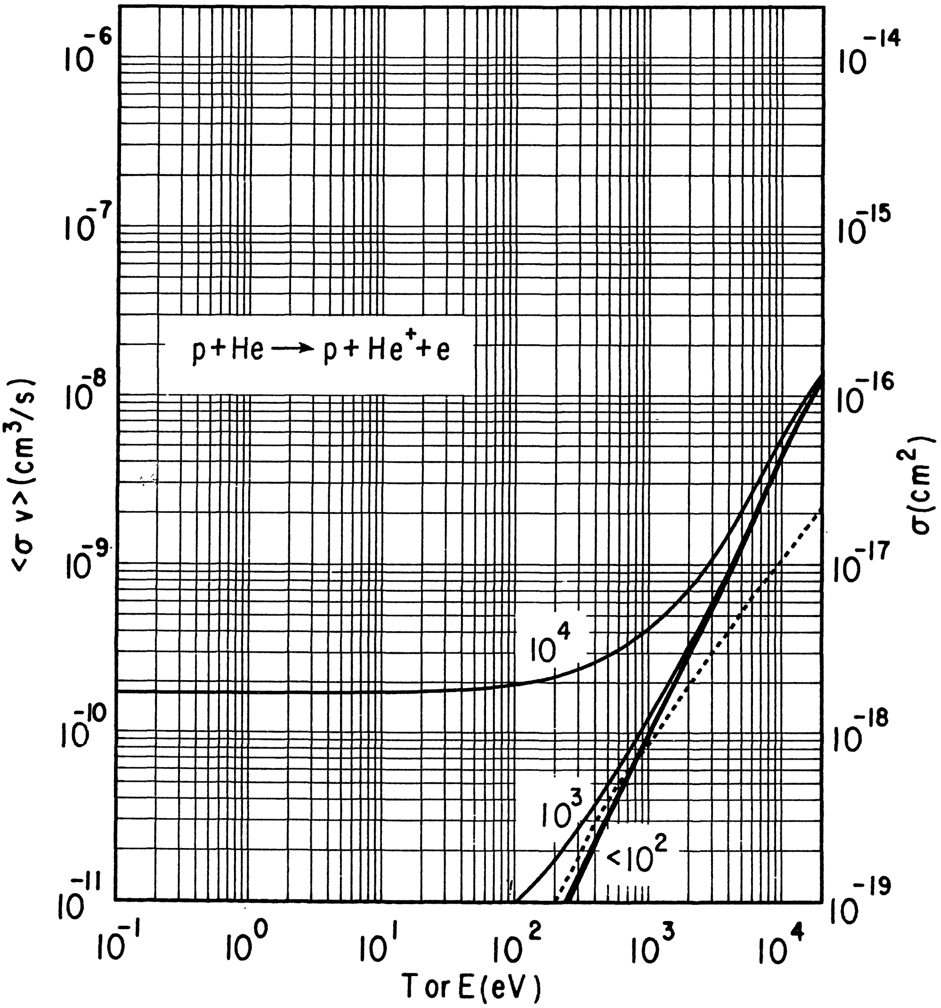
Cross Section:

$E \geq 10^{4}$ eV: $\sigma_{ion} = \sigma_{exp}$.

References: Freeman and Jones (1974); Sataka et al. (1981)

$E = E_{th} - 10^{4}$ eV: $\sigma_{ion} = \sigma_{se}^{ext}$.

Comment: σ_{se}^{ext} is an extrapolation to low energies of σ_{exp} between 10^{4} and 10^{6} eV. This extrapolation is close to the polynomial fit extrapolation of Freeman and Jones (1974).


p + He → p + He$^+$ + e
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v>$ (cm^3/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
σ(cm^2)
10^4
10^3
$<10^2$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

3.3.3 $\boxed{p + He(1s^2|^1S) \rightarrow p + He^*(1s2p|^1P)}$

$E_{th} = 19.819$ eV, $\Delta E^{(-)} = E_{th}$.

Cross Section:

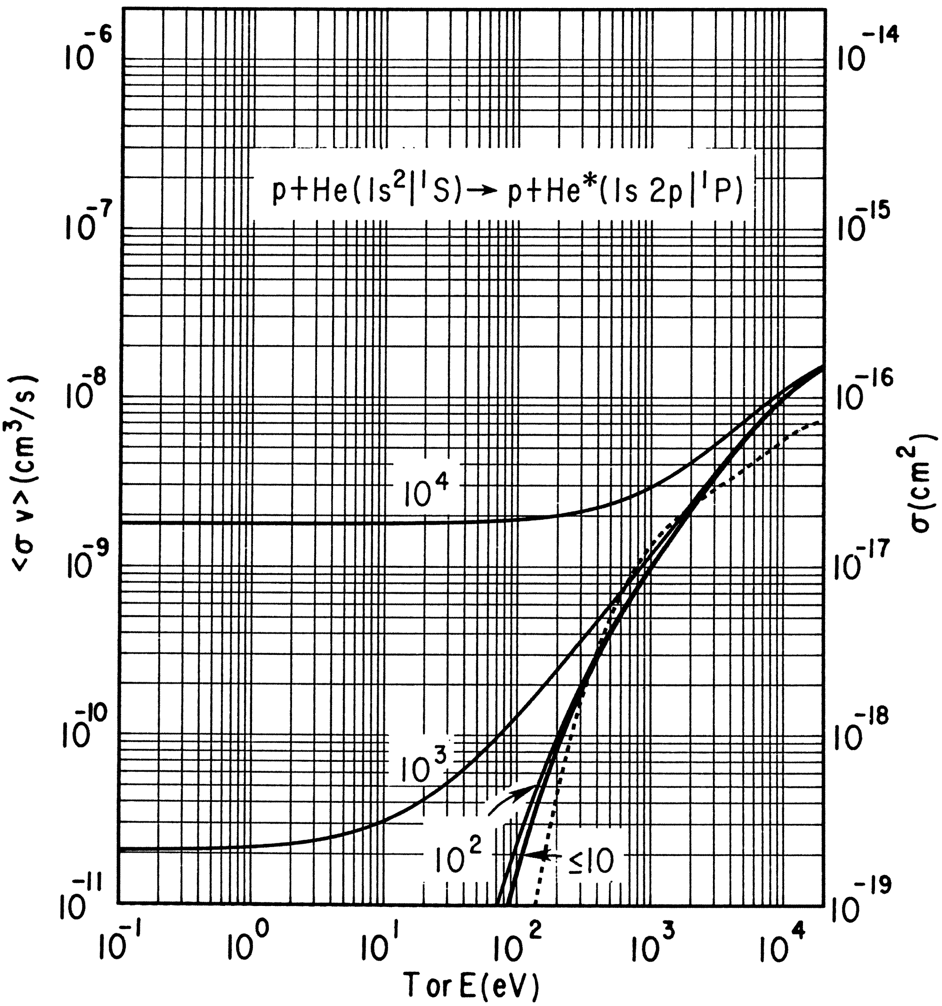
$$\sigma_{exc}^{DACC}(2p) = 2.10 \times 10^{-16} \, D(\beta_{1,2p}) \, [cm^2] \, ,$$

$$\beta_{1,2p} = \frac{0.3171}{v^2} \, ,$$

$$v = 63246 \times 10^{-3} \, (E_p[eV])^{1/2} \, ,$$

$D(\beta_{1,2p})$: see Appendix C.

Comment: $\sigma_{exc}^{DACC}(2p)$ contains a factor of 2, to account for the two electrons in He. At energies corresponding to $\beta \gtrsim 0.5$, the cross section is uncertain to within a factor of 2.



$p + He(1s^2 \, ^1S) \rightarrow p + He^*(1s\,2p \, ^1P)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$<\sigma v> (cm^3/s)$
$\sigma (cm^2)$
10^4
10^3
10^2
≤ 10
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

3.3.4 $\boxed{p+He(1s^2|^1S) \rightarrow p+He^*(1s3p|^1P), \quad (1sn, \ n \geq 3)}$

$$E_{th}(n) = E_{np}^{exc}(^1P), \quad \Delta E^{(-)}(n) = E_{th}(n).$$

Cross Sections:

$$\sigma_{exc}^{DACC}(1 \rightarrow n) = 3.52 \times 10^{-16} \frac{\lambda_{1n}}{\omega_{1n}} D(\beta_{1n}) \ [cm^2],$$

$$\lambda_{1n} = \left(\frac{f_{1s \rightarrow np}}{2\omega_{1,np}}\right)^{1/2}, \quad \beta_{1n} = \frac{\lambda_{1n}\omega_{1,np}}{v^2}, \quad \omega_{1,np} = \frac{E_{np}^{exc}(^1P)}{2Ry},$$

$$v = 6.3246 \times 10^{-3} E^{1/2},$$

$f_{1s \rightarrow np}$: oscillator strength for 1s→np transition (see Appendix A.4)

For $E_{n,p}^{exc}$ (^1P) and $D(\beta_{1n})$ see Appendix A.3 and C, respectively.

Comment: A factor of 2 has been introduced to account for the two electrons in He. For $\beta \gtrsim 0.5$, $\sigma_{exc}^{DACC}(1 \rightarrow n)$ is uncertain to within a factor of 2.

3.3.5 $\boxed{p+He^*(n) \rightarrow p+He^*(m), \quad (n\geq 2,\ m>n)}$

$E_{th} = E_n^{ion} - E_m^{ion} = \Delta E_{nm};\ \Delta E^{(-)} = \Delta E_{nm}.$

Cross Section:

$$\sigma_{exc}^{DACC}(n\rightarrow m) = 3.52 \times 10^{-16} \frac{\lambda_{nm}}{\omega_{nm}} D(\beta_{nm})[cm^2] ,$$

$$\lambda_{nm} = (f_{nm}/2\omega_{nm})^{1/2} , \quad \beta_{nm} = \frac{\lambda_{nm}\ \omega_{nm}}{v^2} , \quad \omega_{n,m} = \frac{\Delta E_{nm}}{2Ry} ,$$

$$v = 6.3246 \times 10^{-3} E^{1/2} ,$$

f_{nm}: oscillator strength for the $n \rightarrow m$ transition (see Appendix A.4 and B).

$D(\beta_{nm})$: see Appendix C.

Comments:

(1) $n\rightarrow m$ denotes all the dipole-allowed transitions between $n(\equiv n\ell)$ and $m(\equiv m\ell')$ states. If for n=2 the states are specified with their additional quantum numbers (i.e., $n\equiv 2\ell|^{2S+1}L$), then $m\equiv m\ell'|^{2S+1}L'$, with $\ell' = \ell\pm 1$ and $L' = L\pm 1$. For $n\geq 3$, n and m can be treated as "average" levels, taking an average for all the quantities involved $(\Delta E_{nm}, f_{n\rightarrow m})$.

(2) A factor of 2 is introduced in σ_{exc}^{DACC} to account for the two electrons in He.

(3) The overall uncertainty in σ_{exc}^{DACC} for $\beta \gtrsim 0.5$ is within a factor of 2.

3.3.6a $\boxed{p+He^{*}(1s2s|^{1}S) \rightarrow H^{*}(2s)+He^{+}(1s)}$

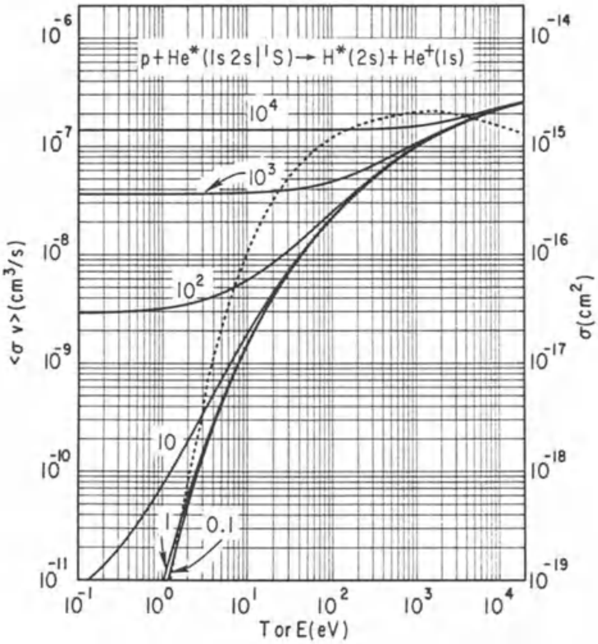
3.3.6b $\boxed{p+He^{*}(1s2s|^{3}S) \rightarrow H^{*}(2s)+He^{+}(1s)}$

$E_{th}(a) = E_{th}(b) = 0 \quad <\Delta E^{(+)}_{H^*}> \simeq <\Delta E^{(+)}_{He^+}> \simeq 0.$

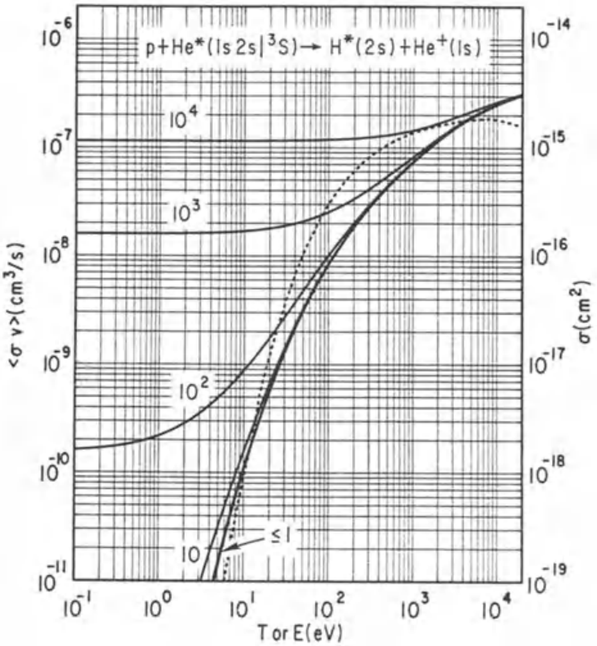
Cross Sections:

$\sigma_{cx} = \sigma_{RZD}.$

Comment: The cross sections σ_{cx} have been calculated using the Demkov formula (see e.g., Smirnov 1973), with the coupling matrix elements calculated by the asymptotic method (Smirnov 1973).



p + He*(1s 2s | ¹S) → H*(2s) + He⁺(1s)
10⁴
10³
10²
10
1
0.1
<σ v> (cm³/s)
σ (cm²)
T or E (eV)



p + He*(1s 2s | ³S) → H*(2s) + He⁺(1s)
10⁴
10³
10²
10
≤1
<σ v> (cm³/s)
σ (cm²)
T or E (eV)

3.3.7a $\boxed{p+He^*(1s2p|^1 P) \rightarrow H^*(2p)+He^+(1s)}$

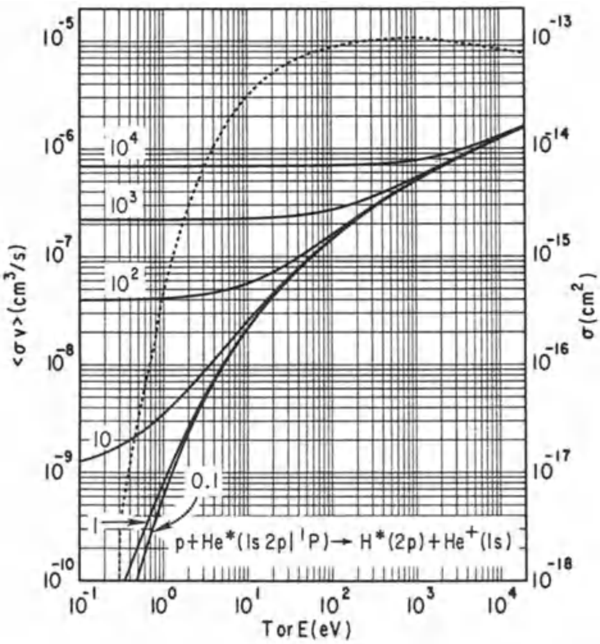
3.3.7b $\boxed{p+He^*(1s2p|^3 P) \rightarrow H^*(2p)+He^+(1s)}$

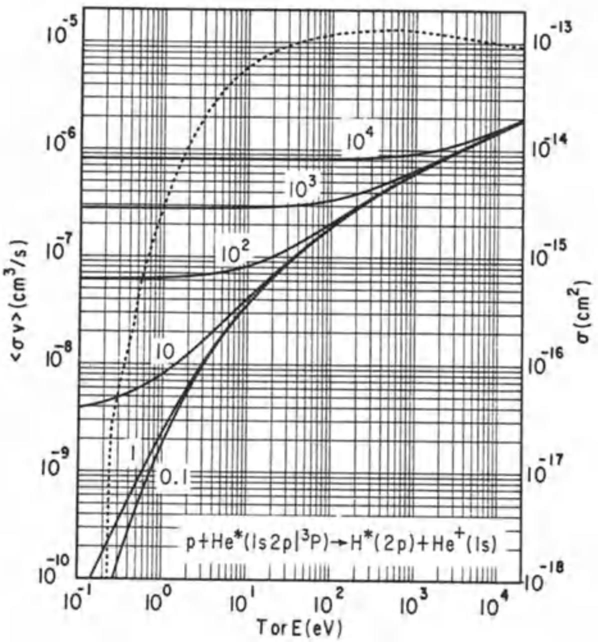
$E_{th}(a,b) \approx 0, \quad \Delta E^{(\pm)}(a,b) \approx 0.$

<u>Cross Sections</u>:

$\sigma_{cx} = \sigma_{RZD}.$

<u>Comment</u>: σ_{cx} have been calculated by the Demkov formula (Smirnov 1973) with coupling matrix elements from the asymptotic theory (Smirnov 1973).


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$<\sigma v>(cm^3/s)$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$\sigma(cm^2)$
10^4
10^3
10^2
10
0.1
1
$p + He^*(1s2p|^1P) \rightarrow H^*(2p) + He^+(1s)$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$<\sigma v>(cm^3/s)$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$\sigma(cm^2)$
10^4
10^3
10^2
10
1
0.1
$p + He^*(1s2p|^3P) \rightarrow H^*(2p) + He^+(1s)$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)

3.3.8 $p+He^*(1s,n) \rightarrow H^*(n)+He^+(1s), \quad (n \geq 3)$

$$E_{th}(n) \simeq \Delta E^{(\pm)}(n) \simeq 0.$$

Cross Sections:

$$n = 3: \quad \sigma_{cx} \approx \sigma_{cx}^{res}[p + H^*(n=3)] \qquad \text{(see figure in Sect. 3.1.9)},$$

$$n \geq 4: \quad \sigma_{cx}^{c\ell} \simeq 1.58 \times 10^{-15} \frac{n^4}{1 + 0.8(vn)^{2/5} + 2.6\,(vn)} \left[cm^2\right],$$

$$v = 6.3246 \times 10^{-3} E^{1/2} .$$

Comments:

(1) For $n \geq 3$, $He^*(1s,n)$ can be treated as a hydrogenic system with an effective quantum number $n^* = (2 <E_n^{ion}>_L)^{-1/2}$.

(2) σ_{cx}^{cl} is a classical expression for charge exchange (Smirnov 1973), valid for $nv \lesssim v_o$, where $v_o = 2.19 \times 10^8$ cm/sec.

3.3.9 $\boxed{p+He^*(1s,n) \rightarrow p+He^++e, \quad (n \geq 2)}$

$$E_{th} = E_n^{ion}, \quad \Delta E^{(-)} = E_n^{ion} + E_e .$$

Cross Section:

$$\sigma_{ion}^{BEA}(n) = 0, \quad \text{for } \alpha < 0.207,$$

$$= 5.867 \times 10^{-17} \, n^4 \left(\alpha - \frac{0.164}{\alpha^2} + \frac{0.1875}{\alpha^2(\alpha+1)}\right) [cm^2]$$

$$\text{for } 0.207 < \alpha < 1.207 ,$$

$$= 1.467 \times 10^{-16} \, n^4 \, \frac{1}{\alpha^2} \left(1 - \frac{0.15}{\alpha^2 - 1}\right) [cm^2]$$

$$\text{for } \alpha > 1.207 .$$

$$\alpha = 6.3246 \times 10^{-3} \, n\left(E[eV]\right)^{1/2} ,$$

$$n = \left(Ry/E_n^{ion}\right)^{1/2} .$$

Comment: For $n = 2$, $n \equiv (2\ell|^{2S+1}L)$, where $\ell = 0,1$, $L = 0,1$, and $S = 0,1$. For $n \geq 3$, the states can be treated as degenerate and an average value for E_n^{ion} can be used (see Appendix A.3).

3.3.10 $\boxed{p+He^{*}(1s,n) \rightarrow p+He^{+*}(n)+e,\ (n\geq 2)}$

$E_{th} = 54.4$ eV, $\Delta E_p^{(-)} = E_{th} + E_e$.

Cross Section:

$$\sigma_{ion}^{BEA}(1s) = 0, \quad \text{for } \alpha < 0.207\ ,$$

$$= 5.867 \times 10^{-17} \left(\alpha - \frac{0.164}{\alpha^2} + \frac{0.1875}{\alpha^2(\alpha+1)}\right) \left[cm^2\right]$$

$$\text{for } 0.207 < \alpha < 1.207\ ,$$

$$= 1.467 \times 10^{-16} \frac{1}{\alpha^2} \left(1 - \frac{0.15}{(\alpha^2-1)}\right) \left[cm^2\right]$$

$$\text{for } \alpha > 1.207\ .$$

$$\alpha = 3.1623 \times 10^{-3} \left(E[eV]\right)^{1/2}\ .$$

Comment: The inner-shell electron is ionized in this reaction. In σ_{ion}^{BEA}, the screening by the outer electron is neglected.

Chapter 4

Collision Processes and Reactions of H_2^+ Ions

4.1 General Remarks

(1) The cross sections σ_{j,H_2^+} for excitation, ionization, and dissociation processes in $H_2^+ + A$ ($A = H, H_2, He$) collisions can be approximately related to the corresponding cross sections $\sigma_{j,p}$ for p + A processes by the scaling relation

$$\sigma_{j,H_2^+}\left(E_{H_2^+}\right) \approx \sigma_{j,p}\left(2E_p\right) .$$

This relation is valid at least in the energy region above the cross section maximum.

(2) The reaction rate coefficients $\alpha_{j,H_2^+}(E_o)$ and $\alpha_{j,p}(E_o)$ (E_o being the energy of the neutral particle A) at the temperatures $T_{H_2^+} \approx T_p$ are related by

$$\alpha_{j,H_2^+}\left(E_o\right) = \kappa\, \alpha_{j,p}\left(E_o\right) ,$$

$$\kappa = \left[\mu(p,A)/\mu(H_2^+,A)\right]^{3/2} ,$$

where $\mu(B,A)$ is the reduced mass of the system B + A.

(3) The rate coefficient $\alpha_{cx}(H_2^+, H)$ for the $H_2^+ + H \rightarrow H_2 + H^+$ reaction is related to the coefficent $\alpha_{cx}(H^+, H_2)$ of the inverse reaction by $\alpha_{cx}(H_2^+, H; E_o) \approx g\, \alpha_{cx}(H^+, H_2; 2E_o)$, where $g = 1/4$ assuming $T_p \approx T_{H_2^+}$, and E_o is the energy of H.

(4) The energetics (E_{th}, $\Delta E^{(\pm)}$, etc.) for the H_2^+ + A reactions remain the same as for the corresponding p + A reactions.

4.2 Collisions of H_2^+ with H

4.2.1 $\boxed{H_2^+(1s\sigma_g;v) + H(1s) \rightarrow H_2^{+*}(2p\sigma_u)+H(1s) \rightarrow H^+ + H^0 + H(1s), \quad (v = 0-9)}$

$<E_{th}>_{\bar{v}\ FC} \simeq 6$ eV, $<\Delta E_H^{(-)}>_{\bar{v},FC} \simeq 11$ eV.

Cross Section:

$$\sigma_{diss}^{exc} = \sum_{v=0}^{9} g(v)\ \sigma_{diss}^{exc,B}(v) \approx \sigma_{diss}^{exc}(\bar{v}=4),$$

$$E = 1 \times 10^3 - 2 \times 10^4 \text{ eV: } \sigma_{diss}^{exc} = \sigma_{diss}^{exc,B}(\bar{v}=4)\ .$$

Reference: Takayanagi and Suzuki (1978)

$$E = E_{th} - 10^3 \text{ eV: } \sigma_{diss}^{exc} = \sigma_{ext}^{B}(\bar{v} = 4).$$

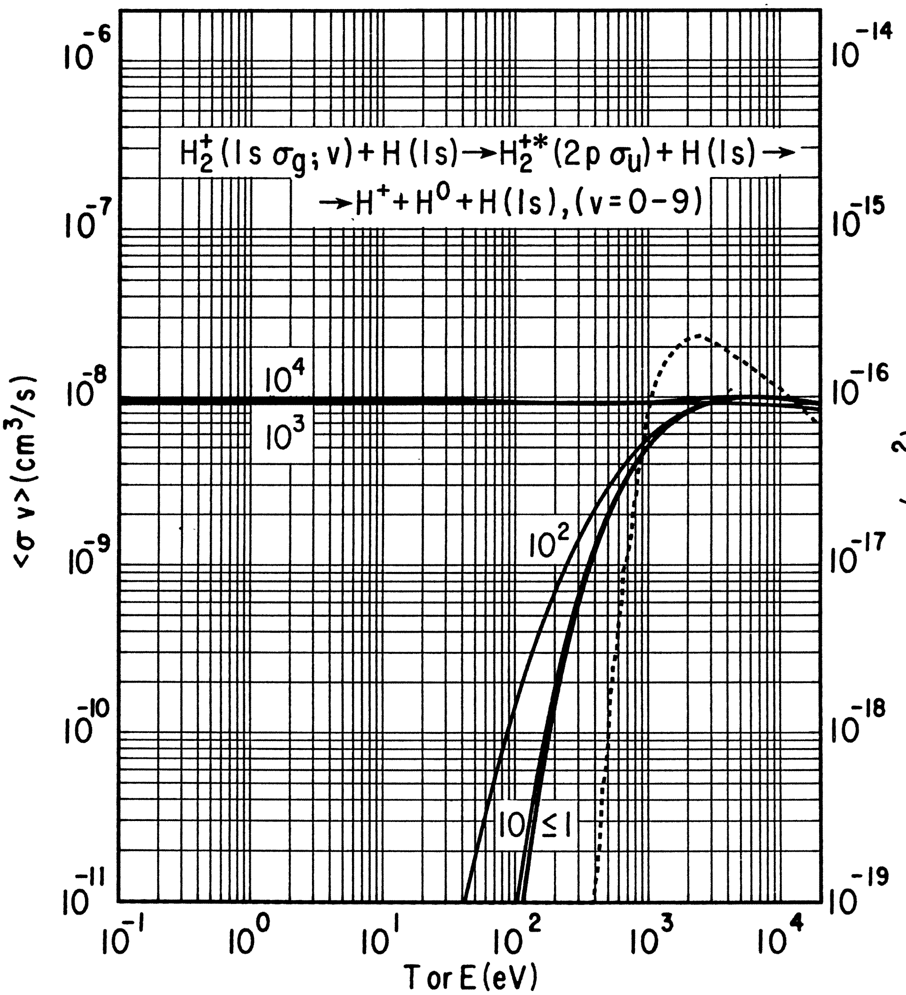
Mean Energy of Products:

$$<E_{H^o}>_{FC,\bar{v},\Delta\varepsilon} \approx <E_{H^+}>_{FC,\bar{v},\Delta\varepsilon} \simeq 4.5 \text{ eV.}$$

Comments:

(1) The averaging of $\sigma_{diss}^{exc,B}$ (v) from Takayanagi and Suzuki (1978) with the populations g(v) of different vibrational states of $H_2^+(v)$ (Busch and Dunn 1972) gives a result close to $\sigma_{diss}^{exc,B}$ (v=4).

(2) The mean energies $<E>_{\bar{v},FC}$ are averaged values over the Franck-Condon region for $\bar{v}$ = 4, and for the products the average is also over a distribution $\Delta\varepsilon$ between 0 and 9 eV. Equipartition of the dissociating energy of the $2p\sigma_u$ state between the products is assumed.


$H_2^+(1s\,\sigma_g; v) + H(1s) \rightarrow H_2^{+*}(2p\,\sigma_u) + H(1s) \rightarrow$
$\rightarrow H^+ + H^0 + H(1s), (v = 0-9)$
10^4
10^3
10^2
10
≤ 1
$\langle \sigma v \rangle (cm^3/s)$
$\sigma (cm^2)$
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^0
10^1
10^2
10^3
10^4

4.3 Collisions of H_2^+ with H_2

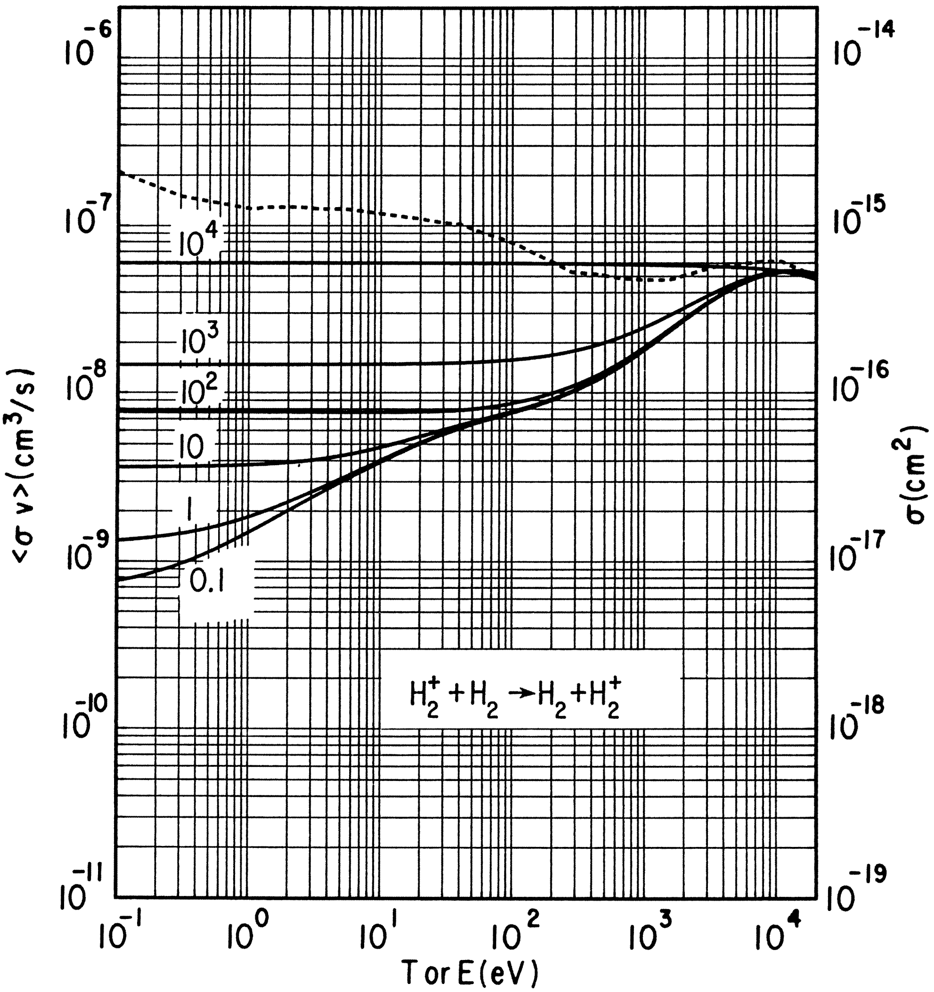
4.3.1 $\boxed{H_2^+ + H_2 \rightarrow H_2 + H_2^+}$

<u>Cross Section</u>:

$E = 0.1 - 2 \times 10^4$ eV: $\sigma_{cx} = \sigma_{exp}^{fit}$.

Reference: Jones (1977)

<u>Comment</u>: σ_{exp}^{fit} is a fit to the experimental data.



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{4}
10^{3}
10^{2}
10
1
0.1
$H_2^+ + H_2 \rightarrow H_2 + H_2^+$
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

4.3.2 $\boxed{H_2^+ + H_2 \rightarrow H_2^+ + H_2^+ + e}$

$E_{th} = 15.4$ eV, $\Delta E^{(-)}_{H_2^+} = E_{th} + E_e$.

Cross Section:

$E = E_{th} - 400$ eV: $\sigma_{ion} = \sigma_{se}^{ext}$,

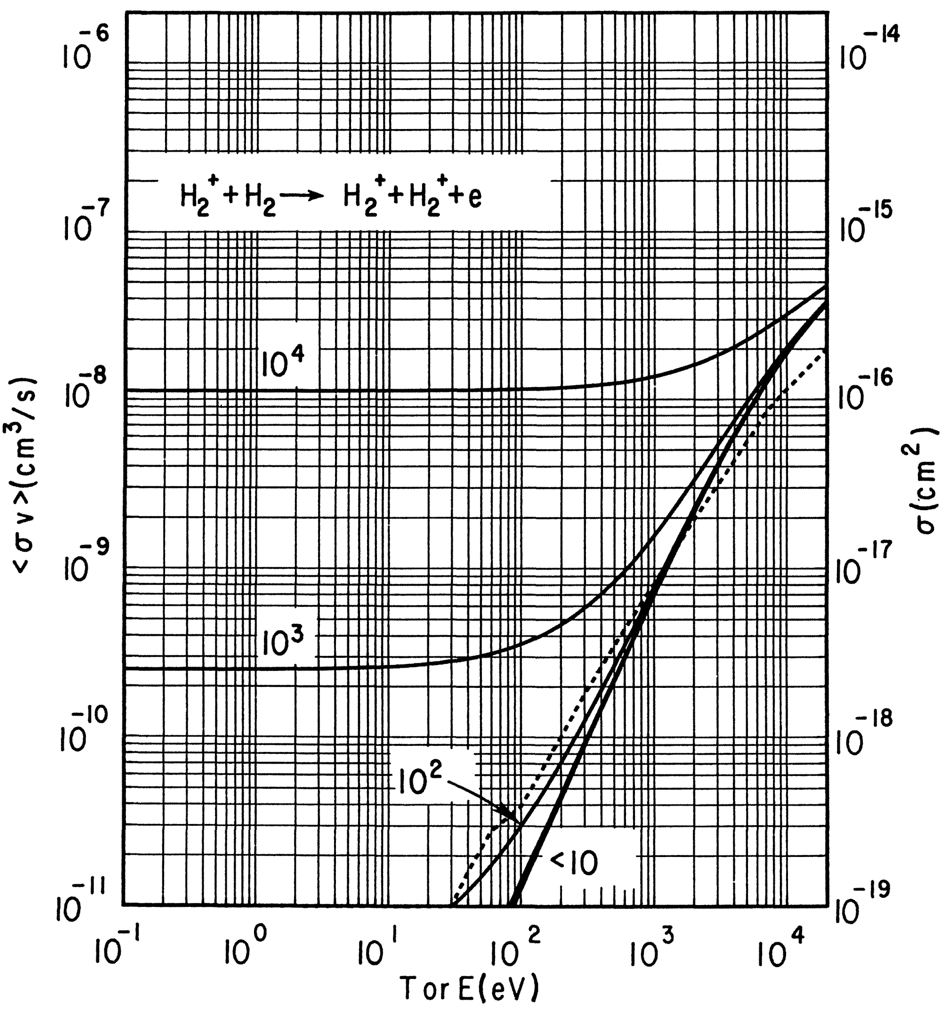
$E = 400 - 2 \times 10^4$ eV: $\sigma_{ion} = \langle\sigma_{ion}\rangle_{exp}$.

Reference: Sataka et al. (1981)

Comments:

(1) $\langle\sigma_{ion}\rangle_{exp}$ is an average over the experimental data.

(2) σ_{se}^{ext} is a DACC-type (exponential decrease) extension of $\langle\sigma_{ion}\rangle_{exp}$.



$H_2^+ + H_2 \rightarrow H_2^+ + H_2^+ + e$
10^4
10^3
10^2
<10
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$

4.3.3 $\boxed{H_2^+ + H_2 \rightarrow H_3^+ + H}$

$E_{th} = 0.0$ eV

Cross Section:

$E \leq 10$ eV: $\sigma = \sigma_{exp}$.

Reference: Jones (1977)

$E \geq 10$ eV: $\sigma = \sigma_{se}^{ext}$.

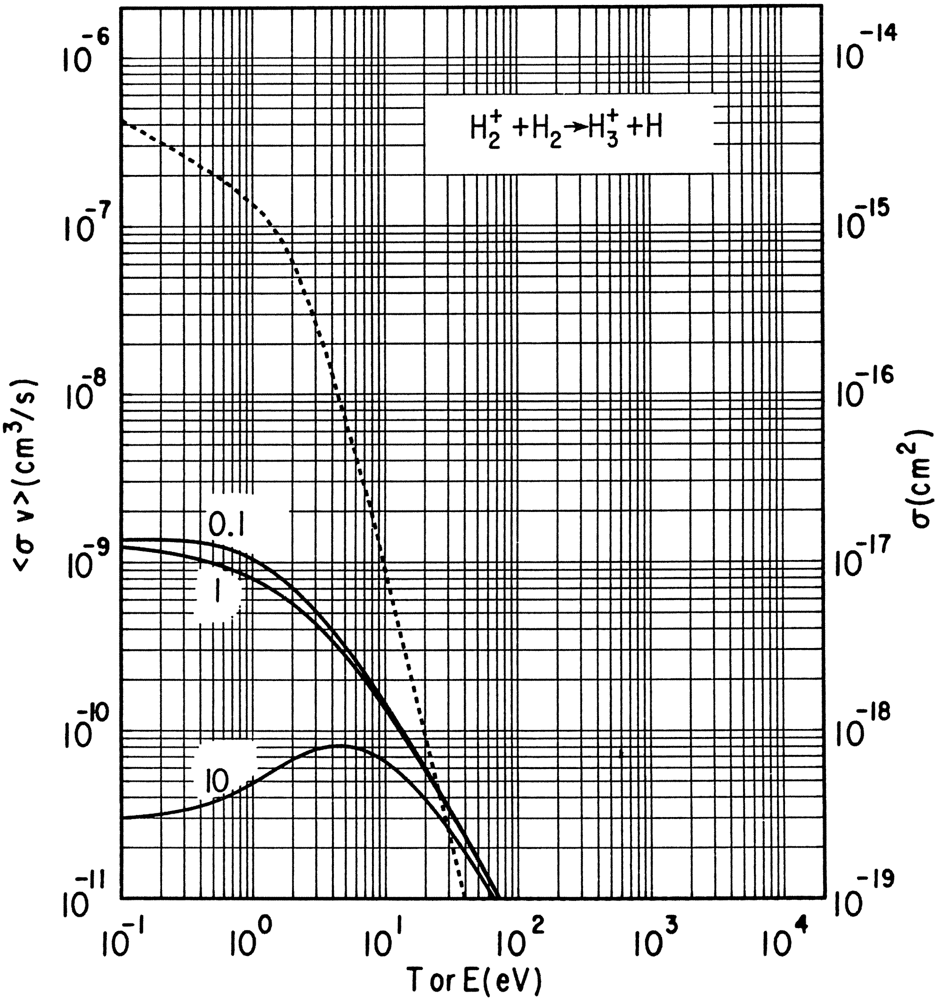
Mean Energy of Products:

$\langle E_{H_3^+} \rangle \simeq \langle E_H \rangle \simeq 0.585$ eV.

Comments:

(1) The reaction is exothermic by 1.17 eV (Christoffersen et al. 1964). We assume that the fragments share this energy equally.

(2) The extrapolation of σ in the region above 10 eV is in accord with the analytic fit extrapolation of Jones (1977).



$H_2^+ + H_2 \rightarrow H_3^+ + H$
0.1
1
10
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v>(cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma(cm^2)$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T or E(eV)

4.4 Collisions of H_2^+ with He

4.4.1 $\boxed{H_2^+ + He \rightarrow H_2^+ + He^+ + e}$

$E_{th} = 24.58$ eV, $\quad \Delta E^{(-)}_{H_2^+} = E_{th}$.

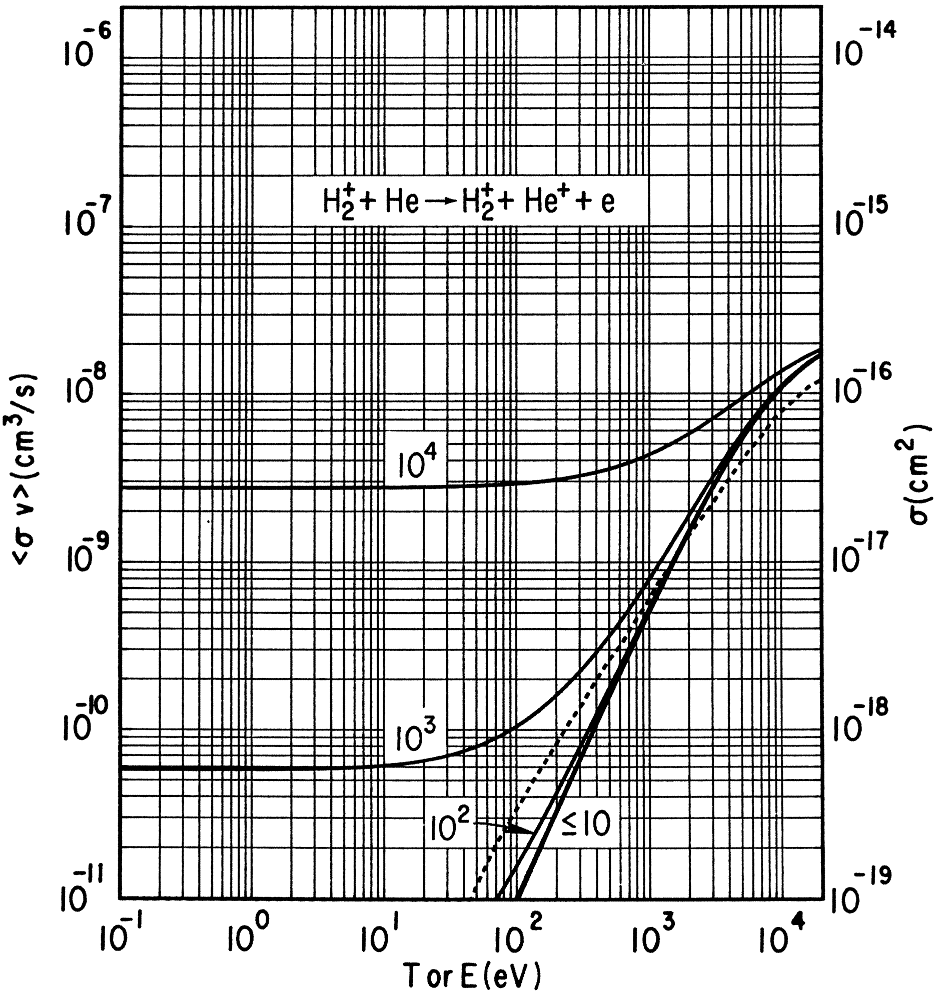
Cross Section:

$E = E_{th} - 400$ eV: $\quad \sigma_{ion} = \sigma_{se}^{ext}$,

$E = 400 - 2 \times 10^4$ eV: $\quad \sigma_{ion} = \sigma_{exp}$.

Reference: Sataka et al. (1981)

Comment: σ_{se}^{ext} is an extrapolation of σ_{exp}, which preserves the slope of the experimental curve in the range of 400-2000 eV.



$H_2^+ + He \rightarrow H_2^+ + He^+ + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^4
10^3
10^2
≤ 10
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

Chapter 5

Collision Processes of He^+

5.1 General Remarks

(1) The cross sections σ_{j,He^+} for direct processes (excitation, ionization, dissociation) in $He^+ + A$ ($A = H, H_2, He$) collisions can be obtained (approximately) from the cross sections $\sigma_{j,p}$ of the corresponding $p + A$ processes by scaling the energy of the latter:

$$\sigma_{j,He^+}\left(E_{He^+}\right) \simeq \sigma_{j,p}\left(\frac{M(He^+)}{M(p)}\,E_p\right),$$

$M(He^+)$ and $M(p)$ are the He^+ and p masses, respectively. This scaling is at least valid for energies above the cross section maximum.

(2) The rate coefficients $\alpha_{j,He^+}\left(E_o\right)$ and $\alpha_{j,p}(E_o)$ for a given energy E_o of particle A and for $T_{He^+} \simeq T_p$ are related by

$$\alpha_{j,He^+}\left(E_o\right) = \kappa_{He^+}\alpha_{j,p}\left(E_o\right),$$

$$\kappa_{He^+} = \left[\mu(p,A)/\mu(He,A)\right]^{3/2},$$

where $\mu(B,A)$ is the reduced mass of A + B.

(3) The energetics (E_{th}, $\Delta E^{(\pm)}$, etc) for the $He^+ + A$ reactions are the same as for the corresponding $p + A$ reactions.

(4) For some specific reactions, σ_j and $\alpha_j(E_o)$ are presented separately in the remainder of this chapter.

5.2 Collisions of He^+ with H_2

5.2.1 $\boxed{He^+ + H_2 \rightarrow He^+ + H_2^+ + e}$

$$E_{th} = 15.4 \text{ eV}, \quad \Delta E^{(-)}_{He^+} = E_{th} + E_e .$$

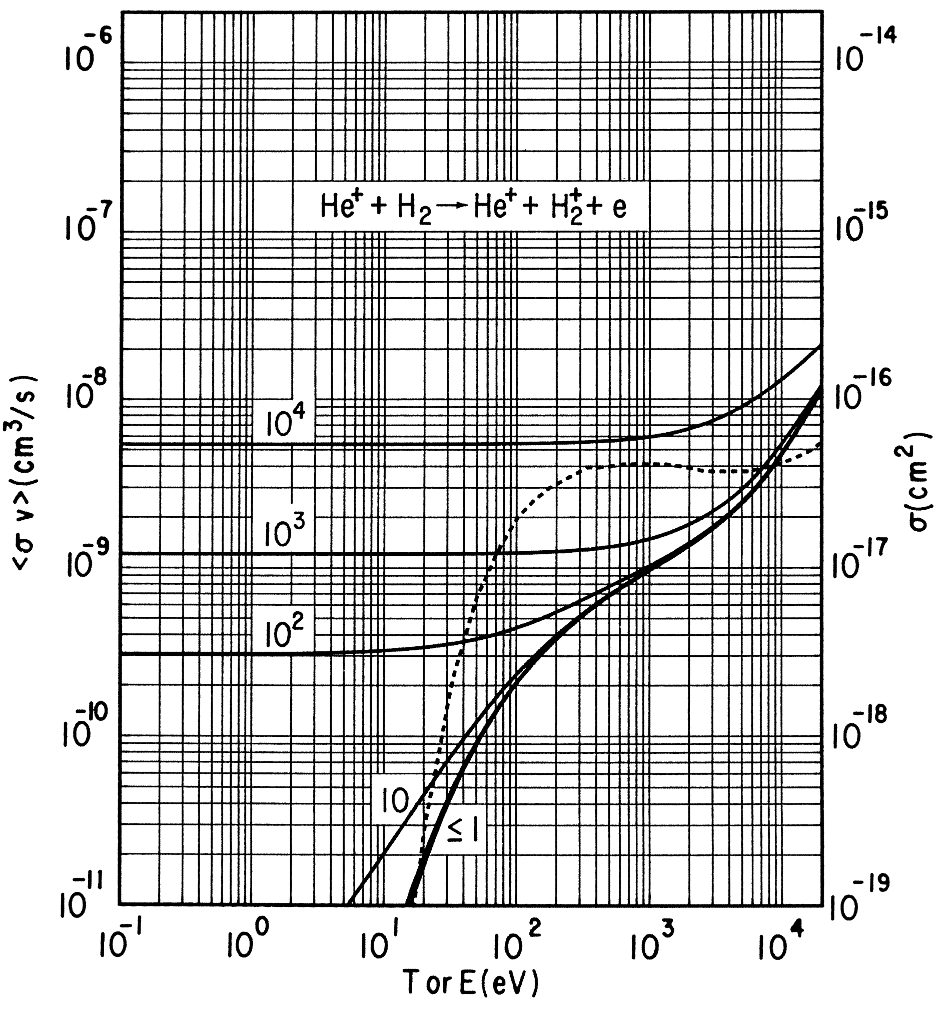
<u>Cross Section</u>:

$$E = E_{th} - 10^2 \text{ eV:} \quad \sigma_{ion} = \sigma_{se}^{ext} ,$$

$$E \geq 10^2 \text{ eV:} \quad \sigma_{ion} = \sigma_{exp} .$$

Reference: Sataka et al. (1981)

<u>Comment</u>: σ_{se}^{ext} is an extrapolation of σ_{exp}, according to the DACC behavior of σ in the low energy region (see Sect. 3.1.5 and Appendix C).



$He^+ + H_2 \rightarrow He^+ + H_2^+ + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$<\sigma v> (cm^3/s)$
$\sigma (cm^2)$
10^4
10^3
10^2
10
≤ 1
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

5.2.2 $\boxed{He^+ + H_2 \rightarrow He + H_2^+}$

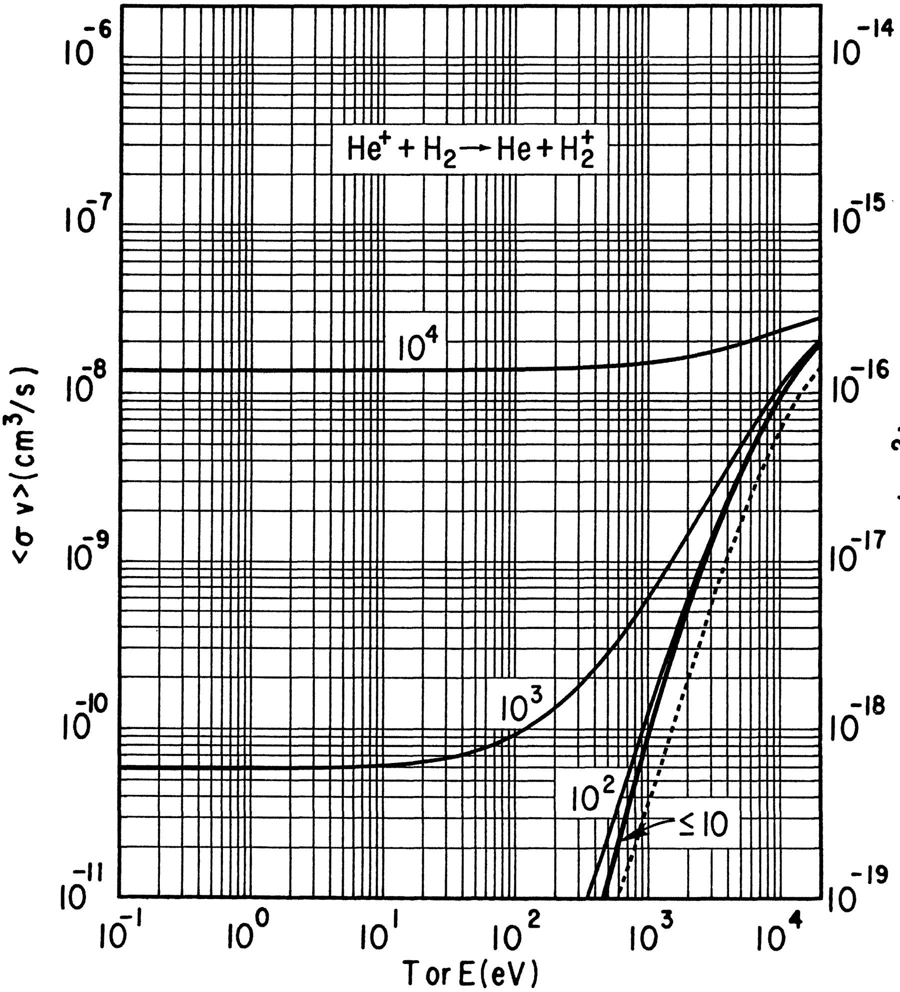
Cross Section:

$E \leq 10^4$ eV: $\sigma_{cx} = \sigma_{se}^{RZD}$,

$E \geq 10^4$ eV: $\sigma_{cx} = \sigma_{exp}$.

Reference: Okuno (1978)

Comment: σ_{se}^{RZD} is obtained by matching the Rosen-Zener-Demkov cross section (see Smirnov 1973) with σ_{exp} in the region $E > 10^4$ eV.


He$^+$ + H$_2$ → He + H$_2^+$
10^4
10^3
10^2
≤ 10
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)
<σ v> (cm^3/s)
σ (cm^2)

5.2.3 $\boxed{He^{+}+H_2 \rightarrow He+H^{+}+H}$

$E_{th} = 0$; $\Delta E^{(+)}_{He^+} = 3.1$ eV, $\langle \Delta E^{(+)}_{H^+} \rangle \approx \langle \Delta E^{(+)}_{H^o} \rangle \simeq 1.85$ eV.

Cross Section:

E = 0.1 - 20 eV: $\sigma^{diss}_{cx} = \sigma^{N}_{fit}$.

Reference: Jones et al. (1980)

E = 20 - 50 eV: $\sigma^{diss}_{cx} = \sigma_{exp}$.

Reference: Rozett and Koski (1968)

E = 50 - 400 eV: $\sigma^{diss}_{cx} = \sigma^{ext(<)}_{exp}$,

E = 400 - 2 × 10^3 eV: $\sigma^{diss}_{cx} = \sigma_{exp}$.

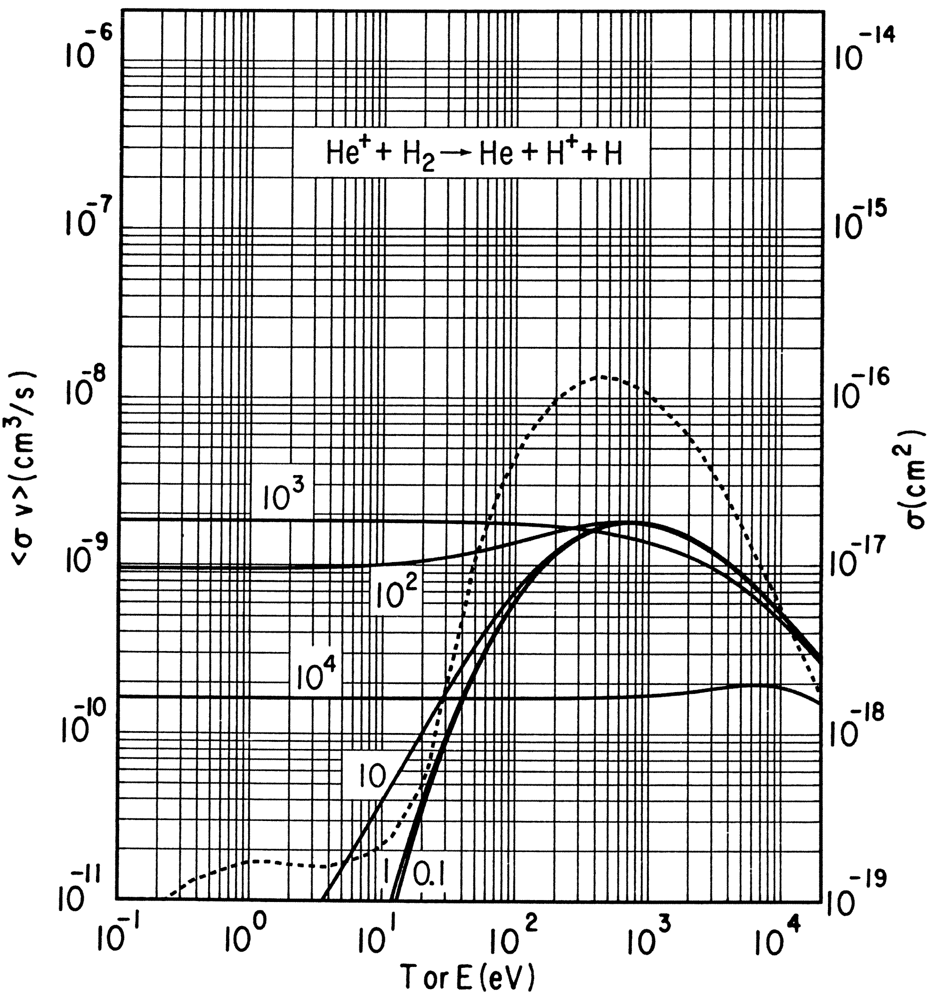
Reference: Stedeford and Hasted (1955)

E ≥ 2 × 10^3: $\sigma^{diss}_{cx} = \sigma^{ext(>)}_{exp}$.

Comments:

(1) σ^{N}_{exp} is the experimental cross section (in arbitrary units) from Jones et al. (1980), normalized to the data of Rozett and Koski (1968) in the region 20-40 eV.

(2) $\sigma^{ext(<)}_{exp}$ is an interpolation between the two sets of experimental cross sections in the regions indicated above, while $\sigma^{ext(>)}_{exp}$ is a Born-type extrapolation of experimental data from Stedeford and Hasted (1955).



He⁺ + H₂ → He + H⁺ + H
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
<σ v> (cm³/s)
σ(cm²)
10³
10²
10⁴
10
1
0.1
10^-1
10^0
10^1
10^2
10^3
10^4
T or E (eV)

5.3 Collisions of He^+ with He

5.3.1 $\boxed{He^+ + He \rightarrow He + He^+}$

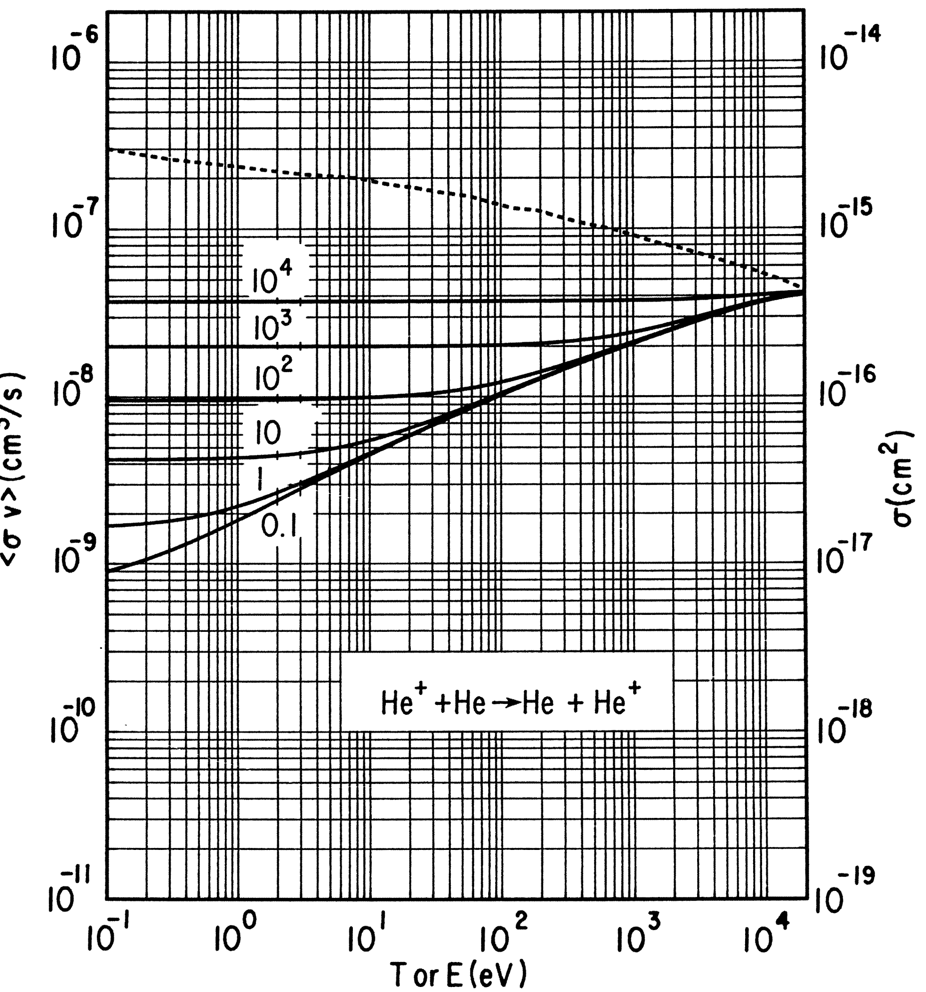
$E_{th} = 0.$

Cross Section:

$E = E_{th} - 2 \times 10^4$: $\sigma_{cx} = \sigma_{exp}^{fit}$.

Reference: Nakai et al. (1984)

Comment: σ_{exp}^{fit} is a fit to experimental data.



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^4
10^3
10^2
10
1
0.1
$\langle \sigma v \rangle (cm^3/s)$
$\sigma (cm^2)$
$He^+ + He \rightarrow He + He^+$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

5.3.2 $\boxed{He^{+} + He \rightarrow He^{+} + He^{+} + e}$

$E_{th} = 24.58$ eV, $\quad \Delta E^{(-)}_{He^{+}} = E_{th} + E_{e}$.

Cross Section:

$E = E_{th} - 60$ eV: $\quad \sigma_{ion} = \sigma^{ext}_{se}$.

$E \geq 60$ eV: $\quad \sigma_{ion} = \langle\sigma_{ion}\rangle_{exp}$.

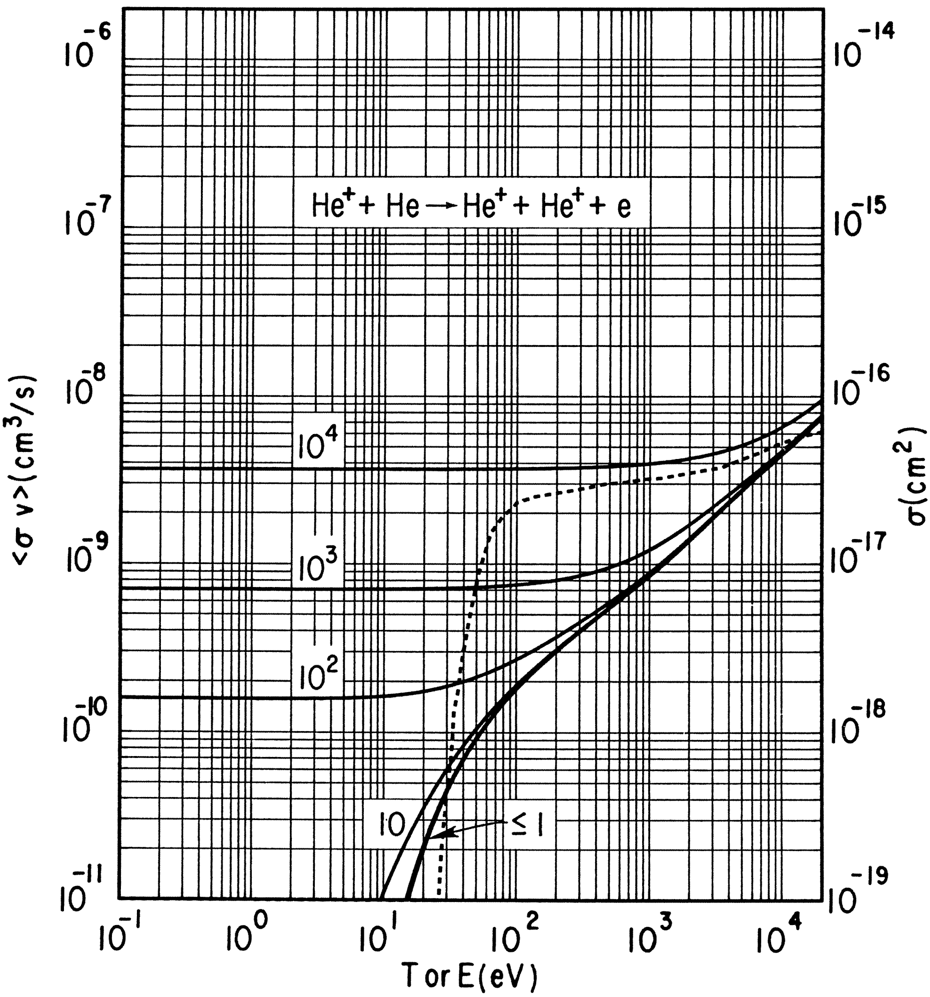
Reference: Sataka et al. (1981)

Comments:

(1) $\langle\sigma_{ion}\rangle_{exp}$ is an average over the experimental data.

(2) σ^{ext}_{se} is an extrapolation of $\langle\sigma_{ion}\rangle_{exp}$, according to the low energy behavior of σ^{DACC}_{ion} (see Sect. 3.1.5 and Appendix C).

(3) For the mean energy of the ejected electron see the Introduction.


He⁺ + He → He⁺ + He⁺ + e
<σ v>(cm³/s)
σ(cm²)
T or E(eV)
10⁴
10³
10²
10
≤ 1
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴

Chapter 6

Collision Processes of He^{2+}

6.1 Collisions of He^{2+} with H

6.1.1 $\boxed{He^{2+} + H(1s) \rightarrow He^{2+} + H^*(n), \quad (n \geq 2)}$

$$E_{th} = Ry\left(1 - \frac{1}{n^2}\right), \quad \Delta E^{(-)}_{He^{2+}} = E_{th}.$$

<u>Cross Section:</u>

$$\sigma_{exc}(n) = \sigma^{DACC}_{exc}(n) = 3.52 \times 10^{-16} \frac{\lambda_{1n}}{\omega_{1n}} D(\beta_{1n})[cm^2],$$

$$\omega_{1n} = \frac{1}{2}\left(1 - \frac{1}{n^2}\right), \quad \lambda_{1n} = \left(f_{1n}/2\omega_{1n}\right)^{1/2},$$

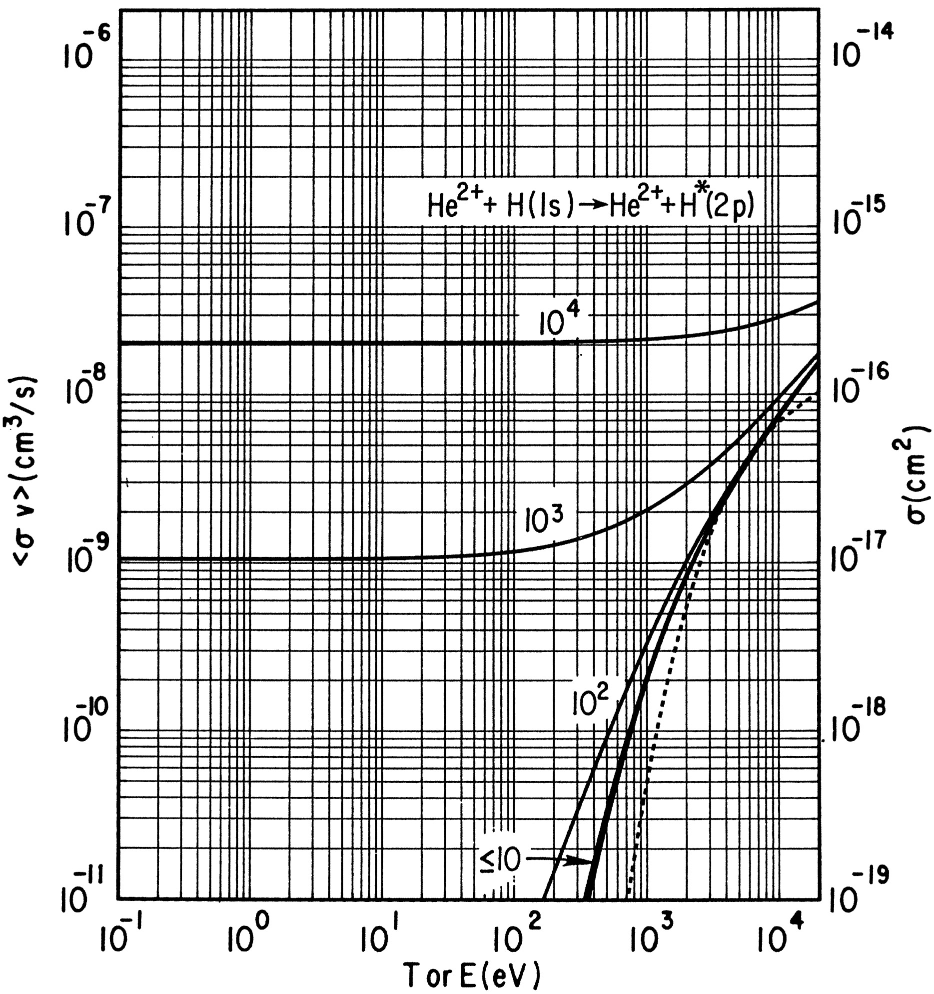
$$\beta_{1n} = \frac{2\omega_{1n}\lambda_{1n}}{v^2},$$

f_{1n}: oscillator strength for 1s→np transition (see Appendix A.2),

$$v = 3.162 \times 10^{-3}\left(E[eV]\right)^{1/2},$$

$D(\beta_{1n})$: see Appendix C.

<u>Comment</u>: $\sigma^{DACC}_{exc}(n)$ contains contributions only from 1s→np transitions. The uncertainty of $\sigma^{DACC}_{exc}(n)$ for $\beta > 0.3$ is probably within a factor of 2, and increases with increasing n.


$He^{2+} + H(1s) \rightarrow He^{2+} + H^*(2p)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^4
10^3
10^2
≤ 10
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

6.1.2 $\boxed{He^{2+} + H^*(n) \rightarrow He^{2+} + H^*(m), \ (n \geq 2, \ m > n)}$

$$E_{th} = Ry\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \equiv \Delta E_{nm} \quad , \quad \Delta E^{(-)}_{He^{2+}} = \Delta E_{nm} \quad .$$

Cross Section:

$$\sigma_{exc}(n \rightarrow m) = \sigma^{DACC}_{nm} = \frac{3.52 \times 10^{-16} \lambda_{nm}}{\omega_{nm}} D(\beta_{nm})[cm^2] \ ,$$

$$\omega_{nm} = \frac{1}{2}\left(\frac{1}{n^2} - \frac{1}{m^2}\right) ,$$

$$\lambda_{nm} = \left(f_{nm}/2\omega_{nm}\right)^{1/2} ,$$

$$\beta_{nm} = \frac{2\lambda_{nm}\omega_{nm}}{v^2_{nm}} ,$$

f_{nm}: oscillator strength (see Appendix A.2),

$$v = 3.162 \times 10^{-3} E^{1/2} ,$$

$D(\beta_{nm})$: see Appendix C.

Comment: Only the contribution of dipole-allowed $n \rightarrow m$ transitions is included in σ^{DACC}_{nm}. The uncertainty in the cross section for $\beta > 0.3$ is within a factor of 2.

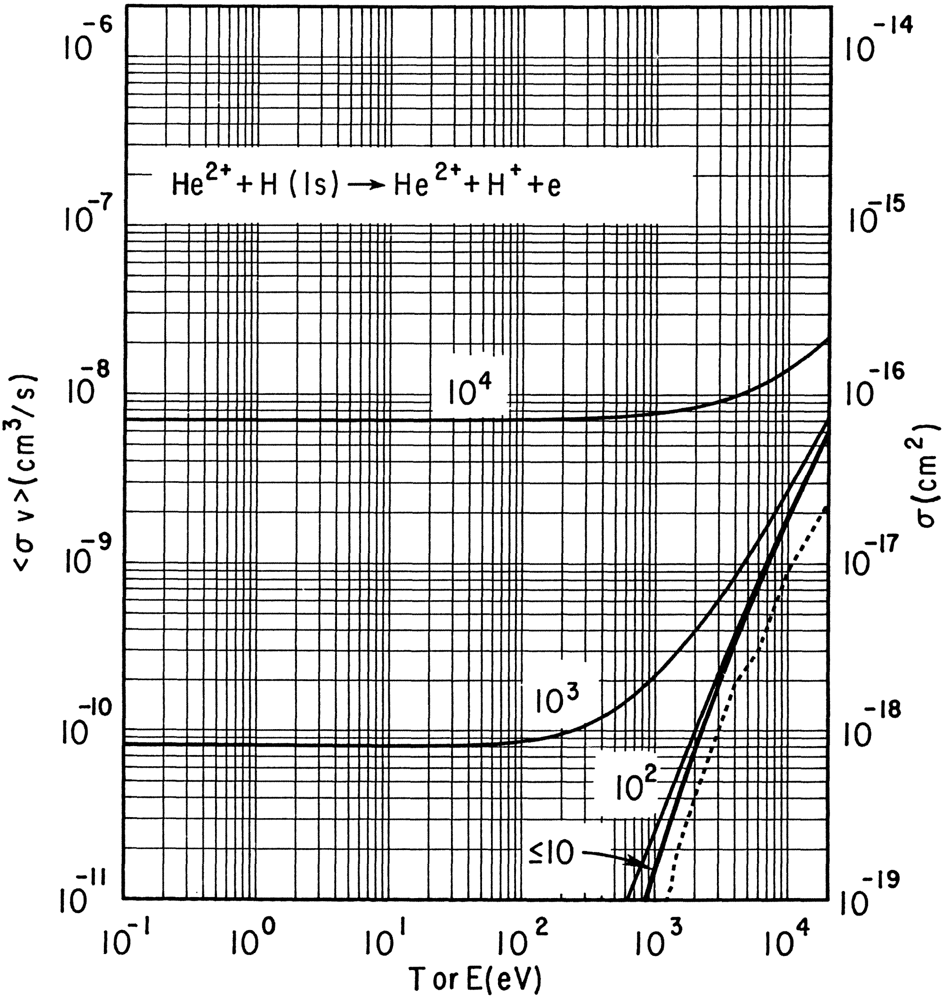
6.1.3 $\boxed{He^{2+} + H(1s) \rightarrow He^{2+} + H^{+} + e}$

$E_{th} = 13.6$ eV, $\Delta E^{(-)}_{He^{2+}} = E_{th} + E_e$.

Cross Section:

$E = E_{th} - 2 \times 10^4$ eV: $\sigma_{ion} = \sigma^{DACC}$.

Comment: σ^{DACC}_{se} is obtained by matching σ^{DACC}_{ion} with the experimental data (Shah and Gilbody 1981) in the region $E = (1.25-3.0) \times 10^5$ eV.



He^{2+} + H (1s) → He^{2+} + H^{+} + e
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$<\sigma v>$ (cm^3/s)
σ (cm^2)
10^4
10^3
10^2
≤10
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

6.1.4 $\boxed{He^{2+}+H^*(n) \rightarrow He^{2+}+H^{+}+e, \quad (n\geq 2)}$

$$E_{th}(n) = Ry/n^2 = E_n^{ion}, \quad \Delta E^{(-)}_{He^{2+}} = E_{th}(n) + E_e \ .$$

Cross Section:

$$\sigma_{ion}^{BEA}(n) = 0, \quad \text{for} \quad \alpha < 0.207 \ ,$$

$$= 2.347 \times 10^{-16}\, n^4 \left(\alpha - \frac{0.164}{\alpha^2} + \frac{0.1875}{\alpha^2(\alpha+1)}\right) \ [cm^2] \ ,$$

for $0.207 < \alpha < 1.207$,

$$= 5.868 \times 10^{-16}\, n^4 \frac{1}{\alpha^2} \left(1 - \frac{0.15}{\alpha^2 - 1}\right) \ [cm^2]$$

for $\alpha > 1.207$.

$$\alpha = 3.162 \times 10^{-3}\, n\left(E[eV]\right)^{1/2} \ .$$

6.1.5 $\boxed{He^{2+} + H^*(2s) \rightarrow He^{2+} + H^*(2p)}$

$E_{th} \simeq 0.$

Cross Section:

$$\sigma_{2s\rightarrow 2p} = 6.336 \times 10^{-10} \frac{1}{E} \ln(0.5515\ E)[cm^2].$$

Reference: Chibosov (1969)

Comment: The above expression for $\sigma_{2s\rightarrow 2p}$ is valid for E >> 2 eV.

6.1.6 $\boxed{He^{2+} + H \rightarrow He^{+*}(n=2) + H^{+}}$

$E_{th} \simeq 0.$

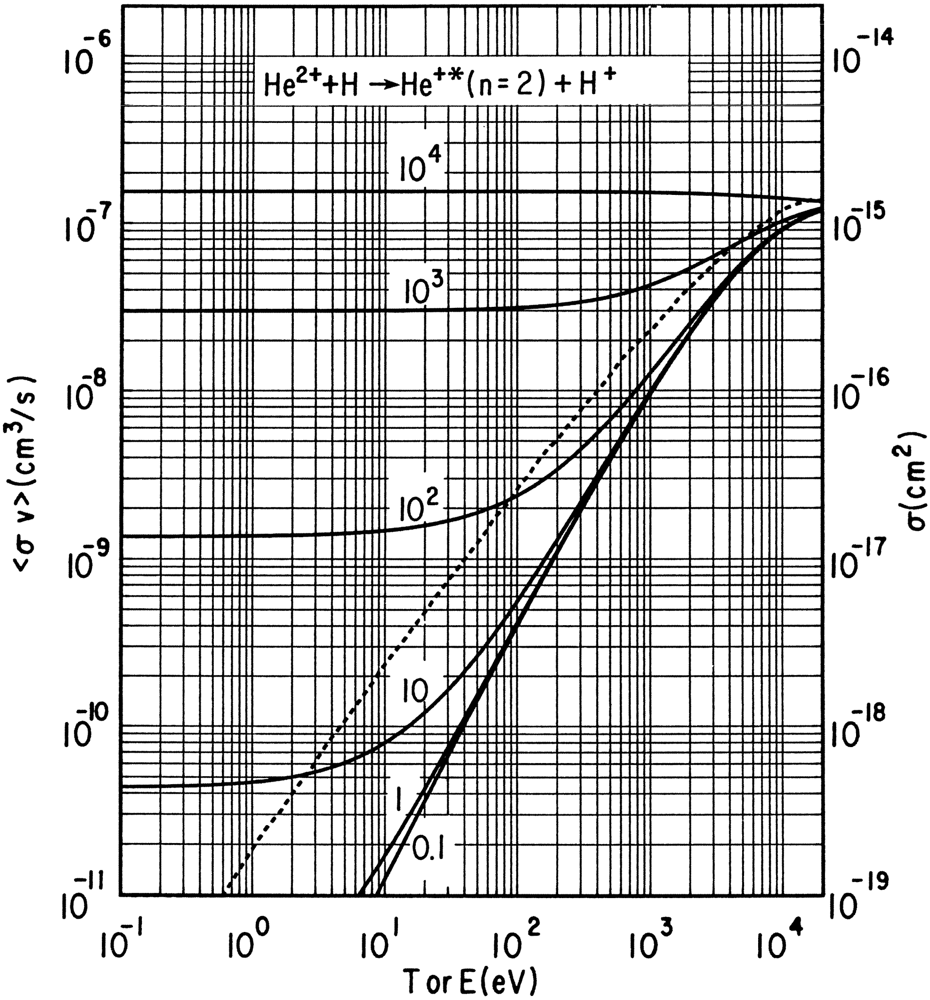
<u>Cross Section</u>:

$E = 0 - 10^3$ eV: $\sigma_{cx}(n{=}2) = \sigma_{se}^{RZD}$.

$E \geq 10^3$ eV: $\sigma_{cx}(n{=}2) = \sigma_{exp}$.

Reference: Shah and Gilbody (1978)

<u>Comment</u>: σ_{se}^{RZD} has been obtained by extrapolation of σ_{exp} using the Rosen-Zener-Demkov model (Smirnov 1973).



$He^{2+} + H \rightarrow He^{+*}(n=2) + H^+$
10^4
10^3
10^2
10
1
0.1
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\langle \sigma v \rangle (cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma (cm^2)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

6.1.7 $\boxed{He^{2+} + H^{*}(n) \rightarrow He^{+*}(n') + H^{+}}$

$n' = 2n$, $n = 2, 4, 6 \ldots.$; $E_{th} \simeq 0.$

$$\sigma_{cx}(n \rightarrow n') = 4.69 \times 10^{-16}\, n^4 \frac{1}{1 + 0.8(vn)^{2/5} + 2.6(vn)} \,[cm^2] ,$$

$$v = 3.1623 \times 10^{-3}\, E^{\frac{1}{2}} ,$$

$n' = 2n-1 = 3,5,7,\ldots$; $E_{th} = \frac{Ry}{2}\left(\frac{1}{n'^2} - \frac{1}{(n' + 1)^2}\right)$,

$$\sigma_{cx}(2 \rightarrow 3) = 0.75 \quad \sigma_{cx}(2 \rightarrow 4) ,$$

$$\sigma_{cx}(3 \rightarrow 5) = 0.80 \quad \sigma_{cx}(3 \rightarrow 6) ,$$

$$\sigma_{cx}(4 \rightarrow 7) = 0.85 \quad \sigma_{cx}(4 \rightarrow 8) .$$

Comment: The expression for $\sigma_{cx}(n \rightarrow n')$ ($n' = 2n$) is based on a classical model for quasi-resonant charge-exchange processes (Smirnov 1973; Janev 1983). The values for $\sigma_{cx}(n \rightarrow 2n-1)$ are estimates to within ±50%.

6.2 Collisions of He^{2+} with H_2

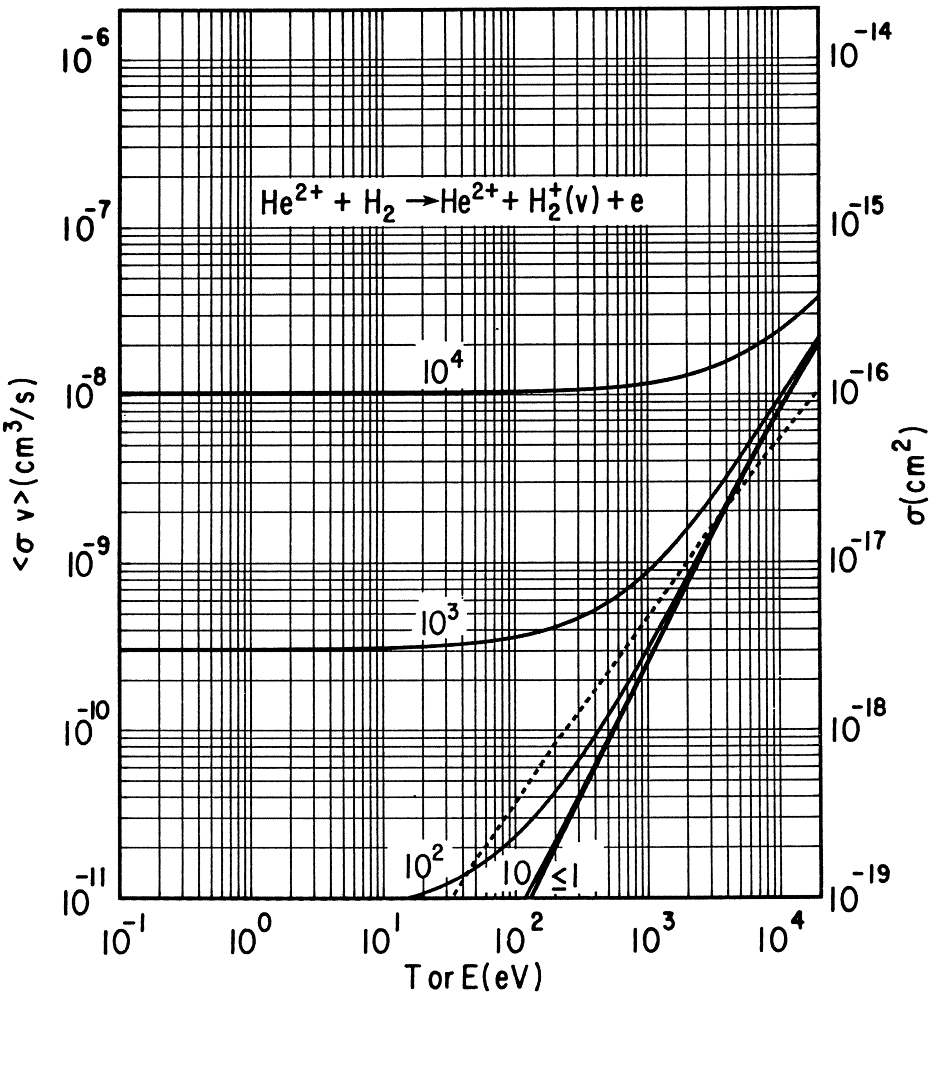
6.2.1 $\boxed{He^{2+} + H_2 \rightarrow He^{2+} + H_2^+(v) + e}$

$E_{th} = 15.4$ eV, $\Delta E^{(-)}_{He^{2+}} = E_{th} + E_e$.

Cross Section:

$E = E_{th} - 2 \times 10^4$ eV: $\sigma_{ion} = \sigma^{ext}_{se}$

Comment: σ^{ext}_{se} is an extrapolation of the experimental data (Sataka et al. 1981) from the region 1.5×10^5 to 6×10^5 eV, made by retaining the same slope seen in its exponential decrease. The uncertainty in σ in the figure could be as much a factor of 5 because this extrapolation is from a region where there are too few data points to define the slope well. All the reaction rate coefficients shown reflect this uncertainty in σ.



$He^{2+} + H_2 \rightarrow He^{2+} + H_2^+(v) + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v> (cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma (cm^2)$
10^4
10^3
10^2
10
≤ 1
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

6.2.2 $\boxed{He^{2+} + H_2 \rightarrow He^{2+} + H(1s) + H(1s)}$

6.2.3 $\boxed{He^{2+} + H_2 \rightarrow He^{2+} + H(1s) + H^+ + e}$

Comments:

(1) The cross sections of the reactions above can be obtained by scaling the corresponding p + H_2 reactions: $\sigma_{j,He^{2+}}\left(E_{He^{2+}}\right) = 4\sigma_{j,p}(4E_p)$. This scaling is valid only well above the energy where the cross section is a maximum.

(2) The reaction rates $\alpha_{j,He^{2+}}$ are related to $\alpha_{j,p}$ by

$$\alpha_{j,He^{2+}}(E_o) = 2^{3/2}\,\alpha_{j,p}(E_o),$$

where $E_o = E_{H_2}$, and $T_{He^{2+}} \simeq T_p$ is assumed.

(3) The energetics (E_{th}, $\Delta E^{(\pm)}$) is the same as in the p + H_2 case.

6.3 Collisions of He^{2+} with He

6.3.1 $\boxed{He^{2+} + He \rightarrow He + He^{2+}}$

$E_{th} \simeq 0.$

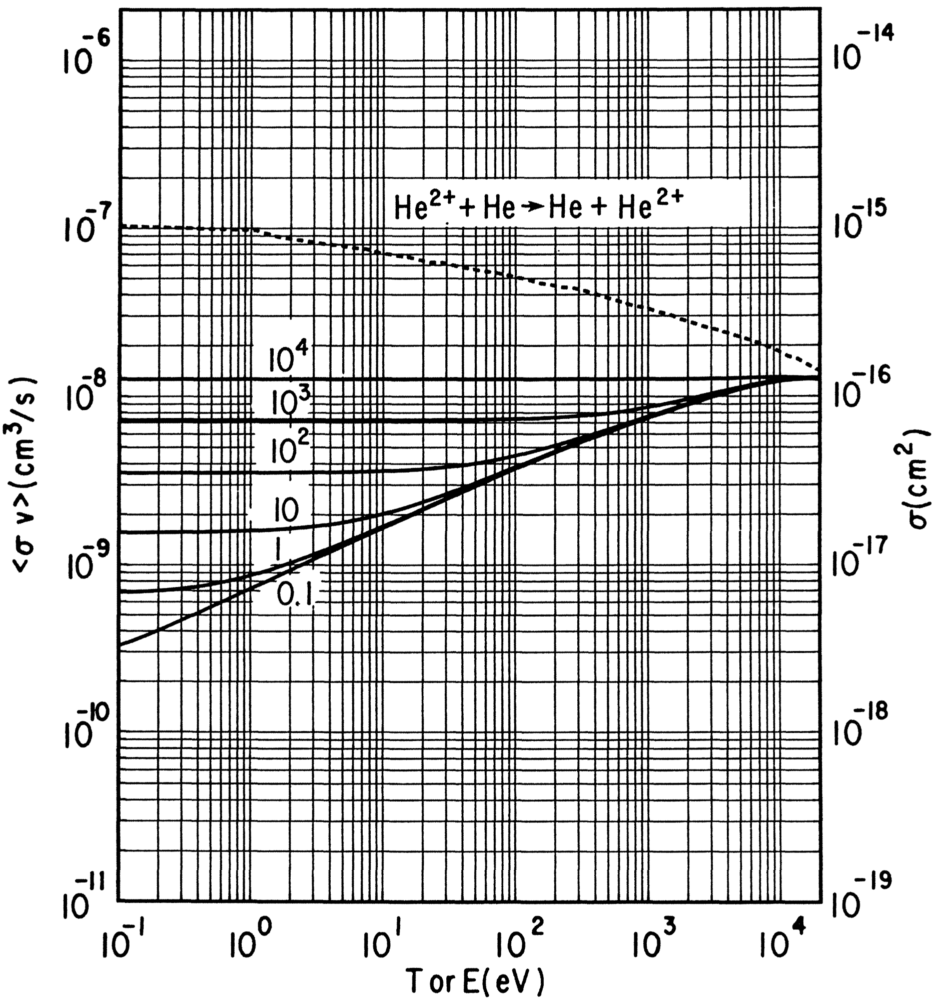
Cross Section:

$E \leq 800$ eV: $\sigma_{cx} = \sigma_{se}^{ext}$.

$E \geq 800$ eV: $\sigma_{cx} = \langle\sigma_{cx}\rangle_{exp,th}$.

Reference: Janev and Gallagher (1984)

Comment: $\langle\sigma_{cx}\rangle_{exp,th}$ is an average over the experimental and theoretical data. σ_{se}^{ext} is an extrapolation of $\langle\sigma_{cx}\rangle_{exp,th}$ according to the asymptotic theory of resonant charge transfer (Smirnov 1973).



$He^{2+} + He \rightarrow He + He^{2+}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^4
10^3
10^2
10
1
0.1
$<\sigma v>(cm^3/s)$
$\sigma(cm^2)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E(eV)

6.3.2 $\boxed{He^{2+} + He \rightarrow He^{2+} + He^{+} + e}$

$E_{th} = 24.588$ eV , $\Delta E^{(-)}_{He^{2+}} = E_{th} + E_e$.

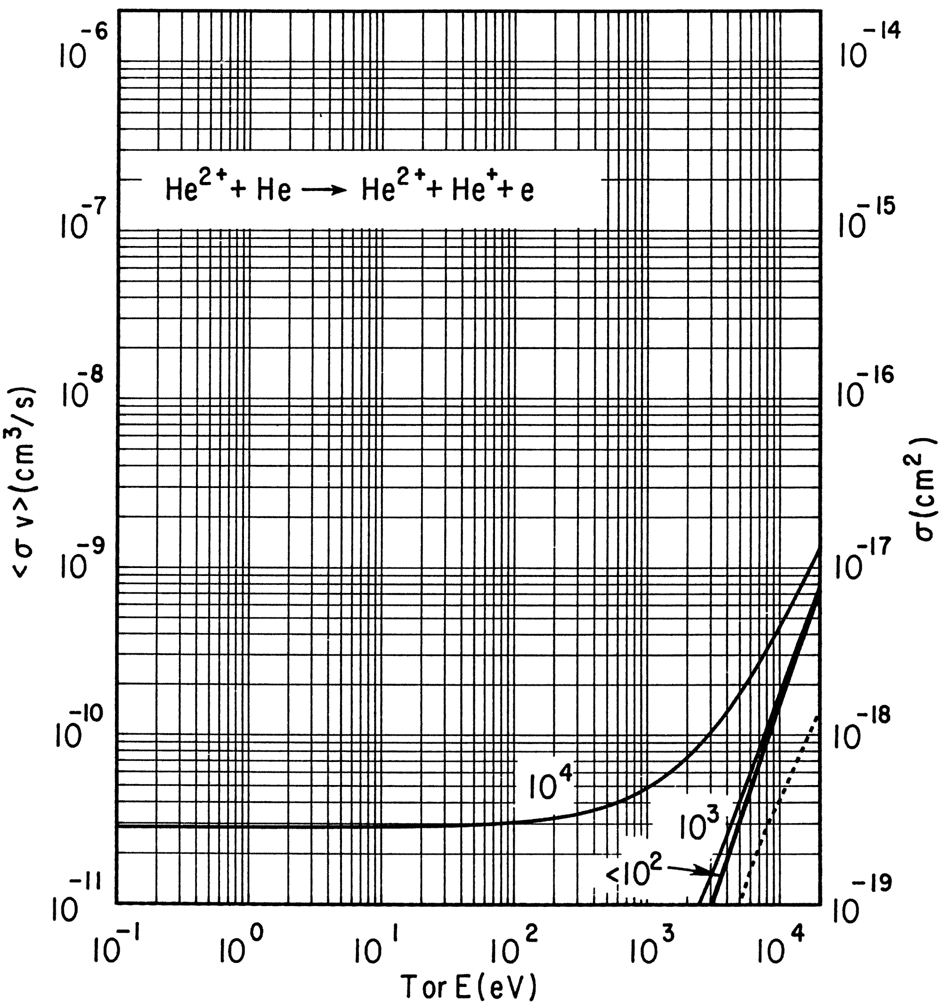
<u>Cross Section</u>:

$E \le 5 \times 10^4$ eV: $\sigma_{ion} = \sigma^{ext}_{exp}$,

$E \ge 5 \times 10^4$ eV: $\sigma_{ion} = \sigma_{exp}$.

Reference: Afrosimov et al. (1975), Shah and Gilbody (1985)

<u>Comments</u>: The data of Afrosimov et al. (1975) in the region 5×10^4 eV - 1.5 $\times 10^5$ eV match the slope of the low-energy part of the data by Shah and Gilbody (1985) in the region 2.5×10^5 eV - 5×10^6 eV. The cross section σ^{ext}_{exp} is an extrapolation of the low energy part of σ_{exp} keeping the same slope as the experimental curve.



$He^{2+} + He \longrightarrow He^{2+} + He^{+} + e$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle \sigma v \rangle (cm^3/s)$
$\sigma (cm^2)$
10^4
10^3
$<10^2$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

6.3.3 $\boxed{He^{2+} + He^{*}(1snl) \rightarrow He^{2+} + He^{+}(1s) + e, \quad (n \geq 2)}$

$$E_{th}(n) = E_n^{ion} \;, \qquad \Delta E^{(-)}_{He^{2+}} = E_{th} + E_e .$$

Cross Section:

$$\sigma_{ion}^{BEA}(n) = 0, \quad \text{for} \quad \alpha < 0.207 \;,$$

$$= 2.347 \times 10^{-16} \, (n^*)^4 \left(\alpha - \frac{0.164}{\alpha^2} + \frac{0.1875}{\alpha^2(\alpha+1)}\right) [cm^2]$$

$$\text{for } 0.207 < \alpha < 1.207 \;,$$

$$= 5.868 \times 10^{-16} \, (n^*)^4 \, \frac{1}{\alpha^2} \left(1 - \frac{0.15}{\alpha^2 - 1}\right) [cm^2]$$

$$\text{for} \quad \alpha > 1.207.$$

$$\alpha = 3.162 \times 10^{-3} \, n^*(E[eV])^{1/2} \;,$$

$$n^* = (Ry/E_n^{ion})^{1/2} \quad .$$

Comments: For n = 2, the ℓ substates may be distinguished by taking $E_n^{ion} = E_{n\ell}^{ion}$. For $n \geq 3$, the states may be considered degenerate with some average energy E_n (see Appendix A.3).

Chapter 7

Collision Processes of H^-

7.1 Electron Collisions with H^-

7.1.1 $\boxed{e_1 + H^- \rightarrow \bar{e}_1 + H(1s) + \bar{e}_2}$

$$E_{th} = 0.75 \text{ eV}, \quad \Delta E_{e_1}^{(-)} = E_{th} + E_{\bar{e}_2} \ .$$

Cross Section:

$$E = E_{th} - 3.0 \text{ eV}: \quad \sigma_{det} = \sigma_{exp}^{ext},$$

$$E = 3 - 10^3 \text{ eV}: \quad \sigma_{det} = \sigma_{exp},$$

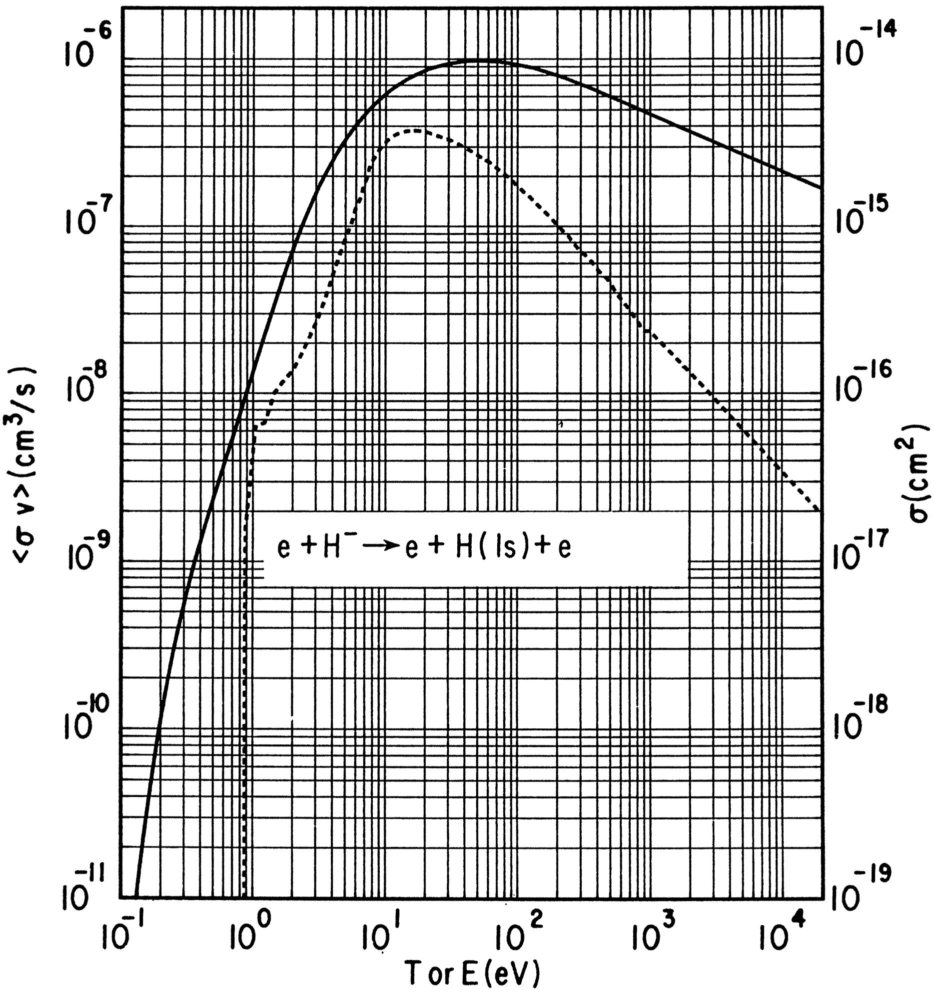
$$E = 10^3 - 2 \times 10^4 \text{ eV}: \quad \sigma_{det} = \sigma_{se}^{B} \ .$$

Reference: Takayanagi and Suzuki (1978)

Comments:

(1) σ_{exp}^{ext} is an extrapolation of σ_{exp} down to the threshold.

(2) σ_{se}^{B} is a Born-type extension of σ_{exp}.



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\langle\sigma v\rangle (cm^3/s)$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\sigma (cm^2)$
$e + H^- \rightarrow e + H(1s) + e$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

7.1.2 $\boxed{e_1 + H^- \rightarrow \bar{e}_1 + H^+ + 2\bar{e}_2}$

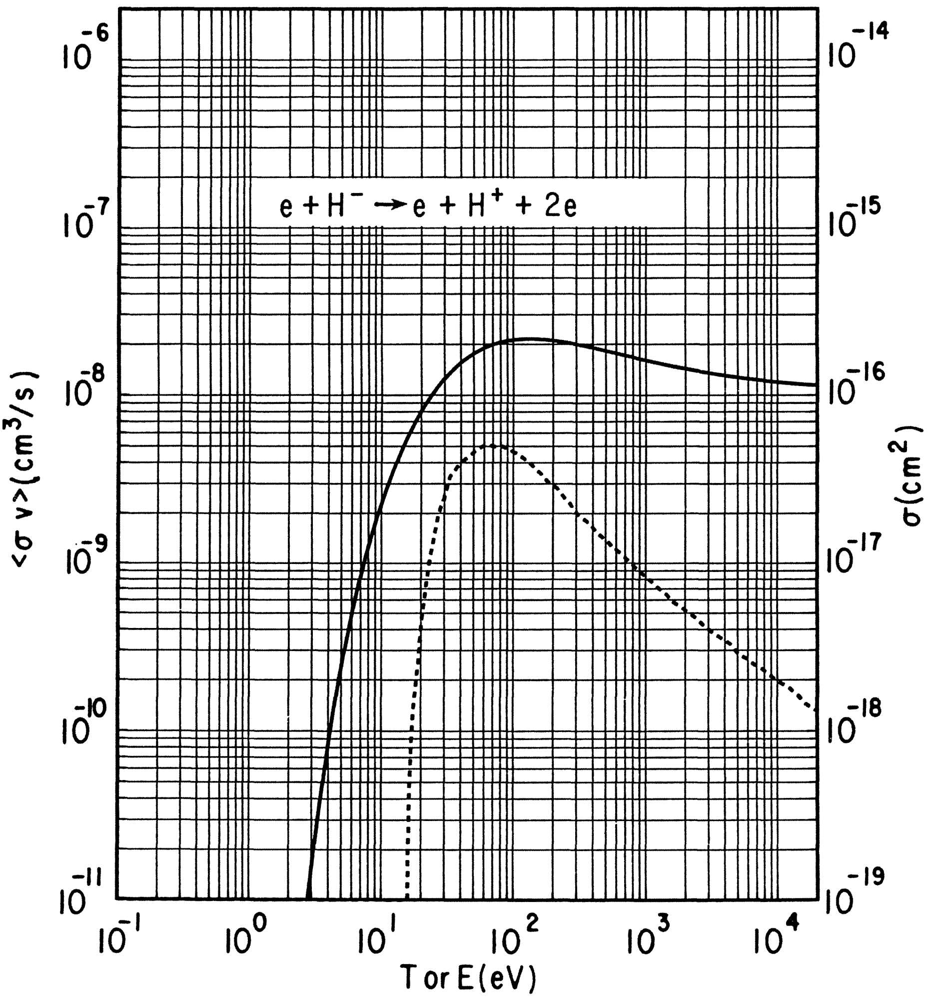
$E_{th} = 14.35$ eV, $\langle \Delta E_{e_1}^{(-)} \rangle = E_{th} + 2E_{\bar{e}_2}$.

Cross Section:

$E = E_{th} - 10^3$ eV: $\sigma_{det} = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

$E = 10^3 - 2 \times 10^4$ eV: $\sigma_{det} = \sigma_{se}^B$.



e + H⁻ → e + H⁺ + 2e
<σ v>(cm³/s)
σ(cm²)
T or E(eV)
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻¹
10⁰
10¹
10²
10³
10⁴

7.2 Proton Collisions with H^-

7.2.1 $\boxed{p+H^- \rightarrow p+H+e}$

$E_{th} = 0.75$ eV , $\Delta E_p^{(-)} = E_{th} + E_e$.

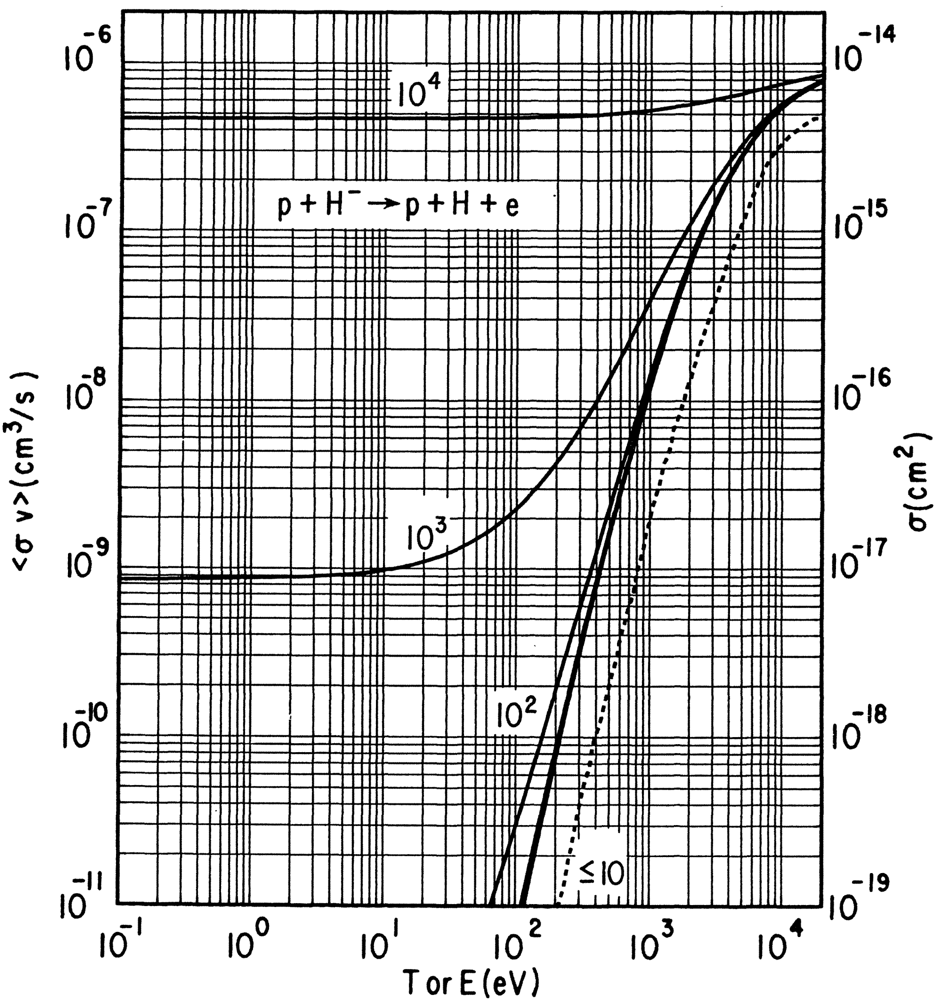
Cross Section:

$E = 200 - 2 \times 10^3$ eV: $\sigma_{det} = \sigma_{se}^{N,ext}$,

$E \geq 2 \times 10^3$ eV: $\sigma_{det} = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

Comment: $\sigma_{se}^{N,ext}$ is an extrapolation of σ_{exp} obtained by normalizing the scaled σ_{det} of the $e + H^-$ case to σ_{exp} in the region 300 eV to 2×10^4 eV.



p + H⁻ → p + H + e
10^4
10^3
10^2
≤10
$\langle\sigma v\rangle$ (cm^3/s)
σ (cm^2)
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

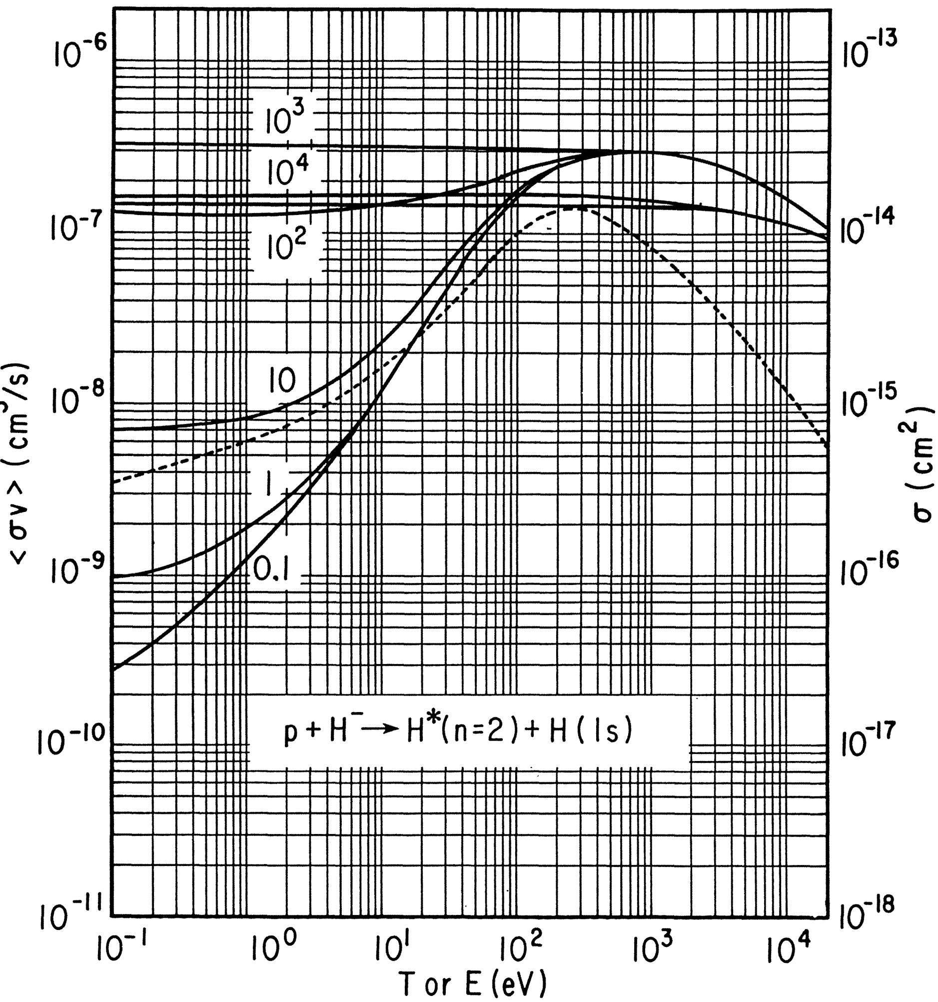
7.2.2 $\boxed{p+H^- \rightarrow H^*(n=2)+H(1s)}$

$E_{th} \simeq 0.$

Cross Section:

$E = 0.1 - 2 \times 10^4$ eV: $\sigma_{rec} = \sigma_{se}^{LZ}(n=2)$.

Comment: $\sigma_{se}^{LZ}(n=2)$ has been obtained by normalizing the calculated Landau-Zener cross section to the experimental cross section (Szucs et al 1984 and Peart, Bennett and Dolder 1985) in the region of its maximum (100-500 eV). These new experimental values differ considerably from the earlier results summarized in Takayanagi and Suzuki (1978), but agree well with theoretical calculations (cf. discussion by Peart et al 1985).



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$<\sigma v>$ (cm^3/s)
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
σ (cm^2)
10^3
10^4
10^2
10
1
0.1
$p + H^- \rightarrow H^*(n=2) + H(1s)$
10^{-1}
10^0
10^1
10^2
10^3
10^4
T or E (eV)

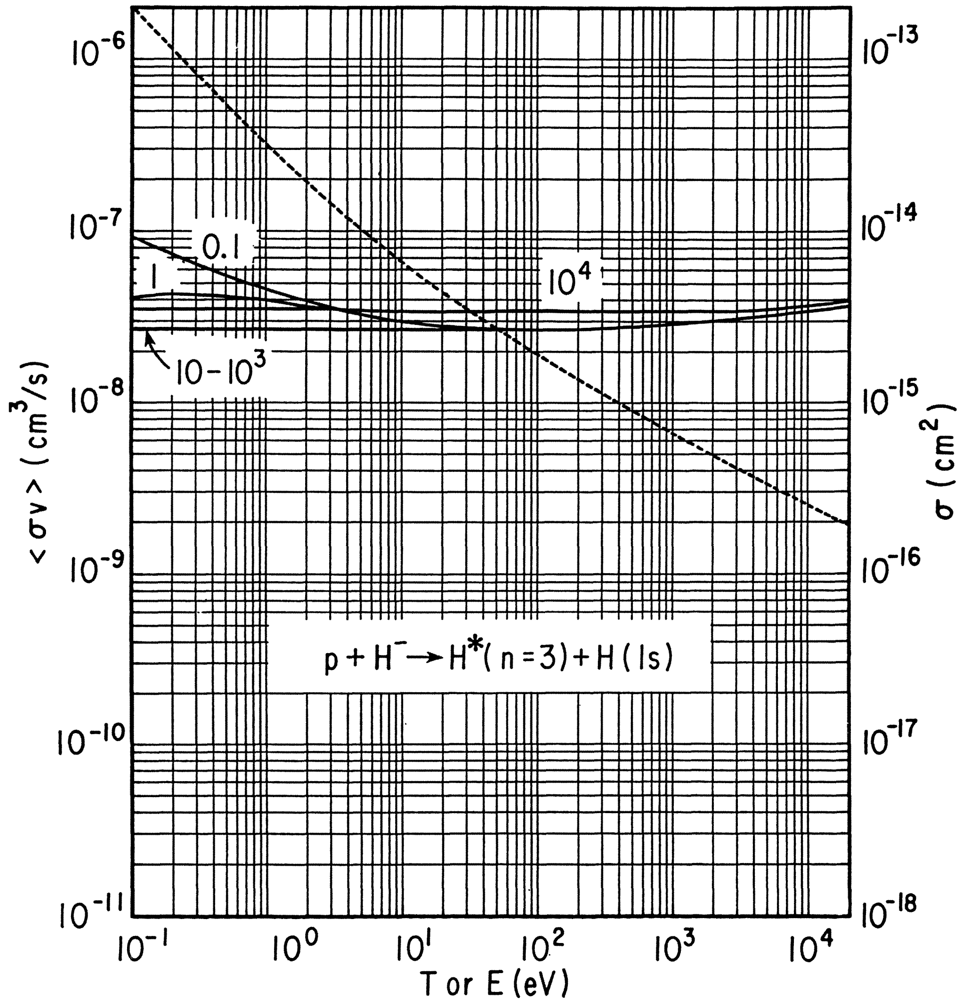
7.2.3 $\boxed{p+H^- \rightarrow H^*(n=3)+H(1s)}$

$E_{th} = 0.$

Cross Section:

$E = 0.1 - 2 \times 10^4$ eV: $\sigma_{rec} = \sigma_{se}^{LZ}(n=3).$

Comment: σ_{se}^{LZ} has been obtained by normalizing the Landau-Zener cross section σ_{LZ} (n=3) to the experimental data (Szucs et al. 1984 and Peart et al. 1985) in the region E $\leq$ 20 eV. These new data differ considerably from the earlier results summarized in Takayanagi and Suzuki (1978), but agree well with theoretical calculations (cf. discussion by Peart et al. 1985).


10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
0.1
1
10^4
$10-10^3$
$\langle \sigma v \rangle$ (cm^3/s)
σ (cm^2)
T or E (eV)
$p + H^- \rightarrow H^*(n=3) + H(1s)$

7.3 Collisions of H with H^-

7.3.1 $\boxed{H^- + H(1s) \rightarrow H(1s) + H^-(1s)}$

$E_{th} = 0.$

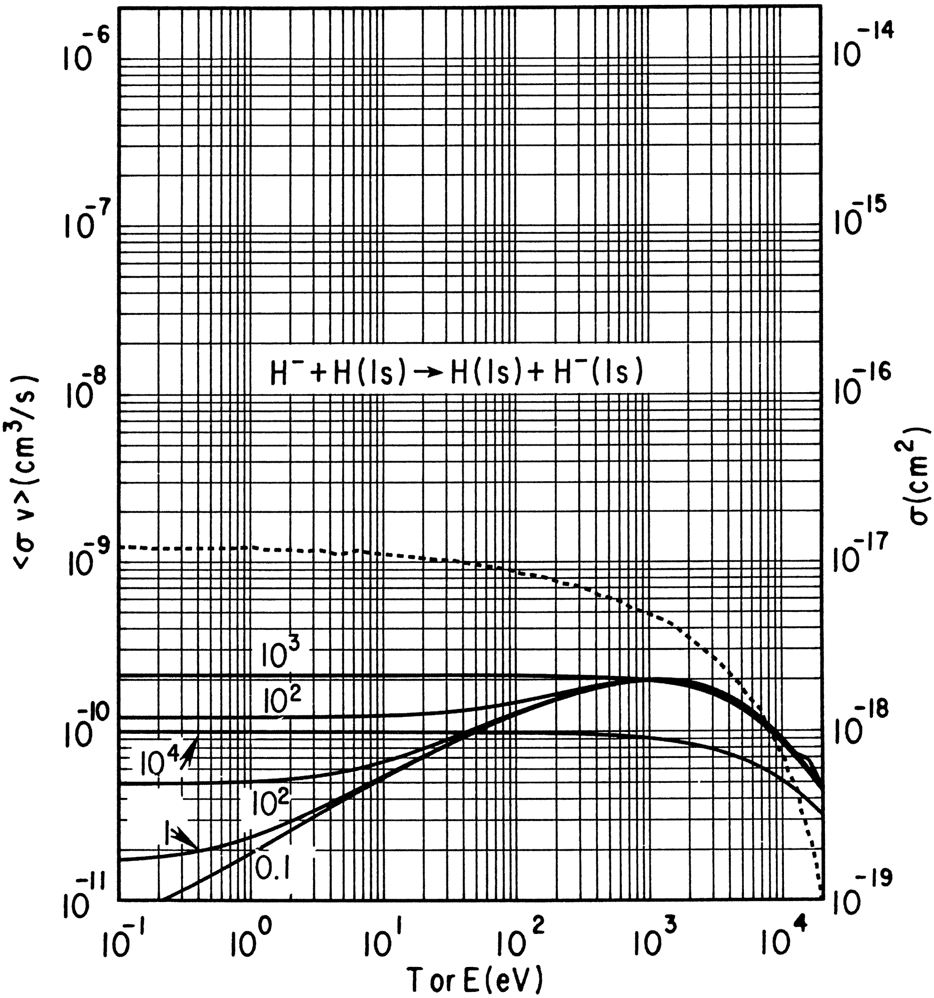
Cross Section:

E ≤ 30 eV: $\sigma_{cx} = \sigma_{cx}^{ext}$,

E ≥ 30 eV: $\sigma_{cx} = \sigma_{exp}$.

Reference: Takayanagi and Suzuki (1978)

Comment: σ_{cx}^{ext} is an extrapolation of σ_{exp} using the asymptotic theory of resonant charge-exchange reactions (Smirnov 1973).



$H^- + H(1s) \rightarrow H(1s) + H^-(1s)$
$\langle\sigma v\rangle (cm^3/s)$
$\sigma (cm^2)$
T or E (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^3
10^2
10^4
10^2
1
0.1

7.3.2a $\boxed{H^- + H \rightarrow H_2^{-*}(\Sigma_g) \rightarrow H + H + e}$

7.3.2b $\boxed{H^- + H \rightarrow H_2^{-*}(\Sigma_u) \rightarrow H_2 + e}$

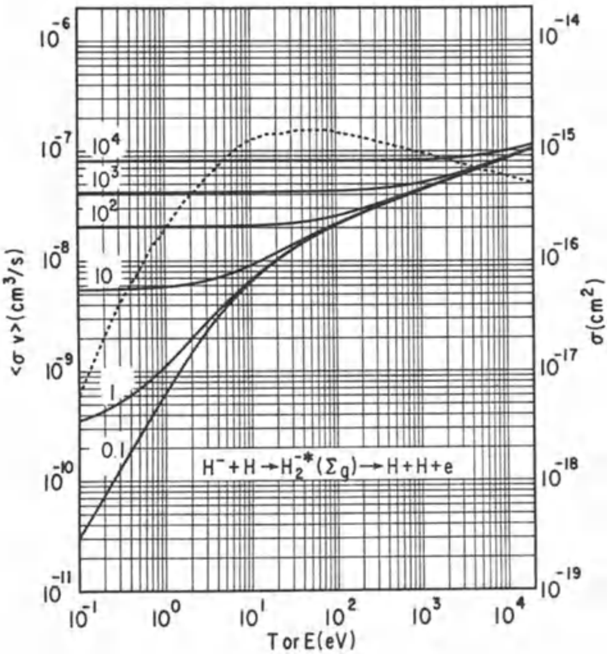
E_{th} (a) = E_{th} (b) = 0.

Cross Section:

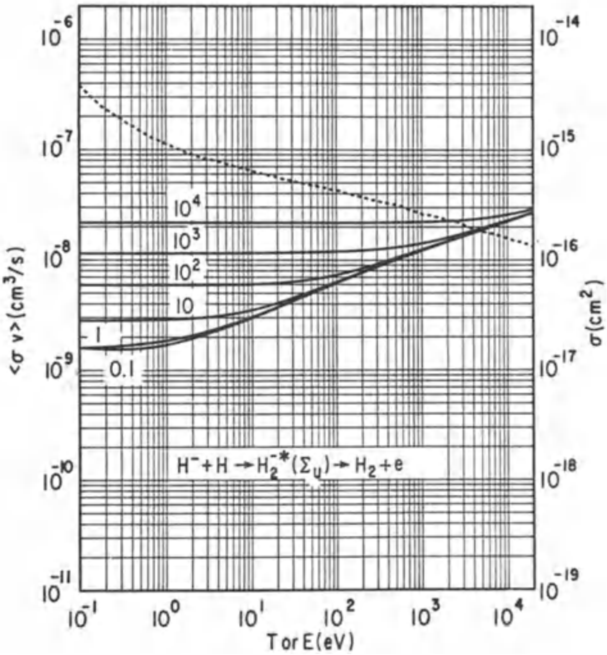
$$\sigma_{det}^{diss} (a) = \sigma_{se}(a),$$

$$\sigma_{det}^{ass} (b) = \sigma_{se} (b).$$

Comment: $\sigma_{se}(a)$ and $\sigma_{se}(b)$ have been determined from the theoretical cross sections of Browne and Dalgarno (1969) by normalizing their sum to the experimental cross section σ_{det} of Hummer et al. (1960) in the region 500 eV to 4×10^4 eV.



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle\sigma v\rangle$ (cm^3/s)
σ (cm^2)
10^4
10^3
10^2
10
1
0.1
$H^- + H \rightarrow H_2^{-*}(\Sigma_g) \rightarrow H + H + e$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\langle\sigma v\rangle$ (cm^3/s)
σ (cm^2)
10^4
10^3
10^2
10
1
0.1
$H^- + H \rightarrow H_2^{-*}(\Sigma_u) \rightarrow H_2 + e$
10^{-1} 10^0 10^1 10^2 10^3 10^4
T or E(eV)

Chapter 8

Analytic Fits

In this chapter, we present analytic fits for σ and $\langle\sigma v\rangle$ as functions of energy and temperature. We present the coefficients with 13 digits, though, in most cases, fewer digits are sufficient. We discuss the required number of digits in each section.

8.1 Fits for σ

For calculating reaction rate coefficients for arbitrary values of E and T it is useful to have fits for σ. In most cases, it is difficult to obtain the fits near threshold due to the steep behavior of σ. We fit all cross sections with a 9-term (8th-order) polynomial,

$$\ell n\ \sigma = \sum_{n=0}^{8} a_n\ (\ell n\ E)^n\ .$$

The coefficients were determined by a least-squares match of the fit to the data with weighting designed to de-emphasize the points in the steep part of the curve. The tables list the coefficients a_n for all the reactions.

For a number of reactions the cross sections are well fit by the formula

$$\sigma = a \left(\frac{E_{th}}{E}\right)^n \ell n \left(\frac{E}{E_{th}}\right),$$

which is an empirical modification of the Bethe-Born formula. The parameters a and n were evaluated in two ways. We used a least-squares minimization with respect to the parameters a and n with: (1) a uniform weighting, and (2) a weighting ignoring the points at energies below the peak in σ. The first method provides a better match to the entire cross section, but may be inaccurate for the large-E asymptotic dependence. The second method gives a better asymptotic dependence at the expense of a poorer match near the peak. The threshold behavior in the latter case is reasonably accurate because the formula forces it, and this method avoids the problem of the points on the steep part of the curve unduly influencing the least-squares error. Each of these methods works better for different reactions and the tables contain either or both if the match is good. These fits are not as accurate as the polynomial fit, having errors ~ 10^{-2}, but are smoother. The polynomial fits have oscillatory behavior when their errors are ~ 10^{-2}. We label the parameters a and n in the Born-like formula by aBorn,1 and nBorn,1 for the fits obtained by performing a least-squares fit to all points, and by aBorn,2 and nBorn,2 for those obtained with only the points after the peak in σ.

These tables also provide the minimum cross section (σ_{min}, in cm^2) at the minimum energy (E_{min}, in eV) for the points considered, and the maximum cross section (σ_{max}, in cm^2) over the energy range 0.1 eV to 20 keV. In some cases, σ_{max} is not the absolute maximum as can be seen in the figures since σ is

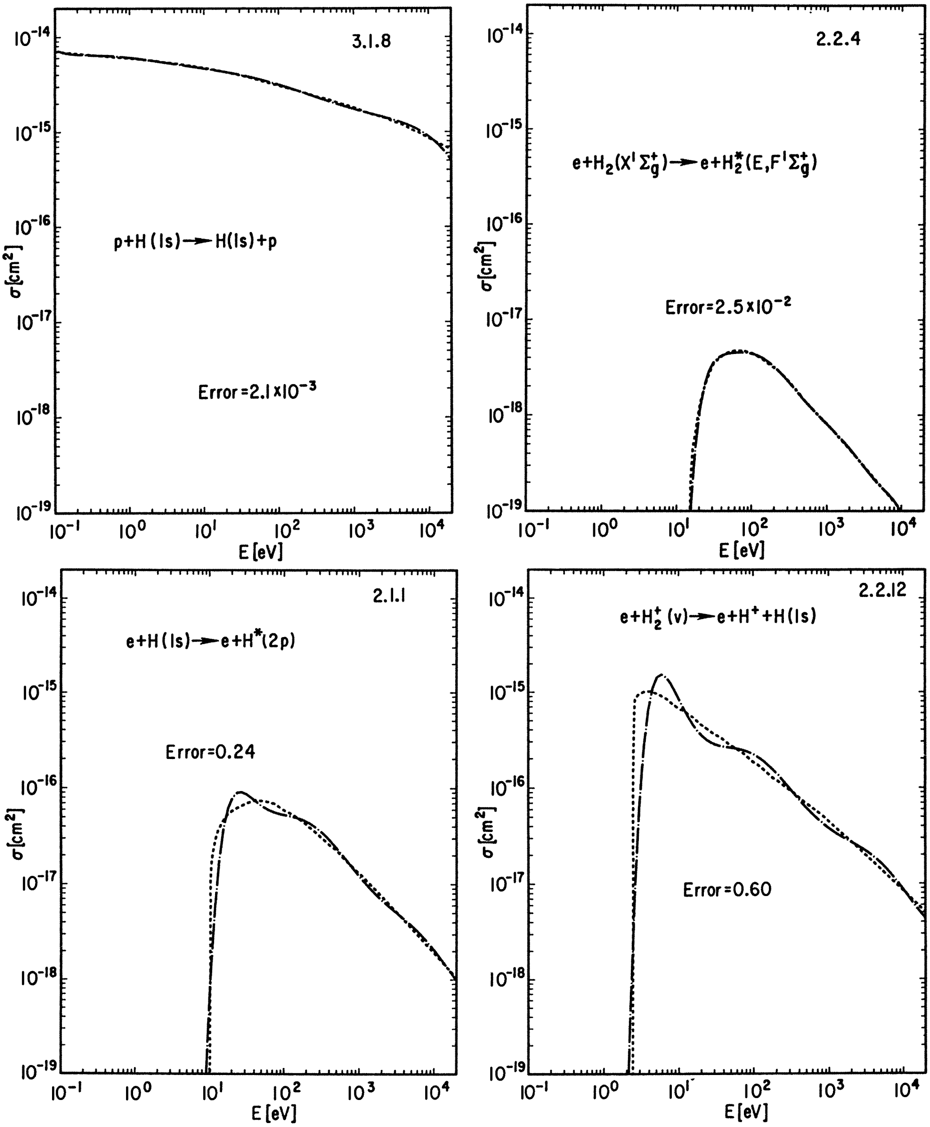


Fig. 8.1 Polynomial fits for four reactions with different errors: original curve (dotted line); fit (dot-dash line).

still increasing for energies either ≥ 20 keV, or ≤ 0.1 eV. Finally, the tables list errors for all of the fits. In general, fits with errors > 0.1 have problems near threshold and should be compared to the curves in the text to determine if they are suitable for a particular calculation. In most of these cases their usefulness depends on the energy range of interest. In order to present some idea of the quality of the fits associated with a given error, we show several polynomial fits with different error values in Fig. 8.1. Fits with errors less than 10^{-2} are nearly indistinguishable from the original curves.

Figure 8.2 is a comparison of the two Born-like fits for reaction 2.1.1. While the errors are very similar for both, the figure displays differences that are present in most of the fits given in the text; the first Born-like fit generally fits the low-energy region, E $\lesssim$ 100 to 200 eV, near the peak, while the second Born-like fit gives a better fit at higher energies. Figure 8.3 shows typical best and worst fits for the two Born-like formulas.

We have also checked for the minimum number of digits of the coefficients that must be used in order not to have any significant change in the quality of the fit. There is no change in error or appearance of the curves of any significance for most of the fits if the coefficients contain only seven

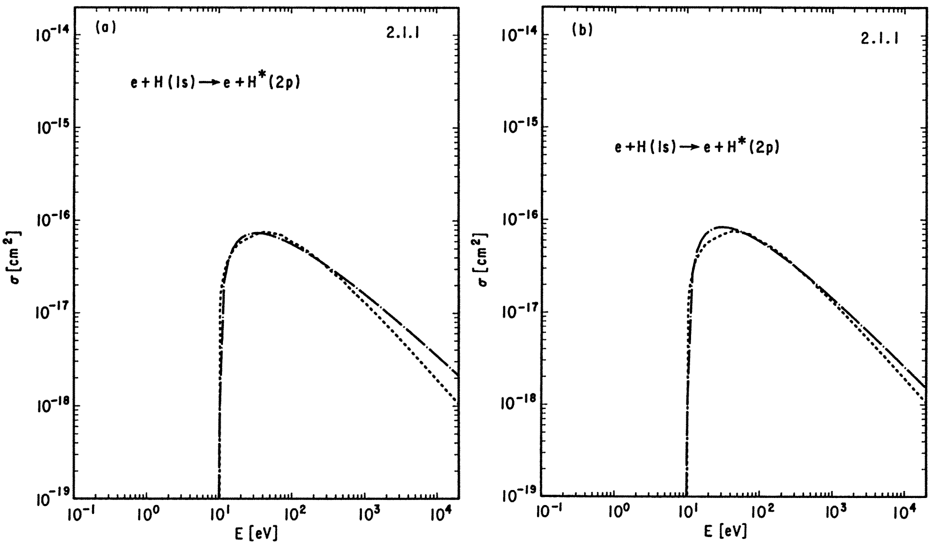


Fig. 8.2 A comparison of Born-like fits (dot-dash lines) to the original curve (dotted line) for the same reaction (2.1.1). (a) Born,1 and (b) Born,2.

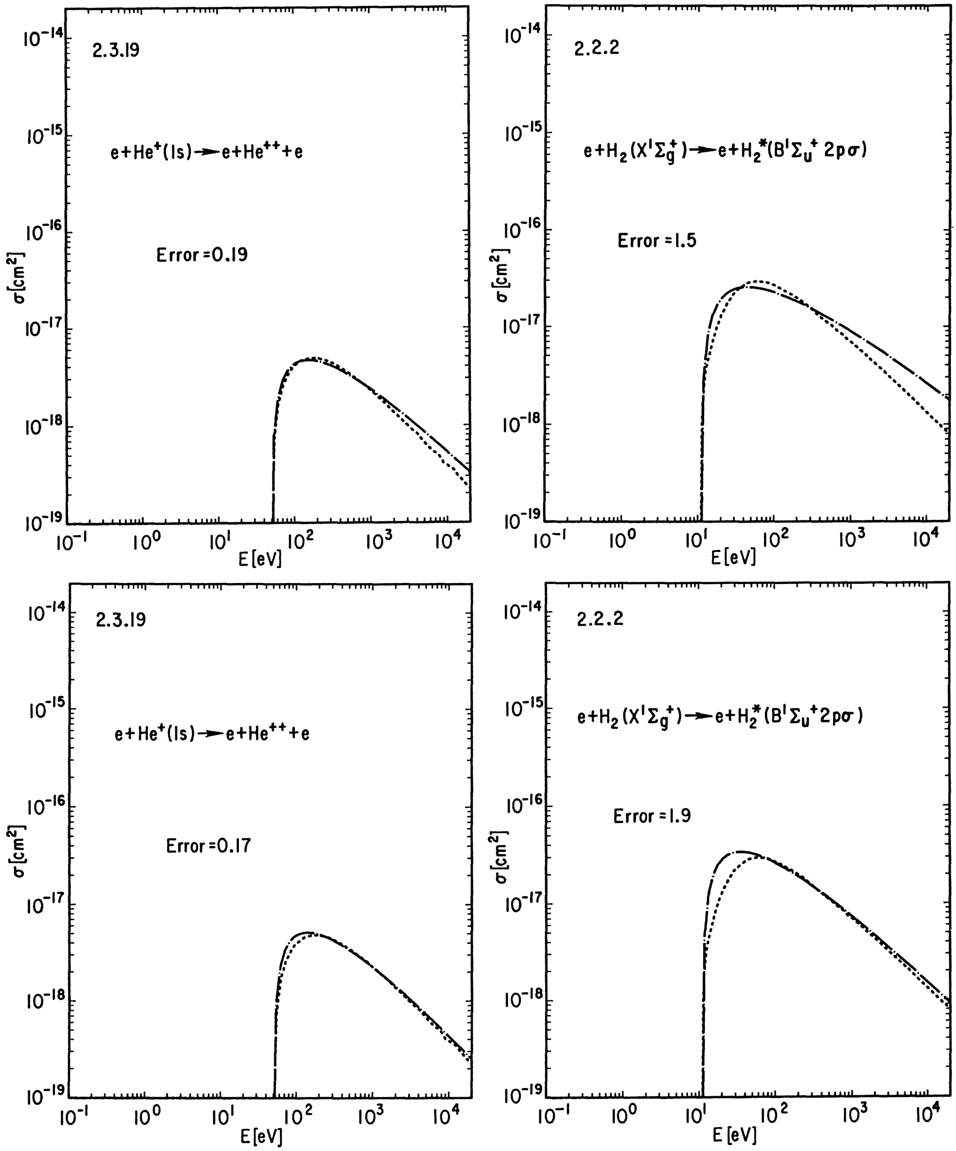


Fig. 8.3 Typical best (left, reaction 2.3.19) and worst (right, reaction 2.2.2) fits (dash-dot lines) using the two Born-like formulas compared to the original curve (dotted line). The top panels show Born,1 and the bottom Born,2.

digits instead of the full complement. However, for the following reactions, we recommend using at least:

8 digits for 2.2.4, 2.2.7, 2.2.11, 2.3.1b, 2.3.2, 2.3.19,
3.1.2, 3.1.10,
4.2.1,
5.1.2,
6.1.1, 6.1.3, and
7.2.1;

10 digits for 2.2.5, 2.3.15, and
3.1.6; and

12 digits for 2.3.3a-d.

Fits requiring more than eight significant figures should be used with care. In particular, fits for 2.25, 2.3.3a, 2.3.3c, and 2.3.3d are not recommended.

Reaction 2.1.1 $e + H(1s) \rightarrow e + H^{*}(2p)$

a0	-4.991816994666e+02	a1	6.320402753550e+02	a2	-3.652213752597e+02
a3	1.165699645892e+02	a4	-2.250557133404e+01	a5	2.695101794905e+00
a6	-1.958839549072e-01	a7	7.917154881015e-03	a8	-1.365267533573e-04

E_{min} 1.08e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.50e-17 Error 2.36e-01

aBorn,1= 1.68301e-16 nBorn,1= 8.44454e-01
E_{min} 1.08e+01 $\sigma(E_{min})$ 1.00e-19 Error 5.16e-01

aBorn,2= 2.08151e-16 nBorn,2= 9.18070e-01
E_{min} 1.08e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.95e-01

Reaction 2.1.2 $e + H(1s) \rightarrow e + H^{*}(2s)$

a0	-1.773223143614e+03	a1	2.868021256119e+03	a2	-2.019174875577e+03
a3	7.913558639288e+02	a4	-1.890880793711e+02	a5	2.824418882926e+01
a6	-2.579116350676e+00	a7	1.318146425812e-01	a8	-2.890652428531e-03

E_{min} 1.08e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.91e-17 Error 3.00e-01

Reaction 2.1.3 $e + H^{*}(2s) \rightarrow e + H^{*}(2p)$

a0	-3.015144307129e+01	a1	-8.929446571004e-01	a2	-5.730368414517e-03
a3	4.111473087803e-04	a4	-3.370055284368e-05	a5	2.817934394179e-06
a6	-1.944521853229e-07	a7	8.570956054828e-09	a8	-1.688382595819e-10

E_{min} 1.00e-01 $\sigma(E_{min})$ 6.06e-13 σ_{max} 6.06e-13 Error 1.75e-10

A more extensive analytic formula is given in the text.

Reaction 2.1.4 $e + H^{*}(n) \rightarrow e + H^{*}(m)$ $m > n, m \neq 2$

An analytic formula is given in the text.

Reaction 2.1.5 $e + H(1s) \rightarrow e + H^+ + e$

a0	-7.778213049931e+02	a1	9.540190857268e+02	a2	-5.227766973807e+02
a3	1.592701052833e+02	a4	-2.952557198074e+01	a5	3.413024145539e+00
a6	-2.405520814365e-01	a7	9.465181268476e-03	a8	-1.594325350979e-04

E_{min} 1.43e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.15e-17 Error 1.11e-01

aBorn,1= 1.53753e-16 nBorn,1= 8.61942e-01
E_{min} 1.43e+01 $\sigma(E_{min})$ 1.00e-19 Error 8.84e-01

aBorn,2= 2.34616e-16 nBorn,2= 1.02119e+00
E_{min} 1.43e+01 $\sigma(E_{min})$ 1.00e-19 Error 5.01e-01

Reaction 2.1.6 $e + H^*(2s) \rightarrow e + H^+ + e$

a0	-1.323829114032e+02	a1	1.651239202115e+02	a2	-1.140121644712e+02
a3	4.230980472378e+01	a4	-9.296147227462e+00	a5	1.243911606504e+00
a6	-9.947722917370e-02	a7	4.367280737208e-03	a8	-8.092922245217e-05

E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 8.30e-16 Error 2.93e-01

aBorn,1= 1.87046e-15 nBorn,1= 8.93875e-01
E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 Error 7.51e-01

aBorn,2= 2.57396e-15 nBorn,2= 1.01823e+00
E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 Error 7.62e-01

Reaction 2.1.7 $e + H^*(3) \rightarrow e + H^+ + e$

a0	-5.210905240460e+01	a1	4.541756148570e+01	a2	-3.994563990284e+01
a3	1.774554892576e+01	a4	-4.490170942194e+00	a5	6.717581547587e-01
a6	-5.875054514668e-02	a7	2.774373803025e-03	a8	-5.460792035331e-05

E_{min} 1.55e00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 5.76e-15 Error 5.89e-01
A more general analytic formula is given in the text.

Reaction 2.2.1a $e + H_2(v=0) \rightarrow e + H_2(v=1)$

a0	-4.063959689566e+01	a1	1.636189705461e+01	a2	-3.342841685940e+01
a3	3.479549344686e+01	a4	-2.082704506646e+01	a5	7.301916128338e+00
a6	-1.477679988432e+00	a7	1.596127782326e-01	a8	-7.118499383243e-03

E_{min} 8.95e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 4.79e-17 Error 3.82e-02

Reaction 2.2.1b $e + H_2(v=0) \rightarrow e + H_2(v=2)$

a0	-4.401593275820e+01	a1	-5.428337849062e+00	a2	2.781894563620e+01
a3	-3.059898206514e+01	a4	1.618430684710e+01	a5	-4.799622608369e+00
a6	8.162961901622e-01	a7	-7.445555845412e-02	a8	2.825425451852e-03

E_{min} 1.38e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 8.61e-18 Error 7.10e-04
Not valid for E < 1.1 or E > 300 eV.

Reaction 2.2.2 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(B^1\Sigma_u^+ 2p\sigma)$

a0	-4.293519441750e+02	a1	5.112210939087e+02	a2	-2.848127939455e+02
a3	8.831033879636e+01	a4	-1.665959177505e+01	a5	1.957960915869e+00
a6	-1.401282416514e-01	a7	5.591134833381e-03	a8	-9.537010324465e-05

E_{min} 1.25e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.94e-17 Error 1.04e-01

aBorn,1= 1.10665e-17 nBorn,1= 8.08245e-01
E_{min} 1.38e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.52e+00

aBorn,2= 4.71632e-17 nBorn,2= 1.37760e+00
E_{min} 1.38e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.86e+00

Reaction 2.2.3 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(C^1\Pi_u 2p\pi)$

a0	-8.194268487911e+02	a1	9.870509999996e+02	a2	-5.309554319119e+02
a3	1.591702330888e+02	a4	-2.912103674573e+01	a5	3.332102780153e+00
a6	-2.330596118299e-01	a7	9.119178195801e-03	a8	-1.529895022672e-04

E_{min} 1.58e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.80e-17 Error 1.18e-01

aBorn,1= 6.74162e-17 nBorn,1= 8.01562e-01
E_{min} 1.58e+01 $\sigma(E_{min})$ 1.00e-19 Error 4.64e-01

aBorn,2= 1.15646e-16 nBorn,2= 1.00587e+00
E_{min} 1.58e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.15e+00

Reaction 2.2.4 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(E,F^1\Sigma_g^+)$

a0	-1.285300373043e+03	a1	1.791037396609e+03	a2	-1.109180722424e+03
a3	3.858482892334e+02	a4	-8.239751178005e+01	a5	1.105885445011e+01
a6	-9.113361334764e-01	a7	4.218997111854e-02	a8	-8.407951365268e-04

E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 4.77e-18 Error 2.51e-02

Reaction 2.2.5 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(b^3\Sigma_u^+,\ a^3\Sigma_g^+,$ and $c^3\Pi_u)$
$\rightarrow e + H(1s) + H(1s)$

a0	-2.297914361380e+05	a1	5.303988579693e+05	a2	-5.316636672593e+05
a3	3.022690779470e+05	a4	-1.066224144320e+05	a5	2.389841369114e+04
a6	-3.324526406357e+03	a7	2.624761592546e+02	a8	-9.006246604428e+00

E_{min} 1.08e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.92e-17 Error 5.62e-01

Reaction 2.2.6 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(1s\sigma_g, n\ell\lambda|^1\Lambda) \rightarrow e + H(1s) + H^*(2s)$

a0	-1.157041752123e+03	a1	1.501936271844e+03	a2	-8.611938700508e+02
a3	2.754926257351e+02	a4	-5.380465012731e+01	a5	6.573972423327e+00
a6	-4.912318139657e-01	a7	2.054926773000e-02	a8	-3.689035889972e-04

E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.64e-17 Error 1.12e-01

aBorn,1= 3.90596e-17 nBorn,1= 9.29053e-01
E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.41e-01

aBorn,2= 4.72962e-17 nBorn,2= 1.00759e+00
E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.72e-01

Reaction 2.2.7 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u;n\ell\lambda|Q_2{}^1\Pi_u) \rightarrow e + H^*(2p) + H^*(2s)$

a0 -2.057786420733e+04 a1 2.950256031919e+04 a2 -1.831052572622e+04
a3 6.414232477826e+03 a4 -1.387462186158e+03 a5 1.898300554210e+02
a6 -1.604843781908e+01 a7 7.667894395976e-01 a8 -1.585946768503e-02
E_{min} 2.88e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.19e-18 Error 1.73e-02

aBorn,1= 1.14191e-17 nBorn,1= 1.29810e+00
E_{min} 2.88e+01 $\sigma(E_{min})$ 1.00e-19 Error 9.63e-02

aBorn,2= 1.05756e-17 nBorn,2= 1.25115e+00
E_{min} 2.88e+01 $\sigma(E_{min})$ 1.00e-19 Error 7.37e-02

Reaction 2.2.8 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u;\ n=3) \rightarrow e + H(1s) + H^*(n=3)$

a0 -3.287645365957e+03 a1 5.014406168806e+03 a2 -3.348881857725e+03
a3 1.262084567851e+03 a4 -2.934110683163e+02 a5 4.308239201745e+01
a6 -3.902409019508e+00 a7 1.994401403354e-01 a8 -4.405117731369e-03
E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.79e-18 Error 5.54e-03

aBorn,1= 4.23517e-18 nBorn,1= 9.45107e-01
E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.02e-01

aBorn,2= 6.12160e-18 nBorn,2= 1.10089e+00
E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.17e-01

Reaction 2.2.9 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^+(v) + e$

a0 -1.387609624141e+03 a1 1.699141305899e+03 a2 -9.108411850551e+02
a3 2.719534700245e+02 a4 -4.949789923430e+01 a5 5.628121884179e+00
a6 -3.908551117391e-01 a7 1.517692897197e-02 a8 -2.526183660091e-04
E_{min} 1.87e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.11e-16 Error 1.94e-01

aBorn,2= 3.58910e-16 nBorn,2= 1.01326e+00
E_{min} 1.87e+01 $\sigma(E_{min})$ 1.00e-19 Error 7.46e-01

Reaction 2.2.10 $e + H_2(X^1\Sigma_g^+) \rightarrow e + [H_2^+(\Sigma_g \text{ and } \Sigma_u) + e] \rightarrow e + H^+ + H(1s) + e$

a0 -3.833822745947e+03 a1 5.694871055047e+03 a2 -3.683040395270e+03
a3 1.338526896657e+03 a4 -2.988408134179e+02 a5 4.197687137005e+01
a6 -3.624797562843e+00 a7 1.760638946986e-01 a8 -3.685905968490e-03
E_{min} 2.11e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 5.75e-18 Error 2.17e-02

Reaction 2.2.11 $e + H_2^+(v) \rightarrow e + H^+ + H^+ + e$ (v=0-9)

a0 -7.175166253949e+02 a1 8.527284836302e+02 a2 -4.615650223553e+02
a3 1.402626692658e+02 a4 -2.611719315325e+01 a5 3.047273508837e+00
a6 -2.175218173132e-01 a7 8.689141623830e-03 a8 -1.488365280435e-04
E_{min} 1.79e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.74e-17 Error 2.37e-02

Reaction 2.2.12 $e + H_2^+(v) \rightarrow e + H_2^{+*}(2p\sigma_u) \rightarrow e + H^+ + H(1s)$, $(v = 0 - 9)$

a0	-8.734971153234e+01	a1	1.018145800541e+02	a2	-7.763161913681e+01
a3	3.095286370113e+01	a4	-7.178129093553e+00	a5	1.001376002948e+00
a6	-8.276605899370e-02	a7	3.731813613454e-03	a8	-7.068946002778e-05

E_{min} 2.70e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.01e-15 Error 6.04e-01

Reaction 2.2.13 $e + H_2^+(v) \rightarrow e + H_2^{+*}\ (2p\pi_u) \rightarrow e + H^+ + H^*(n=2$ $(v=0=9)$

a0	-1.261570316476e+03	a1	1.600546555479e+03	a2	-8.875792683132e+02
a3	2.730297710707e+02	a4	-5.103300875879e+01	a5	5.943996543464e+00
a6	-4.220104525394e-01	a7	1.672668012176e-02	a8	-2.838410215959e-04

E_{min} 1.44e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 5.06e-17 Error 4.05e-02

aBorn,1= 1.35488e-16 nBorn,1= 1.04143e+00
E_{min} 1.44e+01 $\sigma(E_{min})$ 1.00e-19 Error 4.20e-01

aBorn,2= 1.38216e-16 nBorn,1= 1.04143e+00
E_{min} 1.44e+01 $\sigma(E_{min})$ 1.00e-19 Error 4.20e-01

Reaction 2.2.14 $e + H_2^+(v) \rightarrow H(1s) + H^*(n)$ $(v=0-9,\ n \geq 2)$

a0	-3.479249259777e+01	a1	-1.103564847459e+00	a2	-1.817595501089e-13
a3	1.913718292296e-13	a4	-8.296778314084e-15	a5	-3.945007662626e-14
a6	1.480375530361e-14	a7	-2.096231848232e-15	a8	1.067937159826e-16

E_{min} 1.00e-01 $\sigma(E_{min})$ 9.85e-15 σ_{max} 9.85e-15 Error 1.74e-25

Reaction 2.2.15 $e + H_3^+ \rightarrow H + H + H$ or $\rightarrow H_2(v > 5) + H^*(n=2)$

a0	-3.497403537065e+01	a1	-9.050073352581e-01	a2	-6.875577121635e-13
a3	1.212286779103e-13	a4	1.320680420105e-13	a5	-6.368710212825e-14
a6	1.136465595184e-14	a7	-9.184755712215e-16	a8	2.814743077081e-17

E_{min} 1.00e-01 $\sigma(E_{min})$ 5.20e-15 σ_{max} 5.20e-15 Error 1.12e-24

Reaction 2.2.16 $e + H_3^+ \rightarrow e + H^+ + 2H$

a0	-1.180802127731e+03	a1	1.469242595864e+03	a2	-8.010903182743e+02
a3	2.427879961198e+02	a4	-4.477455604823e+01	a5	5.150533546464e+00
a6	-3.613881605497e-01	a7	1.416168832727e-02	a8	-2.376509206426e-04

E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.36e-16 Error 5.22e-01

aBorn,1= 1.38785e-15 nBorn,1= 7.41773e-01
E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 Error 9.17e-01

aBorn,2= 1.75195e-15 nBorn,2= 8.18483e-01
E_{min} 1.65e+01 $\sigma(E_{min})$ 1.00e-19 Error 9.58e-01

Reaction 2.2.17 $e + H_2(v \geq 4) \rightarrow (H_2^-)^* \rightarrow H^- + H$

a0 -3.533068072400e+01	a1 -1.305146001161e+00	a2 -5.402400752335e-01
a3 -1.929128735755e-01	a4 -3.998229471894e-01	a5 -2.442412657121e-01
a6 7.577527589687e-03	a7 4.268454076562e-02	a8 9.029646852927e-03

E_{min} 1.00e-01 $\sigma(E_{min})$ 8.94e-16 σ_{max} 1.03e-15 Error 6.40e-04
Not valid for E > 5 eV.

Reaction 2.3.1a $e + He(1s^2|^1S) \rightarrow e + He^*(1s2p|^1P)$

a0 -1.035570462579e+03	a1 1.215931704603e+03	a2 -6.359454827397e+02
a3 1.861198276080e+02	a4 -3.333317507125e+01	a5 3.741542703002e+00
a6 -2.572201220135e-01	a7 9.910988972511e-03	a8 -1.640390854438e-04

E_{min} 2.18e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 9.79e-18 Error 3.00e-02

aBorn,1= 1.92235e-17 nBorn,1= 7.83233e-01
E_{min} 2.18e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.78e-01

aBorn,2= 2.57557e-17 nBorn,2= 8.83509e-01
E_{min} 2.18e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.03e-01
A more extensive analytic formula is given in the text.

Reaction 2.3.1b $e + He(1s^2|^1S) \rightarrow e + He^*(1s3p|^1P)$

a0 -2.634840114580e+03	a1 3.509384108909e+03	a2 -2.045577442205e+03
a3 6.707125167844e+02	a4 -1.352829871406e+02	a5 1.719155337173e+01
a6 -1.344786986986e+00	a7 5.923822227197e-02	a8 -1.125813888453e-03

E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.35e-18 Error 1.62e-02

aBorn,1= 4.99196e-18 nBorn,1= 8.11369e-01
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.08e-01

aBorn,2= 6.56234e-18 nBorn,2= 9.07863e-01
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 9.15e-02
A more extensive analytic formula is given in the text.

Reaction 2.3.2 $e + He(1s^2|^1S) \rightarrow e + He^*(1s2s|^1S)$

a0 -1.340229681600e+04	a1 2.117221297932e+04	a2 -1.450345815377e+04
a3 5.610930330567e+03	a4 -1.341090060181e+03	a5 2.028369172741e+02
a6 -1.896426422663e+01	a7 1.002440728214e+00	a8 -2.294532805220e-02

E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.72e-18 Error 1.23e-01

aBorn,1= 1.16605e-17 nBorn,1= 1.52195e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.30e-01

aBorn,2= 1.01757e-17 nBorn,2= 1.42944e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.68e-01
An analytic formula for σ for this and other $n\ell|^1L$ states is given in the text.

Reaction 2.3.3a $e + He(1s^2|^1S) \rightarrow e + He^*(1s2s|^3S)$

a0 -5.203190079746e+07 a1 1.114126390950e+08 a2 -1.041333130230e+08
a3 5.549110256155e+07 a4 -1.843990770358e+07 a5 3.912927216807e+06
a6 -5.177965474575e+05 a7 3.906790796143e+04 a8 -1.286793467718e+03
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.08e-18 Error 3.46e-01
This fit is not recommended.

aBorn,1= 2.57061e-17 nBorn,1= 4.07784e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 6.90e-01

aBorn,2= 4.23197e-17 nBorn,2= 5.18074e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.32e+00
An analytic formula for σ is given in the text.

Reaction 2.3.3b $e + He(1s^2|^1S) \rightarrow e + He^*(1s2p|^3P)$

a0 -4.793169045161e+06 a1 9.882446793715e+06 a2 -8.888886013658e+06
a3 4.555681859005e+06 a4 -1.455138589620e+06 a5 2.966235458426e+05
a6 -3.768463275632e+04 a7 2.728166188657e+03 a8 -8.616903005294e+01
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.89e-18 Error 1.70e-01

aBorn,1= 1.87693e-17 nBorn,1= 2.84919e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 6.02e-01

aBorn,2= 2.73848e-17 nBorn,2= 3.37724e+00
E_{min} 2.17e+01 $\sigma(E_{min})$ 1.00e-19 Error 6.43e-01
An analytic formula for σ is given in the text.

Reaction 2.3.3c $e + He(1s^2|^1S) \rightarrow e + He^*(1s3s|^3S)$

a0 -4.788014731830e+08 a1 1.022518413821e+09 a2 -9.540217735841e+08
a3 5.079285422983e+08 a4 -1.687812725605e+08 a5 3.584473999432e+07
a6 -4.751258664024e+06 a7 3.593838762943e+05 a8 -1.187665518764e+04
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 8.49e-19 Error 9.16e-02
This fit is not recommended.

aBorn,1= 6.73891e-18 nBorn,1= 3.38203e+00
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.57e-01

aBorn,2= 8.73337e-18 nBorn,2= 3.82261e+00
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.10e-01
An analytic formula for σ is given in the text.

Reaction 2.3.3d $e + He(1s^2|^1S) \rightarrow e + He^*(1s3p|^3P)$

a0 -3.936065650971e+07 a1 8.116028811410e+07 a2 -7.306391247418e+07
a3 3.750824079156e+07 a4 -1.200982299576e+07 a5 2.456048818627e+06
a6 -3.132802195794e+05 a7 2.278831373521e+04 a8 -7.237641204949e+02
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.62e-18 Error 1.85e-01
This fit is not recommended.

aBorn,1= 1.32373e-17 nBorn,1= 3.41922e+00
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.91e-01

aBorn,2= 1.67554e-17 nBorn,2= 3.81681e+00
E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 Error 4.46e-01
An analytic formula for σ is given in the text.

Reaction 2.3.4a $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s2s|^1S)$

a0	-3.767284614946e+01	a1	1.242374777500e+01	a2	-1.733730671197e+01
a3	1.065193441154e+01	a4	-3.545021903004e+00	a5	6.760042577381e-01
a6	-7.381907066438e-02	a7	4.291139737209e-03	a8	-1.029193004464e-04

E_{min} 8.96e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 6.14e-16 Error 4.84e-01

aBorn,1= 2.18988e-15 nBorn,1= 1.34842e+00
E_{min} 8.96e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.14e+00

aBorn,2= 2.23252e-15 nBorn,2= 1.36293e+00
E_{min} 8.96e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.23e+00
An analytic formula for σ is given in the text.

Reaction 2.3.4b $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s2s|^1P)$

a0	-5.319933965992e+01	a1	4.744554023140e+01	a2	-4.844985223676e+01
a3	2.500468700294e+01	a4	-7.374551620285e+00	a5	1.290076459738e+00
a6	-1.322635763531e-01	a7	7.335813534997e-03	a8	-1.698321860588e-04

E_{min} 1.56e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.07e-16 Error 4.17e-01

aBorn,1= 1.10118e-15 nBorn,1= 1.35219e+00
E_{min} 1.56e+00 $\sigma(E_{min})$ 1.00e-19 Error 9.62e-01

aBorn,2= 1.11692e-15 nBorn,2= 1.36330e+00
E_{min} 1.56e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.02e+00
An analytic formula for σ is given in the text.

Reaction 2.3.4c $e + He^*(1s2s|^1S) \rightarrow e + He^*(1s2p|^3P)$

a0	-3.317860766309e+01	a1	-5.306038723803e-01	a2	-2.695255954243e+00
a3	2.632267872941e+00	a4	-1.099156687924e+00	a5	2.377305480208e-01
a6	-2.790496421908e-02	a7	1.688187005669e-03	a8	-4.125774276276e-05

E_{min} 3.90e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.41e-15 Error 6.04e-01

aBorn,1= 8.65146e-15 nBorn,1= 1.35184e+00
E_{min} 3.90e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.57e+00

aBorn,2= 8.78111e-15 nBorn,2= 1.36352e+00
E_{min} 3.90e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.67e+00
An analytic formula for σ is given in the text.

Reaction 2.3.4d $e + He^*(1s2p|^3P) \rightarrow e + He^*(1s2p|^1P)$

a0	-3.550958147337e+01	a1	-2.148096190520e+00	a2	3.301727694779e-01
a3	1.489817873888e+00	a4	-1.281057689191e+00	a5	4.334863480750e-01
a6	-7.269238026113e-02	a7	6.015845378859e-03	a8	-1.962092219181e-04

E_{min} 2.62e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 4.39e-16 Error 2.60e-01

aBorn,1= 1.62992e-15 nBorn,1= 1.37522e+00
E_{min} 2.62e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.37e+00

aBorn,2= 1.59075e-15 nBorn,2= 1.36145e+00
E_{min} 2.62e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.29e+00
An analytic formula for σ is given in the text.

Reaction 2.3.5a $e + He^{*}(1s2s|^{1}S) \rightarrow e + He^{*}(1s2p|^{1}P)$

a0	-3.325138159927e+01	a1	6.965673711167e+00	a2	-9.102522690164e+00
a3	5.178880611636e+00	a4	-1.570251042131e+00	a5	2.686249148763e-01
a6	-2.602715945748e-02	a7	1.332101581144e-03	a8	-2.797505613652e-05

E_{min} 6.77e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.44e-14 Error 7.36e-01

aBorn,2= 4.26417e-14 nBorn,2= 8.79209e-01
E_{min} 6.87e-01 $\sigma(E_{min})$ 1.00e-19 Error 1.56e+00
An analytic formula for σ is given in the text.

Reaction 2.3.5b $e + He^{*}(1s2s|^{3}S) \rightarrow e + He^{*}(1s2p|^{3}P)$

a0	-4.190861763587e+01	a1	2.589117787777e+01	a2	-2.543442341964e+01
a3	1.224262304780e+01	a4	-3.287256784979e+00	a5	5.142698379467e-01
a6	-4.655881399807e-02	a7	2.259789810984e-03	a8	-4.548031395449e-05

E_{min} 1.15e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.52e-15 Error 5.53e-01
An analytic formula for σ is given in the text.

Reaction 2.3.6a $e + He^{*}(1s2s|^{1}S) \rightarrow e + He^{*}(1s3p|^{1}P)$

a0	-7.945340796384e+01	a1	7.952123040074e+01	a2	-5.901873964305e+01
a3	2.336041841867e+01	a4	-5.418217641105e+00	a5	7.574234290606e-01
a6	-6.273863245111e-02	a7	2.833779484304e-03	a8	-5.374700574749e-05

E_{min} 2.72e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.68e-16 Error 2.62e-01
An analytic formula for σ is given in the text.

Reaction 2.3.6b $e + He^{*}(1s2s|^{3}S) \rightarrow e + He^{*}(1s3p|^{3}P)$

a0	-8.720058224600e+01	a1	8.669127167337e+01	a2	-6.125632963824e+01
a3	2.323452528088e+01	a4	-5.206449941296e+00	a5	7.082705099324e-01
a6	-5.741257577852e-02	a7	2.548456501150e-03	a8	-4.765136776607e-05

E_{min} 3.14e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.66e-17 Error 1.61e-01

aBorn,2= 1.95245e-16 nBorn,2= 8.39781e-01
E_{min} 3.14e+00 $\sigma(E_{min})$ 1.00e-19 Error 5.55e-01
An analytic formula for σ is given in the text.

Reaction 2.3.7a $e + He^{*}(1s2p|^{1}P) \rightarrow e + He^{*}(1s3d|^{1}D)$

a0	-6.380148486246e+01	a1	6.207791717177e+01	a2	-5.009739526736e+01
a3	2.108909461860e+01	a4	-5.130498771379e+00	a5	7.448846309387e-01
a6	-6.362451646494e-02	a7	2.947637642636e-03	a8	-5.710909679690e-05

E_{min} 2.05e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.73e-15 Error 6.02e-01

aBorn,2= 7.85272e-15 nBorn,2= 8.59826e-01
E_{min} 2.05e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.21e+00
An analytic formula for σ is given in the text.

Reaction 2.3.7b $e + He^{*}(1s2p|^{3}P) \rightarrow e + He^{*}(1s3d|^{3}D)$

a0	-7.355382422374e+01	a1	7.757733939986e+01	a2	-6.021028662561e+01
a3	2.456897613696e+01	a4	-5.830267812736e+00	a5	8.299661528547e-01
a6	-6.978241370066e-02	a7	3.191768833116e-03	a8	-6.118911403921e-05

E_{min} 2.35e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.01e-15 Error 5.79e-01

aBorn,2= 5.69936e-15 nBorn,2= 8.78100e-01
E_{min} 2.35e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.12e+00
An analytic formula for σ is given in the text.

Reaction 2.3.9 $e + He(1s^{2}|^{1}S) \rightarrow e + He^{+} + e$

a0	-1.864515653677e+03	a1	2.200039160012e+03	a2	-1.13502043008e+03
a3	3.275368136458e+02	a4	-5.782773248653e+01	a5	6.398861014578e+00
a6	-4.337092983841e-01	a7	1.647885719077e-02	a8	-2.690038700620e-04

E_{min} 2.50e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.75e-17 Error 5.25e-02

aBorn,2= 2.66551e-15 nBorn,2= 1.02404e+00
E_{min} 5.45e+00 $\sigma(E_{min})$ 1.00e-19 Error 8.86e-01

Reaction 2.3.10a $e + He^{*}(1s2s|^{1}S) \rightarrow e + He^{+}(1s) + e$

a0	-1.588165958608e+02	a1	2.025096794972e+02	a2	-1.359677027927e+02
a3	4.931464639049e+01	a4	-1.062291122924e+01	a5	1.397102480527e+00
a6	-1.100503977820e-01	a7	4.767747225791e-03	a8	-8.732475392853e-05

E_{min} 4.11e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 8.05e-16 Error 4.12e-01

aBorn,1= 1.76528e-15 nBorn,1= 8.45023e-01
E_{min} 4.11e+00 $\sigma(E_{min})$ 1.00e-19 Error 8.55e-01

aBorn,2= 2.22317e-15 nBorn,2= 9.31407e-01
E_{min} 4.11e+00 $\sigma(E_{min})$ 1.00e-19 Error 6.68e-01
An analytic formula for σ is given in the text.

Reaction 2.3.10b $e + He^{*}(1s2p|^{1}P) \rightarrow e + He^{+}(1s) + e$

a0	-1.307379836148e+02	a1	1.632174408167e+02	a2	-1.129614525216e+02
a3	4.199589716864e+01	a4	-9.233643615441e+00	a5	1.235205673096e+00
a6	-9.868890735893e-02	a7	4.326993699443e-03	a8	-8.006280122436e-05

E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.14e-15 Error 3.47e-01

aBorn,1= 2.44771e-15 nBorn,1= 8.44077e-01
E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.02e+00

aBorn,2= 3.10641e-15 nBorn,2= 9.33260e-01
E_{min} 3.58e+00 $\sigma(E_{min})$ 1.00e-19 Error 8.13e-01
An analytic formula for σ is given in the text.

Reaction 2.3.10c $e + He^{*}(1s2s|^{3}S) \rightarrow e + He^{+}(1s) + e$

a0	-2.339247199323e+02	a1	3.108263537901e+02	a2	-2.004035199806e+02
a3	7.013664348852e+01	a4	-1.464607997646e+01	a5	1.875537708304e+00
a6	-1.443996329241e-01	a7	6.134194672052e-03	a8	-1.104612714554e-04

E_{min} 5.45e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 9.37e-16 Error 5.07e-01

aBorn,1= 2.44417e-15 nBorn,1= 9.85122e-01
E_{min} 5.45e+00 $\sigma(E_{min})$ 1.00e-19 Error 8.95e-01

aBorn,2= 2.66551e-15 nBorn,2= 1.02404e+00
E_{min} 5.45e+00 $\sigma(E_{min})$ 1.00e-19 Error 8.86e-01
An analytic formula for σ is given in the text.

Reaction 2.3.10d $e + He^{*}(1s2p|^{3}P) \rightarrow e + He^{+}(1s) + e$

a0	-1.514909720389e+02	a1	1.917899987253e+02	a2	-1.291695579859e+02
a3	4.694225725512e+01	a4	-1.012623462168e+01	a5	1.333169086771e+00
a6	-1.050969063989e-01	a7	4.555911465700e-03	a8	-8.348482513741e-05

E_{min} 4.14e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 9.85e-16 Error 4.18e-01

aBorn,1= 2.09009e-15 nBorn,1= 8.39105e-01
E_{min} 4.14e+00 $\sigma(E_{min})$ 1.00e-19 Error 1.16e+00

aBorn,2= 2.72108e-15 nBorn,2= 9.37659e-01
E_{min} 4.14e+00 $\sigma(E_{min})$ 1.00e-19 Error 9.35e-01
An analytic formula for σ is given in the text.

Reaction 2.3.12 $e + He^{*}(1sn\ell|^{2S+1}L) \rightarrow e + He^{+*}(n\ell) + e$

a0	-2.149046249050e+04	a1	2.587653680045e+04	a2	-1.349616963351e+04
a3	3.975822003764e+03	a4	-7.236994991416e+02	a5	8.336945178595e+01
a6	-5.937449760897e+00	a7	2.390910599514e-01	a8	-4.169354418025e-03

E_{min} 5.71e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.10e-17 Error 1.27e-01

aBorn,1= 4.41503e-17 nBorn,1= 1.48779e+00
E_{min} 5.71e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.50e-01

aBorn,2= 4.20803e-17 nBorn,2= 1.45655e+00
E_{min} 5.71e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.98e-01
An analytic formula for σ is given in the text.

Reaction 2.3.14 $e + He^{+}(1s) \rightarrow e + He^{+*}(2p)$

a0	-4.215091396506e+03	a1	4.764415543278e+03	a2	-2.333572119719e+03
a3	6.411861251368e+02	a4	-1.081470970453e+02	a5	1.147267078966e+01
a6	-7.480739782521e-01	a7	2.743315170494e-02	a8	-4.335336435784e-04

E_{min} 4.32e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.70e-17 Error 1.66e-01

aBorn,1= 4.51430e-17 nBorn,1= 9.28386e-01
E_{min} 4.32e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.96e-01

aBorn,2= 4.19403e-17 nBorn,2= 8.97086e-01
E_{min} 4.32e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.07e-01
An analytic formula for σ is given in the text.

Reaction 2.3.15 $e + He^{+}(1s) \rightarrow e + He^{+*}(2s)$

a0	-4.363513156598e+04	a1	6.029422825525e+04	a2	-3.615014929003e+04
a3	1.227349742282e+04	a4	-2.581215777982e+03	a5	3.443868798585e+02
a6	-2.847203555533e+01	a7	1.333878006451e+00	a8	-2.711798666500e-02

E_{min} 4.33e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.29e-18 Error 1.27e-01

aBorn,1= 1.55600e-17 nBorn,1= 1.68750e+00
E_{min} 4.33e+01 $\sigma(E_{min})$ 1.00e-19 Error 3.88e-01

aBorn,2= 1.31202e-17 nBorn,2= 1.55578e+00
E_{min} 4.33e+01 $\sigma(E_{min})$ 1.00e-19 Error 2.24e-01
An analytic formula for σ is given in the text.

Reaction 2.3.19 $e + He^{+}(1s) \rightarrow e + He^{2+} + e$

a0	-6.397975729831e+03	a1	7.234572604639e+03	a2	-3.553226640490e+03
a3	9.838309068727e+02	a4	-1.679762955979e+02	a5	1.811299630401e+01
a6	-1.205027911620e+00	a7	4.524170259779e-02	a8	-7.342485039293e-04

E_{min} 5.74e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 4.84e-18 Error 6.16e-02

aBorn,1= 1.11824e-17 nBorn,1= 8.89614e-01
E_{min} 5.74e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.88e-01

aBorn,2= 1.35777e-17 nBorn,2= 9.66349e-01
E_{min} 5.74e+01 $\sigma(E_{min})$ 1.00e-19 Error 1.70e-01

Reaction 3.1.1 $p + H(1s) \rightarrow p + H^{*}(2p)$

a0	1.498711267601e+03	a1	-1.883748471843e+03	a2	9.798674598591e+02
a3	-2.840533664327e+02	a4	5.025004769585e+01	a5	-5.555355513127e+00
a6	3.748565821577e-01	a7	-1.412032135035e-02	a8	2.274926861613e-04

E_{min} 5.01e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.09e-17 Error 2.54e-03
Not valid for E < 30 eV.

Reaction 3.1.2 $p + H(1s) \rightarrow p + H^{*}(2s)$

a0	2.829875237564e+03	a1	-6.116917512897e+03	a2	3.922809899060e+03
a3	-1.246183868116e+03	a4	2.285990672320e+02	a5	-2.546914306461e+01
a6	1.706611319064e+00	a7	-6.339871351017e-02	a8	1.005024483671e-03

E_{min} 6.00e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 9.15e-18 Error 1.95e-03
Not valid for E < 400 eV.

Reaction 3.1.3 $p + H^{*}(2s) \rightarrow p + H^{*}(2p)$

a0	-7.074596259394e+01	a1	1.053200029604e+02	a2	-9.022427163873e+01
a3	3.938090329805e+01	a4	-9.804841353212e+00	a5	1.447083362703e+00
a6	-1.251503545319e-01	a7	5.855600339770e-03	a8	-1.143715732966e-04

E_{min} 1.76e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.61e-11 Error 2.20e+00
This fit not recommended. Use the analytic formula for σ given in the text.

Reaction 3.1.6 $p + H(1s) \rightarrow p + H^+ + e$

a0	-3.476414561951e+06	a1	2.961782930805e+06	a2	-1.100587541308e+06
a3	2.329850579421e+05	a4	-3.073181275800e+04	a5	2.586508086362e+03
a6	-1.356488358412e+02	a7	4.053120293214e+00	a8	-5.282803274226e-02

E_{min} 1.52e+03 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.53e-16 Error 1.16e-02

An analytic formula for σ is given in the text.

Reaction 3.1.8 $p + H(1s) \rightarrow H(1s) + p$

a0	-3.274123792568e+01	a1	-8.916456579806e-02	a2	-3.016990732025e-02
a3	9.205482406462e-03	a4	2.400266568315e-03	a5	-1.927122311323e-03
a6	3.654750340106e-04	a7	-2.788866460622e-05	a8	7.422296363524e-07

E_{min} 1.00e-01 $\sigma(E_{min})$ 7.00e-15 σ_{max} 7.00e-15 Error 2.25e-03

Reaction 3.1.9 $p + H(1s) \rightarrow H^*(2p) + p$

a0	-2.197571949935e+01	a1	-4.742502251260e+01	a2	3.628013140596e+01
a3	-1.423003075866e+01	a4	3.273090240144e+00	a5	-4.557928912260e-01
a6	3.773588347458e-02	a7	-1.707904867106e-03	a8	3.251203344615e-05

E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.97e-17 Error 3.29e-03

Not valid for $E < 10$ eV.

Reaction 3.1.10 $p + H(1s) \rightarrow H^*(2s) + p$

a0	-1.327325087764e+04	a1	1.317576614520e+04	a2	-5.683932157858e+03
a3	1.386309780149e+03	a4	-2.089794561307e+02	a5	1.992976245274e+01
a6	-1.173800576157e+00	a7	3.902422810767e-02	a8	-5.606240339932e-04

E_{min} 2.62e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.20e-17 Error 1.03e-03

Reaction 3.1.11a $p + H^*(2) \rightarrow H^*(2) + p$

a0	-3.160064085208e+01	a1	-1.063971267559e-01	a2	1.758632420708e-02
a3	-1.343032128288e-02	a4	-2.158483440621e-03	a5	2.016888852861e-03
a6	-3.768535435172e-04	a7	2.790447577960e-05	a8	-7.334007645451e-07

E_{min} 1.00e-01 $\sigma(E_{min})$ 2.50e-14 σ_{max} 2.50e-14 Error 9.57e-04

Reaction 3.1.11b $p + H^*(3) \rightarrow H^*(3) + p$

a0	-3.007479360386e+01	a1	-1.033159234538e-01	a2	-5.813424077828e-03
a3	3.520834872493e-03	a4	-1.498488713106e-04	a5	-4.614034275366e-04
a6	1.226477420816e-04	a7	-1.180475816996e-05	a8	3.892872672032e-07

E_{min} 1.00e-01 $\sigma(E_{min})$ 1.07e-13 σ_{max} 1.07e-13 Error 2.04e-04

Reaction 3.2.1a $p + H_2(j=0) \rightarrow p + H_2(j')$ $(j' \geq 2)$

a0	-3.351219959966e+01	a1	-1.635225977493e-01	a2	-6.547019337483e-02
a3	-2.075062265158e-03	a4	-4.874756961659e-03	a5	-4.660550753949e-03
a6	2.817993595595e-04	a7	2.508118915628e-04	a8	-2.791892312099e-05

E_{min} 1.00e-01 $\sigma(E_{min})$ 3.23e-15 σ_{max} 3.23e-15 Error 8.28e-04

Reaction 3.2.1b $p + H_2(j=1) \rightarrow p + H_2(j')$ $(j' \geq 3)$

a0	-3.393406708822e+01	a1	-1.040291133860e-01	a2	-2.235808125213e-02
a3	-3.320456299848e-02	a4	-2.081525199080e-02	a5	1.897906681845e-03
a6	1.657385114123e-03	a7	-3.410682026726e-04	a8	1.868694684385e-05

E_{min} 1.00e-01 $\sigma(E_{min})$ 2.19e-15 σ_{max} 2.19e-15   Error 4.08e-04
Not valid for E > 2000 eV.

Reaction 3.2.2 $p + H_2(v=0) \rightarrow p + H_2(v > 0)$

a0	-4.048908822949e+01	a1	3.404344799771e+00	a2	-1.787578523150e+00
a3	1.394845302080e+00	a4	-5.775848321190e-01	a5	1.183902638008e-01
a6	-1.276577600153e-02	a7	6.983034334039e-04	a8	-1.531189559106e-05

E_{min} 6.02e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.24e-15   Error 2.22e-02

Reaction 3.2.3 $p + H_2 \rightarrow H(1s) + H_2^+$

a0	-8.965985910240e+01	a1	1.057326823133e+02	a2	-8.364373343149e+01
a3	3.396650519934e+01	a4	-7.931279499027e+00	a5	1.110667708159e+00
a6	-9.213077375317e-02	a7	4.170940125995e-03	a8	-7.937779949951e-05

E_{min} 2.72e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.03e-15   Error 2.46e-01

Reaction 3.2.4a $p + D_2 \rightarrow D^+ + HD$ or $(H + D)$

a0	-3.514598267631e+01	a1	-1.638772651981e+00	a2	-3.145916075331e-01
a3	2.614991388325e-01	a4	2.453621020680e-03	a5	-2.572795334322e-02
a6	5.870493979209e-03	a7	-5.239437578054e-04	a8	1.696795511874e-05

E_{min} 1.00e-01 $\sigma(E_{min})$ 2.47e-15 σ_{max} 2.47e-15   Error 3.74e-02

Reaction 3.2.4b $p + D_2 \rightarrow D + HD^+$

a0	-3.793844403725e+03	a1	1.562579182141e+04	a2	-2.785112864175e+04
a3	2.778553560654e+04	a4	-1.698201826254e+04	a5	6.517141981195e+03
a6	-1.535237801461e+03	a7	2.031763319972e+02	a8	-1.157681794201e+01

E_{min} 2.72e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.33e-17   Error 3.79e-01

Reaction 3.2.5 $p + H_2 \rightarrow p + H_2^+(v \leq 9) + e$

a0	1.681920096116e+01	a1	-8.751084517093e+01	a2	5.024534132103e+01
a3	-1.560982391827e+01	a4	2.931478842554e+00	a5	-3.421137108600e-01
a6	2.429148918124e-02	a7	-9.612735627840e-04	a8	1.625014598463e-05

E_{min} 4.36e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.19e-16   Error 2.51e-04
Not valid for E < 30 eV.

Reaction 3.2.6 $p + H_2^+(v) \rightarrow p + H(1s) + H^+$

a0	-5.100296089295e+01	a1	-7.618139241529e+00	a2	9.925169617893e+00
a3	-4.105615029225e+00	a4	9.552023306824e-01	a5	-1.333440043499e-01
a6	1.095282998853e-02	a7	-4.868705304669e-04	a8	9.034188174517e-06

E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.79e-15   Error 9.54e-04
Not valid for E < 10 eV.

Reaction 3.3.1 $p + He \rightarrow H + He^+$

a0	-4.883734637847e+01	a1	-7.864577316892e+00	a2	1.051518602966e+01
a3	-4.731600895321e+00	a4	1.169830752883e+00	a5	-1.750344914778e-01
a6	1.574934435872e-02	a7	-7.784849464356e-04	a8	1.611953487366e-05

E_{min} 1.73e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.79e-16 Error 8.53e-04
Not valid for E < 10 eV.

Reaction 3.3.2 $p + He \rightarrow p + He^+ + e$

a0	4.624871765081e+03	a1	-4.745692532499e+03	a2	2.081508647511e+03
a3	-5.150987820537e+02	a4	7.872087768079e+01	a5	-7.611766573851e+00
a6	4.549589444268e-01	a7	-1.537511000653e-02	a8	2.250170199350e-04

E_{min} 2.00e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.90e-17 Error 1.58e-04

Reaction 3.3.3 $p + He(1s^2|^1S) \rightarrow p + He^*(1s2p|^1P)$

a0	-1.817859864600e+03	a1	1.862928035048e+03	a2	-8.556804144556e+02
a3	2.228609435255e+02	a4	-3.580573984427e+01	a5	3.624830875484e+00
a6	-2.255912682713e-01	a7	7.890547281314e-03	a8	-1.188134235646e-04

E_{min} 1.38e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 7.73e-17 Error 1.91e-05
A more extensive analytic formula is given in the text.

Reaction 3.3.6a $p + He^*(1s2s|^1S) \rightarrow H^*(2s) + He^+(1s)$

a0	-4.488921384477e+01	a1	4.960932531533e+00	a2	-3.262576803403e-01
a3	-2.936130156727e-01	a4	9.830719566023e-02	a5	-1.436613419090e-02
a6	1.109137228313e-03	a7	-4.365781757124e-05	a8	6.819428318304e-07

E_{min} 1.26e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.13e-15 Error 6.71e-04

Reaction 3.3.6b $p + He^*(1s2s|^3S) \rightarrow H^*(2s) + He^+(1s)$

a0	-4.848650583528e+01	a1	-3.932691714215e+00	a2	7.523124596576e+00
a3	-3.127572865354e+00	a4	6.776405973062e-01	a5	-8.713461726775e-02
a6	6.707424051145e-03	a7	-2.863198766538e-04	a8	5.218187112892e-06

E_{min} 6.06e+00 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.85e-15 Error 7.93e-04
Not valid for E < 5.

Reaction 3.3.7a $p + He^*(1s2p|^1P) \rightarrow H^*(2p) + He^+(1s)$

a0	-3.761174237974e+01	a1	3.151158037643e+00	a2	-9.333114666012e-01
a3	2.699732305042e-01	a4	-7.727620729277e-02	a5	1.499779990623e-02
a6	-1.669176505953e-03	a7	9.612733086019e-05	a8	-2.222038029912e-06

E_{min} 3.02e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.07e-14 Error 6.71e-03

Reaction 3.3.7b $p + He^*(1s2p|^3P) \rightarrow H^*(2p) + He^+(1s)$

a0	-3.567086579938e+01	a1	2.166873578000e+00	a2	-8.322452040300e-01
a3	3.967778327802e-01	a4	-1.418439656872e-01	a5	2.883195206911e-02
a6	-3.206621198950e-03	a7	1.828199967957e-04	a8	-4.182687867891e-06

E_{min} 2.61e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.32e-14 Error 7.49e-02

Reaction 4.2.1 $H_2^+(1s\sigma_g;v) + H(1s) \rightarrow H_2^{+*}(2p\sigma_u) + H(1s) \rightarrow$
$\rightarrow H^+ + H + H(1s)$, $(v = 0 - 9)$

a0	1.885518121144e+04	a1	-1.730109845144e+04	a2	6.789143089426e+03
a3	-1.495308617111e+03	a4	2.025858786888e+02	a5	-1.731165351422e+01
a6	9.120053117120e-01	a7	-2.709481429950e-02	a8	3.476220959653e-04

E_{min} 3.96e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.99e-16 Error 2.02e-03
Not valid for E < 300 eV.

Reaction 4.3.1 $H_2^+ + H_2 \rightarrow H_2 + H_2^+$

a0	-3.427958758517e+01	a1	-7.121484125189e-02	a2	4.690466187943e-02
a3	-8.033946660540e-03	a4	-2.265090924593e-03	a5	-2.102414848737e-04
a6	1.948869487515e-04	a7	-2.208124950005e-05	a8	7.262446915488e-07

E_{min} 1.00e-01 $\sigma(E_{min})$ 2.10e-15 σ_{max} 2.10e-15 Error 3.91e-04

Reaction 4.3.2 $H_2^+ + H_2 \rightarrow H_2^+ + H_2^+ + e$

a0	-2.383489439121e+02	a1	2.384368432909e+02	a2	-1.263102889116e+02
a3	3.746454397894e+01	a4	-6.767700946931e+00	a5	7.629123486032e-01
a6	-5.246096809457e-02	a7	2.014116839267e-03	a8	-3.310073123768e-05

E_{min} 3.67e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.30e-16 Error 1.11e-04

Reaction 4.3.3 $H_2^+ + H_2 \rightarrow H_3^+ + H$

a0	-3.422188283057e+01	a1	-7.733921420462e-01	a2	-4.625452844356e-01
a3	-2.307540053739e-01	a4	3.188925541844e-02	a5	3.622033742962e-02
a6	-5.093822617734e-03	a7	-2.420060478318e-03	a8	4.634259500837e-04

E_{min} 1.00e-01 $\sigma(E_{min})$ 4.26e-15 σ_{max} 4.26e-15 Error 2.99e-04
Not valid for E > 40 eV.

Reaction 4.4.1 $H_2^+ + He \rightarrow H_2^+ + He^+ + e$

a0	-1.279183240553e+02	a1	7.851907373534e+01	a2	-3.133748457688e+01
a3	6.817786375262e+00	a4	-8.395843945734e-01	a5	5.456579807937e-02
a6	-1.161799515932e-03	a7	-5.185457132932e-05	a8	2.416658401748e-06

E_{min} 4.52e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.30e-16 Error 1.34e-04

Reaction 5.2.1 $He^+ + H_2 \rightarrow He^+ + H_2^+ + e$

a0	-2.325294713788e+02	a1	2.137835372191e+02	a2	-1.060826620181e+02
a3	3.048034248334e+01	a4	-5.472938698614e+00	a5	6.242016892196e-01
a6	-4.400795546393e-02	a7	1.751040972949e-03	a8	-3.008006324086e-05

E_{min} 1.90e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 5.51e-17 Error 3.94e-03

Reaction 5.2.2 $He^+ + H_2 \rightarrow He + H_2^+$

a0	-1.108066480195e+04	a1	1.008755280085e+04	a2	-4.018540037373e+03
a3	9.114656395741e+02	a4	-1.288151812962e+02	a5	1.162404023738e+01
a6	-6.543944103705e-01	a7	2.101966590407e-02	a8	-2.949737399468e-04

E_{min} 5.84e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.39e-16 Error 1.86e-04

Reaction 5.2.3 $He^+ + H_2 \rightarrow He + H^+ + H$

a0	-4.311350879235e+01	a1	5.515944942674e-02	a2	-5.606069194725e-01
a3	1.291230751283e-01	a4	1.533686418592e-01	a5	-6.125769782521e-02
a6	8.886802346189e-03	a7	-5.806431060224e-04	a8	1.440125514216e-05

E_{min} 2.33e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.33e-16 Error 2.66e-02
Not valid for E < 0.3 eV.

Reaction 5.3.1 $He^+ + He \rightarrow He + He^+$

a0	-3.369296194290e+01	a1	-8.324653178943e-02	a2	6.660151719388e-03
a3	-3.592504363592e-03	a4	-1.745382918016e-04	a5	1.497204460315e-04
a6	-2.152122621503e-05	a7	1.473684503283e-06	a8	-4.401831552698e-08

E_{min} 1.00e-01 $\sigma(E_{min})$ 3.00e-15 σ_{max} 3.00e-15 Error 5.63e-05

Reaction 5.3.2 $He^+ + He \rightarrow He^+ + He^+ + e$

a0	-1.126408326504e+03	a1	1.221414787395e+03	a2	-5.910936989464e+02
a3	1.609170847736e+02	a4	-2.693537704047e+01	a5	2.837798810047e+00
a6	-1.837630539164e-01	a7	6.688462818228e-03	a8	-1.048046510736e-04

E_{min} 2.88e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 6.12e-17 Error 1.13e-02

Reaction 6.1.1 $He^{2+} + H(1s) \rightarrow He^{2+} + H^*(2p)$

a0	-3.935171502778e+03	a1	3.121350934839e+03	a2	-1.090958722369e+03
a3	2.154761368634e+02	a4	-2.615076564408e+01	a5	1.988438495730e+00
a6	-9.217310084360e-02	a7	2.372722474405e-03	a8	-2.585687269696e-05

E_{min} 7.18e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.03e-16 Error 1.19e-05
A more extensive analytic formula is given in the text.

Reaction 6.1.3 $He^{2+} + H(1s) \rightarrow He^{2+} + H^+ + e$

a0	-4.108092972648e+05	a1	3.538162825295e+05	a2	-1.328131904744e+05
a3	2.837637619784e+04	a4	-3.774364805704e+03	a5	3.200454272008e+02
a6	-1.689565219222e+01	a7	5.077317110574e-01	a8	-6.650084296041e-03

E_{min} 1.34e+03 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.60e-16 Error 9.63e-04

Reaction 6.1.4 $He^{2+} + H(n) \rightarrow He^{2+} + H^+ + e$ $(n \geq 2)$

An analytic formula for σ is given in the text.

Reaction 6.1.6 $He^{2+} + H \rightarrow He^{+*}(n=2) + H^+$

a0	-4.315145081040e+01	a1	1.153902751649e+00	a2	-1.770607674796e-03
a3	-4.249237424243e-02	a4	2.552430939448e-02	a5	-6.612097121922e-03
a6	8.587538946329e-04	a7	-5.501612272760e-05	a8	1.373936349802e-06

E_{min} 6.00e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 1.36e-15 Error 2.92e-04

Reaction 6.2.1 $He^{2+} + H_2 \rightarrow He^{2+} + H_2^+(v) + e$

a0	-3.888955469991e+01	a1	-9.866429655660e+00	a2	5.655068418984e+00
a3	-1.577966214613e+00	a4	2.645599512156e-01	a5	-2.758466438253e-02
a6	1.761704594534e-03	a7	-6.345561877676e-05	a8	9.903373373326e-07

E_{min} 3.31e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.87e-16 Error 6.85e-05
Not valid for E < 30 eV.

Reaction 6.3.1 $He^{2+} + He \rightarrow He + He^{2+}$

a0	-3.459818117569e+01	a1	-8.748942423786e-02	a2	-2.445604128495e-02
a3	2.392295193337e-03	a4	9.876388162277e-04	a5	-2.282012750308e-04
a6	3.598361283629e-06	a7	1.940270105613e-06	a8	-1.105794797036e-07

E_{min} 1.00e-01 $\sigma(E_{min})$ 1.03e-15 σ_{max} 1.03e-15 Error 1.74e-04

Reaction 6.3.2 $He^{2+} + He \rightarrow He^{2+} + He^+ + e$

a0	1.416740796235e+06	a1	-1.119008170939e+06	a2	3.857965046775e+05
a3	-7.583813526516e+04	a4	9.297450568358e+03	a5	-7.279675981729e+02
a6	3.555154263032e+01	a7	-9.901755546104e-01	a8	1.204251833183e-02

E_{min} 4.75e+03 $\sigma(E_{min})$ 1.00e-19 σ_{max} 2.50e-17 Error 3.33e-05

Reaction 7.1.1 $e + H^- \rightarrow e + H(1s) + e$

a0	-3.934913643088e+01	a1	7.492484197616e+00	a2	-6.138735352362e+00
a3	3.326569253609e+00	a4	-1.040328294213e+00	a5	1.834296974839e-01
a6	-1.814008493227e-02	a7	9.403286251360e-04	a8	-1.989848289161e-05

E_{min} 9.06e-01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 3.75e-15 Error 2.64e-01

Reaction 7.1.2 $e + H^- \rightarrow e + H^+ + 2e$

a0	-7.448448227127e+02	a1	8.696721447863e+02	a2	-4.584681915725e+02
a3	1.353555608991e+02	a4	-2.446848674683e+01	a5	2.771980281770e+00
a6	-1.922085761453e-01	a7	7.462384021984e-03	a8	-1.243029551161e-04

E_{min} 1.66e+01 $\sigma(E_{min})$ 1.00e-19 σ_{max} 5.06e-17 Error 3.39e-02

Reaction 7.2.1 $p + H^- \rightarrow p + H + e$

a0	-1.050889816750e+04	a1	1.054502629910e+04	a2	-4.618343915803e+03
a3	1.147184656009e+03	a4	-1.766806773292e+02	a5	1.727351520643e+01
a6	-1.046726308683e+00	a7	3.593652631660e-02	a8	-5.350831095528e-04

E_{min} 2.25e+02 $\sigma(E_{min})$ 1.00e-19 σ_{max} 4.76e-15 Error 1.18e-03

Reaction 7.2.2 $p + H^- \rightarrow H^*(n=2) + H(1s)$

a0	-3.498808881328e+01	a1	2.152450508307e-01	a2	-2.356286641829e-02
a3	5.494715530438e-02	a4	5.379328883390e-03	a5	-6.055070213687e-03
a6	9.991683287907e-04	a7	-6.636255640130e-05	a8	1.612283845094e-06

E_{min} 1.00e-01 $\sigma(E_{min})$ 3.30e-16 σ_{max} 1.38e-14 Error 2.29e-03

Reaction 7.2.3 $p + H^- \rightarrow H^*(n=3) + H(1s)$

a0	-3.114793359560e+01	a1	-7.730205271965e-01	a2	5.492043775127e-02		
a3	-2.733249841523e-03	a4	-1.228312883866e-03	a5	4.350498278844e-04		
a6	-6.216595007254e-05	a7	4.120468065072e-06	a8	-1.039784996359e-07		
E_{min}	1.00e-01	$\sigma(E_{min})$	2.25e-13	σ_{max}	2.25e-13	Error	5.93e-05

Reaction 7.3.1 $H^- + H(1s) \rightarrow H(1s) + H^-(1s)$

a0	-3.896158248196e+01	a1	-2.677306137623e-03	a2	-6.353177906590e-03		
a3	-7.238847698066e-03	a4	1.297916639224e-03	a5	5.654591683916e-04		
a6	-2.351925503212e-04	a7	2.913484058046e-05	a8	-1.229505901932e-06		
E_{min}	1.00e-01	$\sigma(E_{min})$	1.23e-17	σ_{max}	1.23e-17	Error	4.04e-04

Reaction 7.3.2a $H^- + H \rightarrow H_2^{-*}(\Sigma_g) \rightarrow H + H + e$

a0	-3.617990822381e+01	a1	1.166151722958e+00	a2	-1.419286024586e-01		
a3	-1.111959587916e-02	a4	-1.725059947629e-03	a5	1.590403561378e-03		
a6	-2.531961443012e-04	a7	1.669782349801e-05	a8	-4.097257966950e-07		
E_{min}	1.00e-01	$\sigma(E_{min})$	6.09e-18	σ_{max}	1.54e-15	Error	3.23e-04

Reaction 7.3.2b $H^- + H \rightarrow H_2^{-*}(\Sigma_u) \rightarrow H_2 + e$

a0	-3.441529065653e+01	a1	-3.393482086017e-01	a2	5.665917047817e-02		
a3	-9.051504593339e-03	a4	7.660604175354e-04	a5	-4.271264623381e-05		
a6	-1.572737493346e-07	a7	2.576076771707e-07	a8	-1.200719193800e-08		
E_{min}	1.00e-01	$\sigma(E_{min})$	3.84e-15	σ_{max}	3.84e-15	Error	9.90e-05

8.2 Polynomial Fits for $\langle\sigma v\rangle$ for Fixed E: Electron Reactions

We present nine-term polynomial fits for $\langle\sigma v\rangle$ for the electron reactions with the following formula

$$\ln \langle\sigma v\rangle = \sum_{n=0}^{8} b_n \, (\ln T)^n \ .$$

For these reactions the energy of the target particle can be considered to be zero. For all of the fits, we list the coefficients b_n, the errors, the minimum temperature T_{min} (in eV) that was fit, $\langle\sigma v\rangle$ (in cm^3/s) at the minimum temperature, and the maximum $\langle\sigma v\rangle$ (in cm^3/s) over the temperature range 0.1 eV to 20 keV. In all cases, the errors are small and the fits cannot be distinguished from the data on a plot of the kind used for the figures in the text. To produce nearly perfect fits, it is necessary to use only six digits of each coefficient.

This section only includes the electron reactions, even though one can also make similar fits for the heavy-particle reactions at fixed values of the incident particle energy. We do not present these latter fits because the double fits (functions of E and T) given in the next section are of a more general applicability, though less accurate and more cumbersome to use.

Reaction 2.1.1 $e + H(1s) \rightarrow e + H^*(2p)$

b0	-2.814949375869e+01	b1	1.009828023274e+01	b2	-4.771961915818e+00
b3	1.467805963618e+00	b4	-2.979799374553e-01	b5	3.861631407174e-02
b6	-3.051685780771e-03	b7	1.335472720988e-04	b8	-2.476088392502e-06

T_{min} 1.26e+00 $\langle\sigma v\rangle(T_{min})$ 4.78e-12 $\langle\sigma v\rangle_{max}$ 3.18e-08 Error 1.51e-05

Reaction 2.1.2 $e + H(1s) \rightarrow e + H^*(2s)$

b0	-2.833259375256e+01	b1	9.587356325603e+00	b2	-4.833579851041e+00
b3	1.415863373520e+00	b4	-2.537887918825e-01	b5	2.800713977946e-02
b6	-1.871408172571e-03	b7	6.986668318407e-05	b8	-1.123758504195e-06

T_{min} 1.26e+00 $\langle\sigma v\rangle(T_{min})$ 3.54e-12 $\langle\sigma v\rangle_{max}$ 3.22e-09 Error 3.33e-06

Reaction 2.1.3 $e + H^*(2s) \rightarrow e + H^*(2p)$

b0	-1.219616012805e+01	b1	-3.859057071006e-01	b2	-6.509976401685e-03
b3	4.981099209058e-04	b4	-4.184102479407e-05	b5	3.054358926267e-06
b6	-1.328567638366e-07	b7	8.974535105058e-10	b8	1.010269574757e-10

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.18e-05 $\langle\sigma v\rangle_{max}$ 1.18e-05 Error 2.16e-11

Reaction 2.1.4a $e + H(n=1) \rightarrow e + H^*(n=3)$

b0	-3.113714569232e+01	b1	1.170494035550e+01	b2	-5.598117886823e+00
b3	1.668467661343e+00	b4	-3.186788446245e-01	b5	3.851704802605e-02
b6	-2.845199866183e-03	b7	1.171512424827e-04	b8	-2.059295818495e-06

T_{min} 1.58e+00 $\langle\sigma v\rangle(T_{min})$ 2.32e-12 $\langle\sigma v\rangle_{max}$ 6.09e-09 Error 3.54e-06

Reaction 2.1.4b $e + H^*(n=2) \rightarrow e + H^*(n=3)$

b0	-1.515830911091e+01	b1	1.923956400537e+00	b2	-9.275338417712e-01
b3	3.370367299915e-01	b4	-8.758162223598e-02	b5	1.409066167839e-02
b6	-1.325225954526e-03	b7	6.672025878086e-05	b8	-1.387615199713e-06

T_{min} 1.58e-01 $\langle\sigma v\rangle(T_{min})$ 9.92e-12 $\langle\sigma v\rangle_{max}$ 2.00e-06 Error 4.99e-05

Reaction 2.1.5 $e + H(1s) \rightarrow e + H^{+} + e$

b0 -3.271396786375e+01	b1 1.353655609057e+01	b2 -5.739328757388e+00
b3 1.563154982022e+00	b4 -2.877056004391e-01	b5 3.482559773737e-02
b6 -2.631976175590e-03	b7 1.119543953861e-04	b8 -2.039149852002e-06

T_{min} 2.00e+00 $\langle\sigma v\rangle(T_{min})$ 7.22e-12 $\langle\sigma v\rangle_{max}$ 3.11e-08 Error 1.71e-05

Reaction 2.1.6 $e + H^{*}(2s) \rightarrow e + H^{+} + e$

b0 -1.973476726029e+01	b1 3.992702671457e+00	b2 -1.773436308973e+00
b3 5.331949621358e-01	b4 -1.181042453190e-01	b5 1.763136575032e-02
b6 -1.616005335321e-03	b7 8.093908992682e-05	b8 -1.686664454913e-06

T_{min} 3.98e-01 $\langle\sigma v\rangle(T_{min})$ 8.87e-12 $\langle\sigma v\rangle_{max}$ 1.71e-07 Error 7.10e-05

Reaction 2.1.7 $e + H^{*}(3) \rightarrow e + H^{+} + e$

b0 -1.566968719411e+01	b1 1.719661170920e+00	b2 -8.365041963678e-01
b3 2.642794957304e-01	b4 -6.527754894629e-02	b5 1.066883130107e-02
b6 -1.041488149422e-03	b7 5.457216484634e-05	b8 -1.177539827071e-06

T_{min} 1.26e-01 $\langle\sigma v\rangle(T_{min})$ 2.00e-12 $\langle\sigma v\rangle_{max}$ 6.80e-07 Error 9.85e-05

A more general analytic formula is given in the text.

Reaction 2.1.8 $e + H^{+} \rightarrow H^{*}(n\ell) + h\nu$; See text.

Reaction 2.2.1a $e + H_2(v=0) \rightarrow e + H_2(v=1)$

b0 -2.017212494454e+01	b1 9.563952280637e-01	b2 -6.931474225637e-01
b3 1.673671529631e-01	b4 -3.228762898855e-02	b5 5.838603222226e-03
b6 -8.580542691302e-04	b7 7.456311623168e-05	b8 -2.666978300757e-06

T_{min} 1.58e-01 $\langle\sigma v\rangle(T_{min})$ 5.83e-12 $\langle\sigma v\rangle_{max}$ 2.60e-09 Error 2.55e-06

Reaction 2.2.1b $e + H_2(v=0) \rightarrow e + H_2(v=2)$

b0 -2.265507686305e+01	b1 2.239943592222e+00	b2 -1.099426577160e+00
b3 2.339027647223e-01	b4 -2.528511103871e-02	b5 6.851302489620e-04
b6 1.253426182224e-04	b7 -1.253475051672e-05	b8 3.545892878015e-07

T_{min} 3.98e-01 $\langle\sigma v\rangle(T_{min})$ 5.93e-12 $\langle\sigma v\rangle_{max}$ 7.07e-10 Error 2.74e-07

Reaction 2.2.2 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^{*}(B^1\Sigma_u^+ 2p\sigma)$

b0 -3.081902926338e+01	b1 1.038866780735e+01	b2 -4.259768348687e+00
b3 1.181228673120e+00	b4 -2.277513907465e-01	b5 2.900576728856e-02
b6 -2.287591474628e-03	b7 1.004346442778e-04	b8 -1.869930069131e-06

T_{min} 2.00e+00 $\langle\sigma v\rangle(T_{min})$ 9.88e-12 $\langle\sigma v\rangle_{max}$ 1.47e-08 Error 9.52e-06

Reaction 2.2.3 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(C^1\Pi_u 2p\pi)$

b0	-3.348199796300e+01	b1	1.371702271009e+01	b2	-5.922607900694e+00
b3	1.709719148860e+00	b4	-3.505232830275e-01	b5	4.834376067841e-02
b6	-4.131406425550e-03	b7	1.948388368131e-04	b8	-3.854278715563e-06

T_{min} 2.00e+00 $<\sigma v>(T_{min})$ 3.59e-12 $<\sigma v>_{max}$ 1.39e-08 Error 8.14e-05

Reaction 2.2.4 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(E,F^1\Sigma_g^+)$

b0	-3.646589741675e+01	b1	1.430361969329e+01	b2	-6.074430521073e+00
b3	1.677305768580e+00	b4	-3.128705597349e-01	b5	3.805424730473e-02
b6	-2.860085821803e-03	b7	1.199641410078e-04	b8	-2.142231851104e-06

T_{min} 3.16e+00 $<\sigma v>(T_{min})$ 5.27e-12 $<\sigma v>_{max}$ 2.23e-09 Error 2.11e-06

Reaction 2.2.5 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(b^3\Sigma_u^+,\ a^3\Sigma_g^+,$ and $c^3\Pi_u) \rightarrow$

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

b0	-2.858072836568e+01	b1	1.038543976082e+01	b2	-5.383825026583e+00
b3	1.950636494405e+00	b4	-5.393666392407e-01	b5	1.006916814453e-01
b6	-1.160758573972e-02	b7	7.411623859122e-04	b8	-2.001369618807e-05

T_{min} 1.26e+00 $<\sigma v>(T_{min})$ 3.25e-12 $<\sigma v>_{max}$ 3.82e-09 Error 1.07e-06

Reaction 2.2.6 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(1s\sigma_g,\ n\ell\lambda|^1\Lambda) \rightarrow e + H(1s) + H^*(2s)$

b0	-3.454175591367e+01	b1	1.412655911280e+01	b2	-6.004466156761e+00
b3	1.589476697488e+00	b4	-2.775796909649e-01	b5	3.152736888124e-02
b6	-2.229578042005e-03	b7	8.890114963166e-05	b8	-1.523912962346e-06

T_{min} 2.51e+00 $<\sigma v>(T_{min})$ 7.88e-12 $<\sigma v>_{max}$ 6.92e-09 Error 2.74e-06

Reaction 2.2.7 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u;\ n\ell\lambda|Q_2{}^1\Pi_u) \rightarrow e + H^*(2p) + H^*(2s)$

b0	-4.794288960529e+01	b1	2.629649351119e+01	b2	-1.151117702256e+01
b3	2.991954880790e+00	b4	-4.949305181578e-01	b5	5.236320848415e-02
b6	-3.433774290547e-03	b7	1.272097387363e-04	b8	-2.036079507592e-06

T_{min} 5.01e+00 $<\sigma v>(T_{min})$ 6.48e-12 $<\sigma v>_{max}$ 1.31e-09 Error 3.76e-07

Reaction 2.2.8 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^*(2p\sigma_u; n=3) \rightarrow e + H(1s) + H^*(n=3)$

b0	-3.884976142596e+01	b1	1.520368281111e+01	b2	-6.078494762845e+00
b3	1.535455119900e+00	b4	-2.628667482712e-01	b5	2.994456451213e-02
b6	-2.156175515382e-03	b7	8.826547202670e-05	b8	-1.558890013181e-06

T_{min} 3.98e+00 $<\sigma v>(T_{min})$ 4.09e-12 $<\sigma v>_{max}$ 7.73e-10 Error 6.05e-06

Reaction 2.2.9 $e + H_2(X^1\Sigma_g^+) \rightarrow e + H_2^+(v) + e$

b0	-3.568640293666e+01	b1	1.733468989961e+01	b2	-7.767469363538e+00
b3	2.211579405415e+00	b4	-4.169840174384e-01	b5	5.088289820867e-02
b6	-3.832737518325e-03	b7	1.612863120371e-04	b8	-2.893391904431e-06

T_{min} 2.00e+00 $<\sigma v>(T_{min})$ 2.34e-12 $<\sigma v>_{max}$ 5.18e-08 Error 6.45e-06

Reaction 2.2.10 e + $H_2(X^1\Sigma_g^+)$ → e + [$H_2^+(\Sigma_g$ and $\Sigma_u)$ + e] → e + H + (1s) + e

b0	-3.834597006782e+01	b1	1.426322356722e+01	b2	-5.826468569506e+00
b3	1.727940947913e+00	b4	-3.598120866343e-01	b5	4.822199350494e-02
b6	-3.909402993006e-03	b7	1.738776657690e-04	b8	-3.252844486351e-06

T_{min} 3.98e+00 $\langle\sigma v\rangle(T_{min})$ 3.74e-12 $\langle\sigma v\rangle_{max}$ 2.89e-09 Error 4.61e-05

Reaction 2.2.11 e + $H_2^+(v)$ → e + H^+ + H^+ + e, (v=0-9)

b0	-3.746192301092e+01	b1	1.559355031108e+01	b2	-6.693238367093e+00
b3	1.981700292134e+00	b4	-4.044820889297e-01	b5	5.352391623039e-02
b6	-4.317451841436e-03	b7	1.918499873454e-04	b8	-3.591779705419e-06

T_{min} 3.16e+00 $\langle\sigma v\rangle(T_{min})$ 5.23e-12 $\langle\sigma v\rangle_{max}$ 9.06e-09 Error 2.26e-05

Reaction 2.2.12 e + $H_2^+(v)$ → e + $H_2^{+*}(2p\sigma_u)$ → e + H^+ + H(1s), (v=0-9)

b0	-1.781416067709e+01	b1	2.277799785711e+00	b2	-1.266868411626e+00
b3	4.296170447419e-01	b4	-9.609908013189e-02	b5	1.387958040699e-02
b6	-1.231349039470e-03	b7	6.042383126281e-05	b8	-1.247521040900e-06

T_{min} 2.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.23e-12 $\langle\sigma v\rangle_{max}$ 1.15e-07 Error 8.64e-05

Reaction 2.2.13 e + $H_2^+(v)$ → e + $H_2^{+*}(2p\pi_u)$ → e + H^+ + H^*(n=2) (v=0-9)

b0	-3.408905929046e+01	b1	1.573560727511e+01	b2	-6.992177456733e+00
b3	1.852216261706e+00	b4	-3.130312806531e-01	b5	3.383704123189e-02
b6	-2.265770525273e-03	b7	8.565603779673e-05	b8	-1.398131377085e-06

T_{min} 2.00e+00 $\langle\sigma v\rangle(T_{min})$ 5.03e-12 $\langle\sigma v\rangle_{max}$ 1.77e-08 Error 2.05e-06

Reaction 2.2.14 e + $H_2^+(v)$ → H(1s) + H^*(n) (v=0-9, n ≥ 2)

b0	-1.670435653561e+01	b1	-6.035644995682e-01	b2	-1.942745783445e-08
b3	-2.005952284492e-07	b4	2.962996104431e-08	b5	2.134293274971e-08
b6	-6.353973401838e-09	b7	6.152557460831e-10	b8	-2.025361858319e-11

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 2.23e-07 $\langle\sigma v\rangle_{max}$ 2.23e-07 Error 3.30e-13

Reaction 2.2.15 e + H_3^+ → H + H + H or: → H_2(v > 5) + H^*(n=2)

b0	-1.700270758355e+01	b1	-4.050073042947e-01	b2	1.018733477232e-08
b3	-1.695586285687e-08	b4	1.564311217508e-10	b5	1.979725412288e-09
b6	-4.395545994733e-10	b7	3.584926377078e-11	b8	-1.024189019465e-12

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.05e-07 $\langle\sigma v\rangle_{max}$ 1.05e-07 Error 3.27e-15

Reaction 2.2.16 e + H_3^+ → e + H^+ + 2H

b0	-3.078408636631e+01	b1	1.509421488513e+01	b2	-7.349167207324e+00
b3	2.320966107642e+00	b4	-4.818077551719e-01	b5	6.389229162737e-02
b6	-5.161880953089e-03	b7	2.303985092606e-04	b8	-4.344846146197e-06

T_{min} 1.26e+00 $\langle\sigma v\rangle(T_{min})$ 9.46e-13 $\langle\sigma v\rangle_{max}$ 4.18e-07 Error 6.20e-05

Reaction 2.2.17 $e + H_2(v \geq 4) \rightarrow (H_2^-)^* \rightarrow H^- + H$

b0 -1.774398466232e+01	b1 -6.207038732492e-01	b2 -2.811412695673e-01
b3 2.540958044519e-02	b4 6.643467825225e-03	b5 -8.877629159412e-04
b6 -3.705776394283e-04	b7 9.313511559362e-05	b8 -5.995758360037e-06

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.58e-08 $\langle\sigma v\rangle_{max}$ 2.70e-08 Error 4.67e-07

Reaction 2.3.1a $e + He(1s^2|^1S) \rightarrow e + He^*(1s2p|^1P)$

b0 -4.076450793433e+01	b1 1.847216050626e+01	b2 -7.553534847500e+00
b3 1.936036716566e+00	b4 -3.278509524847e-01	b5 3.627243238755e-02
b6 -2.509995616613e-03	b7 9.829302307697e-05	b8 -1.659516418994e-06

T_{min} 3.98e+00 $\langle\sigma v\rangle(T_{min})$ 7.72e-12 $\langle\sigma v\rangle_{max}$ 6.23e-09 Error 1.17e-06

Reaction 2.3.1b $e + He(1s^2|^1S) \rightarrow e + He^*(1s3p|^1P)$

b0 -4.439802014466e+01	b1 2.170928173941e+01	b2 -9.582182742745e+00
b3 2.631183876455e+00	b4 -4.687644097236e-01	b5 5.361959275824e-02
b6 -3.786601021417e-03	b7 1.500190728471e-04	b8 -2.548241584846e-06

T_{min} 5.01e+00 $\langle\sigma v\rangle(T_{min})$ 5.50e-12 $\langle\sigma v\rangle_{max}$ 1.55e-09 Error 1.10e-06

Reaction 2.3.2 $e + He(1s^2|^1S) \rightarrow e + He^*(1s2s|^1S)$

b0 -3.944902284550e+01	b1 1.801440475215e+01	b2 -7.941287139217e+00
b3 2.108879073816e+00	b4 -3.656365579422e-01	b5 4.130418209599e-02
b6 -2.921666597766e-03	b7 1.171506777488e-04	b8 -2.027094391374e-06

T_{min} 3.16e+00 $\langle\sigma v\rangle(T_{min})$ 2.84e-12 $\langle\sigma v\rangle_{max}$ 7.92e-10 Error 4.16e-06

Reaction 2.3.3a $e + He(1s^2|^1S) \rightarrow e + He^*(1s2s|^3S)$

b0 -3.907389635096e+01	b1 1.922614839789e+01	b2 -9.704341826798e+00
b3 3.077375531860e+00	b4 -6.879793654863e-01	b5 1.062748336765e-01
b6 -1.074378374967e-02	b7 6.372192184143e-04	b8 -1.676476511183e-05

T_{min} 3.16e+00 $\langle\sigma v\rangle(T_{min})$ 4.52e-12 $\langle\sigma v\rangle_{max}$ 2.53e-10 Error 8.14e-10

Reaction 2.3.3b $e + He(1s^2|^1S) \rightarrow e + He^*(1s2p|^3P)$

b0 -4.126478834982e+01	b1 2.115462440402e+01	b2 -1.037798544679e+01
b3 3.223448557463e+00	b4 -7.047523358686e-01	b5 1.058143518376e-01
b6 -1.030712489010e-02	b7 5.837301581720e-04	b8 -1.454656422289e-05

T_{min} 3.98e+00 $\langle\sigma v\rangle(T_{min})$ 8.87e-12 $\langle\sigma v\rangle_{max}$ 3.32e-10 Error 8.73e-10

Reaction 2.3.3c $e + He(1s^2|^1S) \rightarrow e + He^*(1s3s|^3S)$

b0 -4.403421631102e+01	b1 2.245729554242e+01	b2 -1.077239790242e+01
b3 3.245104419002e+00	b4 -6.897865199057e-01	b5 1.022237988347e-01
b6 -1.003860681229e-02	b7 5.860847901785e-04	b8 -1.537517028977e-05

T_{min} 5.01e+00 $\langle\sigma v\rangle(T_{min})$ 5.43e-12 $\langle\sigma v\rangle_{max}$ 9.25e-11 Error 7.14e-10

Reaction 2.3.3d $e + He(1s^2|^1S) \rightarrow e + He^*(1s3p|^3P)$

b0	-4.364496383346e+01	b1	2.269089069271e+01	b2	-1.084808588246e+01
b3	3.247690604813e+00	b4	-6.828905628843e-01	b5	9.957070020879e-02
b6	-9.564409022565e-03	b7	5.429268148822e-04	b8	-1.376622041888e-05

T_{min} 5.01e+00 $\langle\sigma v\rangle(T_{min})$ 9.95e-12 $\langle\sigma v\rangle_{max}$ 1.79e-10 Error 6.08e-10

Reaction 2.3.4a $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s2s|^1S)$

b0	-1.744584533214e+01	b1	7.146118553487e-01	b2	-4.873579904205e-01
b3	1.481188090592e-01	b4	-3.507761998312e-02	b5	5.690374429946e-03
b6	-5.623763509155e-04	b7	3.001973812574e-05	b8	-6.601806234046e-07

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.46e-11 $\langle\sigma v\rangle_{max}$ 3.80e-08 Error 5.08e-05

Reaction 2.3.4b $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s2s|^1P)$

b0	-1.844735966200e+01	b1	1.427274973351e+00	b2	-8.091153742158e-01
b3	2.487008240878e-01	b4	-5.643723514177e-02	b5	8.601493865150e-03
b6	-8.023972821093e-04	b7	4.085320629082e-05	b8	-8.650886326975e-07

T_{min} 1.58e-01 $\langle\sigma v\rangle(T_{min})$ 3.93e-12 $\langle\sigma v\rangle_{max}$ 2.52e-08 Error 4.76e-05

Reaction 2.3.4c $e + He^*(1s2s|^1S) \rightarrow e + He^*(1s2p|^3P)$

b0	-1.615322214290e+01	b1	1.433777584524e-01	b2	-2.487826648613e-01
b3	7.026918912149e-02	b4	-1.553687005936e-02	b5	2.421396865761e-03
b6	-2.348531854752e-04	b7	1.243991031364e-05	b8	-2.729353858047e-07

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 4.15e-09 $\langle\sigma v\rangle_{max}$ 9.87e-08 Error 8.49e-06

Reaction 2.3.4d $e + He^*(1s2p|^3P) \rightarrow e + He^*(1s2p|^1P)$

b0	-1.799224192385e+01	b1	5.839648278021e-03	b2	-1.939973920965e-01
b3	5.349246643243e-02	b4	-1.150308510199e-02	b5	1.759192625459e-03
b6	-1.689530419550e-04	b7	8.909865872231e-06	b8	-1.951982101314e-07

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.76e-09 $\langle\sigma v\rangle_{max}$ 1.53e-08 Error 4.25e-06

Reaction 2.3.5a $e + He^*(1s2s|^1S) \rightarrow e + He^*(1s2p|^1P)$

b0	-1.421481564800e+01	b1	9.816324588875e-01	b2	-3.700239299608e-01
b3	9.320731611434e-02	b4	-2.517642644099e-02	b5	4.899403741414e-03
b6	-5.506956047085e-04	b7	3.192647759391e-05	b8	-7.407861678228e-07

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 1.01e-09 $\langle\sigma v\rangle_{max}$ 1.78e-06 Error 7.22e-05

Reaction 2.3.5b $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s2p|^3P)$

b0	-1.524234054303e+01	b1	1.457459036199e+00	b2	-6.089961105515e-01
b3	1.908341260995e-01	b4	-4.902955652013e-02	b5	8.357212748265e-03
b6	-8.436990703093e-04	b7	4.535984449474e-05	b8	-9.983744250475e-07

T_{min} 1.00e-01 $\langle\sigma v\rangle(T_{min})$ 3.98e-12 $\langle\sigma v\rangle_{max}$ 1.15e-06 Error 1.38e-04

Reaction 2.3.6a $e + He^*(1s2s|^1S) \rightarrow e + He^*(1s3p|^1P)$

b0	-2.012491737344e+01	b1	2.975868118455e+00	b2	-1.241263834768e+00
b3	4.133514681102e-01	b4	-1.015874512196e-01	b5	1.570108000623e-02
b6	-1.424919814936e-03	b7	6.934961916285e-05	b8	-1.396714673826e-06

T_{min} 3.16e-01 $\langle\sigma v\rangle(T_{min})$ 4.88e-12 $\langle\sigma v\rangle_{max}$ 7.94e-08 Error 9.99e-06

Reaction 2.3.6b $e + He^*(1s2s|^3S) \rightarrow e + He^*(1s3p|^3P)$

b0	-2.168967273514e+01	b1	3.469927386366e+00	b2	-1.500284971036e+00
b3	4.514495446931e-01	b4	-9.830380729357e-02	b5	1.412098625701e-02
b6	-1.235528152366e-03	b7	5.912904162725e-05	b8	-1.182410155429e-06

T_{min} 3.98e-01 $\langle\sigma v\rangle(T_{min})$ 2.79e-12 $\langle\sigma v\rangle_{max}$ 1.86e-08 Error 2.22e-05

Reaction 2.3.7a $e + He^*(1s2p|^1P) \rightarrow e + He^*(1s3d|^1D)$

b0	-1.685934192513e+01	b1	2.084943159821e+00	b2	-8.554198255397e-01
b3	2.987507152419e-01	b4	-8.260619461169e-02	b5	1.427561766421e-02
b6	-1.419997912094e-03	b7	7.446342219961e-05	b8	-1.594736923452e-06

T_{min} 1.58e-01 $\langle\sigma v\rangle(T_{min})$ 2.29e-12 $\langle\sigma v\rangle_{max}$ 6.12e-07 Error 6.74e-05

Reaction 2.3.7b $e + He^*(1s2s|^3P) \rightarrow e + He^*(1s3d|^3D)$

b0	-1.733661165939e+01	b1	2.317215831044e+00	b2	-9.924882089292e-01
b3	3.415918344358e-01	b4	-9.030135166591e-02	b5	1.508647305121e-02
b6	-1.468232978539e-03	b7	7.588691677324e-05	b8	-1.608841144485e-06

T_{min} 2.00e-01 $\langle\sigma v\rangle(T_{min})$ 5.66e-12 $\langle\sigma v\rangle_{max}$ 4.46e-07 Error 6.51e-05

Reaction 2.3.9 $e + He(1s^2|^1S) \rightarrow e + He^+ + e$

b0	-4.409864886561e+01	b1	2.391596563469e+01	b2	-1.075323019821e+01
b3	3.058038757198e+00	b4	-5.685118909884e-01	b5	6.795391233790e-02
b6	-5.009056101857e-03	b7	2.067236157507e-04	b8	-3.649161410833e-06

T_{min} 3.16e+00 $\langle\sigma v\rangle(T_{min})$ 1.83e-12 $\langle\sigma v\rangle_{max}$ 2.46e-08 Error 1.06e-05

Reaction 2.3.10a $e + He^*(1s2s|^1S) \rightarrow e + He^+(1s) + e$

b0	-2.043240580802e+01	b1	4.673025479860e+00	b2	-2.068053911581e+00
b3	6.103799741884e-01	b4	-1.268205164080e-01	b5	1.740804412692e-02
b6	-1.474132011694e-03	b7	6.914279610834e-05	b8	-1.368015031384e-06

T_{min} 3.98e-01 $\langle\sigma v\rangle(T_{min})$ 1.72e-12 $\langle\sigma v\rangle_{max}$ 2.04e-07 Error 3.70e-05

Reaction 2.3.10b $e + He^*(1s2p|^1P) \rightarrow e + He^+(1s) + e$

b0	-1.946719737710e+01	b1	4.039554859050e+00	b2	-1.792264505398e+00
b3	5.357588980704e-01	b4	-1.142854169815e-01	b5	1.614022386298e-02
b6	-1.401937207088e-03	b7	6.717110442234e-05	b8	-1.352531071210e-06

T_{min} 3.16e-01 $\langle\sigma v\rangle(T_{min})$ 1.07e-12 $\langle\sigma v\rangle_{max}$ 2.61e-07 Error 4.96e-05

Reaction 2.3.10c $e + He^{*}(1s2s|^{3}S) \rightarrow e + He^{+}(1s) + e$

b0	-2.061635956597e+01	b1	5.212998266179e+00	b2	-2.421560769610e+00
b3	7.237890101587e-01	b4	-1.480837244899e-01	b5	1.981796970055e-02
b6	-1.635383361916e-03	b7	7.495465496705e-05	b8	-1.454005255301e-06

T_{min} 5.01e-01 $\langle\sigma v\rangle(T_{min})$ 7.17e-12 $\langle\sigma v\rangle_{max}$ 2.12e-07 Error 2.71e-05

Reaction 2.3.10d $e + He^{*}(1s2p|^{3}P) \rightarrow e + He^{+}(1s) + e$

b0	-1.988624861383e+01	b1	4.310402355871e+00	b2	-1.896654131474e+00
b3	5.547033134672e-01	b4	-1.146241097190e-01	b5	1.568822815337e-02
b6	-1.326558850059e-03	b7	6.217750779265e-05	b8	-1.229838359991e-06

T_{min} 3.98e-01 $\langle\sigma v\rangle(T_{min})$ 5.08e-12 $\langle\sigma v\rangle_{max}$ 2.34e-07 Error 3.01e-05

Reaction 2.3.12 $e + He^{*}(1sn\ell|^{2S+1}L) \rightarrow e + He^{+*}(n\ell) + e$

b0	-6.896861656133e+01	b1	4.483212792736e+01	b2	-1.838301143477e+01
b3	4.508647323762e+00	b4	-7.148481765711e-01	b5	7.375319623123e-02
b6	-4.780158615887e-03	b7	1.766513036839e-04	b8	-2.837371604097e-06

T_{min} 7.94e+00 $\langle\sigma v\rangle(T_{min})$ 7.62e-12 $\langle\sigma v\rangle_{max}$ 5.15e-09 Error 1.12e-06

Reaction 2.3.13 $e + He^{+}(1s) \rightarrow He^{*}(1sn\ell|^{2S+1}L) + h\nu$

See text for analytic formulas.

Reaction 2.3.14 $e + He^{+}(1s) \rightarrow e + He^{+*}(2p)$

b0	-5.731132225657e+01	b1	3.618757468205e+01	b2	-1.568012557533e+01
b3	4.060438624043e+00	b4	-6.700744538238e-01	b5	7.100638013026e-02
b6	-4.682434354620e-03	b7	1.749898327054e-04	b8	-2.831521166310e-06

T_{min} 5.01e+00 $\langle\sigma v\rangle(T_{min})$ 2.96e-12 $\langle\sigma v\rangle_{max}$ 1.37e-08 Error 1.24e-06

Reaction 2.3.15 $e + He^{+}(1s) \rightarrow e + He^{+*}(2s)$

b0	-5.754975783112e+01	b1	3.459060731107e+01	b2	-1.462527320845e+01
b3	3.680688204381e+00	b4	-5.969493660071e-01	b5	6.279719136636e-02
b6	-4.138222038101e-03	b7	1.551309719300e-04	b8	-2.522897333444e-06

T_{min} 6.31e+00 $\langle\sigma v\rangle(T_{min})$ 4.41e-12 $\langle\sigma v\rangle_{max}$ 1.23e-09 Error 1.19e-06

Reaction 2.3.19 $e + He^{+}(1s) \rightarrow e + He^{2+} + e$

b0	-6.871040990212e+01	b1	4.393347632635e+01	b2	-1.848066993568e+01
b3	4.701626486759e+00	b4	-7.692466334492e-01	b5	8.113042097303e-02
b6	-5.324020628287e-03	b7	1.975705312221e-04	b8	-3.165581065665e-06

T_{min} 7.94e+00 $\langle\sigma v\rangle(T_{min})$ 2.62e-12 $\langle\sigma v\rangle_{max}$ 4.01e-09 Error 1.04e-06

Reaction 7.1.1 $e + H^- \rightarrow e + H(1s) + e$

b0 -1.801849334273e+01	b1 2.360852208681e+00	b2 -2.827443061704e-01
b3 1.623316639567e-02	b4 -3.365012031363e-02	b5 1.178329782711e-02
b6 -1.656194699504e-03	b7 1.068275202678e-04	b8 -2.631285809207e-06

T_{min} 1.26e-01 $<\sigma v>(T_{min})$ 7.72e-12 $<\sigma v>_{max}$ 9.73e-07 Error 3.51e-03

Reaction 7.1.2 $e + H^- \rightarrow e + H^+ + 2e$

b0 -3.637051952368e+01	b1 1.586803736621e+01	b2 -6.478287148158e+00
b3 1.735140500106e+00	b4 -3.233529702765e-01	b5 4.020531565638e-02
b6 -3.114827827749e-03	b7 1.347768741748e-04	b8 -2.478586915713e-06

T_{min} 2.51e+00 $<\sigma v>(T_{min})$ 4.61e-12 $<\sigma v>_{max}$ 2.15e-08 Error 3.47e-06

8.3 Double Polynomial Fits for $\langle \sigma v \rangle$

For reactions between two heavy particles, it is important to have the reaction rate coefficients as a function of the temperature T of the plasma particles and the energy E of the incident particle. We have fit $<\sigma v>$ as a function of T and E by constructing nine by nine term polynomial fits for $\ell n <\sigma v>$ in terms of ℓn E and ℓn T in the form

$$\ell n <\sigma v> = \sum_{i=0}^{8} \sum_{j=0}^{8} a_{ij} (\ell n E)^i (\ell n T)^j ,$$

and list the coefficients a_{ij} in the tables.

These fits should be used with some care. They are valid for the range 0.1 eV < E < 20 keV and 0.1 eV < T < 20 keV provided $<\sigma v> > 10^{-11}$ cm^3/s. We made no attempt to fit very low values of $<\sigma v>$ since this tends to reduce the accuracy of the fit at larger values. Since no attempt was made to fit these low values, it is possible that the fit may give high (incorrect) values of $<\sigma v>$ outside the range of E and T for which $<\sigma v> > 10^{-11}$ cm^3/s. In using these tables the reader should be aware that if the fit gives a value of $<\sigma v> > 10^{-11}$ cm^3/s, it is not a sufficient condition for the fit to be accurate. It must be checked that E and T are in the range for which $<\sigma v>$ is truly $> 10^{-11}$ cm^3/s. We made a substantial effort to eliminate spurious larger values of $<\sigma v>$ in the entire range 0.1 eV < E < 20 keV and 0.1 eV < T < 20 keV, but it was impossible to check all values in this range. In some cases (reactions 3.2.4b and 4.3.3) it was not feasible to eliminate spuriously large values of $<\sigma v>$, and we note these cases in the corresponding tables.

The tables provide an error for each fit which is the average root-mean-square error in the fit, relative to the maximum, $<\sigma v>_{max}$, of $<\sigma v>$ in the entire E, T range. The error is given by

$$\text{Error} = \frac{1}{N<\sigma v>_{max}} \left[\sum_{ij} \left(<\sigma v>_{ij} - <\sigma v>^{fit}_{ij}\right)^2\right]^{1/2},$$

where $<\sigma v>_{ij}$ and $<\sigma v>^{fit}_{ij}$ are the values of the calculated and the fit $<\sigma v>$'s, respectively, at the points E_i and T_j, and N is the number of values included in the sum. Only terms with $<\sigma v> > 10^{-11}$ cm^3/s are included in the sum.

In addition to the error provided, the fits have been graded on a scale of A through D, and Fig. 8.4 shows examples of each of these categories of fit. The error range is approximately:

Grade	Error
A	$\leq 3\times10^{-4}$
B	$3\times10^{-4} - 1\times10^{-3}$
C	$1\times10^{-3} - 3\times10^{-3}$
D	$\geq 3\times10^{-3}$

Fits for grades A and B should be accurate within the error in the data. Fits for grade C are nearly so, and those for grade D are a good approximation, but may not be sufficiently accurate for some applications. These fits cover five orders of magnitude in each of two variables and more accurate fits with possibly fewer coefficients could be made in a more restricted range. In particular, only seven out of 47 of the double fits are in category D over the entire temperature range considered here (0.1 eV to 20 keV). However, for a slightly less restrictive range (1 eV < T < 20 keV) only four reactions (3.1.1, 3.1.2, 3.2.1a, and 4.2.1) fall in the D category, and of these only 4.2.1 has any range where the differences exceed 20% - 30% at temperatures above 1 eV. Finally, only the first eight digits of the coefficients need to be used for the fits since the errors hardly change compared to using ten or more digits. Reaction 3.1.10 is improved very slightly, however, by keeping ten digits.

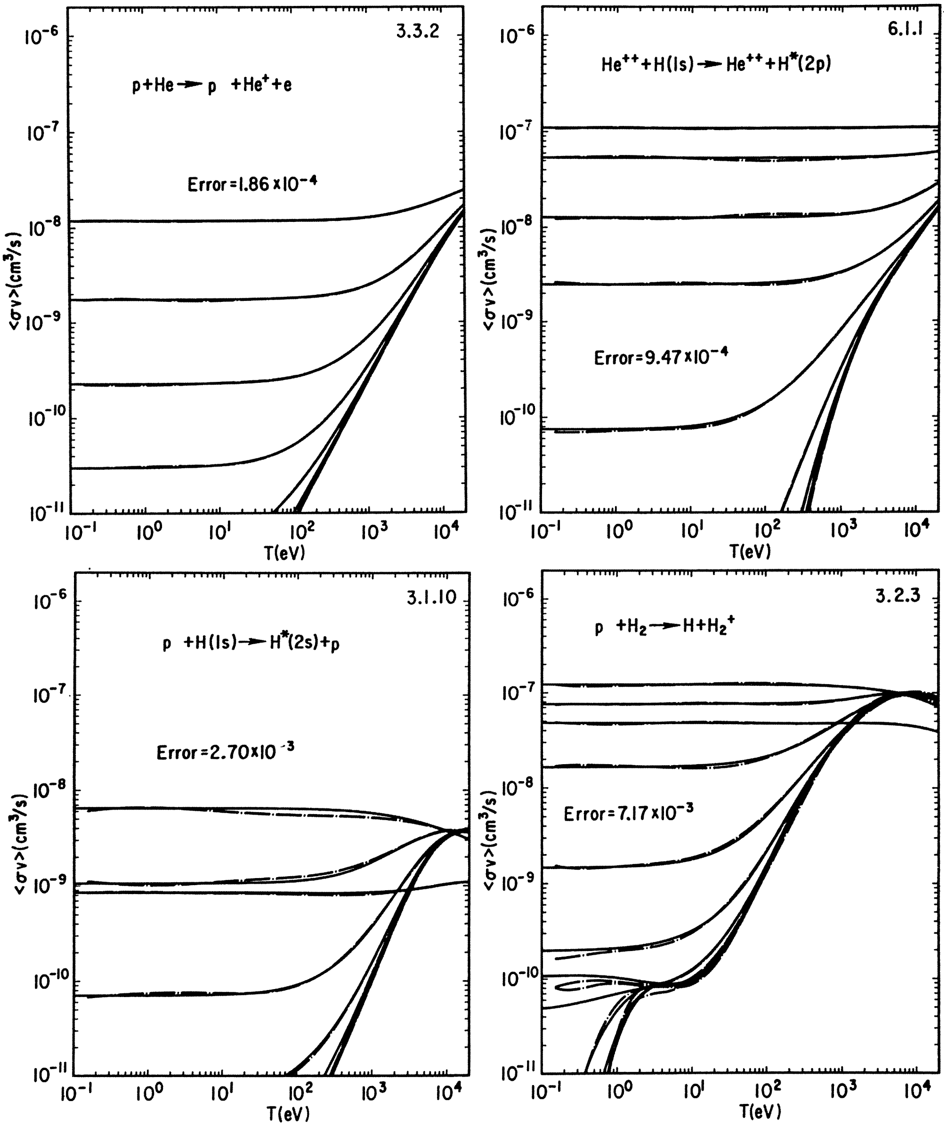


Fig. 8.4 Representative double fits (dot-dash lines) for <σv> in the four error categories compared to the original curves (solid lines).

Reaction 3.1.1 $p + H(1s) \rightarrow p + H^*(2p)$

T Index \ E Index	0	1	2
0	-6.261494333673e+01	1.976921673516e+01	-4.770700042332e+00
1	2.417692686638e+01	-1.641857278453e+01	5.395012240434e+00
2	-4.051480211975e+00	4.191026443943e+00	-2.252096048936e+00
3	-1.318153914548e+00	1.189223903948e-01	4.211072262111e-01
4	7.528061358848e-01	-2.607978652180e-01	-2.386725153241e-02
5	-1.498666287447e-01	5.494605745283e-02	-3.642074979445e-03
6	1.512983951035e-02	-5.414151972843e-03	6.902343394169e-04
7	-7.735934229437e-04	2.658505260322e-04	-4.272194199546e-05
8	1.590699544686e-05	-5.245923671227e-06	9.478841315945e-07

T Index \ E Index	3	4	5
0	1.033248569152e+00	-2.868779139503e-01	6.404381294137e-02
1	-1.414868849757e+00	3.184423304843e-01	-4.982800665252e-02
2	7.292508717933e-01	-1.433443925906e-01	1.696153624540e-02
3	-1.843635318950e-01	3.265971640208e-02	-2.763613623053e-03
4	2.201347577554e-02	-3.551163806974e-03	2.007525885427e-04
5	-5.612540938735e-04	4.481699611261e-05	2.535074888925e-06
6	-1.334876998570e-04	2.919499398918e-05	-1.991423479045e-06
7	1.298404615938e-05	-2.701941401993e-06	1.791270932567e-07
8	-3.581309543014e-07	7.633070244335e-08	-5.593302645030e-09

T Index \ E Index	6	7	8
0	-8.140654835343e-03	5.192124519721e-04	-1.297112781664e-05
1	4.662131405403e-03	-2.320827027679e-04	4.724538772162e-06
2	-1.171374695689e-03	4.320048440550e-05	-6.523542632649e-07
3	9.516447719628e-05	4.017247431177e-07	-7.031689068197e-08
4	2.320428113156e-06	-6.344720465694e-07	1.688277259644e-08
5	8.398201633252e-08	-4.021594027671e-08	1.420992975620e-09
6	-1.026348613432e-07	1.519024137139e-08	-3.851106645960e-10
7	5.539305326395e-09	-8.915090538633e-10	1.877667458640e-11
8	-8.712370707504e-12	1.172349575278e-11	-1.236556517200e-13

Error 4.08e-03 (D)

Reaction 3.1.2 $p + H(1s) \rightarrow p + H^*(2s)$

T Index \ E Index	0	1	2
0	-3.303672309056e+01	5.435398491796e-02	-4.479069874895e-01
1	8.129573868895e-02	-1.573070446304e-01	-2.343645075304e-01
2	-1.367357596276e+00	1.264162602757e-01	9.132454530131e-02
3	2.430769064611e-01	-4.277967668065e-03	4.379389784137e-02
4	1.762729645847e-01	-1.171278439692e-02	-2.284640793483e-02
5	-6.257579731175e-02	3.045403958595e-03	4.069924950563e-03
6	8.093824710704e-03	-3.259338404156e-04	-3.654555742323e-04
7	-4.766590709264e-04	1.630335031310e-05	1.697015649467e-05
8	1.073880975629e-05	-3.135178689449e-07	-3.290603109143e-07

T Index \ E Index	3	4	5
0	-6.207816515028e-02	4.982680171938e-02	2.631060067396e-03
1	4.641882710210e-02	7.584683292302e-03	-1.878798454594e-03
2	-2.504726147521e-02	3.623287819690e-03	-5.425414507567e-04
3	-3.802802560195e-03	-4.458407685510e-03	1.053772036026e-03
4	4.085275116537e-03	6.304577672385e-04	-2.393639075300e-04
5	-8.856894051785e-04	6.116944101767e-05	8.195766073173e-06
6	8.857371143951e-05	-1.967353079496e-05	2.374701722762e-06
7	-4.353073546873e-06	1.500381004201e-06	-2.478107830550e-07
8	8.576165925108e-08	-3.781894053698e-08	6.945366389669e-09

T Index \ E Index	6	7	8
0	-2.180659228486e-03	2.245818225902e-04	-7.072385408498e-06
1	2.999568075912e-05	1.180308123781e-05	-5.753191579259e-07
2	7.217756265772e-05	-5.369814852090e-06	1.555461051039e-07
3	-8.298313802105e-05	1.948415887525e-06	1.941860942555e-08
4	2.472786370494e-05	-1.023360259850e-06	1.277393659635e-08
5	-2.180680441264e-06	1.728454123757e-07	-4.691407260680e-09
6	-3.745411947057e-08	-1.145030836069e-08	5.454860678474e-10
7	1.282096306376e-08	2.790689700798e-10	-2.878902181247e-11
8	-4.240491240271e-10	-1.382267062457e-12	6.143782726250e-13

Error 4.49e-03 (D)

Reaction 3.1.3 $p + H^*(2s) \rightarrow p + H^*(2p)$

E Index	0	1	2
T Index			
0	-9.990724901145e+00	5.351348305631e-01	4.939529241653e-02
1	6.537727443011e-01	-5.280296904194e-01	6.425969893761e-02
2	-1.241140027113e-01	2.060077489360e-01	-7.862588561762e-02
3	7.149154773117e-03	-4.485819636159e-02	2.658545734784e-02
4	-5.339018890395e-03	6.460674060103e-03	-3.577827264905e-03
5	1.800856199793e-03	-6.601657449132e-04	8.937792817252e-05
6	-2.467032039166e-04	4.579703537623e-05	2.480990637873e-05
7	1.545051869941e-05	-1.863242109937e-06	-2.397125514853e-06
8	-3.690040224068e-07	3.246974149460e-08	6.587817957450e-08

E Index	3	4	5
T Index			
0	-5.106541840021e-02	-1.828656123929e-03	3.278050583806e-03
1	3.146872034794e-02	-7.747008551462e-03	-2.009436212555e-05
2	-1.590857166173e-03	6.697068316092e-03	-1.587286144423e-03
3	-2.091225617309e-03	-1.807442248515e-03	5.583369851577e-04
4	6.191341147148e-04	1.098333544712e-04	-5.443789910797e-05
5	-1.018025884107e-04	3.338304419913e-05	-3.089670487553e-06
6	1.151440883472e-05	-6.871587246464e-06	8.975741200024e-07
7	-7.605187577154e-07	4.906237903385e-07	-5.574178438230e-08
8	2.067476350932e-08	-1.254526895853e-08	1.104305607237e-09

E Index	6	7	8
T Index			
0	-5.540100092190e-04	3.801593003417e-05	-9.608738344988e-07
1	1.517188390097e-04	-1.513420504861e-05	4.584486596613e-07
2	1.684564123048e-04	-8.692146674273e-06	1.773890443608e-07
3	-6.883882904255e-05	4.004504488417e-06	-9.090763486841e-08
4	7.663155026086e-06	-4.749223957327e-07	1.111022258304e-08
5	-7.483785818283e-08	2.292140559850e-08	-8.177571335015e-10
6	-1.732595885303e-08	-3.335002305887e-09	1.547780692175e-10
7	-1.171822397960e-09	4.663773505803e-10	-1.825227169097e-11
8	1.095408126793e-10	-1.896445830085e-11	6.805323199305e-13

Error 1.02e-03 (C)

Reaction 3.1.6 $p + H(1s) \rightarrow p + H^+ + e$

E Index / T Index	0	1	2
0	-1.617454916209e+02	1.767238902030e+01	-4.334843983767e+01
1	1.021458246570e+02	-7.102574692619e+01	3.855259623260e+01
2	-5.712267930902e+01	4.246688953154e+01	-1.316883030631e+01
3	2.140540272484e+01	-1.128638171243e+01	2.145592145856e+00
4	-4.767517412803e+00	1.661679851896e+00	-1.467281287038e-01
5	6.293295208376e-01	-1.476754423056e-01	-2.915256218527e-03
6	-4.858173640838e-02	8.175790218529e-03	1.092542891192e-03
7	2.031177914273e-03	-2.732531913524e-04	-6.205102802216e-05
8	-3.557982934756e-05	4.398387454014e-06	1.158798945435e-06

E Index / T Index	3	4	5
0	2.464254915383e+01	-5.439093405254e+00	5.959975304236e-01
1	-1.283426276878e+01	2.357085001656e+00	-2.391382925527e-01
2	2.369698902002e+00	-2.961732508220e-01	2.789277301925e-02
3	-1.506665823159e-01	-9.917174972226e-04	8.562387824450e-05
4	-8.144926683660e-03	1.935894665907e-03	-1.340759667335e-04
5	2.231505500086e-03	-1.679264493005e-05	-5.927455645560e-06
6	-2.210941355372e-04	5.532386419162e-08	5.820264508685e-07
7	1.310924337643e-05	-1.121430499351e-06	7.694068657107e-08
8	-3.431837053957e-07	5.960280736984e-08	-4.972708712807e-09

E Index / T Index	6	7	8
0	-3.361958123977e-02	8.706597041685e-04	-6.359765062372e-06
1	1.289667246580e-02	-3.140899683782e-04	1.742836004704e-06
2	-1.858739201548e-03	7.343984485463e-05	-1.235536456998e-06
3	9.235982885753e-05	-8.601564864429e-06	2.257852760280e-07
4	9.875232214392e-06	-6.467790579320e-07	1.608335682237e-08
5	-1.680823118052e-06	1.734797315767e-07	-3.855914336143e-09
6	3.019916624608e-08	2.523651535182e-09	-3.556222618473e-10
7	6.889325889968e-09	-1.719633613108e-09	7.627265694554e-11
8	-3.171970185702e-10	7.332933714195e-11	-2.960493966948e-12

Error 2.51e-03 (C)

Reaction 3.1.8 p + H(1s) → H(1s) + p

T Index \ E Index	0	1	2
0	-1.829079581680e+01	1.640252721210e-01	3.364564509137e-02
1	2.169137615703e-01	-1.106722014459e-01	-1.382158680424e-03
2	4.307131243894e-02	8.948693624917e-03	-1.209480567154e-02
3	-5.754895093075e-04	6.062141761233e-03	1.075907881928e-03
4	-1.552077120204e-03	-1.210431587568e-03	8.297212635856e-04
5	-1.876800283030e-04	-4.052878751584e-05	-1.907025662962e-04
6	1.125490270962e-04	2.875900435895e-05	1.338839628570e-05
7	-1.238982763007e-05	-2.616998139678e-06	-1.171762874107e-07
8	4.163596197181e-07	7.558092849125e-08	-1.328404104165e-08

T Index \ E Index	3	4	5
0	9.530225559189e-03	-8.519413589968e-04	-1.247583860943e-03
1	7.348786286628e-03	-6.343059502294e-04	-1.919569450380e-04
2	-3.675019470470e-04	1.039643390686e-03	-1.553840717902e-04
3	-8.119301728339e-04	8.911036876068e-06	3.175388949811e-05
4	1.361661816974e-04	-1.008928628425e-04	1.080693990468e-05
5	1.141663041636e-05	1.775681984457e-05	-3.149286923815e-06
6	-4.340802793033e-06	-7.003521917385e-07	2.318308730487e-07
7	3.517971869029e-07	-4.928692832866e-08	1.756388998863e-10
8	-9.170850253981e-09	3.208853883734e-09	-3.952740758950e-10

T Index \ E Index	6	7	8
0	3.014307545716e-04	-2.499323170044e-05	6.932627237765e-07
1	4.075019351738e-05	-2.850044983009e-06	6.966822400446e-08
2	2.670827249272e-06	7.695300597935e-07	-3.783302281524e-08
3	-4.515123641755e-06	2.187439283954e-07	-2.911233951880e-09
4	5.106059413591e-07	-1.299275586093e-07	5.117133050290e-09
5	3.105491554749e-08	2.274394089017e-08	-1.130988250912e-09
6	-6.030983538280e-09	-1.755944926274e-09	1.005189187279e-10
7	-1.446756795654e-10	7.143183138281e-11	-3.989884105603e-12
8	2.739558475782e-11	-1.693040208927e-12	6.388219930167e-14

Error 8.88e-04 (B)

Reaction 3.1.9 $p + H(1s) \rightarrow H^*(2p) + p$

T Index \ E Index	0	1	2
0	-7.537230406957e+01	4.362515351094e+01	-1.318797741915e+01
1	5.056939990348e+01	-4.322632990301e+01	1.243803991192e+01
2	-2.304556023867e+01	1.808673367993e+01	-5.041889107660e+00
3	5.946693576057e+00	-4.192991836651e+00	1.150647211570e+00
4	-9.025227545139e-01	5.941171802341e-01	-1.616667927236e-01
5	8.062506740891e-02	-5.340479630862e-02	1.424698941315e-02
6	-3.996458180607e-03	3.028277898563e-03	-7.611581001083e-04
7	9.092787501258e-05	-1.009830499229e-04	2.216348373380e-05
8	-4.227552753922e-07	1.538300832396e-06	-2.615703495579e-07

T Index \ E Index	3	4	5
0	3.884832686395e-01	6.956399122965e-01	-1.768051294154e-01
1	-6.391999122917e-01	-4.102677587957e-01	1.022299957977e-01
2	4.302521809170e-01	6.674825725277e-02	-1.905495347022e-02
3	-1.437283377093e-01	4.745169406603e-03	8.000515536149e-04
4	2.533878850824e-02	-2.550521752939e-03	1.202073413278e-04
5	-2.271818162002e-03	2.517099528196e-04	-1.115096374756e-05
6	7.750647375638e-05	-3.466368199953e-06	1.352159519053e-07
7	1.503739282859e-06	-7.169612925965e-07	-3.978675907993e-09
8	-1.204847091978e-07	2.957975348352e-08	7.777167529587e-10

T Index \ E Index	6	7	8
0	1.957698184804e-02	-1.056851602712e-03	2.265661905063e-05
1	-1.064957247532e-02	5.395365812293e-04	-1.089046627301e-05
2	1.819440410123e-03	-8.006107003062e-05	1.352840661769e-06
3	-9.926992183313e-05	4.294899850373e-06	-6.488121891471e-08
4	6.513242953616e-06	-1.107878363495e-06	3.840860903452e-08
5	-1.478504972220e-06	2.121938496244e-07	-7.452662892489e-09
6	1.959691983490e-08	-4.994907944039e-09	2.384601530335e-10
7	1.365715388161e-08	-1.203216169780e-09	3.140684652583e-11
8	-6.927312822621e-10	6.265289730204e-11	-1.756983474278e-12

Error 2.14e-03 (C)

Reaction 3.1.10 p + H(1s) → $H^*(2s)$ + p

T Index \ E Index	0	1	2
0	-9.454040572046e+01	3.575745803548e+01	-1.510443829941e+01
1	6.768817040733e+01	-5.227279271076e+01	1.701370184857e+01
2	-3.843706771660e+01	2.980450196644e+01	-8.131009677919e+00
3	1.385221298623e+01	-9.039653668981e+00	2.086424489113e+00
4	-3.117564250516e+00	1.631432036287e+00	-3.080742439399e-01
5	4.327242290244e-01	-1.819412845040e-01	2.620862225175e-02
6	-3.575580797373e-02	1.236067989017e-02	-1.200955067032e-03
7	1.606326046639e-03	-4.707337881721e-04	2.380595128998e-05
8	-3.014539201968e-05	7.726558074630e-06	-5.572946409399e-08

T Index \ E Index	3	4	5
0	4.295083359171e+00	-5.229601897556e-01	-7.946315775931e-03
1	-3.003110377892e+00	3.010370634031e-01	-1.508174268564e-02
2	9.231651795395e-01	-3.487948145308e-02	1.651938581961e-03
3	-1.650992173822e-01	-7.573668823425e-03	1.643120830451e-03
4	1.839941901217e-02	1.873700049273e-03	-3.898508080526e-04
5	-1.170843781709e-03	-7.837602630428e-05	1.901716727239e-05
6	2.536771557591e-05	-8.991629432058e-06	1.917169241407e-06
7	1.205300240917e-06	8.541173405977e-07	-2.062752779297e-07
8	-5.817548248007e-08	-1.874443584825e-08	4.932865323528e-09

T Index \ E Index	6	7	8
0	7.914390432835e-03	-6.838905496435e-04	1.882232072017e-05
1	5.550437127230e-05	2.964326783525e-05	-9.736741374779e-07
2	-6.142591967279e-04	6.119831154619e-05	-1.838162822528e-06
3	-7.419534566620e-06	-7.945476516010e-06	3.130407892340e-07
4	2.719285839940e-05	-8.813515513714e-07	1.079647425709e-08
5	-2.516543465515e-06	1.865515247748e-07	-5.301524876773e-09
6	-7.319251234821e-08	-5.372098865883e-09	3.196679636762e-10
7	1.560273243360e-08	-3.793947135803e-10	-2.054614693679e-12
8	-4.284893236218e-10	1.548062509417e-11	-1.558508528883e-13

Error 2.70e-03 (C)

Reaction 3.1.11a $p + H^*(2) \rightarrow H^*(2) + p$

E Index / T Index	0	1	2
0	-1.719825327366e+01	1.884984890020e-01	6.897051389182e-02
1	2.142580064300e-01	-9.872388055616e-02	-3.940258746400e-03
2	5.168472844325e-02	6.212920647036e-03	-9.888896994201e-03
3	-1.048694623894e-02	6.029698215976e-03	1.504715422531e-03
4	-1.391648927155e-03	-9.288450680283e-04	5.238686379254e-04
5	1.062236858414e-03	-1.207901919277e-04	-1.467630362018e-04
6	-1.941489579494e-04	3.746697774137e-05	1.105904477472e-05
7	1.443503540040e-05	-3.003621079325e-06	-1.018783959628e-07
8	-3.830825345601e-07	8.083955156001e-08	-1.150674668496e-08

E Index / T Index	3	4	5
0	-1.572342769599e-02	-3.026782383076e-03	2.133841357975e-03
1	7.386092651403e-03	-2.707096061380e-04	-3.315460371996e-04
2	-1.514031260298e-04	7.422527656251e-04	-9.788494576192e-05
3	-1.084990452398e-03	-2.534332965992e-05	6.638160972083e-05
4	1.397189710440e-04	-6.198909026340e-05	4.565982508704e-07
5	2.978558026688e-05	1.074474230594e-05	-2.854550682552e-06
6	-7.191352563366e-06	-2.116398505416e-07	3.026311807218e-07
7	5.019583257618e-07	-5.860162734729e-08	-4.086656000107e-09
8	-1.160924102260e-08	3.001361914394e-09	-3.647228557972e-10

E Index / T Index	6	7	8
0	-3.794323219371e-04	2.766697866894e-05	-7.245291602834e-07
1	6.222275341197e-05	-4.353916183620e-06	1.095768172868e-07
2	-1.538008374846e-06	8.506156759757e-07	-3.579248331944e-08
3	-1.070825967335e-05	6.727768972585e-07	-1.517922643230e-08
4	1.624804729503e-06	-1.835711031271e-07	6.039716625198e-09
5	1.266431527284e-07	1.074561840233e-08	-7.130630889442e-10
6	-2.451278913609e-08	-4.162807697535e-10	6.485611244670e-11
7	4.087633684476e-11	1.064004947231e-10	-5.907545942925e-12
8	5.848501246633e-11	-6.316916199588e-12	2.360870657000e-13

Error 5.81e-04 (B)

Reaction 3.1.11b $p + H^*(3) \rightarrow H^*(3) + p$

T Index \ E Index	0	1	2
0	-1.564176694793e+01	1.700998335355e-01	4.947885926277e-02
1	2.232010663420e-01	-1.049739713449e-01	-2.908751470450e-03
2	5.316235880113e-02	7.036341129098e-03	-1.117747362624e-02
3	-4.935673795010e-03	6.200377256109e-03	1.303552526033e-03
4	-1.741592426003e-03	-1.023534361944e-03	6.993209254704e-04
5	4.843336390075e-04	-1.026575078128e-04	-1.690721678970e-04
6	-4.393060568249e-05	3.646643689823e-05	1.129769317091e-05
7	1.066531598161e-06	-3.043044894680e-06	2.706113202831e-09
8	2.083548419270e-08	8.441512078238e-08	-1.618789305180e-08

T Index \ E Index	3	4	5
0	3.480696525110e-03	-2.016588092927e-03	-2.304544529246e-04
1	7.235971573222e-03	-4.237602215706e-04	-2.525856005478e-04
2	-2.219063125013e-04	8.910349218491e-04	-1.240905152629e-04
3	-1.007225809037e-03	-5.690437985817e-06	5.076337989874e-05
4	1.326302857329e-04	-8.434009637807e-05	6.519707374655e-06
5	2.567668892391e-05	1.430883419261e-05	-3.208617580385e-06
6	-6.607411884531e-06	-3.382705306787e-07	2.749197577537e-07
7	4.871162221333e-07	-6.897801542295e-08	-1.416282255917e-09
8	-1.204005789548e-08	3.636288208820e-09	-4.076090686778e-10

T Index \ E Index	6	7	8
0	1.218034746095e-04	-1.302517417161e-05	4.404350923087e-07
1	4.862602710052e-05	-3.343139362692e-06	8.182936615708e-08
2	-2.780251764272e-07	8.939610410070e-07	-3.949474200870e-08
3	-7.792361018067e-06	4.473546907095e-07	-8.802476545107e-09
4	9.878685208347e-07	-1.545621666271e-07	5.588732113261e-09
5	9.561811139849e-08	1.702219787538e-08	-9.641507489238e-10
6	-1.646787390856e-08	-1.115049016888e-09	8.683886799640e-11
7	4.716863630756e-11	8.023274024363e-11	-4.773160877761e-12
8	3.777088131426e-11	-3.347579230007e-12	1.292746807996e-13

Error 1.54e-04 (A)

Reaction 3.2.1a $p + H_2(j=0) \rightarrow p + H_2(j')$ $(j' \geq 2)$

T Index \ E Index	0	1	2
0	-1.931976581025e+01	-1.131727838595e-02	5.564692006285e-02
1	1.780878236605e-01	-1.304342119382e-01	-2.977647895678e-02
2	-2.541254437243e-02	2.555760073023e-02	-1.343274859600e-02
3	-4.673484115780e-02	7.858332235684e-03	3.183062244762e-03
4	-1.146770335720e-03	-1.657368695811e-03	7.282634108198e-04
5	2.889570096820e-03	-5.065872411962e-05	-1.009959155222e-04
6	-5.181754952484e-04	1.639669433305e-05	-2.569913821108e-05
7	3.889651963743e-05	3.837821202667e-07	4.649279483411e-06
8	-1.107229000254e-06	-7.670491474577e-08	-1.956375986525e-07

T Index \ E Index	3	4	5
0	4.612780090544e-02	-2.004969108653e-02	-5.405622666261e-03
1	2.598050022977e-02	1.347793245045e-03	-2.528774951362e-03
2	-2.445543192015e-03	2.818570059181e-03	-4.999237741132e-05
3	-3.596822533950e-03	2.532346636968e-04	4.009000053692e-04
4	2.613056855048e-04	-2.483817325793e-04	1.398464524064e-07
5	1.042472672998e-04	2.267800856786e-06	-1.589742168453e-05
6	-8.619281945578e-06	7.897307131770e-06	8.582336209267e-07
7	-7.536640398566e-07	-9.405159896274e-07	1.327216559054e-07
8	6.639899136555e-08	3.236749066622e-08	-9.607318326503e-09

T Index \ E Index	6	7	8
0	2.191546075602e-03	-2.320194246052e-04	8.008357976190e-06
1	4.600974334650e-04	-3.107626515638e-05	6.945270043940e-07
2	-1.748459008343e-04	2.776052578344e-05	-1.206654268341e-06
3	-9.738076845118e-05	7.572697075882e-06	-1.827758690708e-07
4	1.815503467330e-05	-2.855321802747e-06	1.239043759009e-07
5	1.897116878857e-06	9.701076200284e-08	-1.311379859022e-08
6	-4.399860357799e-07	2.641401745588e-08	9.621252004735e-11
7	1.171108373785e-08	-1.727778312454e-09	2.797736054220e-11
8	5.928009302898e-10	-5.140400246008e-13	-1.647139266864e-13

Error 2.98e-03 (D)

Reaction 3.2.1b $p + H_2(j=1) \rightarrow p + H_2(j')$ $(j' \geq 3)$

T Index \ E Index	0	1	2
0	-1.973243992807e+01	1.247414117614e-01	9.226482332314e-02
1	1.829696809063e-01	-1.297428942606e-01	-4.048210910881e-02
2	-3.965576412456e-02	3.618197482242e-02	-9.421328372950e-03
3	-4.313466950038e-02	-2.291104293914e-03	6.559525504445e-03
4	9.636266519704e-04	-2.918601086415e-03	-4.932567471708e-04
5	2.253096845378e-03	1.405510037846e-03	-2.369615891213e-04
6	-4.356551994020e-04	-2.600932648209e-04	5.724350136902e-05
7	3.282766964094e-05	2.127068115091e-05	-4.867932845087e-06
8	-9.076785125326e-07	-6.411159887874e-07	1.475347595640e-07

T Index \ E Index	3	4	5
0	-3.714490319222e-02	-1.356114029701e-02	4.100083713039e-03
1	2.971894544949e-02	1.876669259108e-03	-3.322968917828e-03
2	-1.981651027277e-03	1.569164989146e-03	-3.053099313902e-04
3	-1.090766391534e-03	-4.420842120460e-04	3.568181091302e-04
4	5.013178555056e-04	-3.266081392759e-05	-3.038322725843e-05
5	-2.533635465343e-04	4.489607178747e-05	-1.262675526559e-06
6	5.665115351398e-05	-1.000727087071e-05	-4.278214878688e-07
7	-5.233684321566e-06	9.078582661039e-07	1.038286804798e-07
8	1.702995300347e-07	-2.952394683317e-08	-4.770640084428e-09

T Index \ E Index	6	7	8
0	-3.666387513519e-04	1.083946601986e-05	1.351070637014e-08
1	6.903747113211e-04	-5.754069299179e-05	1.739402046218e-06
2	1.988204507361e-05	3.731257202030e-07	-6.182586349800e-08
3	-8.469119247598e-05	8.182865454249e-06	-2.786434350401e-07
4	8.613590729944e-06	-8.986091403746e-07	3.310895101467e-08
5	6.220415471942e-07	-1.315998111932e-07	6.286616924397e-09
6	2.197126754622e-08	1.839451977445e-08	-1.214916175628e-09
7	-2.062547364677e-08	1.216554321342e-10	5.337970791360e-11
8	1.119243083769e-09	-5.101049613696e-11	-1.139621855444e-13

Error 2.05e-03 (C)

Reaction 3.2.2 $p + H_2(v=0) \rightarrow p + H_2(v > 0)$

T Index \ E Index	0	1	2
0	-2.329087453007e+01	5.834682857859e-01	3.016206818784e-01
1	2.119794074231e+00	-4.707130034299e-01	-1.627052975735e-01
2	4.378420793629e-02	7.098659965089e-02	-1.538726713612e-03
3	-1.212485645824e-01	1.716068200911e-02	1.234418739201e-02
4	-6.784743989202e-05	-3.554071145865e-03	-1.963491271592e-03
5	6.091207437528e-03	-5.334937961855e-04	2.680505429999e-06
6	-1.035395322074e-03	1.771858360014e-04	2.137128521413e-05
7	6.956622116761e-05	-1.519815181883e-05	-1.689036732606e-06
8	-1.714843775518e-06	4.355820063409e-07	4.019682578322e-08

T Index \ E Index	3	4	5
0	2.566603966328e-02	-2.256516571421e-02	-5.628180168021e-04
1	2.772025396684e-02	1.100571275815e-02	-3.271820121481e-03
2	-8.406926164519e-03	-1.645206696492e-03	1.346715958215e-03
3	-3.779824694550e-03	9.007565031801e-04	-2.318342461147e-04
4	1.849557056204e-03	-4.387553829325e-04	4.379338463619e-05
5	-3.000343967886e-04	8.809999443469e-05	-8.221671799210e-06
6	2.287377536516e-05	-8.300877832833e-06	8.352812135871e-07
7	-7.931460846045e-07	3.626282328864e-07	-3.748271128306e-08
8	8.837549978855e-09	-5.713862092713e-09	5.406617870326e-10

T Index \ E Index	6	7	8
0	7.740619846564e-04	-8.045484752448e-05	2.526516293312e-06
1	3.282645173821e-04	-1.405235013910e-05	2.050808638586e-07
2	-2.333687223953e-04	1.660986465802e-05	-4.315116954882e-07
3	3.388077149363e-05	-2.302170766555e-06	5.814386667558e-08
4	-1.679616585635e-06	-5.915996895685e-09	1.292933101414e-09
5	2.043346638977e-07	3.266439560921e-09	3.038024520814e-11
6	-3.882583129136e-08	2.553655884029e-09	-1.293452258893e-10
7	2.558173370326e-09	-2.723495529714e-10	1.327159233871e-11
8	-4.963660570583e-11	7.622204418800e-12	-3.884869166334e-13

Error 3.04e-03 (D)

Error is improved to 8.94e-04 (B) if only values of $\langle\sigma v\rangle$ for T > 1 eV are considered.

Reaction 3.2.3 $p + H_2 \rightarrow H(1s) + H_2^+$

E Index T Index	0	1	2
0	-2.393090018673e+01	6.248759475696e-01	4.860672617319e-02
1	1.497880823202e+00	-1.321184618254e+00	1.610180305377e-01
2	-1.108848312589e+00	1.026939763848e+00	-2.764437632008e-01
3	2.723796545755e-01	-3.349189897157e-01	1.525831234833e-01
4	2.721877464232e-02	4.328258310611e-02	-4.172607648071e-02
5	-1.779177173774e-02	4.465034873018e-04	6.494173133750e-03
6	2.547195398346e-03	-6.602886969983e-04	-5.936946344163e-04
7	-1.581068390892e-04	6.000753124589e-05	2.989789198510e-05
8	3.720016363224e-06	-1.724843689004e-06	-6.403267693113e-07

E Index T Index	3	4	5
0	-1.200688114292e-01	8.087736504737e-03	9.460417081363e-03
1	1.165310493854e-01	-3.963918450387e-02	4.451468403951e-03
2	-3.948109106588e-02	3.853676685634e-02	-9.097709483121e-03
3	-9.592981926094e-03	-1.131614493158e-02	3.519316476081e-03
4	1.001163900824e-02	3.016020168360e-04	-4.649867654705e-04
5	-2.726517864643e-03	3.947434451322e-04	-3.560364682888e-06
6	3.516907384191e-04	-7.253981468239e-05	6.007588925145e-06
7	-2.210901325776e-05	5.074761954649e-06	-4.890225279817e-07
8	5.443461456508e-07	-1.285040546716e-07	1.225908917355e-08

E Index T Index	6	7	8
0	-2.128651089328e-03	1.685181886244e-04	-4.665309226730e-06
1	-1.304738719348e-04	-8.714697396102e-06	4.796574269551e-07
2	1.042066219239e-03	-5.955686719189e-05	1.358749516236e-06
3	-4.463914380371e-04	2.672110767494e-05	-6.218012239798e-07
4	7.356430658399e-05	-4.797055206851e-06	1.159195338618e-07
5	-4.585211534749e-06	4.292978331848e-07	-1.209703556619e-08
6	-1.866842996766e-08	-2.383240469589e-08	9.353713300206e-10
7	1.067090708836e-08	1.188959741308e-09	-5.741789281748e-11
8	-1.967393094286e-10	-3.854014407618e-11	1.748544462760e-12

Error 7.17e-03 (D)

Error is improved to 2.24e-03 (C) if only values of <σv> for T > 1 eV are considered.

Reaction 3.2.4a $p + D_2 \rightarrow D^+ + HD$ (or H + D)

T Index \ E Index	0	1	2
0	-2.111896543160e+01	-1.025538356060e-01	-1.465668919808e-01
1	-6.219092009914e-01	6.936787446352e-02	9.499279319950e-02
2	-1.215025308696e-01	8.780031887817e-03	-4.821837782776e-03
3	6.815442586718e-02	-1.525104088494e-02	-7.956267907252e-03
4	2.752449038333e-03	1.225019378208e-03	1.085462645581e-03
5	-5.750611656794e-03	1.232968333824e-03	3.447823950790e-04
6	1.125377790650e-03	-3.422288971501e-04	-1.018650054891e-04
7	-8.919363340228e-05	3.365851906238e-05	9.449139307317e-06
8	2.601744783012e-06	-1.162845386047e-06	-3.033572820292e-07

T Index \ E Index	3	4	5
0	-1.856546171568e-02	1.365853496631e-02	-3.826961311141e-04
1	-1.160097875790e-03	-9.106571030308e-03	1.473315037711e-03
2	4.849238242696e-03	7.525239416510e-04	-7.495029297215e-04
3	1.124986687656e-03	5.331715821535e-04	-1.190706225054e-04
4	-6.853757310073e-04	-1.075209684417e-04	9.573379729918e-05
5	-5.896278139458e-05	3.476245629170e-06	-5.875969746146e-06
6	4.848804836962e-05	-7.966497740323e-08	-2.512498875224e-06
7	-6.135496085718e-06	9.456855386541e-08	3.985794665381e-07
8	2.408475811630e-07	-6.748305167707e-09	-1.666573853398e-08

T Index \ E Index	6	7	8
0	-3.727957061966e-04	4.748991519766e-05	-1.698399806385e-06
1	-1.495473343687e-05	-9.835840608225e-06	4.860991365689e-07
2	1.403289748223e-04	-1.067949058111e-05	2.955867761367e-07
3	5.146965646887e-06	3.731108583161e-07	-2.546014093405e-08
4	-1.739495667153e-05	1.302457212236e-06	-3.566296705821e-08
5	1.552565062442e-06	-1.430402446135e-07	4.485383482007e-09
6	4.667259306147e-07	-3.425538256234e-08	9.189075599465e-10
7	-8.312637284424e-08	6.615368641527e-09	-1.889019472636e-10
8	3.654557715832e-09	-2.995367307547e-10	8.734664246336e-12

Error 7.28e-03 (D)

Error is improved to 6.67e-04 (B) if only values of $\langle\sigma v\rangle$ for T > 1 eV are considered.

Reaction 3.2.4b $p + D_2 \rightarrow D + HD^+$

E Index	0	1	2
T Index			
0	-2.529005922309e+01	3.371688551898e-01	4.693918630510e-02
1	1.881570344354e+00	-5.113434583372e-01	-5.273216405018e-02
2	-8.814004836556e-01	2.968842541690e-01	3.441039128935e-02
3	1.691850902103e-01	-8.619057072559e-02	-5.980460778885e-02
4	-6.652054410222e-02	1.093768968050e-02	5.059893495850e-02
5	2.240305503202e-02	2.436569548502e-04	-1.818236207409e-02
6	-3.819487238341e-03	-2.196174841406e-04	3.110816934408e-03
7	3.069356789436e-04	2.140188150215e-05	-2.512796010299e-04
8	-9.328627869191e-06	-6.680477536797e-07	7.694384931049e-06

E Index	3	4	5
T Index			
0	1.384303400933e-02	2.197297492088e-02	-5.238094233772e-03
1	-5.260928525467e-02	-1.183131187811e-02	1.230475793211e-02
2	1.331208476230e-02	-6.086729631519e-03	-3.440498761785e-03
3	2.992464843607e-02	6.494689656712e-03	-5.095348269685e-03
4	-2.273638325874e-02	-4.060667412372e-03	4.212401093393e-03
5	6.836786141131e-03	1.468739824255e-03	-1.329242365115e-03
6	-1.028059797546e-03	-2.651119233481e-04	2.067742478703e-04
7	7.612976218275e-05	2.242650259038e-05	-1.567120609980e-05
8	-2.199089655518e-06	-7.103958561240e-07	4.597541185577e-07

E Index	6	7	8
T Index			
0	-2.589041456721e-03	5.971878512503e-04	-2.960695486568e-05
1	2.243312170048e-04	-5.598084624364e-04	4.754533831647e-05
2	8.268141028700e-04	3.941921240841e-05	-1.101845343079e-05
3	9.066019513957e-04	-6.629895278703e-05	2.061740481891e-06
4	-9.043842324620e-04	7.471396669600e-05	-1.946743502969e-06
5	2.869803101647e-04	-2.489904593762e-05	7.165571176206e-07
6	-4.325324514439e-05	3.772514035078e-06	-1.135486249420e-07
7	3.158371725991e-06	-2.722540885633e-07	8.321982058577e-09
8	-8.960027960892e-08	7.591855363103e-09	-2.323959696375e-10

Error 1.18e-04 (A)

$\langle\sigma v\rangle$ < 1.0e-11 for E > 100 eV for the entire T range considered here. The fit gives unphysical values for E > 100 eV in this range and should not be used there.

Reaction 3.2.5 $p + H_2 \rightarrow p + H_2^+(v \leq 9) + e$

E Index / T Index	0	1	2
0	-5.367225610927e+01	8.561616047237e+00	1.816558609991e+00
1	1.788157706832e+01	-6.286008716933e+00	-1.245074165012e+00
2	-4.732013902744e+00	1.828154334899e+00	2.297272982398e-01
3	5.202644682964e-01	-2.797342414213e-01	3.359419100500e-02
4	3.521809500536e-02	3.001478994199e-02	-2.022030104793e-02
5	-1.648514003195e-02	-3.511706068001e-03	3.466696529491e-03
6	1.922206340707e-03	3.867557051749e-04	-2.971236668059e-04
7	-1.035405866079e-04	-2.470578459133e-05	1.298468816782e-05
8	2.203112678635e-06	6.255426859518e-07	-2.312060025019e-07

E Index / T Index	3	4	5
0	-1.522333614377e+00	3.759529679375e-01	-4.786079082066e-02
1	1.069094789286e+00	-2.542196973682e-01	3.177817178124e-02
2	-2.574312651499e-01	6.235010781304e-02	-7.498165815343e-03
3	1.396148560079e-02	-5.455674772716e-03	7.627828208046e-04
4	4.167002536339e-03	-2.961138095159e-04	-1.989496685088e-05
5	-7.713464611496e-04	9.296859682627e-05	-4.390690629457e-06
6	4.630325714231e-05	-6.209296988115e-06	7.802446823898e-07
7	-5.951650262538e-07	1.040160519423e-07	-6.013540281517e-08
8	-2.277567397969e-08	2.205724295105e-09	1.764776882153e-09

E Index / T Index	6	7	8
0	3.386576601010e-03	-1.260406274176e-04	1.909653870707e-06
1	-2.284002706788e-03	9.015781280225e-05	-1.528190392357e-06
2	4.874507232153e-04	-1.603249117471e-05	2.009004806425e-07
3	-4.735379021213e-05	9.681751756528e-07	9.137775800355e-09
4	5.017190961057e-06	-3.312351285579e-07	7.657715805259e-09
5	-5.449234862617e-07	8.306829849916e-08	-3.008901804950e-09
6	-9.036886465169e-09	-6.038768586675e-09	3.127724512237e-10
7	5.701208151560e-09	-2.749357161379e-12	-1.065774817217e-11
8	-2.564871978479e-10	9.360384058829e-12	2.125011883790e-14

Error 7.60e-05 (A)

Reaction 3.2.6 $p + H_2^+(v) \rightarrow p + H(1s) + H^+$

E Index / T Index	0	1	2
0	-3.503949588630e+01	3.596223868947e-03	5.850451146780e-01
1	3.056567004229e+00	3.101537521281e-01	-3.802213472822e-01
2	6.995656851497e-01	-1.714310765924e-01	4.075164360191e-02
3	-2.282773440449e-01	2.456336476294e-02	2.462515616912e-02
4	2.032409655024e-02	4.693764706073e-03	-8.013907630788e-03
5	7.333965699110e-04	-2.072064243724e-03	9.248040165878e-04
6	-3.031298255102e-04	2.853271682462e-04	-4.190818382811e-05
7	2.353662179363e-05	-1.783778591788e-05	1.188782788257e-07
8	-6.209682283669e-07	4.280148575920e-07	2.898023610900e-08

E Index / T Index	3	4	5
0	9.474524219612e-02	-3.938575923140e-02	4.666084706751e-03
1	-4.164890965970e-02	3.732884150575e-02	-5.553031214904e-03
2	6.345887908944e-04	-7.388540130210e-03	2.215252505302e-03
3	-1.163184524936e-03	-8.552780029379e-04	-6.842088086239e-05
4	9.714618199968e-04	3.399582328819e-04	-7.945188972850e-05
5	-1.686569365114e-04	-1.260646704530e-05	9.272036136361e-06
6	9.494328352046e-06	-3.548328747232e-06	3.006199198249e-07
7	3.338996422125e-08	3.705771699362e-07	-8.431446572047e-08
8	-1.257918518905e-08	-1.036436256550e-08	3.078907880655e-09

E Index / T Index	6	7	8
0	-3.236705187942e-04	1.538536999072e-05	-3.695652391342e-07
1	2.646628484405e-04	3.287941538949e-06	-4.204509688663e-07
2	-2.704279067013e-04	1.508871496609e-05	-3.179547222229e-07
3	4.711638356898e-05	-4.822026376406e-06	1.518903664812e-07
4	4.045609876795e-06	1.545451740861e-07	-1.283734364199e-08
5	-1.248629759318e-06	6.544957875539e-08	-1.110642504800e-09
6	3.221166999732e-08	-5.258665703836e-09	1.800452602126e-10
7	5.927769241279e-09	-5.999414332265e-11	-4.977523706425e-12
8	-2.953243500461e-10	1.037093087158e-11	-6.464182493927e-14

Error 4.86e-04 (B)

Reaction 3.3.1 $p + He \rightarrow H + He^{+}$

T Index \ E Index	0	1	2
0	-3.353816664129e+01	-4.586784908436e-01	1.594898247008e-01
1	1.781370892516e+00	6.891694453609e-01	-1.611575823430e-01
2	6.707672251154e-01	-3.169866636164e-01	7.765165360131e-02
3	-7.477930071091e-02	3.350898800561e-02	-3.392131794663e-02
4	-8.381713330773e-02	1.622059625803e-02	1.247636271907e-02
5	2.694989933554e-02	-5.889292565221e-03	-2.789567626468e-03
6	-3.290961646690e-03	8.008575628447e-04	3.401335910688e-04
7	1.824292103062e-04	-5.051648761026e-05	-2.091692923886e-05
8	-3.841146748130e-06	1.228049521583e-06	5.084397192524e-07

T Index \ E Index	3	4	5
0	1.993834571954e-01	-2.908726266195e-02	-4.587782047584e-03
1	-1.491282657121e-01	4.812768747296e-02	-3.997981241748e-03
2	2.652950675220e-02	-2.159277544971e-02	5.139425409123e-03
3	8.474034802338e-03	2.748759961113e-03	-1.420567682255e-03
4	-5.507438871028e-03	5.154609993383e-04	1.065291472218e-04
5	1.293406768681e-03	-2.021983674764e-04	1.031174122595e-05
6	-1.563868173318e-04	2.528045360094e-05	-1.979594316338e-06
7	9.545486229202e-06	-1.444453762830e-06	9.506598262937e-08
8	-2.317334470853e-07	3.187947009859e-08	-1.162138178659e-09

T Index \ E Index	6	7	8
0	1.233562953962e-03	-8.959520538477e-05	2.153885795280e-06
1	-1.453386884233e-04	3.438904204074e-05	-1.235017420599e-06
2	-5.776151273370e-04	3.150136684703e-05	-6.720649580897e-07
3	2.214493222620e-04	-1.503183655470e-05	3.810469912151e-07
4	-2.770978822291e-05	2.235082592688e-06	-6.269566270205e-08
5	8.328481121158e-07	-1.256070804240e-07	4.314925565866e-09
6	5.230582879539e-08	2.635177963503e-09	-1.574479246009e-10
7	-8.519235005422e-10	-2.264396092848e-10	9.108750391681e-12
8	-1.347103798052e-10	1.468879806508e-11	-4.188673847162e-13

Error 1.58e-03 (C)

Reaction 3.3.2 p + He → p + He^{+} + e

T Index \ E Index	0	1	2
0	-3.513975817234e+01	-5.242917555404e-01	-3.826194904402e-01
1	-5.385780070980e-01	7.943799641890e-02	1.983252146365e-01
2	9.035205217957e-01	1.231698104678e-01	-4.512064453109e-02
3	6.154592887522e-02	-4.082389668808e-02	8.492939132060e-03
4	-8.683888520960e-02	1.363524072485e-03	-6.877816557895e-04
5	1.850283102315e-02	1.065556461944e-03	-1.981157465961e-04
6	-1.829730723913e-03	-1.792886431140e-04	5.180204798722e-05
7	8.903233974874e-05	1.133222476812e-05	-4.281190983076e-06
8	-1.723417501407e-06	-2.598637070808e-07	1.212392744890e-07

T Index \ E Index	3	4	5
0	1.749071804038e-01	3.379968769905e-02	-1.684873318946e-02
1	-2.966737668036e-02	-2.195230807923e-02	7.987671929803e-03
2	-2.632395045040e-02	9.106381567773e-03	-1.220083366385e-03
3	4.950008931722e-03	-2.125790233999e-03	2.856685316297e-04
4	1.539732094359e-03	1.989843795364e-05	-8.201311837293e-05
5	-5.591852085968e-04	8.588977130038e-05	6.771413834410e-06
6	6.660694317589e-05	-1.557623357777e-05	6.328328243704e-07
7	-3.537756092409e-06	1.101685345092e-06	-1.130645655532e-07
8	7.093957802151e-08	-2.828418079985e-08	4.145168773820e-09

T Index \ E Index	6	7	8
0	2.235958862320e-03	-1.282599958804e-04	2.760095475019e-06
1	-1.078408322383e-03	6.664182706070e-05	-1.576989885173e-06
2	1.013506718990e-04	-5.755496123590e-06	1.585191024717e-07
3	-1.436171240398e-05	5.512329277872e-08	1.055695620784e-08
4	1.095726116510e-05	-4.861620705084e-07	5.080813644487e-09
5	-1.907336915250e-06	1.057876163056e-07	-1.372842995387e-09
6	7.169146469455e-08	-4.866671700650e-09	1.446148171715e-11
7	5.780678333429e-09	-2.912824978296e-10	1.171657019875e-11
8	-3.562927197437e-10	2.049378727457e-11	-5.867221352941e-13

Error 1.18e-04

Reaction 3.3.6a $p + He^{*}(1s2s|^{1}S) \rightarrow H^{*}(2s) + He^{+}(1s)$

E Index / T Index	0	1	2
0	-2.545206891667e+01	4.087721421944e-01	1.586491378549e-01
1	2.913542861083e+00	-4.603441740870e-01	-1.538179897348e-01
2	-2.751712354111e-01	1.679980585979e-01	4.131633234926e-02
3	-2.633545354224e-02	-1.567302034710e-02	-4.520967162781e-04
4	8.622940210562e-03	-3.336538128570e-03	-8.260874599039e-04
5	-2.300706825690e-04	8.171653956449e-04	-4.965497872141e-05
6	-1.125479569857e-04	-5.470534020950e-05	3.466402080937e-05
7	1.223862287149e-05	4.510736761276e-07	-3.432193506153e-06
8	-3.807538916669e-07	4.917383484449e-08	1.058745036988e-07

E Index / T Index	3	4	5
0	5.058971318815e-02	-3.791312599700e-03	-3.833049897763e-03
1	5.222489871516e-03	1.003438746972e-02	-1.168850382452e-03
2	-1.641664176824e-02	-4.107214837202e-03	1.967371773324e-03
3	3.430116367838e-03	2.838382928506e-04	-4.209650788467e-04
4	-9.020143604576e-05	1.347016172889e-04	-4.958012853527e-06
5	1.188821428901e-05	-3.313627492240e-05	8.279160796936e-06
6	-1.041943673755e-05	3.202234108937e-06	-5.675677716610e-07
7	1.271716123512e-06	-1.476246727512e-07	-1.066910658350e-08
8	-4.477991722400e-08	2.709447373704e-09	1.358296626830e-09

E Index / T Index	6	7	8
0	7.950734542136e-04	-5.885681325041e-05	1.541378919766e-06
1	-5.579601385349e-05	1.353899796842e-05	-5.122850004231e-07
2	-2.673125550197e-04	1.566853623054e-05	-3.415999363201e-07
3	7.898192930901e-05	-5.854327119904e-06	1.562313674827e-07
4	-4.094959727394e-06	5.353989855247e-07	-1.913396611346e-08
5	-6.413236333283e-07	4.848646930188e-09	8.121470593220e-10
6	3.608129963110e-08	5.274666256825e-10	-8.954629500955e-11
7	4.563092914087e-09	-4.419337156204e-10	1.449959132985e-11
8	-2.914831320408e-10	2.266195254549e-11	-6.387372749942e-13

Error 2.14e-04 (A)

Reaction 3.3.6b $p + He^{*}(1s2s|^{3}S) \rightarrow H^{*}(2s) + He^{+}(1s)$

T Index \ E Index	0	1	2
0	-3.122938685456e+01	4.028257956860e-01	2.334348862506e-01
1	4.307517366770e+00	-1.334773437980e-01	-2.727882564258e-01
2	-2.361736602090e-02	-1.432708434183e-01	1.201423191752e-01
3	-2.081939800843e-01	9.945616177435e-02	-2.709414076376e-02
4	4.838048334741e-02	-2.358233412220e-02	4.734052652172e-03
5	-4.823009462310e-03	2.401135023266e-03	-8.658412840062e-04
6	1.881322513534e-04	-6.847646462892e-05	1.174757836154e-04
7	1.638221308510e-06	-4.485862371494e-06	-8.367996886287e-06
8	-2.228643990360e-07	2.485885176817e-07	2.302713313337e-07

T Index \ E Index	3	4	5
0	9.957171612712e-02	-1.023449426184e-02	-4.496822279877e-03
1	-6.164153370524e-02	3.370797060231e-02	-3.319571865630e-03
2	1.135420376951e-02	-1.984294955107e-02	4.774462913892e-03
3	6.080332812779e-04	3.775623225478e-03	-1.322011971814e-03
4	-1.366781281246e-03	1.119535101746e-04	8.050305381600e-05
5	4.843193058320e-04	-1.376705233410e-04	1.437228606346e-05
6	-7.634853296888e-05	1.971646855797e-05	-2.212285070187e-06
7	5.557461570216e-06	-1.186541505079e-06	9.199979549866e-08
8	-1.522032174656e-07	2.678514729721e-08	-6.757808737035e-10

T Index \ E Index	6	7	8
0	9.241247688814e-04	-6.358490712348e-05	1.525433983093e-06
1	-8.936775061168e-05	2.722213770738e-05	-1.020668178963e-06
2	-5.033398600438e-04	2.498282187124e-05	-4.741136942425e-07
3	1.886421813109e-04	-1.237062202523e-05	3.083020170351e-07
4	-2.071452083937e-05	1.798870106702e-06	-5.365052965492e-08
5	8.302103147893e-08	-9.892824420452e-08	4.289062541986e-09
6	7.058025912797e-08	4.738735970150e-09	-2.878639826635e-10
7	1.761485514114e-09	-6.097061454789e-10	2.321326366521e-11
8	-2.771866976517e-10	2.928170189987e-11	-8.892938915985e-13

Error 3.14e-04 (B)

Reaction 3.3.7a $p + He^{*}(1s2p|^{1}P) \rightarrow H^{*}(2p) + He^{+}(1s)$

T Index \ E Index	0	1	2
0	-2.096277724233e+01	2.908363629618e-01	1.344210657325e-01
1	1.838253461492e+00	-3.440722063330e-01	-1.075733974740e-01
2	-1.504683700198e-01	1.391168674341e-01	1.407833937250e-02
3	-1.988914332352e-02	-1.827777489629e-02	6.303582937881e-03
4	5.224868789594e-03	-1.503338958950e-03	-1.588632341093e-03
5	7.903708169506e-05	6.281421973346e-04	-5.706206467996e-06
6	-1.088955465421e-04	-5.979073448137e-05	3.124053598819e-05
7	1.035977420345e-05	2.110596750983e-06	-3.069558569915e-06
8	-3.067244916001e-07	-1.576601346659e-08	9.145348279705e-08

T Index \ E Index	3	4	5
0	2.643049515080e-02	-5.367852119278e-03	-1.337347909674e-03
1	1.130230128759e-02	6.583514261893e-03	-1.227749129234e-03
2	-1.376123125770e-02	-8.644040120194e-04	1.013028508387e-03
3	2.150624640205e-03	-4.951984366580e-04	-1.010346550533e-04
4	2.568647734327e-04	1.217005674709e-04	-2.937286287021e-05
5	-7.591611145466e-05	-1.357219951533e-06	4.933729396290e-06
6	3.384790316520e-06	-1.821787693981e-06	5.718370339432e-08
7	2.181939775695e-07	1.762529764553e-07	-4.223388769976e-08
8	-1.459318779306e-08	-5.010568584481e-09	1.790351359196e-09

T Index \ E Index	6	7	8
0	3.643627994364e-04	-2.927921977642e-05	8.016074291976e-07
1	4.333172602701e-05	3.531045210401e-06	-2.066151687336e-07
2	-1.589309518095e-04	1.005180995389e-05	-2.313721814532e-07
3	3.299776657730e-05	-2.892265994707e-06	8.406596588342e-08
4	1.370261783588e-06	9.004843536308e-08	-6.389625540292e-09
5	-7.078827921616e-07	3.342727890413e-08	-3.633168197949e-10
6	1.974622062662e-08	-1.472504522071e-09	1.736212449338e-11
7	4.174185414825e-09	-2.207503317650e-10	5.469661760878e-12
8	-2.233522764425e-10	1.319988966081e-11	-3.154892040215e-13

Error 1.32e-04 (A)

Reaction 3.3.7b $p + He^{*}(1s2p|^{3}P) \rightarrow H^{*}(2p) + He^{+}(1s)$

T Index \ E Index	0	1	2
0	-1.990230529818e+01	2.522093890961e-01	1.239244757420e-01
1	1.500741968514e+00	-2.951590494714e-01	-9.430103505170e-02
2	-1.124864006941e-01	1.201976126897e-01	7.788712358907e-03
3	-1.795417514240e-02	-1.603483373300e-02	7.712444722040e-03
4	5.194941686189e-03	-1.383721748856e-03	-1.777603361970e-03
5	-2.042833130770e-04	6.021103147616e-04	2.064037010474e-05
6	-5.295363277471e-05	-6.246797487185e-05	2.744322340445e-05
7	6.198420111343e-06	2.646123676389e-06	-2.758240361873e-06
8	-1.960046743830e-07	-3.649994467826e-08	8.182448832297e-08

T Index \ E Index	3	4	5
0	1.742021976180e-02	-5.521806381035e-03	-4.054669219838e-04
1	1.218926273762e-02	5.820172532684e-03	-1.295775597112e-03
2	-1.191866922435e-02	-1.362329499044e-04	7.107218103516e-04
3	1.549234171092e-03	-6.809505756955e-04	9.404549508879e-07
4	3.665320868067e-04	1.165229196925e-04	-3.679801125361e-05
5	-1.010994386303e-04	7.956025749673e-06	3.831718379904e-06
6	7.717708517072e-06	-3.365265395665e-06	2.479212041233e-07
7	-1.385756782677e-07	2.808607980980e-07	-5.087249153750e-08
8	-3.853798064799e-09	-7.625575723278e-09	1.871480566627e-09

T Index \ E Index	6	7	8
0	1.843910580845e-04	-1.594987619980e-05	4.473710134751e-07
1	7.954619252281e-05	7.572338624031e-08	-1.024950580103e-07
2	-1.181843011735e-04	7.615476962452e-06	-1.763379176652e-07
3	1.702222446329e-05	-1.814838357759e-06	5.703526185010e-08
4	3.068724996897e-06	-5.005474959780e-08	-2.339128601417e-09
5	-7.153412104701e-07	4.200855361511e-08	-7.453854004436e-10
6	1.745775447721e-08	-2.506978553877e-09	6.748855851556e-11
7	3.524103509748e-09	-9.220739545880e-11	5.381508915908e-13
8	-1.806607060530e-10	7.993276670629e-12	-1.381625354747e-13

Error 1.18e-04 (A)

Reaction 4.2.1 $H_2^+(1s\sigma_g;v) + H(1s) \rightarrow H_2^{+*}(2p\sigma_u) + H(1s)$

$\rightarrow H^+ + H + H(1s)$, (v=0-9)

T Index \ E Index	0	1	2
0	-3.332967494942e+02	1.433058540744e+02	-2.947284166509e+01
1	2.408101998902e+02	-1.362501559544e+02	2.801041076177e+01
2	-8.996254988743e+01	5.285412858800e+01	-1.040643658208e+01
3	2.113931204200e+01	-1.101441118819e+01	1.881216179150e+00
4	-3.311192105349e+00	1.359065776894e+00	-1.560567106434e-01
5	3.429437857518e-01	-1.029838658966e-01	1.219202707337e-03
6	-2.241037042190e-02	4.809469933342e-03	7.390343876677e-04
7	8.329672118744e-04	-1.335338145990e-04	-4.892703647590e-05
8	-1.338140072499e-05	1.818158167900e-06	9.766334115013e-07

T Index \ E Index	3	4	5
0	4.969309555880e+00	-8.148122128593e-01	9.323059658335e-02
1	-2.474427836778e+00	1.543035928035e-01	-3.251763597742e-02
2	5.085589872685e-01	6.361992438909e-02	-2.591606323191e-03
3	-5.077119677970e-02	-1.852297452693e-02	1.600942164119e-03
4	-2.033265136901e-03	9.718962378108e-04	8.040301331558e-06
5	1.601047711063e-03	6.336414922385e-05	-3.788387994691e-05
6	-2.320531548991e-04	2.588021875832e-06	3.001128191660e-06
7	1.473207837914e-05	-1.282873408948e-06	9.991541256156e-09
8	-3.535181371877e-07	5.620757041266e-08	-5.034820677719e-09

T Index \ E Index	6	7	8
0	-5.854170815799e-03	1.656707831222e-04	-1.178234924866e-06
1	5.085816021807e-03	-3.411499000615e-04	8.295196911491e-06
2	-1.089685945002e-03	1.132751576739e-04	-3.266248682724e-06
3	3.805592017920e-05	-8.847884634595e-06	2.721236736970e-07
4	7.171822512541e-07	-7.530004219739e-07	3.651109616529e-08
5	1.786513937009e-06	9.799503679830e-08	-6.480643645772e-09
6	-2.271952317871e-07	1.029652468585e-09	2.338178917351e-10
7	4.685569702988e-09	-2.668266102694e-10	4.756847923643e-12
8	2.048241675655e-10	1.327375467275e-12	-2.566621089266e-13

Error 1.64e-02 (D)

Reaction 4.3.1 $H_2^+ + H_2 \rightarrow H_2 + H_2^+$

T Index \ E Index	0	1	2
0	-2.013143517466e+01	1.875197914224e-01	6.865479604288e-02
1	2.643458086299e-01	-1.177247941077e-01	-6.758032286178e-03
2	7.295645990688e-02	6.053418575149e-03	-1.068656224307e-02
3	-1.022454343675e-02	7.350954380641e-03	6.814213275702e-04
4	-4.801198168030e-03	-1.111612877392e-03	8.373319888351e-04
5	1.141613586234e-03	-1.371389288760e-04	-1.733761953296e-04
6	-3.388853048483e-05	4.426148343648e-05	9.992317920676e-06
7	-6.418225985394e-06	-3.652063962019e-06	1.351312819077e-07
8	3.555592819527e-07	1.012701361110e-07	-1.993091213299e-08

T Index \ E Index	3	4	5
0	6.246595384100e-03	-5.017891372102e-03	-3.907644829287e-04
1	8.585003721992e-03	-3.261863407467e-04	-3.322528542186e-04
2	-9.371235639464e-04	9.735708783528e-04	-9.933049259228e-05
3	-8.156435157073e-04	2.903991825737e-05	3.223596225946e-05
4	1.392977576749e-04	-9.316910697276e-05	8.814981236658e-06
5	1.602610140599e-05	1.464235749797e-05	-2.944711701791e-06
6	-5.333970870280e-06	-2.999105886511e-07	2.275612517364e-07
7	4.285396408056e-07	-7.184302986068e-08	-3.265552364687e-10
8	-1.131561847140e-08	3.678869095972e-09	-3.639982258214e-10

T Index \ E Index	6	7	8
0	2.786239030986e-04	-2.942576591004e-05	9.352275354690e-07
1	6.015471216449e-05	-4.039435357369e-06	9.730479674748e-08
2	-6.786246802840e-06	1.438327767305e-06	-5.530742535057e-08
3	-5.199055182831e-06	2.852443990256e-07	-4.825480212106e-09
4	6.675626166047e-07	-1.325441927019e-07	5.012529587757e-09
5	6.365231650682e-08	1.872976659964e-08	-1.014883015867e-09
6	-1.173422836715e-08	-1.364602870139e-09	9.566404348683e-11
7	1.585228996542e-10	6.431866226702e-11	-4.507074278992e-12
8	2.056662091085e-11	-1.804254277469e-12	9.042973335167e-14

Error 2.58e-04 (A)

Reaction 4.3.2 $H_2^+ + H_2 \rightarrow H_2^+ + H_2^+ + e$

T Index \ E Index	0	1	2
0	-3.361709356815e+01	2.069962590009e+00	-9.010533538327e-01
1	2.233317520475e+00	-2.726590828625e+00	1.643915864856e+00
2	-7.287181470383e-01	1.661423051779e+00	-1.025272729232e+00
3	4.891752418641e-01	-5.973230637071e-01	3.079590537141e-01
4	-1.587248070170e-01	1.357406226261e-01	-4.995160576771e-02
5	2.786295111792e-02	-1.954886177187e-02	4.482229513351e-03
6	-2.710661372128e-03	1.714035434070e-03	-2.108888570649e-04
7	1.370951998574e-04	-8.287462331299e-05	4.245802696647e-06
8	-2.813882491422e-06	1.685813575983e-06	-1.243788238044e-08

T Index \ E Index	3	4	5
0	4.757423977733e-01	-1.173499542871e-01	1.574858380323e-02
1	-5.767723646300e-01	1.225177255213e-01	-1.583053141876e-02
2	3.012750644438e-01	-5.027357052159e-02	5.155737495648e-03
3	-7.997349646419e-02	1.082475428239e-02	-7.031584157104e-04
4	1.041402498039e-02	-1.202077056853e-03	4.396765142500e-05
5	-4.121930331601e-04	2.634686881556e-05	-1.954016523336e-06
6	-4.475697526351e-05	9.018648895762e-06	4.809988527180e-08
7	5.227237760667e-06	-9.414336727644e-07	1.246197373405e-08
8	-1.530261560799e-07	2.877226549741e-08	-8.668284019609e-10

T Index \ E Index	6	7	8
0	-1.166206787765e-03	4.383027530849e-05	-6.348470910454e-07
1	1.209069864044e-03	-4.994507398820e-05	8.566470175705e-07
2	-3.336823259195e-04	1.297196226977e-05	-2.351485202412e-07
3	1.145932327551e-05	8.141233815222e-07	-2.868358002582e-08
4	5.587705467605e-06	-6.600350475588e-07	2.019835260065e-08
5	-3.033359082874e-07	6.422702166049e-08	-2.757788924867e-09
6	-6.552590854175e-08	1.043541445947e-09	1.156250997817e-10
7	6.735598908536e-09	-3.714404901163e-10	1.840510894514e-12
8	-1.644678010990e-10	1.198441513399e-11	-1.614965817473e-13

Error 1.62e-04

Reaction 4.3.3 $H_2^+ + H_2 \rightarrow H_3^+ + H$

T Index \ E Index	0	1	2
0	-2.094582001426e+01	-2.903671854391e-01	-1.484602213957e-01
1	-3.908059227757e-01	5.612290953081e-02	7.311639731340e-02
2	-1.406586222305e-01	3.034165415227e-02	-1.768280719269e-02
3	-2.329090939587e-02	-3.655835575292e-03	-8.362574927676e-04
4	4.478632359998e-03	-2.378407903866e-03	1.315628515286e-03
5	1.028607802560e-03	4.205001381642e-04	-1.125270518181e-04
6	-3.155447765047e-04	1.597095151191e-05	-2.355907533211e-05
7	2.828211032630e-05	-6.662911839399e-06	3.842898711627e-06
8	-8.646163087099e-07	3.261593568923e-07	-1.473565567371e-07

T Index \ E Index	3	4	5
0	-7.788282133984e-02	-2.716693083523e-02	2.888660862916e-03
1	5.829061271518e-02	7.552808963242e-03	-9.437914641041e-03
2	-5.709689089835e-03	7.796493173156e-03	2.150949138545e-03
3	-4.779241336163e-03	-1.812406227884e-03	7.881163019295e-04
4	8.267929702836e-04	-4.230180219524e-04	-2.567042908792e-04
5	1.289639680255e-04	1.253485982824e-04	8.799819972454e-06
6	-3.554580445806e-05	-6.132110996274e-06	2.803562696685e-06
7	2.286178560056e-06	-4.109569999864e-07	-2.529649414563e-07
8	-3.749876424917e-08	2.926978739503e-08	5.144928119898e-09

T Index \ E Index	6	7	8
0	1.962991371294e-03	-2.537688817604e-04	3.167927580722e-06
1	-9.682436127328e-04	6.252187020332e-04	-4.847265436175e-05
2	-5.832002101739e-04	-9.096057686629e-05	1.497380403845e-05
3	1.857587010565e-04	-5.555787804993e-05	2.979712834131e-06
4	2.408905813848e-05	1.512607065092e-05	-1.688827943562e-06
5	-1.011644205055e-05	-1.202093866229e-06	2.611308007476e-07
6	8.619910002153e-07	1.741997695030e-08	-1.925603640419e-08
7	-2.042542214746e-08	1.432103401478e-09	7.102441362723e-10
8	-9.824207587793e-11	-3.870509135647e-11	-1.074647099491e-11

Error 1.90e-04 (A)

$\langle\sigma v\rangle$ < 1.0e-11 for E > 50 eV for the entire T range considered here. The fit gives unphysical values for E > 50 eV in this range and should not be used there.

Reaction 4.4.1 $H_2^+ + He \rightarrow H_2^+ + He^+ + e$

E Index / T Index	0	1	2
0	-4.309726141841e+01	6.475006995833e+00	-1.883249802835e-01
1	1.281172385125e+01	-7.243378485529e+00	5.043373334075e-01
2	-5.890999853236e+00	3.579212080875e+00	-4.030617651034e-01
3	1.885032038426e+00	-1.033881853032e+00	1.536625297945e-01
4	-3.859849765629e-01	1.929288495908e-01	-3.246664649774e-02
5	5.040064801144e-02	-2.379010323165e-02	4.018297415320e-03
6	-4.013079090991e-03	1.869730413126e-03	-2.907360932536e-04
7	1.755528395798e-04	-8.421826651094e-05	1.143340331457e-05
8	-3.214596451062e-06	1.641069021089e-06	-1.897006152308e-07

E Index / T Index	3	4	5
0	-6.707987015268e-01	2.639446649402e-01	-4.723560827520e-02
1	5.831511375074e-01	-2.063394187655e-01	3.239770290912e-02
2	-1.771129376316e-01	6.192783929198e-02	-8.167418547801e-03
3	1.742222425989e-02	-8.070784446837e-03	9.406258713749e-04
4	1.606419041683e-03	1.581892175211e-04	-3.508868395189e-05
5	-4.700427633330e-04	7.455005712397e-05	-5.328157796217e-06
6	3.265369551305e-05	-8.049211111537e-06	1.040817302013e-06
7	-4.917056270388e-07	2.951503045367e-07	-7.703466212797e-08
8	-1.671870630370e-08	-2.615761487320e-09	2.128865104658e-09

E Index / T Index	6	7	8
0	4.533392612738e-03	-2.256809803213e-04	4.569435145102e-06
1	-2.763842540794e-03	1.247895466478e-04	-2.344043545995e-06
2	5.254335475410e-04	-1.537799120839e-05	1.331837837243e-07
3	-3.856233447220e-05	-4.156140436365e-07	5.034959925043e-08
4	3.791183556963e-06	-2.366231626960e-07	5.992973459021e-09
5	-5.795596041141e-07	9.708186393302e-08	-3.488558225848e-09
6	4.399518745143e-10	-7.685681194865e-09	3.468947174405e-10
7	5.520600090967e-09	1.762439907887e-11	-9.396171756462e-12
8	-2.654154152549e-10	1.103963564691e-11	-8.957193708196e-14

Error 8.31e-05 (A)

Reaction 5.2.1 $He^{+} + H_2 \rightarrow He^{+} + H_2^{+} + e$

E Index	0	1	2
T Index			
0	-3.713019551543e+01	4.513880809792e+00	4.465734536727e-01
1	7.312992983242e+00	-4.230698925401e+00	3.363491931239e-01
2	-1.404602569517e+00	1.574352939860e+00	-4.712948306828e-01
3	8.465714459741e-02	-2.805696953923e-01	1.811965461049e-01
4	3.001601051201e-02	1.978938422099e-02	-3.599941390452e-02
5	-9.026893259159e-03	9.283132403167e-04	4.476205535455e-03
6	1.077346431372e-03	-2.592422590385e-04	-3.727829206896e-04
7	-6.008751203326e-05	1.667265275798e-05	1.918105806793e-05
8	1.276481720290e-06	-3.728072837540e-07	-4.453576012678e-07

E Index	3	4	5
T Index			
0	-2.439394070482e-01	4.439220456707e-03	7.345794340485e-03
1	2.216628364304e-01	-5.119093601500e-02	1.943198225007e-03
2	-8.374208591879e-03	2.953035366897e-02	-6.222917082325e-03
3	-3.500869288503e-02	-2.890323734594e-03	2.024599123408e-03
4	1.278467857143e-02	-1.232540236931e-03	-1.666275826514e-04
5	-2.115580254273e-03	3.444824743426e-04	-1.323145031233e-05
6	1.909506623157e-04	-3.388660283649e-05	2.315290984180e-06
7	-9.201901683360e-06	1.408112739218e-06	-6.069498647130e-08
8	1.865212152535e-07	-1.872002189577e-08	-1.479591373403e-09

E Index	6	7	8
T Index			
0	-1.199883122444e-03	7.929882485919e-05	-1.987990204346e-06
1	4.465865599601e-04	-5.004811416214e-05	1.512094392826e-06
2	5.950227580914e-04	-2.787837758738e-05	5.190549973795e-07
3	-2.984004616508e-04	1.902451334721e-05	-4.579503385483e-07
4	4.481020441245e-05	-3.425924289459e-06	9.026683813135e-08
5	-2.146946788021e-06	2.383193769092e-07	-6.906305571460e-09
6	6.088037548996e-09	-7.326969450051e-09	2.239693051242e-10
7	-4.353244789583e-09	4.457527394302e-10	-9.398012612903e-12
8	3.962791753244e-10	-2.513406814921e-11	5.068098237861e-13

Error 8.03e-04 (B)

Reaction 5.2.2 $He^{+} + H_2 \rightarrow He + H_2^{+}$

T Index \ E Index	0	1	2
0	-3.617851314340e+01	8.245563741195e-01	1.415890461293e-01
1	6.564887398262e-01	-3.337749950700e-01	-1.008073891739e-03
2	9.531332794256e-02	-1.931877094955e-02	-2.177569825223e-02
3	-1.790261298028e-02	2.362156898359e-02	2.481269859100e-03
4	7.873069533268e-03	2.305021543232e-05	1.062397303161e-03
5	1.625577954098e-03	-1.341341170672e-03	-2.453799729668e-04
6	-6.243925896235e-04	2.389932224800e-04	1.310149299938e-05
7	5.723897329155e-05	-1.662664310436e-05	4.255519558344e-07
8	-1.690364064992e-06	4.200646087287e-07	-3.882714153340e-08

T Index \ E Index	3	4	5
0	-5.245109545409e-02	2.574263879790e-03	5.081113179086e-03
1	2.353864809890e-02	-8.611685556552e-04	-1.235953005371e-03
2	6.296784545643e-03	8.056466799286e-04	-4.422528088809e-04
3	-3.194145659097e-03	5.097167452777e-05	1.492942136767e-04
4	-2.226509858382e-04	-7.132717180757e-05	1.590997815012e-05
5	2.171893645658e-04	-1.504822330128e-06	-7.627038293158e-06
6	-3.205058255713e-05	3.153131057610e-06	5.374886487540e-07
7	1.892187997659e-06	-3.671662723350e-07	1.240410469109e-08
8	-3.981815711162e-08	1.257613148417e-08	-1.559147916406e-09

T Index \ E Index	6	7	8
0	-1.105146703191e-03	8.466844977067e-05	-2.264180150260e-06
1	2.385360257195e-04	-1.708395525986e-05	4.375864733045e-07
2	5.451070303994e-05	-2.660983244927e-06	4.244385976642e-08
3	-2.350969502990e-05	1.328072187288e-06	-2.480965060631e-08
4	-5.247303578452e-08	-1.381151133836e-07	6.646376709202e-09
5	7.408427546641e-07	-8.825036538220e-10	-1.353868832823e-09
6	-6.764350122786e-08	-8.407299219054e-10	1.978309478483e-10
7	-5.125341539638e-10	2.770888875227e-10	-1.654942575020e-11
8	1.599391141086e-10	-1.434870919386e-11	5.493012109985e-13

Error 6.06e-04 (B)

Reaction 5.2.3 $He^{+} + H_2 \rightarrow He + H^{+} + H$

E Index / T Index	0	1	2
0	-3.569345457680e+01	5.467675953787e+00	-1.525452874272e+00
1	6.602257860447e+00	-5.860473216356e+00	2.567792367148e+00
2	-1.802030727618e+00	2.776708580765e+00	-1.456435131755e+00
3	5.980682857428e-01	-7.669462419521e-01	3.877769522782e-01
4	-1.515033763091e-01	1.355123344697e-01	-5.328079168644e-02
5	2.273923829034e-02	-1.552431054752e-02	3.680122521552e-03
6	-1.950876085219e-03	1.107193551999e-03	-9.861964956657e-05
7	8.879641773477e-05	-4.427419374545e-05	-8.643444105803e-07
8	-1.662550081283e-06	7.525447749722e-07	5.761680732896e-08

E Index / T Index	3	4	5
0	7.645781657996e-01	-2.285145605072e-01	3.561471492616e-02
1	-7.921692885504e-01	1.791134818786e-01	-2.709395158440e-02
2	3.727025613660e-01	-5.373124189344e-02	4.827265290690e-03
3	-9.180531536723e-02	9.188213414014e-03	8.930961476819e-05
4	1.152256687649e-02	-1.182322907825e-03	-1.868126294929e-05
5	-5.961207420320e-04	1.152911876232e-04	-1.321659022007e-05
6	-7.612968632797e-06	-6.066035684733e-06	1.527361008857e-06
7	1.816255353042e-06	4.628107113547e-08	-1.127225337804e-08
8	-4.462116763253e-08	5.201413577832e-09	-2.441066078656e-09

E Index / T Index	6	7	8
0	-3.040755662326e-03	1.357901348722e-04	-2.481641682718e-06
1	2.495321136581e-03	-1.249516606345e-04	2.598469347617e-06
2	-3.006881501965e-04	1.324810154101e-05	-3.023835422188e-07
3	-9.701225760383e-05	7.510874054331e-06	-1.880555391455e-07
4	1.703238064971e-05	-1.506318180829e-06	4.324855274434e-08
5	1.049002267297e-07	7.987013573220e-08	-3.751370813720e-09
6	-4.649027875076e-08	-8.266614643058e-09	4.561224301361e-10
7	-9.674327862739e-09	1.432037876831e-09	-5.371138414560e-11
8	6.786765390955e-10	-6.724210849363e-11	2.191944328954e-12

Error 3.75e-04 (B)

Reaction 5.3.1 $He^{+} + He \rightarrow He + He^{+}$

E Index / T Index	0	1	2
0	-1.992795874184e+01	1.866121633782e-01	5.632774905403e-02
1	2.342319832717e-01	-1.085479286023e-01	-5.796164637185e-03
2	5.150488618567e-02	5.502643799842e-03	-1.070448355458e-02
3	-4.457831664145e-03	6.751016280248e-03	1.348104812381e-03
4	-1.543592188979e-03	-9.368501420643e-04	6.678034019800e-04
5	3.127935819690e-04	-1.564547327374e-04	-1.638591652038e-04
6	-1.478649318411e-05	4.454044051200e-05	1.091423551219e-05
7	-4.796924334410e-07	-3.559977035839e-06	1.429006251276e-08
8	3.623344342191e-08	9.673665606073e-08	-1.626046817162e-08

E Index / T Index	3	4	5
0	-1.523524839309e-03	-2.153750537851e-03	3.308881419986e-04
1	7.964340512260e-03	-2.259674261582e-04	-3.444207072047e-04
2	-2.811049856343e-04	8.802921038196e-04	-1.198248793959e-04
3	-1.009960297392e-03	-2.397230757181e-05	5.675989835329e-05
4	1.271484361215e-04	-7.802314691135e-05	5.096915155186e-06
5	2.743635453507e-05	1.364264736037e-05	-3.146182664420e-06
6	-6.757942983709e-06	-3.524476702306e-07	2.858958575343e-07
7	4.890540879010e-07	-6.293604516614e-08	-2.702231414235e-09
8	-1.188613673713e-08	3.383446775161e-09	-3.684509743141e-10

E Index / T Index	6	7	8
0	-1.293912998397e-05	-4.067520041201e-07	2.451185017055e-08
1	6.164032099379e-05	-4.156975252360e-06	1.009896955766e-07
2	-7.766013174537e-07	9.213287306897e-07	-4.014244306169e-08
3	-8.581799112319e-06	4.932159877322e-07	-9.746139175914e-09
4	1.122093772403e-06	-1.600545758983e-07	5.662679103625e-09
5	9.721160837100e-08	1.677569938034e-08	-9.661966135256e-10
6	-1.739320039203e-08	-1.179041806243e-09	9.352212060009e-11
7	5.123073994873e-11	9.702183602739e-11	-5.755013542991e-12
8	3.976640871840e-11	-4.096335085504e-12	1.667878217006e-13

Error 2.36e-05 (A)

Reaction 5.3.2 $He^+ + He \rightarrow He^+ + He^+ + e$

E Index / T Index	0	1	2
0	-6.749257304678e+01	3.080627051012e+01	-1.145813141153e+01
1	4.329467261355e+01	-4.031602483159e+01	1.707905481142e+01
2	-2.016026525056e+01	2.231984392732e+01	-1.017738982563e+01
3	5.878320131150e+00	-6.882901423348e+00	3.201825080229e+00
4	-1.137799010228e+00	1.302313958330e+00	-5.884044412402e-01
5	1.450552810169e-01	-1.555507288279e-01	6.537275456166e-02
6	-1.155793628115e-02	1.147650951410e-02	-4.329368714852e-03
7	5.167930765975e-04	-4.781324647004e-04	1.576230053609e-04
8	-9.839244996808e-06	8.600494351291e-06	-2.434988045802e-06

E Index / T Index	3	4	5
0	3.388015690088e+00	-7.536552992052e-01	1.094516886818e-01
1	-4.478579850964e+00	8.066021028840e-01	-9.979059856890e-02
2	2.509824455963e+00	-3.656980663805e-01	3.191586604783e-02
3	-7.552669555755e-01	9.255840851869e-02	-4.641142473768e-03
4	1.311191744239e-01	-1.402143172466e-02	3.427843990627e-04
5	-1.323051154888e-02	1.229786796421e-03	-2.028911469770e-05
6	7.369414642692e-04	-5.269558335123e-05	1.766303852396e-06
7	-1.928032791874e-05	3.603057782872e-07	-1.010518517671e-07
8	1.339321812560e-07	3.028039050683e-08	1.838236320858e-09

E Index / T Index	6	7	8
0	-9.463880450938e-03	4.398620168160e-04	-8.450244877636e-06
1	7.955955791002e-03	-3.617178669983e-04	7.048366766523e-06
2	-1.586656930186e-03	3.830211108983e-05	-2.609071874454e-07
3	-1.294999476918e-04	2.388282840962e-05	-7.277202967312e-07
4	6.774806939936e-05	-6.211048957431e-06	1.613570924718e-07
5	-4.743973580278e-06	3.064327230164e-07	-4.853224348333e-09
6	-3.419422565839e-07	4.593362543917e-08	-1.743858127735e-09
7	5.170772455352e-08	-5.600340502767e-09	1.859063429189e-10
8	-1.602801532247e-09	1.701252086315e-10	-5.520060744854e-12

Error 1.35e-03 (C)

Reaction 6.1.1 $He^{2+} + H(1s) \rightarrow He^{2+} + H^{*}(2p)$

T Index \ E Index	0	1	2
0	-3.128291192763e+01	-3.861939808947e-01	-2.544645152942e+00
1	-6.826991894490e-01	-8.408347453138e-01	2.629943082927e-01
2	-1.441334316248e+00	1.422092876991e-01	2.002181867767e-01
3	3.169981863524e-01	1.363426173469e-01	-3.622433372588e-02
4	1.440567980361e-01	-5.023547473715e-02	-2.472425668256e-03
5	-5.309434904043e-02	6.625411757408e-03	1.347168808606e-03
6	6.713712881021e-03	-3.657613813881e-04	-1.801819884810e-04
7	-3.836344721605e-04	4.833466842639e-06	1.173107765224e-05
8	8.388799849538e-06	1.548286845930e-07	-3.101524382401e-07

T Index \ E Index	3	4	5
0	4.669451368190e-01	2.917550661840e-01	-1.053780859061e-01
1	9.881934763967e-02	-5.354197329704e-02	9.617629874772e-03
2	-2.373167102469e-02	-1.943544641502e-02	6.728262805201e-03
3	-2.125279295018e-02	8.196892532228e-03	-1.126751334420e-03
4	5.090021728980e-03	-1.140089320112e-03	6.794493424970e-05
5	-8.841712146365e-05	1.628036645708e-05	-8.948432185115e-06
6	-6.309125180824e-05	1.390057420949e-05	5.519228022295e-07
7	5.917408932712e-06	-1.490516597840e-06	5.820616731175e-08
8	-1.596933841423e-07	4.769562622033e-08	-4.561904992676e-09

T Index \ E Index	6	7	8
0	1.364529328613e-02	-8.022046090155e-04	1.802849723372e-05
1	-8.611117374892e-04	3.908664672328e-05	-7.212446215523e-07
2	-9.041409091166e-04	5.666864142514e-05	-1.373057978697e-06
3	7.645412457648e-05	-2.667684868645e-06	4.124172622729e-08
4	7.368858127714e-06	-1.106305479253e-06	3.817455135007e-08
5	5.678884593513e-07	4.642154492296e-08	-3.598042180209e-09
6	-1.911269421448e-07	6.044313534001e-09	1.456318833459e-10
7	3.639779928913e-09	6.910541467229e-11	-2.002452819345e-11
8	3.328417422480e-10	-2.908652620490e-11	1.180447220494e-12

Error 9.47e-04 (B)

Reaction 6.1.3 $He^{2+} + H(1s) \rightarrow He^{2+} + H^{+} + e$

E Index / T Index	0	1	2
0	-3.213525339461e+01	4.048855987534e-01	-1.459217274977e+00
1	8.616833916021e-01	-6.950245301215e-01	-5.645946950077e-01
2	-1.516319957636e+00	-3.812512076134e-01	1.893299195739e-01
3	1.006874043269e-01	2.037666264960e-01	2.977523227454e-02
4	1.821009470616e-01	-1.888567920879e-03	-1.257914490683e-02
5	-5.204900520164e-02	-1.011975370629e-02	1.459518537491e-03
6	6.024060604719e-03	1.811281409653e-03	-1.071747691134e-04
7	-3.279965879464e-04	-1.255314364414e-04	6.740808642651e-06
8	6.955537637694e-06	3.158339223563e-06	-2.201431842876e-07

E Index / T Index	3	4	5
0	1.832446087964e-01	1.820448886287e-01	-5.894612068336e-02
1	1.997861354267e-01	2.296013792400e-02	-1.598128574471e-02
2	2.287526434742e-02	-2.230595108739e-02	5.497523259018e-03
3	-3.596233294198e-02	4.420728440672e-03	3.823858799635e-04
4	3.554216072576e-03	-5.852198392288e-04	-1.045811648109e-05
5	8.588876790382e-04	2.884916307632e-06	-3.389979591571e-05
6	-1.914502607375e-04	1.361700778479e-05	3.642721103256e-06
7	1.338794701145e-05	-1.635502392200e-06	-3.684855814169e-08
8	-3.236734300402e-07	5.702927636593e-08	-4.938860692978e-09

E Index / T Index	6	7	8
0	7.308767351095e-03	-4.181939938771e-04	9.207950478799e-06
1	2.380832450865e-03	-1.504225027785e-04	3.547002873170e-06
2	-6.993554812224e-04	4.516232482147e-05	-1.154715783315e-06
3	-1.099529103897e-04	7.543892418062e-06	-1.708252421708e-07
4	1.672568631267e-05	-1.836430836869e-06	6.080236805727e-08
5	2.793668955085e-06	3.838407710178e-08	-6.689521714938e-09
6	-3.804617509593e-07	-2.464497412799e-09	8.281161472560e-10
7	5.704885906583e-10	1.543017124482e-09	-8.445486242553e-11
8	7.699246994125e-10	-8.580250216262e-11	3.189523199623e-12

Error 1.32e-03

Reaction 6.1.6 $He^{2+} + H \rightarrow He^{+*}(n=2) + H^{+}$

T Index \ E Index	0	1	2
0	-2.684068918587e+01	1.077159851869e+00	1.611434095003e-01
1	5.117541237230e-01	-3.292088112707e-01	4.193651221864e-02
2	1.598500363509e-01	-3.812957840397e-02	-2.103399170458e-02
3	1.228188346785e-02	1.765620781249e-02	-4.556545487291e-03
4	-4.554467900719e-03	9.457132816015e-04	1.645608151050e-03
5	-2.778583050511e-04	-7.305848198936e-04	4.612991944463e-05
6	1.538644839183e-04	8.140980182115e-05	-4.793549304493e-05
7	-1.499611384855e-05	-3.278119258256e-06	4.727047352918e-06
8	4.697369923421e-07	3.332532647980e-08	-1.433575769997e-07

T Index \ E Index	3	4	5
0	-1.941671951055e-02	-3.364587603920e-03	1.137572625288e-03
1	1.365931518647e-02	-3.060504283824e-03	-2.183962062545e-04
2	5.585565653003e-03	7.325879113415e-04	-3.247877168930e-04
3	-1.963806169076e-03	5.344561040129e-04	1.955747622998e-05
4	-2.070478545640e-04	-1.384142733303e-04	3.281664341316e-05
5	9.376080341880e-05	-4.104939830509e-06	-4.823335474719e-06
6	-6.580665188724e-06	3.695002531601e-06	-2.170325944322e-07
7	-8.828451438638e-08	-3.495383517796e-07	6.589695469087e-08
8	1.452542457751e-08	1.021940844352e-08	-2.746221662026e-09

T Index \ E Index	6	7	8
0	-1.030059621084e-04	1.662587903156e-06	9.868838320179e-08
1	1.038012581189e-04	-9.397899971402e-06	2.755750977475e-07
2	3.172192984549e-05	-9.448677346635e-07	-3.817181255094e-09
3	-1.514747820761e-05	1.426520725713e-06	-4.189371841853e-08
4	-1.906464376446e-06	-4.474317916254e-08	4.942196257155e-09
5	7.911914689813e-07	-4.216279314031e-08	6.314000693621e-10
6	-3.184743031465e-08	3.644605422841e-09	-9.468908601909e-11
7	-4.423644969643e-09	9.850791365204e-11	1.012931336353e-13
8	2.722901729050e-10	-1.217986052601e-11	2.087076950595e-13

Error 3.45e-04 (B)

Reaction 6.2.1 $He^{2+} + H_2 \rightarrow He^{2+} + H_2^+(v) + e$

E Index / T Index	0	1	2
0	-3.740458528875e+01	4.819839382288e+00	-1.368722314416e+00
1	3.697794623317e+00	-4.260575420078e+00	2.274586443382e+00
2	-1.952883135699e-01	1.519624000877e+00	-1.186623344815e+00
3	4.006262224030e-02	-2.914307027385e-01	2.640808145769e-01
4	-4.786632316714e-02	3.732741697654e-02	-2.125640108014e-02
5	1.435334952996e-02	-4.126872601223e-03	-1.316704448334e-03
6	-1.857371914077e-03	3.915654055393e-04	3.686192037472e-04
7	1.126777142893e-04	-2.328456641412e-05	-2.488855854519e-05
8	-2.637987783791e-06	5.796033701332e-07	5.770496917262e-07

E Index / T Index	3	4	5
0	5.415964848279e-01	-1.558092591583e-01	2.673033645460e-02
1	-7.477112914979e-01	1.630231019898e-01	-2.322732220110e-02
2	3.996652574630e-01	-7.388600606929e-02	8.214102149542e-03
3	-9.703573952883e-02	1.783463570481e-02	-1.705433511392e-03
4	8.833454031367e-03	-2.009464031032e-03	2.249935053360e-04
5	5.248086049074e-04	-8.919967388651e-06	-1.246262891020e-05
6	-1.737291298205e-04	2.577341999196e-05	-9.482137841850e-07
7	1.300558673415e-05	-2.344702491575e-06	1.629428614542e-07
8	-3.314156416545e-07	6.741539632029e-08	-5.955349313768e-09

E Index / T Index	6	7	8
0	-2.578884501918e-03	1.294681717674e-04	-2.635783475569e-06
1	2.040440748140e-03	-9.909710584927e-05	2.022083060567e-06
2	-5.623626152450e-04	2.244646297525e-05	-4.065894891850e-07
3	7.664104809530e-05	-8.191992528308e-07	-2.753294486929e-08
4	-9.861657413217e-06	-9.995859937832e-08	1.424254131071e-08
5	1.395191641953e-06	-3.685926734937e-08	-5.729382287379e-10
6	-9.379121901004e-08	7.777171419994e-09	-1.213248180319e-10
7	-2.275396327537e-10	-4.097026715756e-10	1.086349587424e-11
8	1.692734428835e-10	4.442825612279e-12	-2.196742224277e-13

Error 1.95e-04 (A)

Reaction 6.3.1 $He^{2+} + He \rightarrow He + He^{2+}$

E Index / T Index	0	1	2
0	-2.087067966395e+01	1.770710917672e-01	5.286663352724e-02
1	2.094653607929e-01	-1.035630036136e-01	-1.587484833047e-03
2	4.515569927112e-02	7.753021609986e-03	-1.172352137681e-02
3	-2.156818929353e-03	5.844613611271e-03	1.584520908151e-03
4	-1.034417290024e-03	-9.988691720266e-04	6.430330809960e-04
5	6.711410038952e-05	-9.039725081170e-05	-1.686928979307e-04
6	1.634228365980e-05	3.360212044374e-05	1.244878523706e-05
7	-2.018162243333e-06	-2.811596499823e-06	-1.289872750639e-07
8	5.700761275390e-08	7.785762968811e-08	-1.168383579394e-08

E Index / T Index	3	4	5
0	-4.108533645663e-03	-1.682325393036e-03	6.311322867200e-04
1	6.980778548791e-03	-4.701965411677e-04	-2.345754812673e-04
2	7.248911771056e-05	8.809460604163e-04	-1.426429587991e-04
3	-1.074296069145e-03	-1.654629083347e-05	5.761893046505e-05
4	1.311854988163e-04	-7.851442095351e-05	5.422244523002e-06
5	2.782958218572e-05	1.353549005040e-05	-3.148005712744e-06
6	-6.878943315863e-06	-3.391029687238e-07	2.812067777116e-07
7	5.026743092262e-07	-6.291522264312e-08	-2.775917122056e-09
8	-1.243441979051e-08	3.348779288410e-09	-3.430378749002e-10

E Index / T Index	6	7	8
0	-1.034343472222e-04	8.284373934314e-06	-2.585107151364e-07
1	4.656851963845e-05	-3.237799181386e-06	7.973037168095e-08
2	3.719681370598e-06	5.772787018529e-07	-3.063528285547e-08
3	-8.884055251880e-06	5.210682232168e-07	-1.062878498510e-08
4	1.051027365170e-06	-1.540544793432e-07	5.483293214541e-09
5	1.019425830844e-07	1.607622514801e-08	-9.352273349479e-10
6	-1.692119208451e-08	-1.156062045162e-09	9.051243592979e-11
7	8.794108865463e-11	8.904209111206e-11	-5.320379447337e-12
8	3.429943174964e-11	-3.505937279725e-12	1.434656878037e-13

Error 1.09e-04 (A)

Reaction 6.3.2 $He^{2+} + He \rightarrow He^{2+} + He^{+} + e$

T Index \ E Index	0	1	2
0	-3.357512088469e+01	2.481002270207e-01	-2.844754225626e-01
1	2.132558452382e-01	-2.898782569957e-02	-8.859152207456e-02
2	-7.629285367047e-01	-1.246031034296e-02	4.339076002927e-02
3	5.899289086465e-02	3.450829479956e-03	1.171516743657e-02
4	9.617944830667e-02	8.115543683934e-04	-8.351029524143e-03
5	-2.754369102041e-02	-5.252894338980e-04	1.845370884466e-03
6	3.193662877844e-03	9.140552891498e-05	-2.084303350442e-04
7	-1.743435861477e-04	-6.732493173329e-06	1.209578227317e-05
8	3.702563187159e-06	1.817766164959e-07	-2.844186742354e-07

T Index \ E Index	3	4	5
0	-5.040226778288e-02	3.354002274183e-02	-1.866620628241e-03
1	1.729393805563e-02	4.254520286926e-03	-1.601440080094e-03
2	-3.393002840651e-03	1.091192986540e-03	-4.407674396150e-04
3	-1.741588094600e-03	-1.275836278696e-03	3.728086620067e-04
4	1.074669748613e-03	1.010631022949e-04	-4.311397774907e-05
5	-2.123309981019e-04	2.130784765152e-05	-3.112264677191e-06
6	1.979855424701e-05	-3.124685666404e-06	7.997641396203e-07
7	-8.939845877979e-07	9.995018170226e-08	-4.204213158284e-08
8	1.584012353330e-08	7.506298931854e-10	5.227401148548e-10

T Index \ E Index	6	7	8
0	-4.168527021261e-04	5.230828266632e-05	-1.675138710355e-06
1	1.850932900121e-04	-9.312584153371e-06	1.726529087665e-07
2	5.983672818341e-05	-3.329152402921e-06	6.553879080128e-08
3	-3.777955894029e-05	1.581526045462e-06	-2.076968820260e-08
4	5.700910741004e-06	-3.693703626455e-07	9.504432686918e-09
5	-1.055200072961e-07	4.925799326252e-08	-2.289228094874e-09
6	-4.220795463450e-08	-3.412218769390e-09	2.463341794395e-10
7	3.190991837665e-09	1.145196210456e-10	-1.210616102483e-11
8	-5.846914988817e-11	-1.673892090785e-12	2.258466544149e-13

Error 8.04e-05

Reaction 7.2.1 $p + H^- \rightarrow p + H + e$

T Index \ E Index	0	1	2
0	-5.820131282154e+01	-4.418295075826e-01	1.273789037973e+00
1	7.921427713311e+00	4.771816683717e-01	-3.122978202046e-02
2	2.729868361636e+00	-1.003942758610e+00	-1.263868632256e-01
3	-1.702566612373e+00	5.785696129573e-01	-4.732954195668e-03
4	3.973780588321e-01	-1.478528997647e-01	1.158502169314e-02
5	-4.870825299595e-02	1.969477666027e-02	-2.123634522072e-03
6	3.236718833237e-03	-1.407103305708e-03	1.493109405401e-04
7	-1.084755026674e-04	4.998674210260e-05	-3.376656915211e-06
8	1.396208954849e-06	-6.620153170835e-07	-2.627392847530e-08

T Index \ E Index	3	4	5
0	1.527207940425e+00	-7.536424630223e-01	1.439466388013e-01
1	-7.888775801865e-01	3.288138016027e-01	-5.784931758231e-02
2	1.435920376766e-01	-3.733709098912e-02	5.120254991289e-03
3	-1.244717631219e-02	-8.125405039157e-04	5.304019788343e-04
4	1.217335613258e-03	1.744838040179e-05	-6.302890522722e-05
5	-1.652073669891e-04	7.132512952865e-05	-7.166374800128e-06
6	9.210684173413e-06	-6.258784083367e-06	9.976414798586e-07
7	1.518653946410e-07	-5.285593274691e-09	-1.618019219414e-08
8	-1.935457835554e-08	1.017637467796e-08	-9.682272656474e-10

T Index \ E Index	6	7	8
0	-1.390229840299e-02	6.747109860492e-04	-1.308869018310e-05
1	5.240004832333e-03	-2.411772118083e-04	4.478567757510e-06
2	-4.068737543562e-04	1.774870848760e-05	-3.291488867455e-07
3	-5.311181815494e-05	1.788414701774e-06	-8.455601658664e-09
4	8.167685239892e-06	-4.004411200193e-07	6.703922705847e-09
5	-2.654278454630e-08	4.575052609148e-08	-1.985275499541e-09
6	-3.804512852913e-08	-3.484409058380e-09	2.245422239581e-10
7	1.247165282825e-09	1.121719496535e-10	-9.065883281241e-12
8	1.821912346903e-11	-3.038200599319e-13	7.144344819156e-14

Error 5.01e-04 (B)

Reaction 7.2.2 $p + H^- \rightarrow H^*(n=2) + H(1s)$

T Index \ E Index	0	1	2
0	-2.009840732855e+01	2.945311019841e-01	6.747596918807e-02
1	5.206452202262e-01	-1.774365164859e-01	-1.065938217336e-02
2	1.523257622741e-01	9.772247255291e-03	-1.671909485907e-02
3	2.453955732425e-02	1.021908459294e-02	2.438519414977e-03
4	-6.480928896115e-03	-1.242525298942e-03	1.015757625636e-03
5	-1.975172853627e-03	-2.672450143654e-04	-2.328706013052e-04
6	5.435998708470e-04	6.631970392344e-05	9.462039923651e-06
7	-4.472026617583e-05	-4.970789806324e-06	8.120583670855e-07
8	1.251083879369e-06	1.282034444684e-07	-5.184939728768e-08

T Index \ E Index	3	4	5
0	5.281180712235e-02	1.853075990865e-03	-5.214983547816e-03
1	8.534567745269e-03	-2.015642900438e-04	-1.875060648516e-04
2	-2.499942893968e-03	1.198848516168e-03	5.837864405510e-05
3	-2.108370566003e-03	-8.621652320901e-05	1.290879800077e-04
4	2.995184004525e-04	-1.140789673124e-04	-3.180399692215e-06
5	7.043847826279e-05	2.122349981883e-05	-5.763532119771e-06
6	-1.718398943085e-05	-4.277037568906e-07	6.826848999792e-07
7	1.233759362312e-06	-1.215395288499e-07	-1.469076279075e-08
8	-2.971450478059e-08	6.283704324845e-09	-5.567626168906e-10

T Index \ E Index	6	7	8
0	9.106146930077e-04	-6.179659482888e-05	1.518671797497e-06
1	2.166774591691e-05	-7.154959806623e-07	3.341578770132e-10
2	-4.532942700372e-05	4.566989804119e-06	-1.425164722921e-07
3	-1.884472793311e-05	1.063634324920e-06	-2.098030063540e-08
4	3.691852062324e-06	-3.822422186488e-07	1.207671501711e-08
5	2.097347343793e-07	2.744685327018e-08	-1.629591430987e-09
6	-4.961730812520e-08	-1.574040495320e-09	1.647011369051e-10
7	3.375069155440e-10	2.528285218582e-10	-1.407865804427e-11
8	1.064408722092e-10	-1.331534803275e-11	5.209521592110e-13

Error 9.91e-04 (B)

Reaction 7.2.3 $p + H^- \rightarrow H^*(n=3) + H(1s)$

T Index \ E Index	0	1	2
0	-1.708169812006e+01	-1.310597645979e-01	-2.016054239030e-02
1	-1.098675942533e-01	8.969312492472e-02	-1.001934703492e-02
2	-2.424453483379e-02	-7.668315551548e-03	1.118173178217e-02
3	8.542779858410e-03	-5.728980402850e-03	-1.374395114022e-03
4	7.546932951352e-04	1.282616012621e-03	-5.242666757105e-04
5	-4.460619874465e-04	-6.407045514906e-06	1.627184981581e-04
6	5.689498536274e-05	-2.131881433227e-05	-1.769191253093e-05
7	-3.155262052836e-06	2.122673795556e-06	8.581432797541e-07
8	6.668405706096e-08	-6.364778304060e-08	-1.541736278733e-08

T Index \ E Index	3	4	5
0	8.964903471778e-03	6.442616660302e-04	-4.660365148908e-04
1	-5.890144705724e-03	1.384217913807e-03	1.779238684618e-05
2	-1.257344700418e-03	-6.729866629037e-04	2.054778233488e-04
3	1.029305874211e-03	-5.123704753586e-05	-4.411992401625e-05
4	-1.091263631596e-04	5.650953446193e-05	-4.197841783909e-06
5	-2.000801209847e-05	-7.808493438675e-06	1.772154859168e-06
6	5.122279431664e-06	1.659419345620e-07	-1.384458129532e-07
7	-3.925060139873e-07	3.050794133610e-08	1.377776084081e-09
8	1.041255114173e-08	-1.512980436877e-09	1.332411705243e-10

T Index \ E Index	6	7	8
0	6.370816676015e-05	-3.782683702643e-06	8.609188888839e-08
1	-3.013382774299e-05	2.954660809114e-06	-8.931384100116e-08
2	-2.315115305809e-05	1.190025285551e-06	-2.326585429997e-08
3	9.037770228405e-06	-6.768442086761e-07	1.812120616012e-08
4	-5.411932096608e-07	8.415741816738e-08	-2.978331246224e-09
5	-9.596489328029e-08	-2.035464169710e-09	2.147130564694e-10
6	1.037345875045e-08	1.399052051710e-11	-1.531475772097e-11
7	-1.232733782717e-11	-2.816042650663e-11	1.402510343416e-12
8	-1.732775970924e-11	1.621564942355e-12	-5.400526340307e-14

Error 1.23e-05 (A)

Reaction 7.3.1 $H^- + H(1s) \rightarrow H(1s) + H^-(1s)$

E Index	0	1	2
T Index			
0	-2.446549884269e+01	2.282921659881e-01	6.932259053475e-02
1	2.634131317967e-01	-1.250144616925e-01	-6.564104931024e-03
2	5.739515657001e-02	1.401243736042e-02	-1.370769740386e-02
3	-3.083480423288e-03	5.762622642079e-03	1.641868158109e-03
4	-2.155324535935e-03	-1.741051127171e-03	8.917026172582e-04
5	7.685873715096e-05	1.906770746936e-04	-1.497853929999e-04
6	8.087530514888e-05	-1.359658266200e-05	-9.370283912465e-06
7	-1.201616211995e-05	9.404454583406e-07	2.798537842077e-06
8	4.838440948297e-07	-3.591774662931e-08	-1.280487901835e-07

E Index	3	4	5
T Index			
0	-1.460337641019e-02	-1.148284334186e-03	1.888298450789e-03
1	1.034238130425e-02	-1.160529409915e-04	-6.554701103747e-04
2	-1.631710543681e-03	1.504466063314e-03	-1.492959802239e-04
3	-1.158102233053e-03	-1.500016779601e-04	1.333539925260e-04
4	3.323370760750e-04	-1.435851350450e-04	8.827631680416e-08
5	-3.852538752998e-05	3.638688148903e-05	-5.971816791477e-06
6	5.240710288295e-06	-2.673369866914e-06	5.756054051438e-07
7	-6.106253322733e-07	3.599735795836e-09	9.761611536846e-09
8	2.617375100182e-08	4.349591668816e-09	-1.894102703596e-09

E Index	6	7	8
T Index			
0	-5.048413591687e-04	5.442003557424e-05	-2.119938012240e-06
1	1.312358086468e-04	-1.025406435973e-05	2.930874591340e-07
2	-1.535700264182e-05	3.028402252514e-06	-1.223371130502e-07
3	-2.335914959456e-05	1.720243174222e-06	-4.737046201928e-08
4	4.695207254022e-06	-5.743305788389e-07	2.072162215301e-08
5	1.312086122421e-07	3.381300299186e-08	-1.846446053198e-09
6	-4.928206213204e-08	1.359692653300e-09	7.095887472625e-12
7	-9.446355577370e-10	1.324857300193e-11	1.212840280599e-12
8	2.250181340057e-10	-1.085735441577e-11	1.640670966131e-13

Error 2.16e-03 (C)

Reaction 7.3.2a $H^- + H \rightarrow H_2^{-*}(\Sigma_g) \rightarrow H + H + e$

E Index / T Index	0	1	2
0	-2.060381621916e+01	5.309100960058e-01	1.392829074695e-01
1	7.588123099350e-01	-3.576940273729e-01	-1.987510302857e-02
2	6.731769657604e-02	4.484233894719e-02	-2.733782810986e-02
3	-2.921355392156e-02	1.482283181415e-02	5.906948645836e-03
4	-8.146699299025e-04	-3.643845685721e-03	9.773942210504e-04
5	1.155948959822e-03	-2.087103325148e-05	-3.907609724337e-04
6	-1.581407518895e-04	6.895932849865e-05	4.008820591876e-05
7	8.836837813921e-06	-6.605304596227e-06	-1.507273917480e-06
8	-1.822275438433e-07	1.936335851996e-07	1.172227886690e-08

E Index / T Index	3	4	5
0	-2.102641710803e-02	-6.781349963009e-03	2.016215809719e-03
1	2.668242766164e-02	-3.261461848245e-04	-1.366958646410e-03
2	-1.554648294430e-03	2.123755455543e-03	-2.773916489042e-04
3	-2.598822894319e-03	-1.875799348857e-04	1.758361880894e-04
4	4.600843838170e-04	-1.448878357902e-04	-1.060700155439e-06
5	2.315526538554e-05	3.237966723085e-05	-5.841079752828e-06
6	-1.092581698940e-05	-2.012024682441e-06	6.606514619140e-07
7	8.757818250078e-07	-1.331205306048e-08	-1.679915115556e-08
8	-2.240888951133e-08	3.415505655444e-09	-3.436228509229e-10

E Index / T Index	6	7	8
0	-2.021191702941e-04	8.841314274130e-06	-1.379541011203e-07
1	2.452687401131e-04	-1.698794209121e-05	4.269734144618e-07
2	9.627819846149e-07	1.668014583065e-06	-7.372505366253e-08
3	-2.636740402205e-05	1.616979349290e-06	-3.621463869178e-08
4	3.717760767389e-06	-3.932211297595e-07	1.249308982925e-08
5	1.129239553545e-07	3.349164498023e-08	-1.726363311444e-09
6	-3.323645378786e-08	-2.310130864690e-09	1.678089205296e-10
7	7.727272538571e-11	2.259701266295e-10	-1.191390422294e-11
8	8.001148282982e-11	-9.879026759786e-12	3.844676704391e-13

Error 7.20e-05 (A)

Reaction 7.3.2b $H^- + H \rightarrow H_2^{-*}(\Sigma_u) \rightarrow H_2 + e$

T Index \ E Index	0	1	2
0	-2.010720050130e+01	9.270256057913e-02	4.064624494679e-02
1	1.269636887793e-01	-4.008719210304e-02	-1.212200218053e-02
2	3.912641450862e-02	-4.922699464361e-03	-2.358617965735e-03
3	2.444823703314e-03	3.862828408110e-03	6.245030315710e-05
4	-1.375395363511e-03	9.136383818175e-05	3.424787531975e-04
5	7.705307936032e-06	-2.452524870403e-04	-4.618148515540e-05
6	2.808922151936e-05	4.232400689568e-05	-2.685853929702e-06
7	-2.890778521667e-06	-2.902579165065e-06	7.058422006406e-07
8	8.872270416775e-08	7.252699730279e-08	-2.925937563766e-08

T Index \ E Index	3	4	5
0	4.009352818185e-03	-1.538314339134e-03	6.474680671630e-06
1	4.382832251342e-03	5.808750658711e-04	-3.518386094650e-04
2	-9.020736846330e-04	3.801661661405e-04	1.342533092878e-05
3	-3.877053574415e-04	-3.173212632597e-05	2.768229470146e-05
4	3.970724372076e-05	-4.033536057563e-05	2.837106654166e-06
5	2.083693473819e-05	7.210478132956e-06	-2.015504293252e-06
6	-4.253675760089e-06	-4.555400231697e-08	1.858779383984e-07
7	2.828822067547e-07	-5.462822668312e-08	-6.645063119276e-10
8	-6.263750441883e-09	2.637137895225e-09	-3.152813312676e-10

T Index \ E Index	6	7	8
0	2.652929923557e-05	-2.559456729654e-06	7.459443536792e-08
1	4.949650860383e-05	-2.957539611478e-06	6.557962278545e-08
2	-1.447007766306e-05	1.557308263715e-06	-5.100926653114e-08
3	-3.314905595837e-06	1.239094303050e-07	-3.472887336273e-10
4	6.818837404440e-07	-9.934681425484e-08	3.579429434382e-09
5	6.344059934988e-08	1.253846512396e-08	-7.317167395513e-10
6	-1.179832220191e-08	-9.932172729863e-10	7.663678877930e-11
7	-5.638246638305e-11	8.392102689376e-11	-4.907260382466e-12
8	3.426087000167e-11	-3.525203792329e-12	1.448748836700e-13

Error 2.06e-05 (A)

Appendix

A. Oscillator Strengths, Radiative Rates, and Excitation Energies for Hydrogen and Helium

A.1 Oscillator Strengths and Radiative Rates for Hydrogen

Table A.1 Oscillator strengths (f_{nm}) and radiative transition probabilities (A_{mn}) for hydrogen.

Transition $n\ell \rightarrow m\ell'$	f_{nm}	$A_{mn}[s^{-1}]$	Transition $n\ell \rightarrow m\ell'$	f_{nm}	$A_{mn}[s^{-1}]$
1s-2p	0.4162	6.265×10^{8}	3s-4p	0.4847	3.065×10^{6}
1s-3p	7.910×10^{-2}	1.672×10^{8}	3s-5p	0.1210	1.638×10^{6}
1s-4p	2.899×10^{-2}	6.818×10^{7}	3s-6p	5.139×10^{-2}	9.551×10^{5}
1s-5p	1.394×10^{-2}	3.437×10^{7}			
1s-6p	7.800×10^{-3}	1.973×10^{7}	3p-4s	3.225×10^{-2}	1.835×10^{6}
			3p-5s	7.428×10^{-3}	9.046×10^{5}
2p-3s	1.359×10^{-2}	6.313×10^{6}	3p-6s	3.032×10^{-3}	5.071×10^{5}
2p-4s	3.045×10^{-3}	2.578×10^{6}			
2p-5s	1.213×10^{-3}	1.289×10^{6}	3p-4d	0.6183	7.037×10^{6}
2p-6s	6.180×10^{-4}	7.350×10^{5}	3p-5d	0.1392	3.391×10^{6}
			3p-6d	5.614×10^{-2}	1.878×10^{6}
2s-3p	0.4349	2.245×10^{7}			
2s-4p	0.1028	9.668×10^{6}	3d-4p	1.099×10^{-2}	3.475×10^{5}
2s-5p	4.193×10^{-2}	4.948×10^{6}	3d-5p	2.210×10^{-3}	1.495×10^{5}
2s-6p	2.163×10^{-2}	2.858×10^{6}	3d-6p	8.420×10^{-4}	7.824×10^{4}
2p-3d	0.6958	6.465×10^{7}	3d-4f	1.018	1.379×10^{7}
2p-4d	0.1218	2.062×10^{7}	3d-5f	0.1566	4.542×10^{6}
2p-5d	4.437×10^{-2}	9.425×10^{6}	3d-6f	5.389×10^{-2}	2.146×10^{6}
2p-6d	2.163×10^{-2}	5.145×10^{6}			

Reference: Wiese et al. (1966)

A.2 Oscillator Strengths Averaged over Angular Momentum Quantum Number for Hydrogen

Table A.2. Oscillator strengths (f_{nm}) and radiative transition probabilities (A_{mn}) averaged over angular momentum quantum numbers, for hydrogen.

Transition $n \to m$	f_{nm}	$A_{mn}[s^{-1}]$	Transition $n \to m$	f_{nm}	$A_{mn}[s^{-1}]$
1-2(L_α)	0.4162	4.699×10^{8}	3-4(P_α)	0.8421	8.986×10^{6}
1-3(L_β)	7.910×10^{-2}	5.575×10^{7}	3-5(P_β)	0.1506	2.201×10^{6}
1-4(L_γ)	2.899×10^{-2}	1.278×10^{7}	3-6(P_γ)	5.584×10^{-2}	7.783×10^{5}
1-5(L_δ)	1.394×10^{-2}	4.125×10^{6}	3-7(P_δ)	2.768×10^{-2}	3.358×10^{5}
1-6(L_ε)	7.799×10^{-3}	1.644×10^{6}	3-8(P_ε)	1.604×10^{-2}	1.651×10^{5}
2-3(H_α)	0.6407	4.410×10^{7}	4-5	1.038	2.699×10^{6}
2-4(H_β)	0.1193	8.419×10^{6}	4-6	0.1793	7.711×10^{5}
2-5(H_γ)	4.467×10^{-2}	2.530×10^{6}	4-7	6.549×10^{-2}	3.041×10^{5}
2-6(H_δ)	2.209×10^{-2}	9.732×10^{5}	4-8	3.230×10^{-2}	1.424×10^{5}
2-7(H_ε)	1.270×10^{-2}	4.389×10^{5}	4-9	1.870×10^{-2}	7.459×10^{4}

Reference: Wiese et al. (1966)

Johnson formula for f_{nm}:

$$f_{nm}(m>n) = \frac{32}{3(\sqrt{3})\pi}\,\frac{n}{m^3}\,\frac{1}{x^3}\,g(n,x),$$

$$x = 1 - \left(\frac{n}{m}\right)^2,$$

$$g(n,x) = g_0(n) + g_1(n)\,\frac{1}{x} + g_2(n)\,\frac{1}{x^2}\,.$$

Table A.3. Coefficients in the Johnson formula.

n =	1	3	≥ 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	+0.07014	0.02947	$n^{-2}(0.3887 - 1.181\ n^{-1} + 1.470\ n^{-2})$

Reference: Johnson (1972)

A.3 Ionization and Excitation Energies of Low-Lying States of Helium

Table A.4. Ionization and excitation energies of low-lying states 1snℓ of helium, with n=1, 2, 3, 4.

State	Singlets, ^1L		Triplets, ^3L	
1snℓ	$E^{exc}_{n\ell}$[eV]	$E^{ion}_{n\ell}$[eV]	$E^{exc}_{n\ell}$[eV]	$E^{ion}_{n\ell}$[eV]
1s2	24.588			
1s2s	20.614	3.973	19.818	4.769
1s2p	21.217	3.371	20.963	3.625
1s3s	22.919	1.669	22.717	1.871
1s3p	23.086	1.502	23.006	1.582
1s3d	23.073	1.515	23.072	1.515
1s4s	23.672	0.9155	23.529	0.9951
1s4p	23.741	0.8470	23.706	0.8812
1s4d	23.735	0.8529	23.735	0.8530
1s4f	23.736	0.8520	23.736	0.8520

For n = 5, 6, and 7 we use an average over angular momentum and total spin.

Table A.5. Ionization and excitation energies of states of helium with n ≥ 5.

State n	$\langle E^{exc}_{n\ell}\rangle_{\ell,spin}$	$\langle E^{ion}_{n\ell}\rangle_{\ell,spin}$
5	24.07	0.52
6	24.71	0.37
7	24.30	0.29
≥8	$E^{ion}_{1s^2} - \frac{Ry}{n^2}$	Ry/n^2

Based on Wiese et al. (1966).

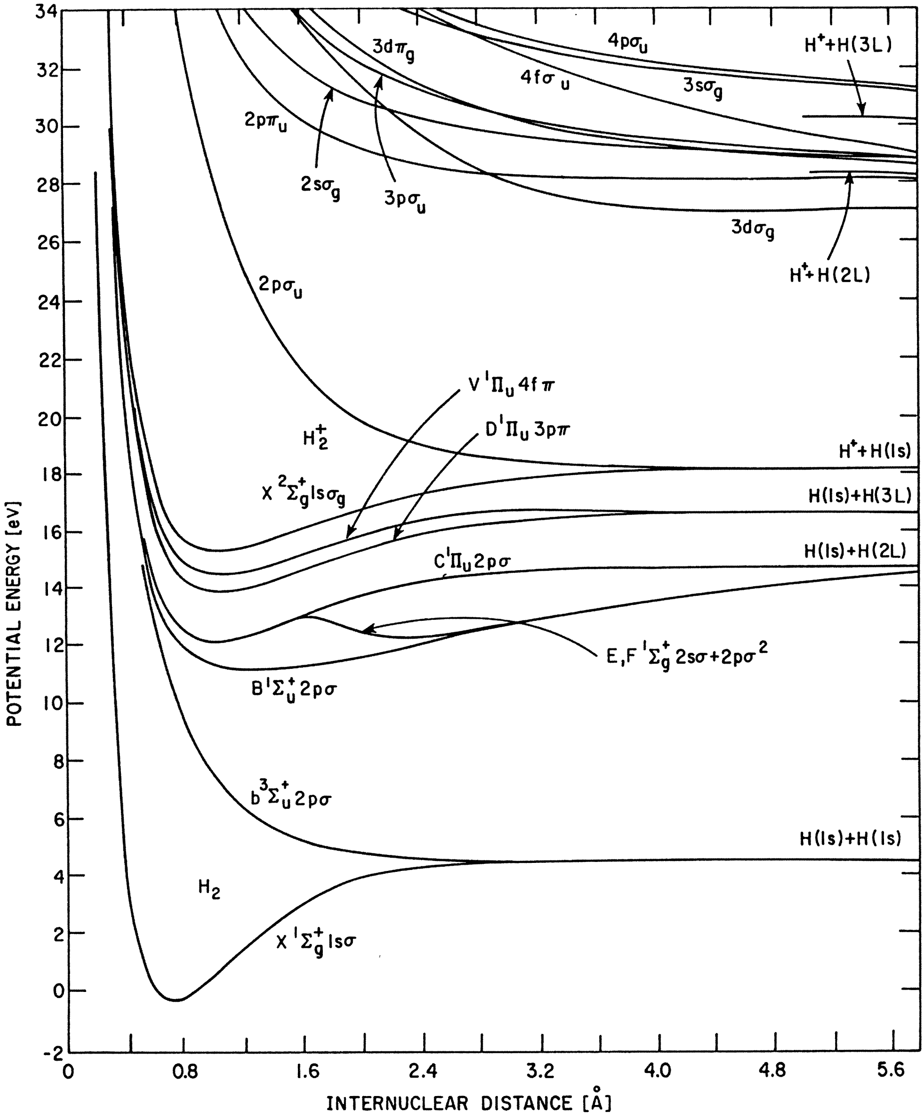
A.4 Oscillator Strengths and Radiative Rates for Helium

Table A.6. Oscillator strengths (f_{nm}) and radiative transition probabilities (A_{mn}) for allowed transitions in helium

Transition		f_{nm}	$A_{mn}[s^{-1}]$
$1s^2$-1s2p	$^1S-^1P^o$	0.276	1.80×10^9
-1s3p	$^1S-^1P^o$	0.0734	5.66×10^8
-1s4p	$^1S-^1P^o$	0.0302	2.46×10^8
-1s5p	$^1S-^1P^o$	0.0153	1.28×10^8
1s2s-1s2p	$^1S-^1P^o$	0.376	1.98×10^6
-1s3p	$^1S-^1P^o$	0.151	1.34×10^7
-1s4p	$^1S-^1P^o$	0.0507	0.72×10^7
-1s5p	$^1S-^1P^o$	0.0221	3.76×10^6
1s2s-1s2p	$^3S-^3P^o$	0.300	1.02×10^7
$^3S-^3P^o$	0.180	1.02×10^7	
$^3S-^3P^o$	0.060	1.02×10^7	
1s2s-1s3p	$^3S-^3P^o$	0.0645	0.95×10^7
-1s4p	$^3S-^3P^o$	0.0231	5.05×10^6
-1s5p	$^3S-^3P^o$	0.0114	2.93×10^6
1s2p-1s3s	$^1P^o-^1S$	0.0480	1.81×10^7
-1s4s	$^1P^o-^1S$	0.834×10^{-2}	0.65×10^7
-1s5s	$^1P^o-^1S$	0.308×10^{-2}	3.13×10^6
1s2p-2s3d	$^1P^o-^1D$	0.711	0.64×10^8
-1s4d	$^1P^o-^1D$	0.122	2.02×10^7
-1s5d	$^1P^o-^1D$	0.0436	0.91×10^7
1s2p-1s3s	$^3P^o-^3D$	0.9693	1.54×10^7
-1s3s	$^3P^o-^3S$	0.0692	0.93×10^7
-1s4s	$^3P^o-^3S$	0.0118	1.06×10^7
-1s5s	$^3P^o-^3S$	0.365×10^{-2}	4.30×10^6
1s2p-1s3d	$^3P^o-^3D$	0.609	0.70×10^8
-1s4d	$^3P^o-^3D$	0.125	2.51×10^7
-1s5d	$^3P^o-^3D$	0.0474	1.17×10^7

Reference: Wiese et al. (1966)

B. Potential Energy Diagram for H_2 and H_2^+



The potential energy curves for hydrogen; see Sharp (1972).

C. Values of the Function $D(\beta)$

$\beta < 10^{-3}$: $D(\beta) = 4\beta \, \ell n(1.4/\beta)$,

$\beta > 10$: $D(\beta) = \frac{\beta}{2} \exp\left(-\sqrt{2\beta}\right)$,

$10^{-3} \le \beta \le 10$: $D(\beta)$ is given in Table C.1.

Table C.1. Values of $D(\beta)$

$1/\beta$	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.25	1.5	2.0	2.5
$D(\beta)$	0.057	0.104	0.135	0.157	0.175	0.194	0.230	0.264	0.296	0.328	0.367	0.388
$1/\beta$	3.0	3.5	4.0	4.5	5	6	8	10	12.5	15	20	25
$D(\beta)$	0.399	0.405	0.410	0.405	0.399	0.380	0.345	0.318	0.285	0.263	0.227	0.205
$1/\beta$	30	40	60	80	100	150	200	300	400	600	800	1000
$D(\beta)$	0.190	0.168	0.141	0.124	0.110	0.092	0.080	0.064	0.054	0.042	0.035	0.028

Reference: Janev and Presnyakov (1980)

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