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ANALYTIC CROSS SECTIONS FOR COLLISIONS OF H, H<sub>2</sub>, HE  
AND LI ATOMS AND IONS WITH ATOMS AND MOLECULES  
IV

July 1996

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Analytic Cross Sections for Collisions of H, H<sub>2</sub>, He and Li Atoms  
and Ions with Atoms and Molecules IV

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(Received June 6, 1996)

Analytic expressions fitted to Barnett's recommended data are given for the reaction cross sections of H, H<sub>2</sub> and He atoms and ions colliding with atoms and molecules. The reactions treated are dissociative collisions and particle interchange reactions. The analytic expressions use the semiempirical functional forms proposed by Green and McNeal and some modified forms to make it possible not only to interpolate but also to extrapolate the recommended data.

Keywords: Cross Section, Dissociative Collision, Particle Interchange Reaction, H, H<sub>2</sub>, He

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H、H<sub>2</sub>、He、Liの原子及びイオンと原子分子の  
衝突に対する解析的断面積 IV

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(1996年6月6日受理)

H、H<sub>2</sub>、Heの原子及びイオンと原子分子との衝突における断面積の推奨値に対して解析的表式をあてはめた。対象にした衝突過程は、解離及び粒子交換反応である。解析的表式として、推奨値の内外挿ができるようにGreen and McNealの経験式を変形したものを探用した。

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本報は、大阪府立大学への委託調査を含む。

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## 1 Introduction

For diagnostics and modeling of plasmas in thermonuclear-fusion research, data on cross sections for inelastic collisions between atoms, molecules and ions, especially of the lightest elements, are important. Barnett [1] published recommended data on such cross sections for the elements of hydrogen, helium and lithium. To facilitate interpolation, he gave also least-squares Chebyshev polynomial fits to the recommended cross sections as a function of projectile energy. The polynomial fits, however, cannot be used for extrapolation, because they often show physically unreasonable behavior just outside the energy range of the data used. This inconvenience can be removed by using analytic expressions that approximate low-energy and high-energy asymptotic trends.

Green and McNeal [2] proposed semiempirical expressions for inelastic collision cross sections of hydrogen atoms and ions with gaseous atoms and molecules. By using the same functional forms as the Green-McNeal expressions and some modified forms, Nakai *et al.* [3] published a number of analytic cross sections for charge transfer of hydrogen atoms and ions colliding with gaseous atoms and molecules. Analytic cross sections are also available for the following reactions: charge transfer of hydrogen atoms and ions colliding with metal vapors [4], single-electron capture of hydrogen ions leading to specified excited states of hydrogen [5], charge transfer of helium atoms and ions colliding with gaseous atoms and molecules [6], single-electron capture by multiply-charged ions colliding with H, H<sub>2</sub> and He [7], and ionization of H, H<sub>2</sub> and He by multiply-charged ions [8]. The publications from Ref. 3 to Ref. 8 are the products of the joint research program of data compilation sponsored by Japan Atomic Energy Research Institute.

Presently a project of formulating analytic expressions fitted to Barnett's recommended data is in progress. In previous reports [9-11], analytic expressions for the cross sections of the following reactions were given:

- (1) Electron capture by H, H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, He<sup>+</sup>, and He<sup>2+</sup> colliding with atoms, molecules, and ions (H, He, Li; H<sub>2</sub>; H<sup>-</sup>, He<sup>+</sup>).
- (2) Electron capture into excited states by H<sup>+</sup>, He<sup>+</sup>, and He<sup>2+</sup> colliding with atoms and molecules (H, He, Li; H<sub>2</sub>).
- (3) Excitation and spectral line emission by H, H<sup>+</sup>, He<sup>+</sup>, He, and He<sup>2+</sup> colliding with atoms and molecules (H, He, Li; H<sub>2</sub>).
- (4) Ionization collisions and charge production by H, H<sup>+</sup>, He, He<sup>+</sup>, and He<sup>2+</sup> colliding with atoms, molecules and ions (H, He, Li; H<sub>2</sub>; He<sup>+</sup>).

- (5) Electron loss or stripping collisions by H, He and  $\text{He}^+$  colliding with atoms and molecules (H, He,  $\text{H}_2$ ).
- (6) Electron detachment collisions by  $\text{H}^-$ ,  $\text{He}^-$  and  $\text{Li}^-$  colliding with atoms, molecules and ions (H, He;  $\text{H}_2$ ;  $\text{H}^+$ ).

The present report is a sequel to the previous reports, and treats the cross sections for dissociative collisions and particle interchange reactions. The possible error of analytic expressions when they are used for the extrapolation of the recommended data was discussed in the previous report [9].

### Acknowledgments

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### References

1. C. F. Barnett, *Atomic Data for Fusion Volume 1: Collisions of H,  $\text{H}_2$ , He and Li Atoms and Ions with Atoms and Molecules*, ed. H. T. Hunter, M. I. Kirkpatrick, I. Alvarez, C. Cisneros, and R. A. Phaneuf, Oak Ridge Natl. Lab. Rep ORNL-6086/V1 (1990).
2. A. E. S. Green and R. J. McNeal, *J. Geophys. Res.* **76**, 133 (1971).
3. Y. Nakai, T. Shirai, T. Tabata, and R. Ito, *At. Data & Nucl. Data Tables* **37**, 69 (1987).
4. T. Tabata, R. Ito, Y. Nakai, T. Shirai, M. Sataka, and T. Sugiura, *Nucl. Instrum. & Methods* **B31**, 375 (1988).
5. T. Tabata, R. Ito, Y. Nakai, T. Shirai, and Y. Funatake, *Partial Cross-Sections for Single-Electron Capture of Hydrogen Ions Colliding with Gaseous Atoms and Molecules*, Osaka Prefect. Radiat. Inst. Tech. Rep. 11 (1990).
6. T. Tabata, R. Ito, Y. Nakai, and T. Shirai, *Cross Sections for Charge Transfer of Helium Atoms and Ions Colliding with Gaseous Atoms and Molecules*, Radiat. Center Osaka Prefect. Tech. Rep. 7 (1987).
7. Y. Nakai, T. Shirai, T. Tabata, and R. Ito, *Phys. Scr.* **T28**, 77 (1989).

8. T. Tabata, R. Ito, T. Shirai, Y. Nakai, H. T. Hunter, and R. A. Phaneuf, At. Plasma-Mater. Interact. Data for Fusion **2**, 91 (1992).
9. R. Ito, T. Tabata, T. Shirai, and R. A. Phaneuf, *Analytic Cross Sections for Collisions of H, H<sub>2</sub>, He and Li Atoms and Ions Colliding with Atoms and Molecules. I*, Jpn. Atm. Energ. Res. Inst. Rep. JAERI-M 93-117 (1993).
10. R. Ito, T. Tabata, T. Shirai, and R. A. Phaneuf, *Analytic Cross Sections for Collisions of H, H<sub>2</sub>, He and Li Atoms and Ions Colliding with Atoms and Molecules. II*, Jpn. Atm. Energ. Res. Inst. Rep. JAERI-Data/Code 94-005 (1994).
11. R. Ito, T. Tabata, T. Shirai, and R. A. Phaneuf, *Analytic Cross Sections for Collisions of H, H<sub>2</sub>, He and Li Atoms and Ions Colliding with Atoms and Molecules. III*, Jpn. Atm. Energ. Res. Inst. Rep. JAERI-Data/Code 95-008 (1995).

## 2 List of Analytic Expressions

In the Tables of the present report the analytic expression used for each reaction is denoted as Equation  $m-n$ , where  $m$  represents the principal number assigned to a group of expressions that use the same basic function or a set of basic functions, and  $n$  represents the subnumber equal to the total number of adjustable parameters in the expression. The list also includes the expressions used in the previous reports of the present series of work.

The meanings of symbols are as follows:

$\sigma$	Cross section of process
$\sigma_0$	Unit of cross section, $10^{-16} \text{ cm}^2$
$E$	Projectile energy (in keV/amu)
$E_R$	Rydberg energy multiplied by the ratio of the atomic mass of projectile species to the electron mass (25.0 keV for the projectiles of H and $H^+$ , 50.0 keV for the projectile of $H_2^+$ , 99.27 keV for the projectiles of $He^+$ and $He^{2+}$ )
$a_i$ ( $i = 1, 2, \dots$ )	Adjustable parameters

**m = 1**

$$n = 1 \quad \sigma = \sigma_0 a_1.$$

**m = 2**

$$n = 2 \quad \sigma = \sigma_0 a_1 (x/E_R)^{a_2}.$$

**m = 3**

$$\begin{aligned} n = 3 \quad & \sigma = f(E) \\ n = 5 \quad & \sigma = f(E) + a_4 f(E/a_5) \\ n = 7 \quad & \sigma = f(E) + a_4 f(E/a_5) + a_6 f(E/a_7), \end{aligned}$$

where

$$f(x) = \sigma_0 a_1 (x/E_R)^{a_2} / [1 + (x/a_3)^{2a_2}].$$

**m = 4**

$$\begin{aligned}
n = 4 \quad & \sigma = f(E) \\
n = 6 \quad & \sigma = f(E) + a_5 f(E/a_6) \\
n = 8 \quad & \sigma = f(E) + a_5 f(E/a_6) + a_7 f(E/a_8) \\
n = 10 \quad & \sigma = f(E) + a_5 f(E/a_6) + a_7 f(E/a_8) + a_9 f(E/a_{10}) \\
n = 12 \quad & \sigma = f(E) + a_5 f(E/a_6) + a_7 f(E/a_8) + a_9 f(E/a_{10}) + a_{11} f(E/a_{12}),
\end{aligned}$$

where

$$f(x) = \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2 + \alpha_4}].$$

### **m = 5**

$$\begin{aligned}
n = 7 \quad & \sigma = f(E, a_2) + a_6 f(E/a_7, a_5) \\
n = 10 \quad & \sigma = f(E, a_2) + a_6 f(E/a_7, a_5) + a_9 f(E/a_{10}, a_8),
\end{aligned}$$

where

$$f(x, \alpha) = \sigma_0 a_1 (x/E_R)^{\alpha} / [1 + (x/a_3)^{\alpha + \alpha_4}].$$

### **m = 6**

$$\begin{aligned}
n = 5 \quad & \sigma = f(E, a_2) \\
n = 6 \quad & \sigma = f(E, a_6) \\
n = 8 \quad & \sigma = f(E, a_6) + a_7 f(E/a_8, a_6) \\
n = 10 \quad & \sigma = f(E, a_6) + a_7 f(E/a_8, a_6) + a_9 f(E/a_{10}, a_6) \\
n = 11 \quad & \sigma = f(E, a_6) + a_8 f(E/a_9, a_7) + a_{10} g(E/a_{11}) \\
n = 12 \quad & \sigma = f(E, a_6) + a_7 f(E/a_8, a_6) + a_9 f(E/a_{10}, a_6) + a_{11} f(E/a_{12}, a_6) \\
n = 14 \quad & \sigma = f(E, a_6) + a_7 f(E/a_8, a_6) + a_9 f(E/a_{10}, a_6) + a_{11} f(E/a_{12}, a_6) \\
& \quad + a_{13} f(E/a_{14}, a_6),
\end{aligned}$$

where

$$f(x, \alpha) = \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2 + \alpha_4} + (x/a_5)^{\alpha_2 + \alpha}]$$

$$g(x) = \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_5)^{\alpha_2 + \alpha_6}].$$

### **m = 7**

- $n = 5 \quad \sigma = f(E, a_2)$   
 $n = 9 \quad \sigma = f(E, a_6) + a_7g(E/a_8, a_2, a_9),$   
 $n = 10 \quad \sigma = f(E, a_6) + a_7g(E/a_8, a_9, a_{10})$   
 $n = 14 \quad \sigma = f(E, a_6) + a_7h(E/a_8) + a_{11}h(E/a_{12}) + a_{13}h(E/a_{14}),$

where

$$\begin{aligned}
 f(x, \alpha) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2+\alpha_4} + (x/a_5)^{\alpha_2+\alpha}] \\
 g(x, \alpha, \beta) &= \sigma_0 a_1 (x/E_R)^{\alpha} / [1 + (x/a_5)^{\alpha+\beta}] \\
 h(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2+\alpha_9} + (x/a_5)^{\alpha_2+\alpha_{10}}].
 \end{aligned}$$

The function  $f(x, \alpha)$  should be computed with double precision arithmetic in Fortran.

### **m = 8**

- $n = 10 \quad \sigma = f(E) + a_9f(E/a_{10})$   
 $n = 13 \quad \sigma = f(E) + a_9f(E/a_{10}) + g(E),$

where

$$\begin{aligned}
 f(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2+\alpha_4} + (x/a_5)^{\alpha_2+\alpha_6} + (x/a_7)^{\alpha_2+\alpha_8}] \\
 g(x) &= \begin{cases} \sigma_0 a_{11} / \{1 + [|x - a_{12}|/a_{13}]^{\alpha_2}\} & \text{for } x \leq 1.2 \times 10^{-2} \text{ keV} \\ 0 & \text{for } x > 1.2 \times 10^{-2} \text{ keV.} \end{cases}
 \end{aligned}$$

### **m = 9**

- $n = 10 \quad \sigma = f(E) + a_5f(E/a_6) + a_7g(E/a_8)$   
 $n = 12 \quad \sigma = f(E) + a_5f(E/a_6) + a_7f(E/a_8) + a_9f(E/a_{10}) + a_{11}h(E/a_{12}),$

where

$$\begin{aligned}
 f(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2+\alpha_4}] \\
 g(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_9)^{\alpha_2+\alpha_{10}} + (x/a_3)^{\alpha_2+\alpha_4}] \\
 h(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_4} / [1 + (x/a_3)^{2\alpha_4}].
 \end{aligned}$$

### **m = 10**

- $n = 10 \quad \sigma = f(E)$   
 $n = 12 \quad \sigma = f(E) + a_{11}f(E/a_{12}),$

where

$$f(x) = \sigma_0 a_1 (x/E_R)^{a_2} / [1 + (x/a_3)^{a_2+a_4} + (x/a_5)^{a_2+a_6} + (x/a_7)^{a_2+a_8} + (x/a_9)^{a_2+a_{10}}].$$

**m = 11**

$$\begin{aligned} n = 9 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_9) \\ n = 10 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_9, a_{10}) \\ n = 11 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_4) + a_9 f(E/a_{10}, a_{11}, a_4) \\ n = 12 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_4) + a_9 f(E/a_{10}, a_{11}, a_{12}) \\ n = 13 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_4) + a_9 f(E/a_{10}, a_2, a_4) \\ &\quad + a_{11} f(E/a_{12}, a_{13}, a_4) \\ n = 14 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_4) + a_9 f(E/a_{10}, a_{11}, a_4) \\ &\quad + a_{12} f(E/a_{13}, a_{14}, a_4), \end{aligned}$$

where

$$f(x, \alpha, \beta) = \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{\alpha+\beta} + (x/a_5)^{\alpha+a_6}].$$

**m = 12**

$$\begin{aligned} n = 12 \quad \sigma &= f(E, 2a_2, a_4) + a_7 g(E/a_8) + a_9 g(E/a_{10}) + a_{11} g(E/a_{12}) \\ n = 14 \quad \sigma &= f(E, a_2, a_4) + a_7 f(E/a_8, a_2, a_4) + a_9 f(E/a_{10}, a_2, a_4) \\ &\quad + a_{11} f(E/a_{12}, a_{13}, a_{14}), \end{aligned}$$

where

$$f(x, \alpha, \beta) = \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{\alpha+\beta} + (x/a_5)^{\alpha+a_6}]$$

$$g(x) = \sigma_0 a_1 (x/E_R)^{a_2} / [1 + (x/a_3)^{2a_2}].$$

**m = 13**

$$\begin{aligned} n = 6 \quad \sigma &= f(E, a_2, a_2) + a_4 f(E/a_5, a_6, a_2) \\ n = 10 \quad \sigma &= f(E, a_2, a_4) + a_5 f(E/a_6, a_2, a_4) + a_7 f(E/a_8, a_9, a_{10}) \\ n = 11 \quad \sigma &= f(E, a_2, a_4) + a_5 f(E/a_6, a_2, a_7) + a_8 f(E/a_9, a_{10}, a_{11}) \\ n = 12 \quad \sigma &= f(E, a_2, a_4) + a_5 f(E/a_6, a_2, a_7) + a_8 f(E/a_9, a_2, a_7) \\ &\quad + a_{10} f(E/a_{11}, a_{12}, a_{12}), \end{aligned}$$

where

$$f(x, \alpha, \beta) = \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{\alpha+\beta}].$$

**m = 14**

$$\begin{aligned}
 n = 8 \quad & \sigma = f(E, a_2) + a_4 f(E/a_5, a_6) + a_7 f(E/a_8, a_6) \\
 n = 10 \quad & \sigma = f(E, a_2) + a_4 g(E/a_5, a_6, a_7) + a_8 g(E/a_9, a_6, a_{10}) \\
 n = 12 \quad & \sigma = g(E, a_2, a_4) + a_5 g(E/a_6, a_7, a_2) + a_8 g(E/a_9, a_2, a_{10}) \\
 & + a_{11} f(E/a_{12}, a_2),
 \end{aligned}$$

where

$$\begin{aligned}
 f(x, \alpha) &= \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{2\alpha}] \\
 g(x, \alpha, \beta) &= \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{\alpha+\beta}].
 \end{aligned}$$

**m = 15**

$$n = 15 \quad \sigma = f(E) + a_7 [g(E, a_8, a_{10}) + h(E/a_{11}) + a_{13} g(E/a_{14}, a_{15}, 2a_{15})],$$

where

$$\begin{aligned}
 f(x) &= \begin{cases} 0 & \text{for } x \leq 1 \text{ keV} \\ \sigma_0 a_1 (x/E_R)^{a_2} / [1 + (x/a_3)^{a_2+a_4} + (x/a_5)^{a_2+a_6}] & \text{for } x > 1 \text{ keV} \end{cases} \\
 g(x, \alpha, \beta) &= \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_9)^{\alpha+\beta}] \\
 h(x) &= \begin{cases} \sigma_0 a_1 (x/E_R)^{a_8} / [1 + (x/a_9)^{a_8+a_{12}}] & \text{for } x < 10 \text{ keV} \\ 0 & \text{for } x \geq 10 \text{ keV.} \end{cases}
 \end{aligned}$$

**m = 16**

$$n = 10 \quad \sigma = f(E, a_2) + a_4 f(E/a_5, a_2) + a_6 f(E/a_7, a_8) + a_9 f(E/a_{10}, a_8),$$

where

$$f(x, \alpha) = \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{2\alpha}].$$

**m = 17**

$$\begin{aligned}
 n = 9 \quad & \sigma = f(E) + a_6 f(E/a_7) + a_8 f(E/a_9) \\
 n = 12 \quad & \sigma = f(E) + a_6 f(E/a_7) + a_8 f(E/a_9) + a_{11} g(E/a_{12}, a_{10}, a_2) \\
 n = 15 \quad & \sigma = f(E) + a_6 g(E/a_7, a_2, a_8) + a_9 h(E/a_{10}, a_{12}) + a_{13} h(E/a_{14}, a_{15}),
 \end{aligned}$$

where

$$f(x) = \sigma_0 a_1 (x/E_R)^{a_2} / [1 + (x/a_3)^{a_2+a_4} + (x/a_5)^{2a_2}]$$

$$g(x, \alpha, \beta) = \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_5)^{\alpha_2+\beta}]$$

$$h(x, \alpha) = \begin{cases} \sigma_0 a_1 (x/E_R)^{\alpha_{11}} / [1 + (x/a_5)^{\alpha_{11}+\alpha}] & \text{for } x \leq 5 \text{ keV} \\ 0 & \text{for } x > 5 \text{ keV.} \end{cases}$$

The functions  $f(x)$  and  $g(x)$  should be computed with double precision arithmetic in Fortran.

### **m = 18**

$$\begin{aligned} n = 8 \quad \sigma &= f(E) + a_7 g(E/a_8, a_2) \\ n = 9 \quad \sigma &= f(E) + a_7 g(E/a_8, a_9) \\ n = 10 \quad \sigma &= f(E) + a_7 g(E/a_8, a_2) + a_9 g(E/a_{10}, a_2) \\ n = 14 \quad \sigma &= f(E) + a_7 h(E/a_8, a_9, a_{10}) + a_{11} h(E/a_{12}, a_{13}, a_{14}), \end{aligned}$$

where

$$\begin{aligned} f(x) &= \sigma_0 a_1 (x/E_R)^{\alpha_2} / [1 + (x/a_3)^{\alpha_2+\alpha_4} + (x/a_5)^{\alpha_2+\alpha_6}] \\ g(x, \alpha) &= \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_5)^{\alpha+\alpha_6}] \\ h(x, \alpha, \beta) &= \sigma_0 a_1 (x/E_R)^\alpha / [1 + (x/a_3)^{\alpha+\beta}]. \end{aligned}$$

### 3 Explanation and List of Tables

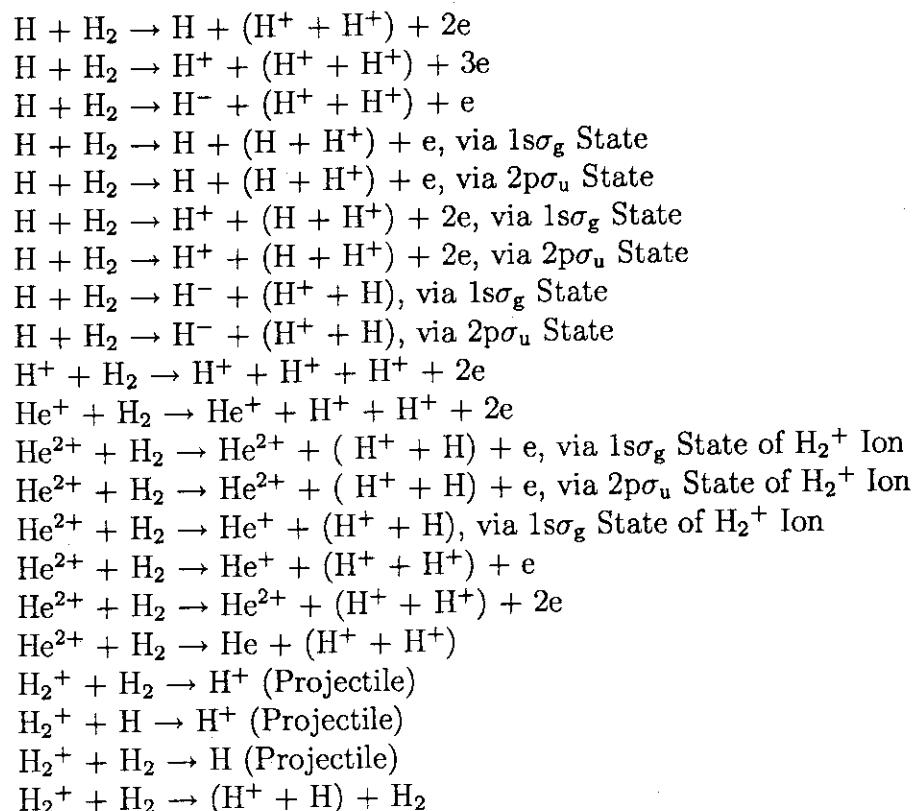
#### Explanation of Tables

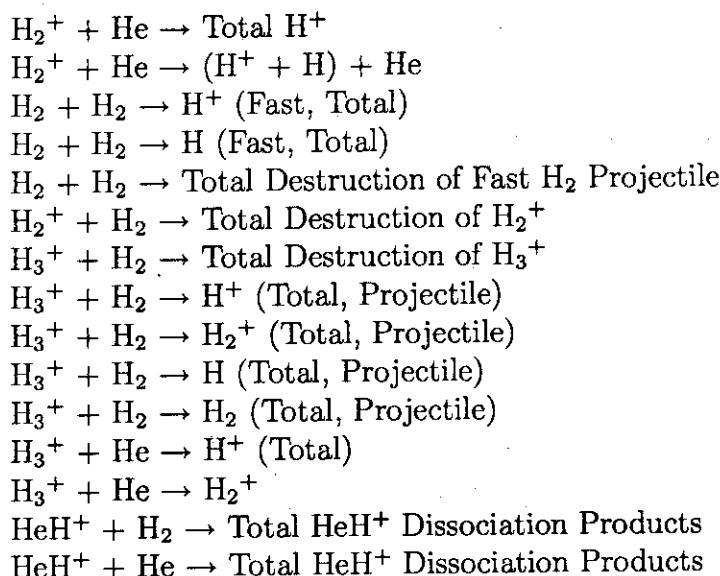
The followings are given for each process:

<i>Range of recommended data</i>	Energy range in which Barnett's recommended data are available
<i>Accuracy</i>	Accuracy of recommended data
<i>Analytic expression</i>	Functional form of analytic expression, values of constants, values of adjustable parameters, and rms and maximum deviations of analytic expression from recommended data

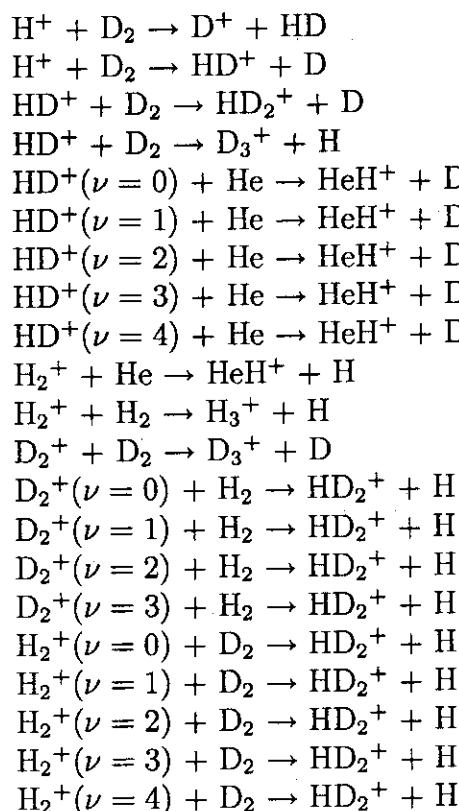
#### List of Tables

##### Dissociative Collisions



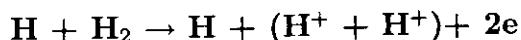


### Interchange Reactions



## 4 Tables of Parameters for Analytic Expressions

### Dissociative Collisions



*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

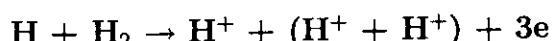
$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.476E-01	2.781E+00	1.556E+01	3.670E-02	3.914E+01	3.5E+00

The value of  $a_6$  was assumed.

The expression represents the recommended data with an rms deviation of 0.9%.

The maximum deviation is 2.0% at 15 keV/amu.

See Graph 1.



*Range of recommended data:*  $5.7 \text{ keV/amu} \leq E \leq 52 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-8,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.369E-02	4.331E+00	1.577E+01	-1.230E+00

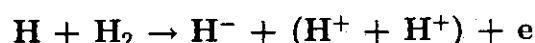
$a_5$	$a_6$	$a_7$	$a_8$
4.089E+01	4.E+00	6.151E-03	1.141E-01

The value of  $a_6$  was assumed.

The expression represents the recommended data with an rms deviation of 3.1%.

The maximum deviation is 7.2% at 13 keV/amu.

See Graph 2.



*Range of recommended data:*  $4.7 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-4,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.280E-02	2.779E+00	1.593E+01	1.027E+00

The expression represents the recommended data with an rms deviation of 2.6%.

The maximum deviation is 4.6% at 15 keV/amu.

See Graph 3.



*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-4,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.656E-01	1.866E+00	8.715E+00	4.652E-01

The expression represents the recommended data with an rms deviation of 0.6%.

The maximum deviation is 1.1% at 50 keV/amu.

See Graph 4.



*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
7.121E-01	2.092E+00	1.187E+01	8.435E-01	2.364E+01	3.841E+00

The expression represents the recommended data with an rms deviation of 0.8%.

The maximum deviation is 1.9% at 6.0 keV/amu.

See Graph 5.

$$\text{H} + \text{H}_2 \rightarrow \text{H}^+ + (\text{H} + \text{H}^+) + 2\text{e}, \text{ via } 1s\sigma_g \text{ State}$$

*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-4,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.388E-03	1.393E+00	6.289E+01	1.442E+00

The expression represents the recommended data with an rms deviation of 1.0%.

The maximum deviation is 1.8% at 5.0 keV/amu.

See Graph 6.

$$\text{H} + \text{H}_2 \rightarrow \text{H}^+ + (\text{H} + \text{H}^+) + 2\text{e}, \text{ via } 2p\sigma_u \text{ State}$$

*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.216E-02	1.996E+00	6.275E+00	-6.420E+00	2.747E+01	1.198E+00

The expression represents the recommended data with an rms deviation of 0.6%.

The maximum deviation is 1.1% at 6.0 keV/amu.

See Graph 7.

$$\text{H} + \text{H}_2 \rightarrow \text{H}^- + (\text{H}^+ + \text{H}), \text{ via } 1s\sigma_g \text{ State}$$

*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-6,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
5.963E-03	1.251E+00	1.725E+01	2.922E+00	2.215E-01	3.383E+00

The expression represents the recommended data with an rms deviation of 0.9%.

The maximum deviation is 1.3% at 6.0 keV/amu.

See Graph 8.

**$H + H_2 \rightarrow H^- + (H^+ + H)$ , via  $2p\sigma_u$  State**

*Range of recommended data:*  $5.0 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 25.0 \text{ keV}$ .

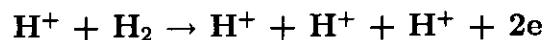
Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
5.546E-01	3.1336E+00	8.565E+00	-2.701E-01	1.347E+01	3.114E+00

The expression represents the recommended data with an rms deviation of 1.4%.

The maximum deviation is 2.7% at 15 keV/amu.

See Graph 9.



*Range of recommended data:*  $1.0 \times 10^2 \text{ keV/amu} \leq E \leq 3.0 \times 10^3 \text{ keV/amu}$ .

*Accuracy:* Within factor of 4.

*Analytic expression:* Equation 4-6,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

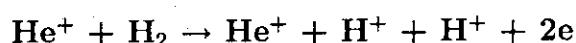
$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
5.800E-02	1.658E-02	2.571E+01	1.957E+00	4.474E-04	2.E+02

The value of  $a_6$  was selected among trial values.

The expression represents the recommended data with an rms deviation of 2.5%.

The maximum deviation is 3.4% at  $1.0 \times 10^3 \text{ keV/amu}$ .

See Graph 10.



*Range of recommended data:*  $2.5 \text{ keV/amu} \leq E \leq 90 \text{ keV/amu}$ .

*Accuracy:* Within factor of 4.

*Analytic expression:* Equation 6-5,  $E_R = 99.27 \text{ keV}$ .

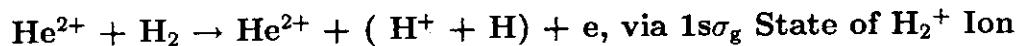
Values of  $a_i$  ( $i = 1, 2, \dots, 5$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
3.684E+02	1.6077E+00	8.518E-01	6.541E-01	1.343E+00

The expression represents the recommended data with an rms deviation of 0.1%.

The maximum deviation is 0.2% at 10 keV/amu.

See Graph 11.



*Range of recommended data:*  $3.8 \text{ keV/amu} \leq E \leq 25 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-6,  $E_R = 99.27 \text{ keV}$ .

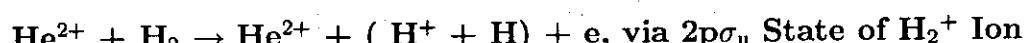
Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.254E+02	3.730E+00	6.882E+00	1.201E+00	8.641E+00	5.666E+00

The expression represents the recommended data with an rms deviation of 1.2%.

The maximum deviation is 2.8% at 4.0 keV/amu.

See Graph 12.



*Range of recommended data:*  $2.5 \text{ keV/amu} \leq E \leq 30 \text{ keV/amu}$ .

*Accuracy:* 30%.

*Analytic expression:* Equation 4-6,  $E_R = 99.27 \text{ keV}$ .

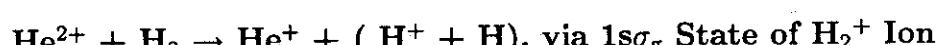
Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.916E+01	2.608E+00	7.639E+00	1.830E+00	4.133E+00	4.926E+00

The expression represents the recommended data with an rms deviation of 3.7%.

The maximum deviation is 7.2% at 5.0 keV/amu.

See Graph 13.



*Range of recommended data:*  $1.3 \text{ keV/amu} \leq E \leq 25 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 3-5,  $E_R = 99.27 \text{ keV}$ .

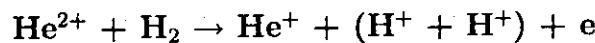
Values of  $a_i$  ( $i = 1, 2, \dots, 5$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
1.363E+00	1.072E+00	2.106E+01	1.154E-01	7.541E-02

The expression represents the recommended data with an rms deviation of 1.1%.

The maximum deviation is 2.5% at 15 keV/amu.

See Graph 14.



*Range of recommended data:*  $1.2 \text{ keV/amu} \leq E \leq 25 \text{ keV/amu}$ .

*Accuracy:* 30%.

*Analytic expression:* Equation 6-8,  $E_R = 99.27 \text{ keV}$ .

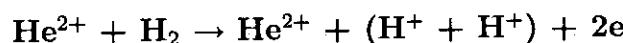
Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
8.930E+00	1.0364E+00	2.022E+01	7.572E-01
$a_5$	$a_6$	$a_7$	$a_8$
1.378E+02	6.914E+00	1.597E+00	1.861E-02

The expression represents the recommended data with an rms deviation of 0.8%.

The maximum deviation is 1.2% at 8.0 keV/amu.

See Graph 15.



*Range of recommended data:*  $2.5 \text{ keV/amu} \leq E \leq 30 \text{ keV/amu}$ .

*Accuracy:* 30%.

*Analytic expression:* Equation 4-6,  $E_R = 99.27 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.742E+01	2.5815E+00	7.696E+00	2.0865E+00	3.951E+00	4.680E+00

The expression represents the recommended data with an rms deviation of 3.1%.

The maximum deviation is 6.0% at 4.0 keV/amu.

See Graph 16.



*Range of recommended data:*  $1.1 \text{ keV/amu} \leq E \leq 25 \text{ keV/amu}$ .

*Accuracy:* 15%.

*Analytic expression:* Equation 6-8,  $E_R = 99.27 \text{ keV}$ .

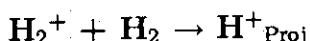
Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.743E+01	1.4064E+00	1.099E+01	3.711E-01

$a_5$	$a_6$	$a_7$	$a_8$
3.1705E+01	3.806E+00	1.909E+00	2.222E-02

The expression represents the recommended data with an rms deviation of 1.3%.  
The maximum deviation is 2.7% at 2.0 keV/amu.

See Graph 17.



*Range of recommended data:*  $1.6 \times 10^{-3}$  keV/amu  $\leq E \leq 5.0 \times 10^{-3}$  keV/amu and  
 $1.5 \text{ keV/amu} \leq E \leq 1.0 \times 10^4 \text{ keV/amu}$ .

*Accuracy:* 25%.

*Analytic expression:* Equation 12-14,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 14$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
4.676E+00	1.436E+00	4.274E+01	6.969E-01	2.404E+02

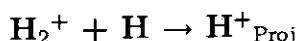
$a_6$	$a_7$	$a_8$	$a_9$	$a_{10}$
3.199E+00	1.272E+00	4.972E-02	3.313E-02	3.643E+01

$a_{11}$	$a_{12}$	$a_{13}$	$a_{14}$
5.423E-01	4.237E-05	5.873E+00	2.146E-01

The expression represents the recommended data with an rms deviation of 3.2%.  
The maximum deviation is 7.2% at 10 keV/amu.

See Graph 18.



*Range of recommended data:*  $1.5 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* 25%.

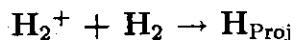
*Analytic expression:* Equation 4-4,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
7.460E+01	9.531E-01	2.162E+00	2.635E-01

The expression represents the recommended data with an rms deviation of 0.5%.  
The maximum deviation is 0.7% at 2.0 keV/amu.

See Graph 19.



*Range of recommended data:*  $2.0 \text{ keV/amu} \leq E \leq 1.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 6-6,  $E_R = 50.0 \text{ keV}$ .

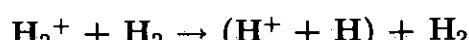
Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.204E+03	1.6282E+00	1.663E+00	-3.641E-02	9.974E+00	2.063E+00

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 0.7% at 7.0 keV/amu.

See Graph 20.



*Range of recommended data:*  $1.0 \times 10^{-2} \text{ keV/amu} \leq E \leq 1.0 \times 10^3 \text{ keV/amu}$ .

*Accuracy:* 40% for  $E \leq 50 \text{ keV/amu}$ , 20% for  $E > 50 \text{ keV/amu}$ .

*Analytic expression:* Equation 6-8,  $E_R = 50.0 \text{ keV}$ .

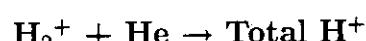
Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.361E+04	1.684E+00	1.921E-01	-1.824E-01
$a_5$	$a_6$	$a_7$	$a_8$
1.225E+00	7.880E-01	3.793E-01	4.925E-03

The expression represents the recommended data with an rms deviation of 1.7%.

The maximum deviation is 3.51% at 4.0 keV/amu.

See Graph 21.



*Range of recommended data:*  $1.0 \text{ keV/amu} \leq E \leq 6.5 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 6-6,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
3.063E+02	1.618E+00	1.702E+00	-2.197E-01	1.320E+01	1.202E+00

The expression represents the recommended data with an rms deviation of 0.8%.

The maximum deviation is 1.8% at 70 keV/amu.

See Graph 22.



*Range of recommended data:*  $9.7 \times 10^{-3}$  keV/amu  $\leq E \leq 2.4 \times 10^{-2}$  keV/amu and  $2.0 \text{ keV/amu} \leq E \leq 1.0 \times 10^3 \text{ keV/amu}$ .

*Accuracy:* Unknown for  $E < 0.1$  keV/amu, 15% for  $2.0 \text{ keV/amu} \leq E \leq 8 \text{ keV/amu}$ , 20% for  $E > 50$  keV/amu.

*Analytic expression:* Equation 6-8,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
5.295E+01	7.224E-01	1.446E+00	4.708E-01

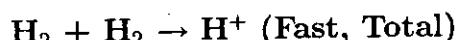
  

$a_5$	$a_6$	$a_7$	$a_8$
1.608E+01	1.336E+00	2.632E-01	3.723E-03

The expression represents the recommended data with an rms deviation of 0.9%.

The maximum deviation is 2.4% at  $1.0 \times 10^2$  keV/amu.

See Graph 23.



*Range of recommended data:*  $2.5 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$  and  $1.5 \times 10^2 \text{ keV/amu} \leq E \leq 6.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 13-10,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 10$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
6.827E-02	5.235E+00	8.514E+01	1.016E+00	8.511E-02

$a_6$	$a_7$	$a_8$	$a_9$	$a_{10}$
5.996E+00	1.054E+01	4.292E-01	5.958E-01	4.234E+00

The expression represents the recommended data with an rms deviation of 1.3%.

The maximum deviation is 2.4% at 20 keV/amu.

See Graph 24.

**$H_2 + H_2 \rightarrow H$  (Fast, Total)**

*Range of recommended data:*  $2.5 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* 40%.

*Analytic expression:* Equation 6-8,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
3.274E+06	8.333E+00	8.920E+00	-7.650E-01
$a_5$	$a_6$	$a_7$	$a_8$
1.116E+01	1.332E+00	1.440E+00	2.085E-01

The expression represents the recommended data with an rms deviation of 0.9%.

The maximum deviation is 1.7% at 20 keV/amu.

See Graph 25.

 **$H_2 + H_2 \rightarrow$  Total Destruction of Fast  $H_2$  Projectile**

*Range of recommended data:*  $1.3 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 6-8,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
5.5916E+13	1.03018E+01	2.062E+00	-1.546E+00
$a_5$	$a_6$	$a_7$	$a_8$
2.867E+00	4.372E-01	5.811E-01	7.600E-02

The expression represents the recommended data with an rms deviation of 0.3%.

The maximum deviation is 0.6% at 40 keV/amu.

See Graph 26.

 **$H_2^+ + H_2 \rightarrow$  Total Destruction of  $H_2^+$** 

*Range of recommended data:*  $1.5 \text{ keV/amu} \leq E \leq 50 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-6,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.226E+01	5.897E-01	2.265E+01	1.466E+00	6.796E-01	1.048E-01

The expression represents the recommended data with an rms deviation of 1.6%.  
The maximum deviation is 2.2% at 10 keV/amu.

See Graph 27.



*Range of recommended data:*  $1.6 \text{ keV/amu} \leq E \leq 35 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-4,  $E_R = 75.0 \text{ keV}$ .

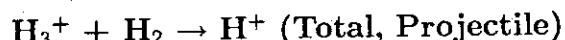
Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.039E+01	4.626E-01	2.652E+01	1.198E+00

The expression represents the recommended data with an rms deviation of 0.7%.

The maximum deviation is 1.2% at 15 keV/amu.

See Graph 28.



*Range of recommended data:*  $4.0 \times 10^{-2} \text{ keV/amu} \leq E \leq 6.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 30%.

*Analytic expression:* Equation 6-8,  $E_R = 75.0 \text{ keV}$ .

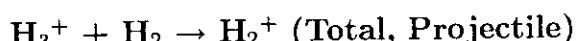
Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.501E+02	1.4706E+00	3.935E+00	-1.321E-01
<hr/>			
$a_5$	$a_6$	$a_7$	$a_8$
3.200E+01	1.3236E+00	2.801E-02	2.306E-03

The expression represents the recommended data with an rms deviation of 1.4%.

The maximum deviation is 3.1% at 10 keV/amu.

See Graph 29.



*Range of recommended data:*  $0.11 \text{ keV/amu} \leq E \leq 6.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 30%.

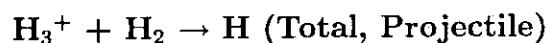
*Analytic expression:* Equation 6-8,  $E_R = 75.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
5.464E+01	1.124E+00	4.273E+00	3.431E-01
$a_5$	$a_6$	$a_7$	$a_8$
4.075E+01	1.565E+00	1.167E-01	4.251E-02

The expression represents the recommended data with an rms deviation of 1.3%.  
The maximum deviation is 3.4% at 4.0 keV/amu.

See Graph 30.



*Range of recommended data:*  $1.5 \text{ keV/amu} \leq E \leq 6.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 30%.

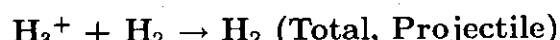
*Analytic expression:* Equation 4-4,  $E_R = 75.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.066E+02	8.844E-01	1.121E+01	9.054E-01

The expression represents the recommended data with an rms deviation of 2.1%.  
The maximum deviation is 3.8% at 20 keV/amu.

See Graph 31.



*Range of recommended data:*  $3.0 \times 10^{-2} \text{ keV/amu} \leq E \leq 6.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 30%.

*Analytic expression:* Equation 4-8,  $E_R = 75.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

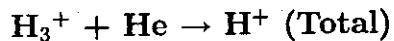
$a_1$	$a_2$	$a_3$	$a_4$
1.713E+01	5.229E-01	1.594E+01	1.675E+00
$a_5$	$a_6$	$a_7$	$a_8$
4.844E-02	2.750E-03	1.025E-02	1.E+02

The value of  $a_8$  was assumed.

The expression represents the recommended data with an rms deviation of 1.9%.

The maximum deviation is 3.1% at 40 keV/amu.

See Graph 32.



*Range of recommended data:*  $1.0 \text{ keV/amu} \leq E \leq 17 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-4,  $E_R = 75.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.076E+01	1.0395E+00	9.034E+00	1.973E-01

The expression represents the recommended data with an rms deviation of 0.3%.

The maximum deviation is 0.6% at 2.0 keV/amu.

See Graph 33.



*Range of recommended data:*  $1.0 \text{ keV/amu} \leq E \leq 17 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-4,  $E_R = 75.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.626E+01	1.0365E+00	8.470E+00	1.E-01

The value of  $a_4$  was assumed.

The expression represents the recommended data with an rms deviation of 1.4%.

The maximum deviation is 2.1% at 2.0 keV/amu.

See Graph 34.



*Range of recommended data:*  $10 \text{ keV/amu} \leq E \leq 2.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-6,  $E_R = 124.3 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
7.527E+00	6.4E-02	3.362E+01	2.065E+00	1.321E-01	1.2E+01

The values of  $a_2$  and  $a_6$  were selected among trial values.

The expression represents the recommended data with an rms deviation of 2.6%.

The maximum deviation is 3.9% at 70 keV/amu.

See Graph 35.

### $\text{HeH}^+ + \text{He} \rightarrow \text{Total HeH}^+$ Dissociation Products

*Range of recommended data:*  $10 \text{ keV/amu} \leq E \leq 2.0 \times 10^2 \text{ keV/amu}$ .

*Accuracy:* 20%.

*Analytic expression:* Equation 4-4,  $E_R = 124.3 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

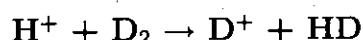
$a_1$	$a_2$	$a_3$	$a_4$
1.131E+02	1.483E+00	1.747E+01	8.169E-01

The expression represents the recommended data with an rms deviation of 1.7%.

The maximum deviation is 3.2% at 15 keV/amu.

See Graph 36.

### Interchange Reactions



*Range of recommended data:*  $4.5 \times 10^{-4} \text{ keV/amu} \leq E \leq 0.1 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-8,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
3.271E+13	2.1322E+00	7.971E-05	9.026E-01

$a_5$	$a_6$	$a_7$	$a_8$
2.419E-04	2.5561E+00	2.440E-03	1.563E+02

The expression represents the recommended data with an rms deviation of 0.8%.

The maximum deviation is 1.6% at  $7.0 \times 10^{-2} \text{ keV/amu}$ .

See Graph 37.



*Range of recommended data:*  $2.2 \times 10^{-3} \text{ keV/amu} \leq E \leq 0.10 \text{ keV/amu}$ .

*Accuracy:* Unknown.

*Analytic expression:* Equation 11-9,  $E_R = 25.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 9$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
2.759E+15	4.E+00	3.630E-03	3.374E+00	1.081E-03

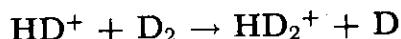
$a_6$	$a_7$	$a_8$	$a_9$
-2.703E+00	4.331E-03	1.7E+00	4.284E-01

The values of  $a_2$  and  $a_8$  were assumed.

The expression represents the recommended data with an rms deviation of 3.2%.

The maximum deviation is 4.9% at  $4.5 \times 10^{-3}$  keV/amu.

See Graph 38.



*Range of recommended data:*  $6.0 \times 10^{-6}$  keV/amu  $\leq E \leq 4.3 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-8,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.682E-01	-3.625E-01	9.038E-04	2.457E+00

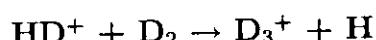
  

$a_5$	$a_6$	$a_7$	$a_8$
2.334E-03	7.277E+00	8.549E-01	1.669E-02

The expression represents the recommended data with an rms deviation of 0.7%.

The maximum deviation is 1.4% at  $7.0 \times 10^{-4}$  keV/amu.

See Graph 39.



*Range of recommended data:*  $6.0 \times 10^{-6}$  keV/amu  $\leq E \leq 4.3 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-8,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
1.751E-02	-4.911E-01	1.085E-03	2.248E+00

$a_5$	$a_6$	$a_7$	$a_8$
2.114E-03	5.457E+00	6.954E-01	9.286E-02

The expression represents the recommended data with an rms deviation of 0.5%.

The maximum deviation is 0.8% at  $4.0 \times 10^{-4}$  keV/amu.

See Graph 40.



*Range of recommended data:*  $1.8 \times 10^{-4}$  keV/amu  $\leq E \leq 1.7 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-4,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, 3, 4$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.496E+01	4.149E-01	3.103E-04	8.541E-01

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 1.0% at  $1.5 \times 10^{-3}$  keV/amu.

See Graph 41.



*Range of recommended data:*  $1.9 \times 10^{-4}$  keV/amu  $\leq E \leq 1.5 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 2-2,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2$ ) are as follows.

$a_1$	$a_2$
1.156E-05	-7.764E-01

The expression represents the recommended data with an rms deviation of 1.6%.

The maximum deviation is 2.8% at  $1.5 \times 10^{-3}$  keV/amu.

See Graph 42.



*Range of recommended data:*  $2.0 \times 10^{-4}$  keV/amu  $\leq E \leq 1.5 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-6,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.996E+04	7.831E-01	1.908E-04	2.171E+00	7.788E-02	1.5E+01

The value of  $a_6$  was selected among trial values.

The expression represents the recommended data with an rms deviation of 0.7%.

The maximum deviation is 1.1% at  $6.0 \times 10^{-4}$  keV/amu.

See Graph 43.



*Range of recommended data:*  $2.0 \times 10^{-4}$  keV/amu  $\leq E \leq 1.5 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 4-6,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.461E+01	2.221E-01	2.921E-04	3.825E+00	7.793E-02	1.E+01

The value of  $a_6$  was selected among trial values.

The expression represents the recommended data with an rms deviation of 1.3%.

The maximum deviation is 2.3% at  $4.0 \times 10^{-4}$  keV/amu.

See Graph 44.



*Range of recommended data:*  $1.8 \times 10^{-4}$  keV/amu  $\leq E \leq 1.5 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 74.95$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.485E+15	2.5228E+00	1.106E-04	1.1876E+00	2.255E-04	3.6967E+00

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 0.9% at  $8.0 \times 10^{-4}$  keV/amu.

See Graph 45.



*Range of recommended data:*  $5.6 \times 10^{-4}$  keV/amu  $\leq E \leq 1.0 \times 10^{-2}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-8,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

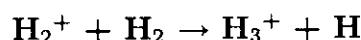
$a_1$	$a_2$	$a_3$	$a_4$
2.737E+13	1.9279E+00	3.738E-05	7.605E-01
$a_5$	$a_6$	$a_7$	$a_8$
2.3543E-04	3.1432E+00	5.774E-03	8.E+01

The value of  $a_8$  was selected among trial values.

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 0.7% at  $2.0 \times 10^{-3}$  keV/amu.

See Graph 46.



*Range of recommended data:*  $1.0 \times 10^{-5}$  keV/amu  $\leq E \leq 7.0 \times 10^{-3}$  keV/amu.

*Accuracy:* 45%.

*Analytic expression:* Equation 6-8,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
5.738E+00	-1.576E-01	1.247E-03	1.843E+00

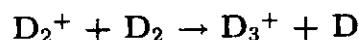
  

$a_5$	$a_6$	$a_7$	$a_8$
3.101E-03	5.619E+00	1.196E+00	7.828E-02

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 0.8% at  $2.0 \times 10^{-4}$  keV/amu.

See Graph 47.



*Range of recommended data:*  $1.6 \times 10^{-4}$  keV/amu  $\leq E \leq 4.2 \times 10^{-3}$  keV/amu.

*Accuracy:* Unknown.

*Analytic expression:* Equation 6-6,  $E_R = 99.90$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
3.678E+14	2.1396E+00	9.267E-05	6.673E-01	5.250E-04	2.1844E+00

The expression represents the recommended data with an rms deviation of 0.4%.

The maximum deviation is 0.9% at  $1.5 \times 10^{-3}$  keV/amu.

See Graph 48.



*Range of recommended data:*  $5.8 \times 10^{-5}$  keV/amu  $\leq E \leq 4.6 \times 10^{-4}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 4-6,  $E_R = 99.90$  keV.

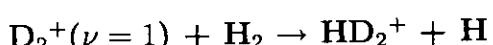
Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.506E+28	4.179E+00	3.908E-05	1.754E+00	8.961E-02	4.171E+00

The expression represents the recommended data with an rms deviation of 2.2%.

The maximum deviation is 3.3% at  $7.0 \times 10^{-5}$  keV/amu.

See Graph 49.



*Range of recommended data:*  $5.7 \times 10^{-5}$  keV/amu  $\leq E \leq 4.6 \times 10^{-4}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 4-6,  $E_R = 99.90$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.081E+03	2.799E-01	5.165E-05	3.099E+00	2.076E-01	4.710E+00

The expression represents the recommended data with an rms deviation of 1.5%.

The maximum deviation is 3.0% at  $7.0 \times 10^{-5}$  keV/amu.

See Graph 50.



*Range of recommended data:*  $5.8 \times 10^{-5}$  keV/amu  $\leq E \leq 4.6 \times 10^{-4}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 4-6,  $E_R = 99.90$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.197E-04	-7.881E-01	1.946E-04	5.093E+00	5.618E-01	2.254E+00

The expression represents the recommended data with an rms deviation of 0.9%.

The maximum deviation is 1.6% at  $2.0 \times 10^{-4}$  keV/amu.

See Graph 51.



*Range of recommended data:*  $5.8 \times 10^{-5} \text{ keV/amu} \leq E \leq 4.6 \times 10^{-4} \text{ keV/amu}$ .

*Accuracy:* 25%.

*Analytic expression:* Equation 4-6,  $E_R = 99.90 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
2.336E-02	-4.308E-01	1.468E-04	3.964E+00	5.513E-01	2.031E+00

The expression represents the recommended data with an rms deviation of 0.7%.

The maximum deviation is 1.5% at  $7.0 \times 10^{-5} \text{ keV/amu}$ .

See Graph 52.



*Range of recommended data:*  $1.7 \times 10^{-4} \text{ keV/amu} \leq E \leq 4.5 \times 10^{-3} \text{ keV/amu}$ .

*Accuracy:* 25%.

*Analytic expression:* Equation 6-8,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
5.386E+30	5.1318E+00	1.022E-04	9.451E-02
$a_5$	$a_6$	$a_7$	$a_8$
1.7844E-04	2.3101E+00	7.600E-02	1.266E+01

The expression represents the recommended data with an rms deviation of 0.3%.

The maximum deviation is 0.5% at  $3.0 \times 10^{-3} \text{ keV/amu}$ .

See Graph 53.



*Range of recommended data:*  $1.7 \times 10^{-4} \text{ keV/amu} \leq E \leq 5.0 \times 10^{-3} \text{ keV/amu}$ .

*Accuracy:* 25%.

*Analytic expression:* Equation 6-8,  $E_R = 50.0 \text{ keV}$ .

Values of  $a_i$  ( $i = 1, 2, \dots, 8$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$
2.232E+20	3.1363E+00	4.970E-05	1.903E-01

$a_5$	$a_6$	$a_7$	$a_8$
1.546E-04	2.3757E+00	1.065E-01	2.E+01

The value of  $a_8$  was selected among trial values.

The expression represents the recommended data with an rms deviation of 0.6%.

The maximum deviation is 1.7% at  $5.0 \times 10^{-4}$  keV/amu.

See Graph 54.



*Range of recommended data:*  $1.7 \times 10^{-4}$  keV/amu  $\leq E \leq 5.4 \times 10^{-3}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 6-6,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.126E+25	4.0784E+00	8.547E-05	5.E-02	1.259E-04	1.0671E+00

The value of  $a_4$  was assumed.

The expression represents the recommended data with an rms deviation of 0.3%.

The maximum deviation is 0.7% at  $4.0 \times 10^{-4}$  keV/amu.

See Graph 55.



*Range of recommended data:*  $1.8 \times 10^{-4}$  keV/amu  $\leq E \leq 5.2 \times 10^{-3}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 6-6,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.423E+29	4.865E+00	1.035E-04	3.518E-01	2.235E-04	1.836E+00

The expression represents the recommended data with an rms deviation of 1.1%.

The maximum deviation is 2.6% at  $5.2 \times 10^{-3}$  keV/amu.

See Graph 56.



*Range of recommended data:*  $1.8 \times 10^{-4}$  keV/amu  $\leq E \leq 4.5 \times 10^{-3}$  keV/amu.

*Accuracy:* 25%.

*Analytic expression:* Equation 6-6,  $E_R = 50.0$  keV.

Values of  $a_i$  ( $i = 1, 2, \dots, 6$ ) are as follows.

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$
1.005E+07	8.896E-01	5.482E-05	4.400E-01	8.879E-04	2.986E+00

The expression represents the recommended data with an rms deviation of 0.3%.

The maximum deviation is 0.5% at  $5.0 \times 10^{-4}$  keV/amu.

See Graph 57.

## 5 Explanation and List of Graphs

### Explanation of Graphs

#### Graphs. Cross section vs Energy

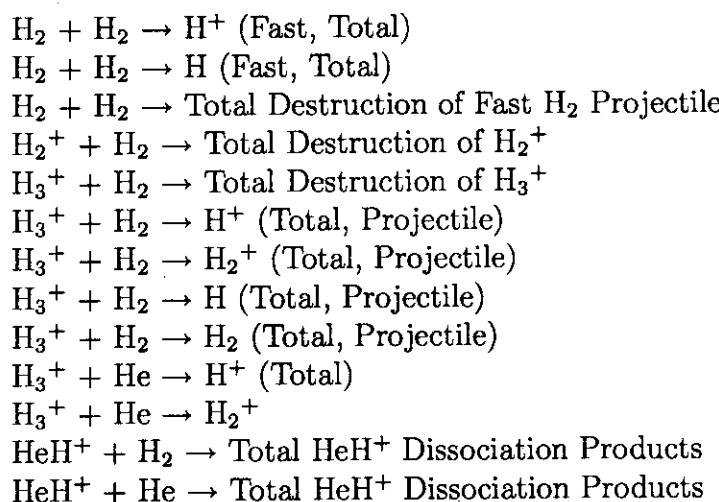
Ordinate    Cross section (in cm<sup>2</sup>)  
 Abscissa    Projectile energy (in eV/amu)

The curve represents the analytic expression, and points, recommended data given by Barnett [1]. The curve is shown, when possible, over the range of projectile energy from  $E_{\min}/10$  to  $10E_{\max}$ , where  $E_{\min}$  and  $E_{\max}$  are the minimum and the maximum energy of the recommended data.

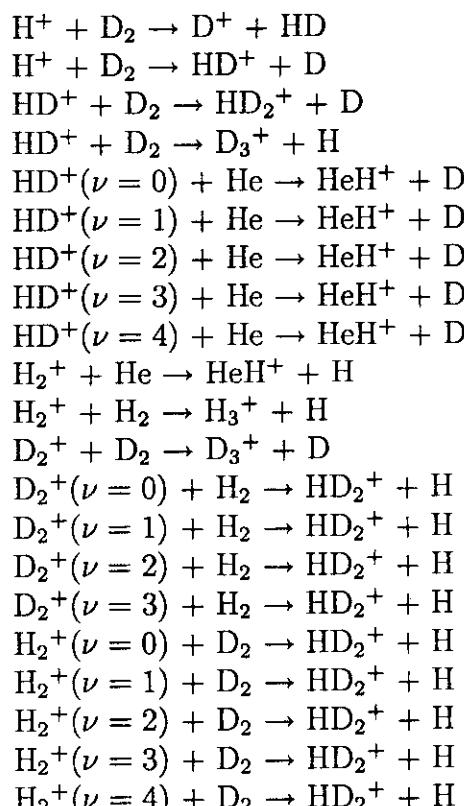
### List of Graphs

#### Dissociative Collisions

$\text{H} + \text{H}_2 \rightarrow \text{H} + (\text{H}^+ + \text{H}^+) + 2e$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^+ + (\text{H}^+ + \text{H}^+) + 3e$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^- + (\text{H}^+ + \text{H}^+) + e$   
 $\text{H} + \text{H}_2 \rightarrow \text{H} + (\text{H} + \text{H}^+) + e, \text{ via } 1s\sigma_g \text{ State}$   
 $\text{H} + \text{H}_2 \rightarrow \text{H} + (\text{H} + \text{H}^+) + e, \text{ via } 2p\sigma_u \text{ State}$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^+ + (\text{H} + \text{H}^+) + 2e, \text{ via } 1s\sigma_g \text{ State}$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^+ + (\text{H} + \text{H}^+) + 2e, \text{ via } 2p\sigma_u \text{ State}$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^- + (\text{H}^+ + \text{H}), \text{ via } 1s\sigma_g \text{ State}$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^- + (\text{H}^+ + \text{H}), \text{ via } 2p\sigma_u \text{ State}$   
 $\text{H}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{H}^+ + \text{H}^+ + 2e$   
 $\text{He}^+ + \text{H}_2 \rightarrow \text{He}^+ + \text{H}^+ + \text{H}^+ + 2e$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He}^{2+} + (\text{H}^+ + \text{H}) + e, \text{ via } 1s\sigma_g \text{ State of H}_2^+ \text{ Ion}$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He}^{2+} + (\text{H}^+ + \text{H}) + e, \text{ via } 2p\sigma_u \text{ State of H}_2^+ \text{ Ion}$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He}^+ + (\text{H}^+ + \text{H}), \text{ via } 1s\sigma_g \text{ State of H}_2^+ \text{ Ion}$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He}^+ + (\text{H}^+ + \text{H}^+) + e$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He}^{2+} + (\text{H}^+ + \text{H}^+) + 2e$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{He} + (\text{H}^+ + \text{H}^+)$   
 $\text{H}_2^+ + \text{H}_2 \rightarrow \text{H}^+ \text{ (Projectile)}$   
 $\text{H}_2^+ + \text{H} \rightarrow \text{H}^+ \text{ (Projectile)}$   
 $\text{H}_2^+ + \text{H}_2 \rightarrow \text{H} \text{ (Projectile)}$   
 $\text{H}_2^+ + \text{H}_2 \rightarrow (\text{H}^+ + \text{H}) + \text{H}_2$   
 $\text{H}_2^+ + \text{He} \rightarrow \text{Total H}^+$   
 $\text{H}_2^+ + \text{He} \rightarrow (\text{H}^+ + \text{H}) + \text{He}$

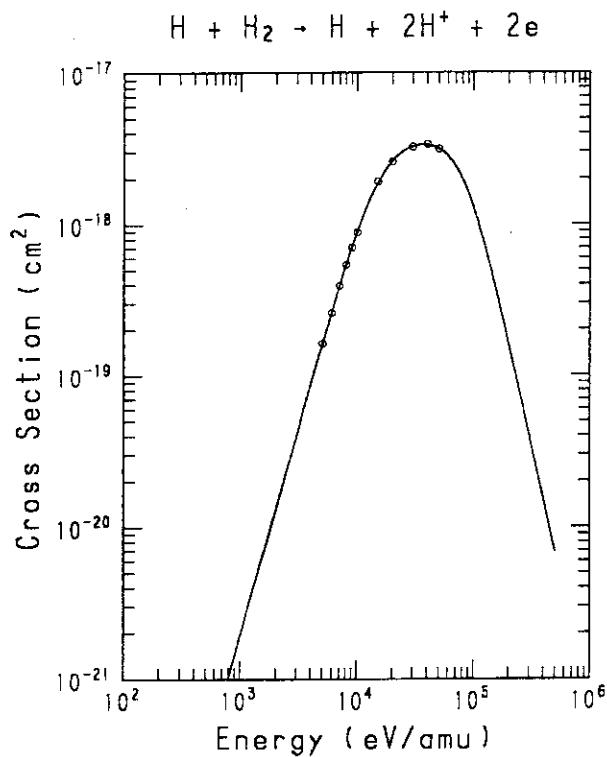


### Interchange Reactions

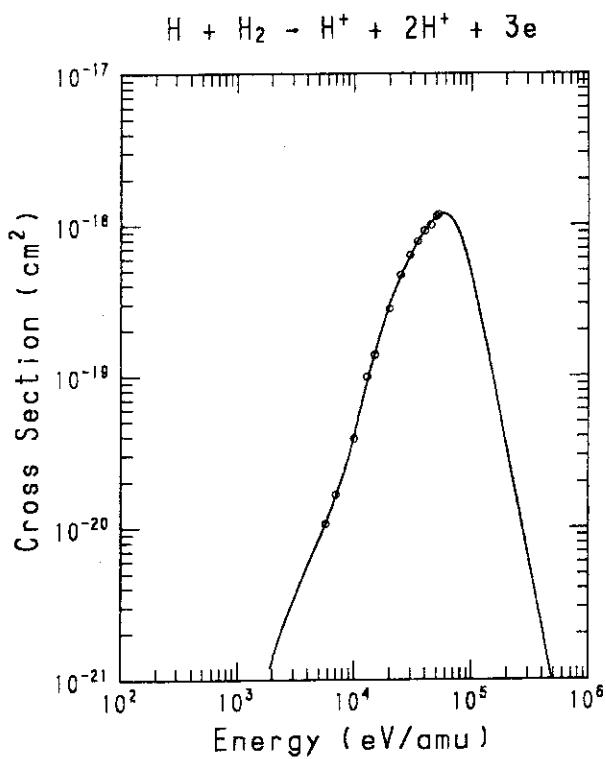


## 6 Graphs of Cross Sections

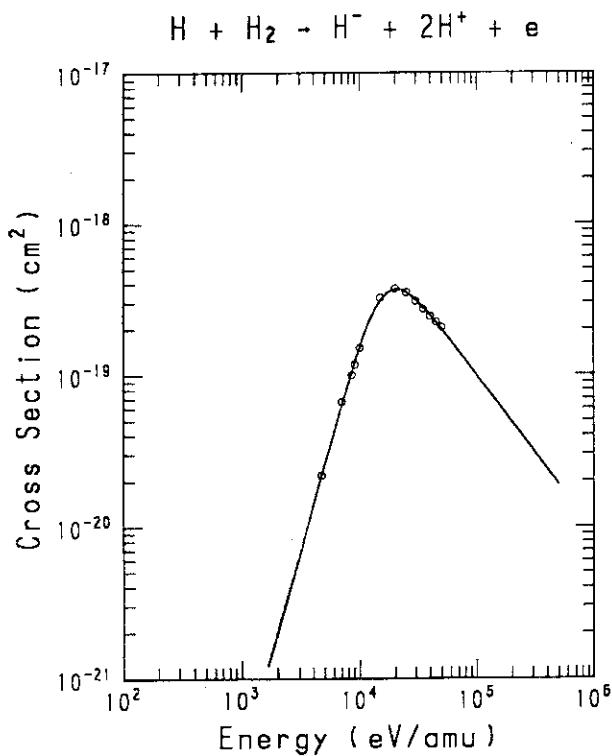
GRAPH 1



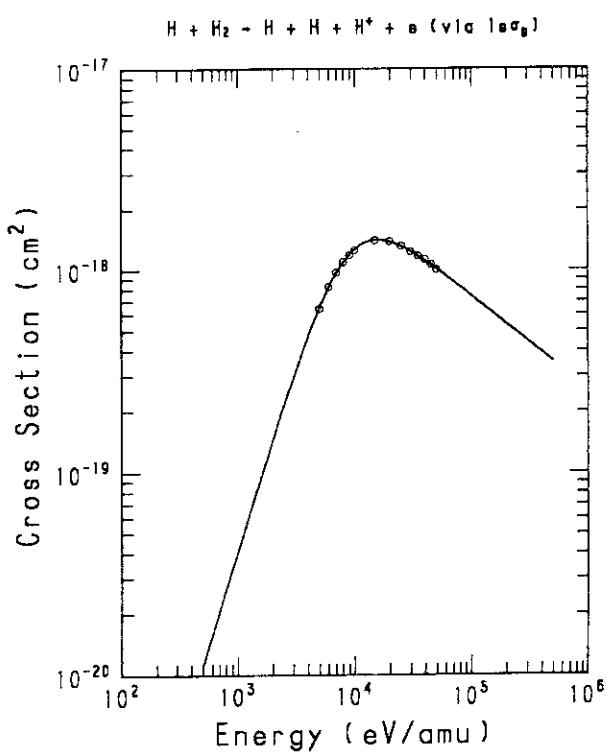
GRAPH 2



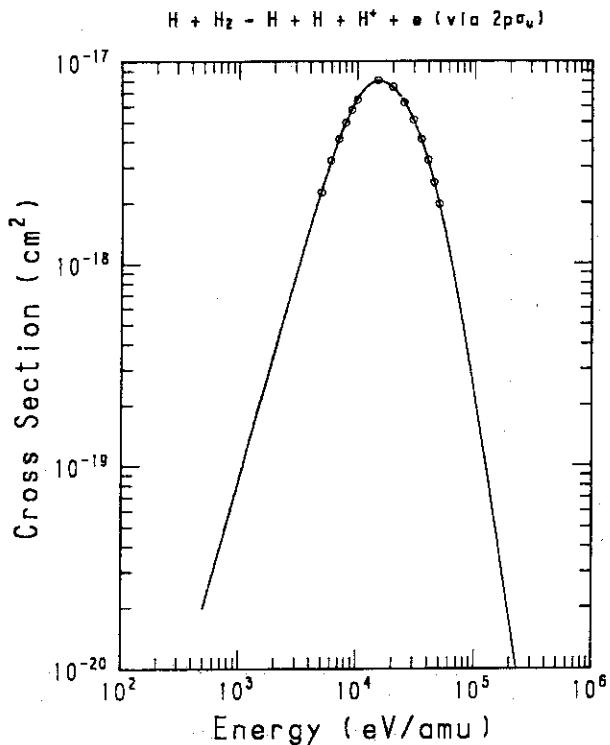
GRAPH 3



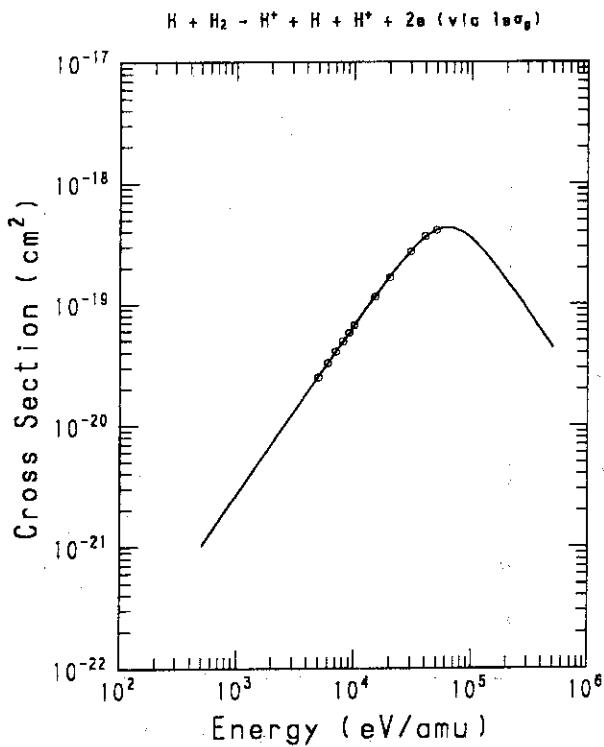
GRAPH 4



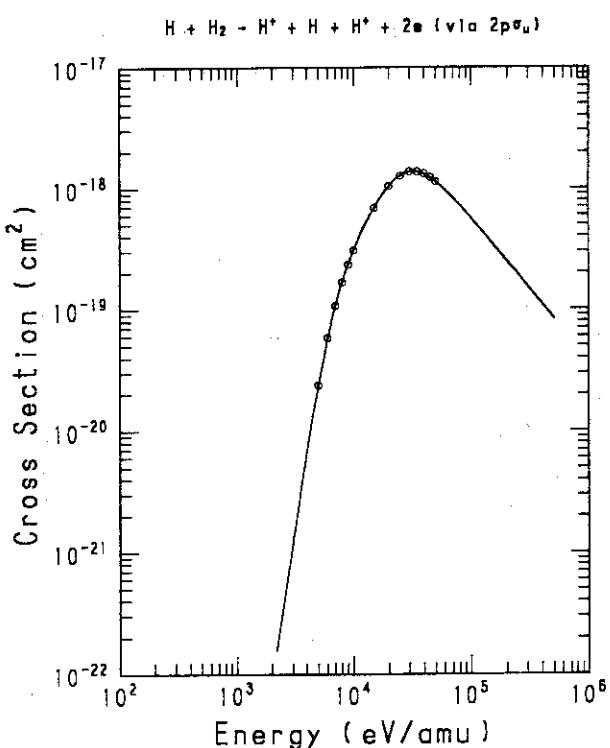
GRAPH 5



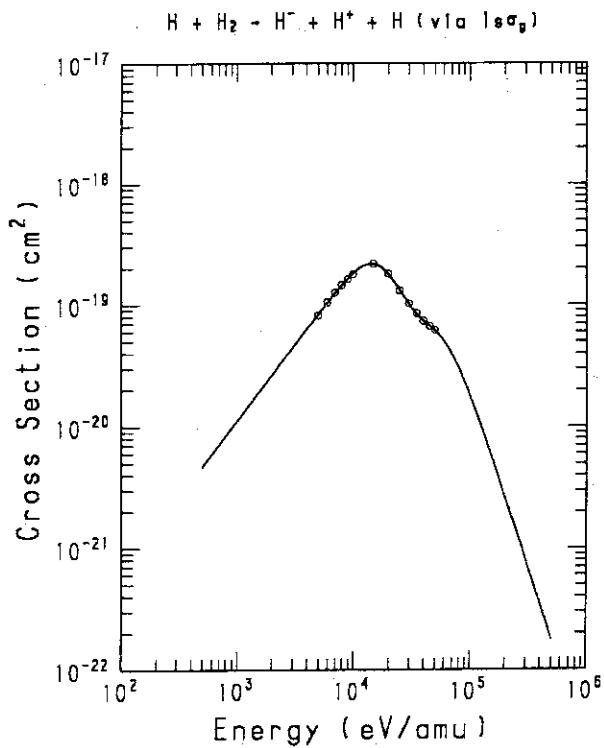
GRAPH 6



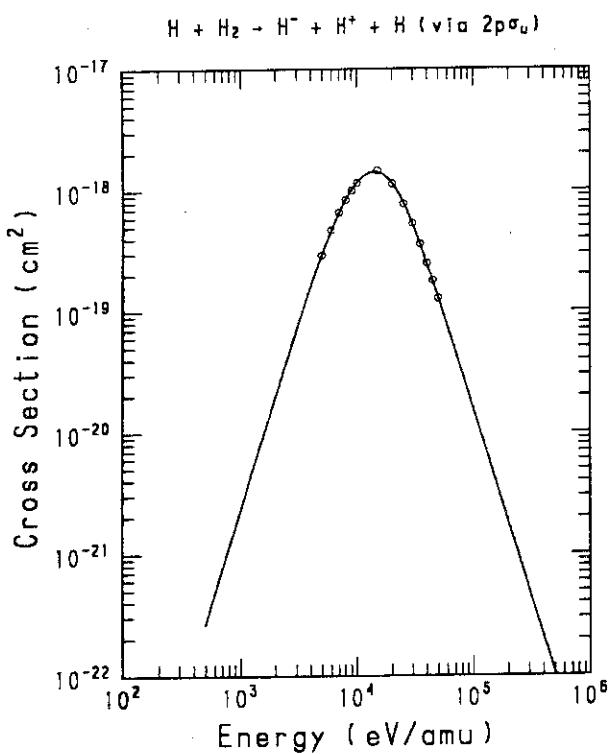
GRAPH 7



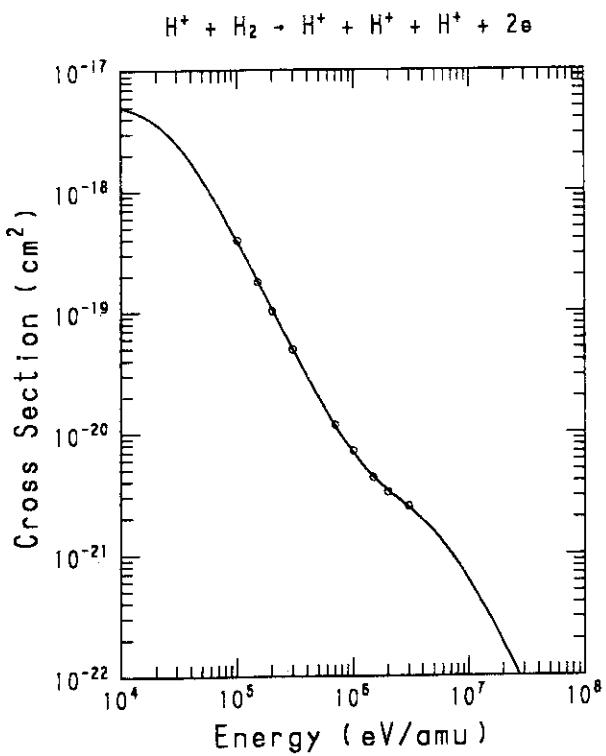
GRAPH 8



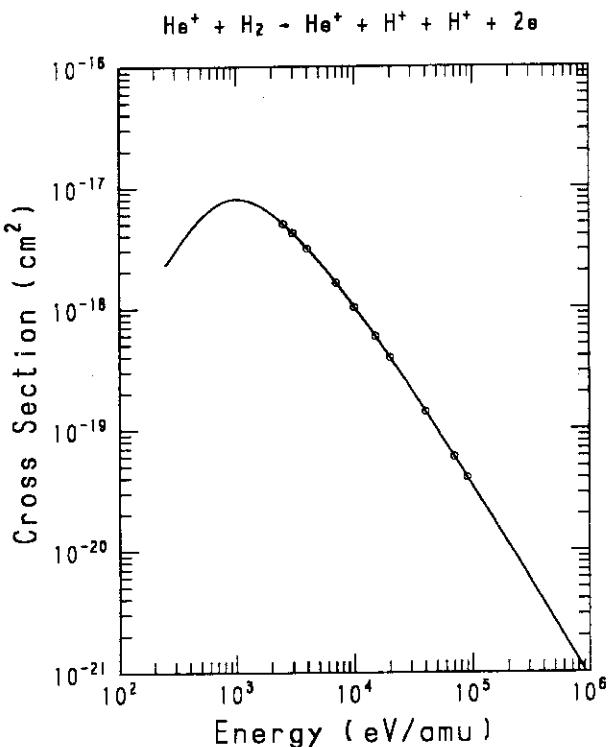
GRAPH 9



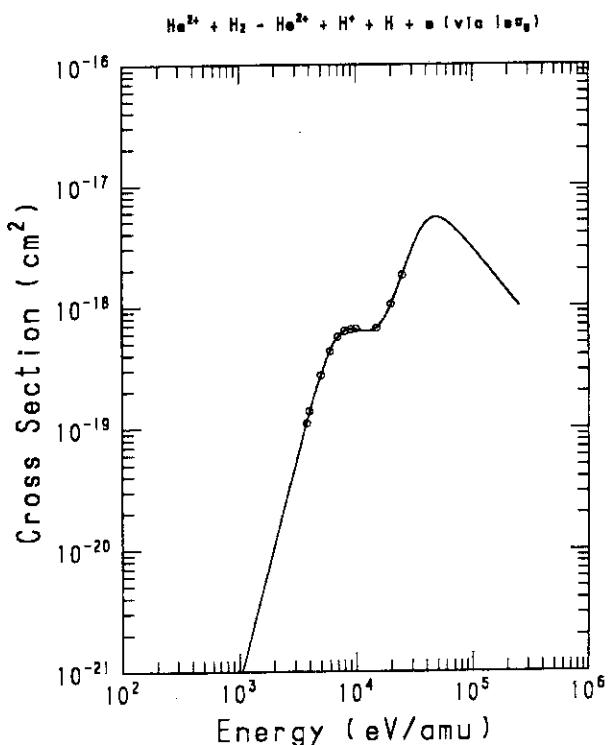
GRAPH 10



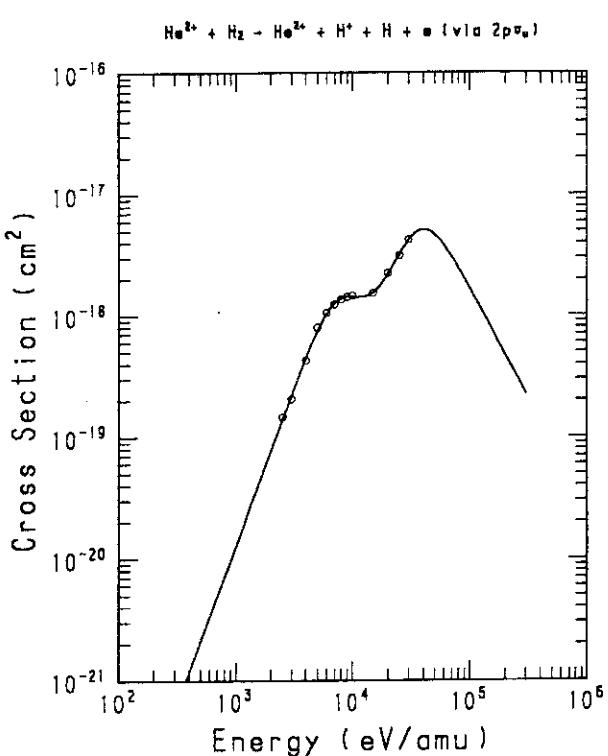
GRAPH 11



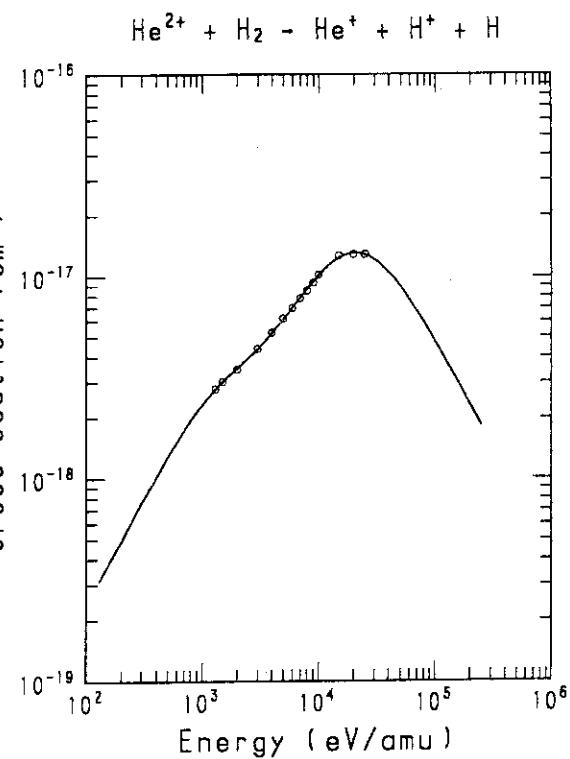
GRAPH 12



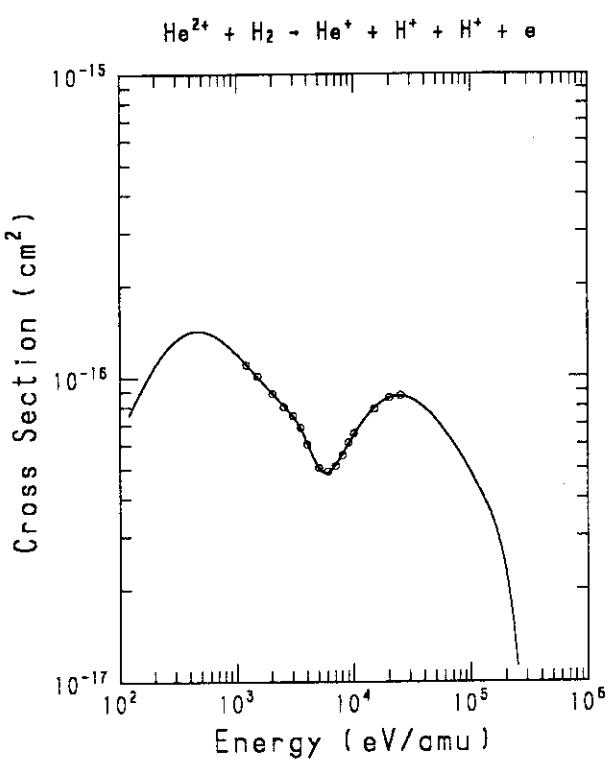
GRAPH 13



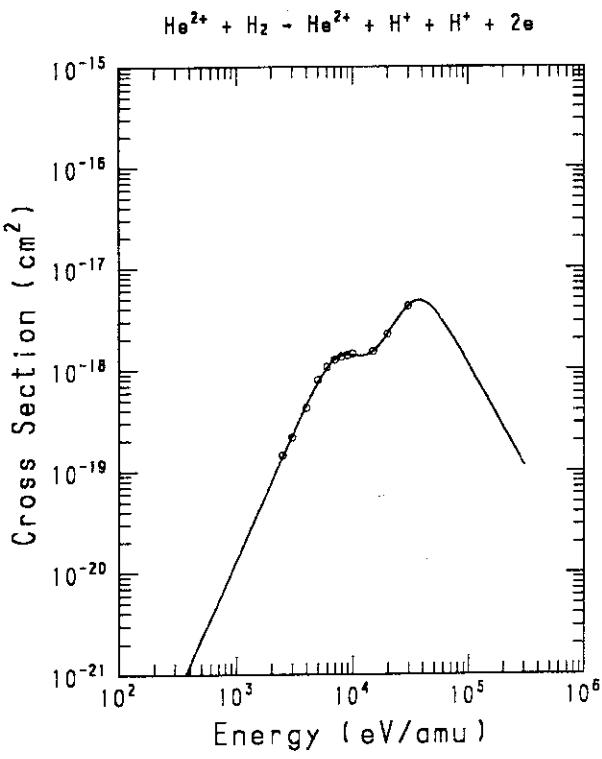
GRAPH 14



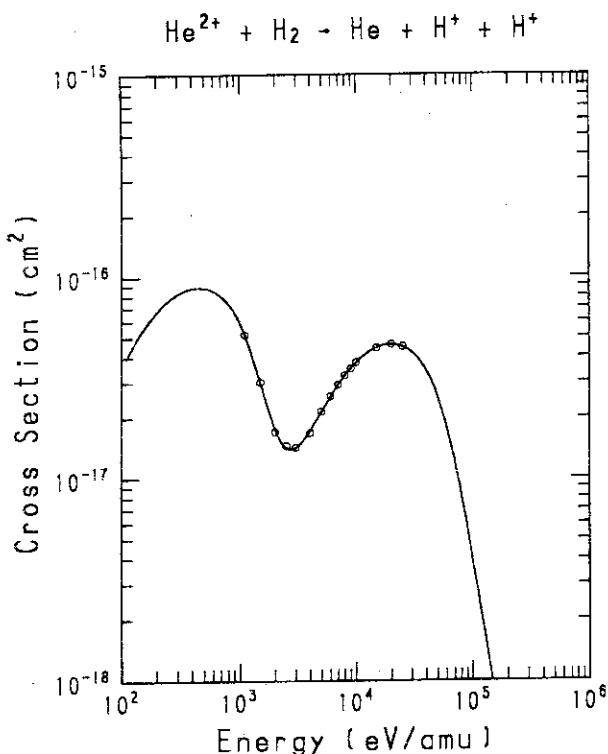
GRAPH 15



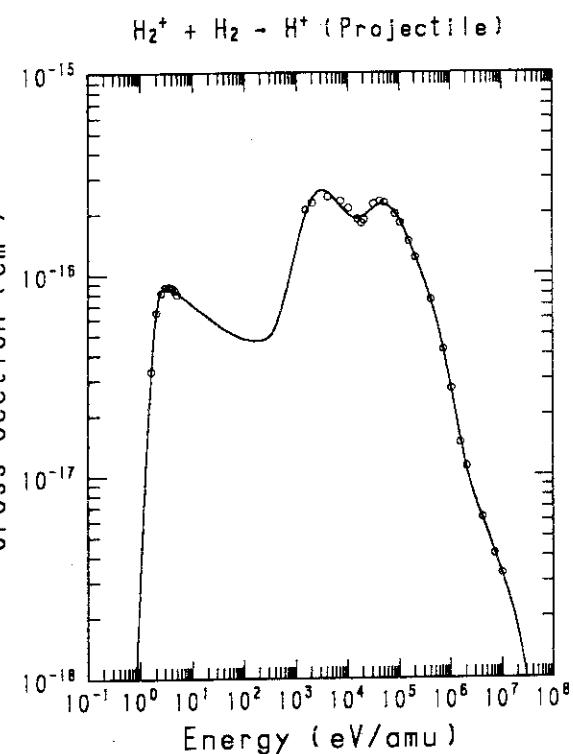
GRAPH 16



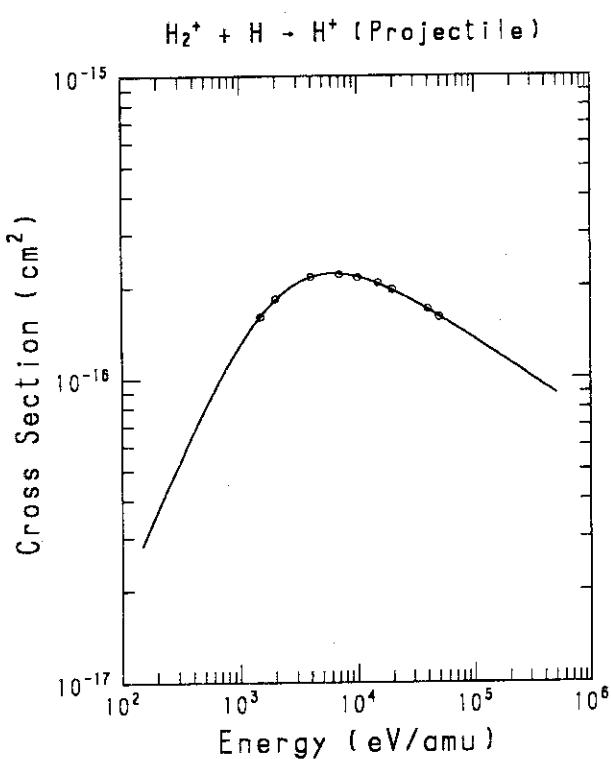
GRAPH 17



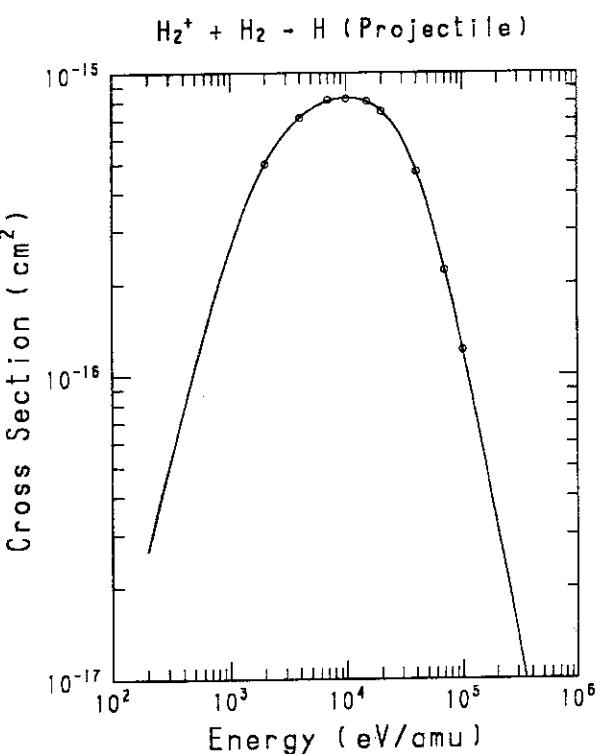
GRAPH 18



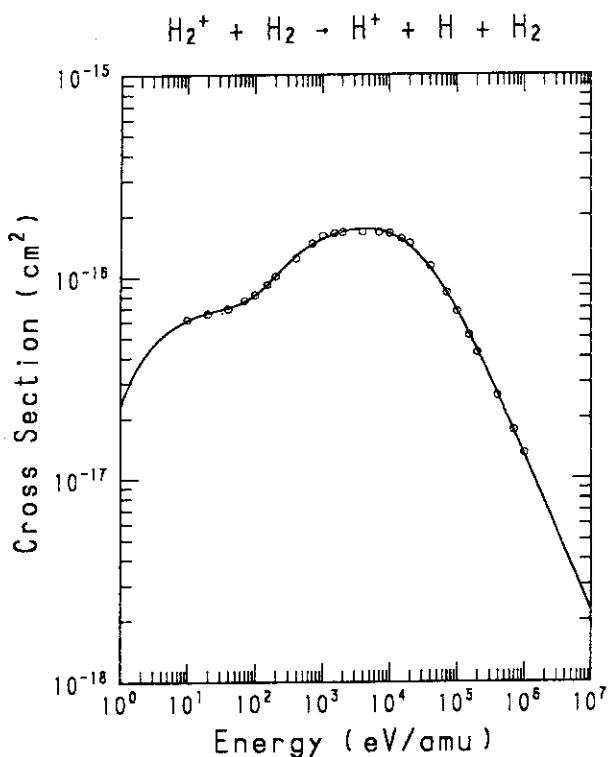
GRAPH 19



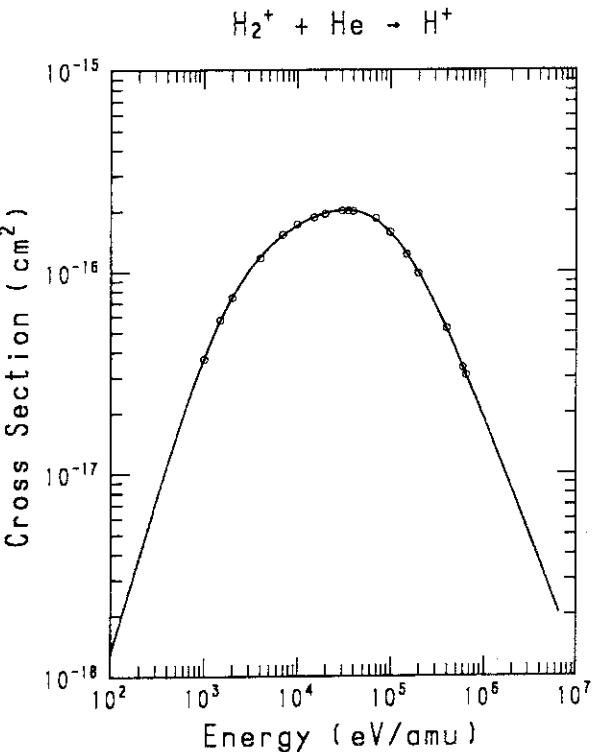
GRAPH 20



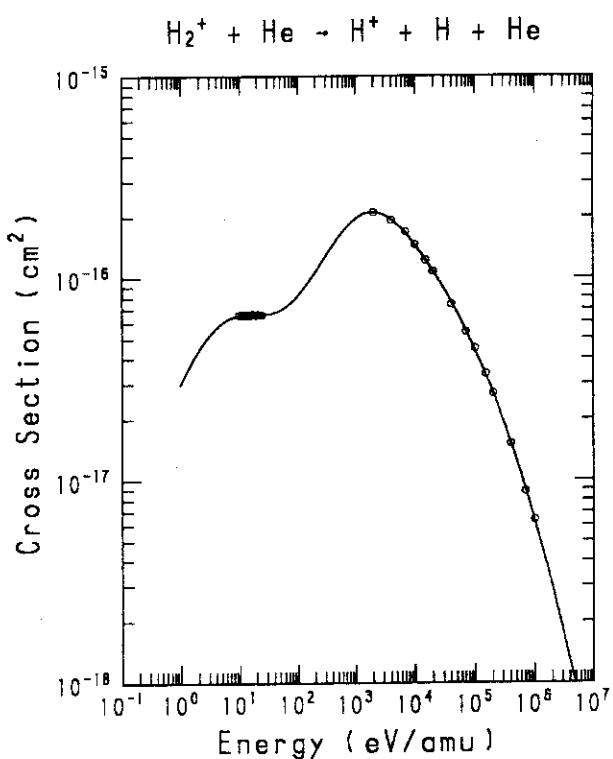
GRAPH 21



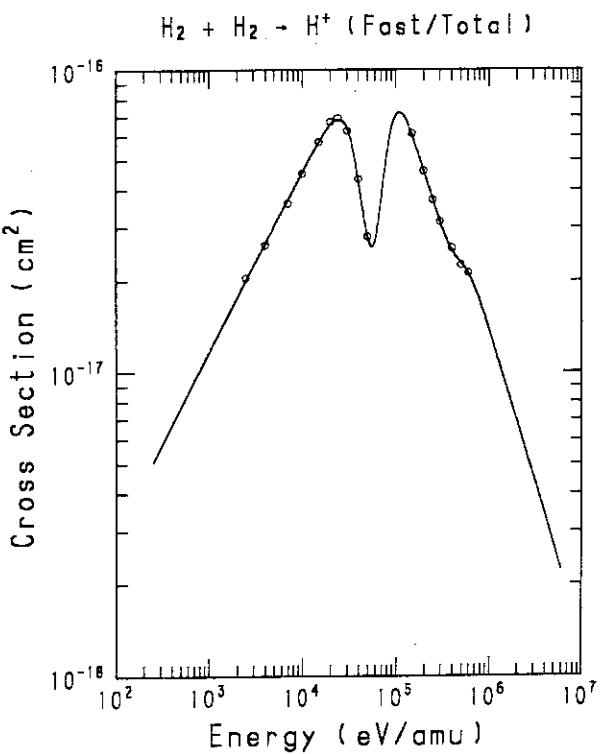
GRAPH 22



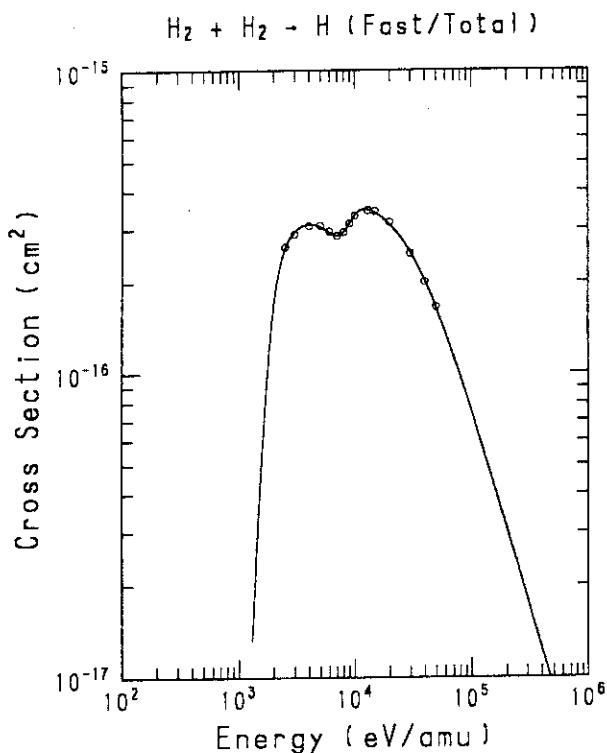
GRAPH 23



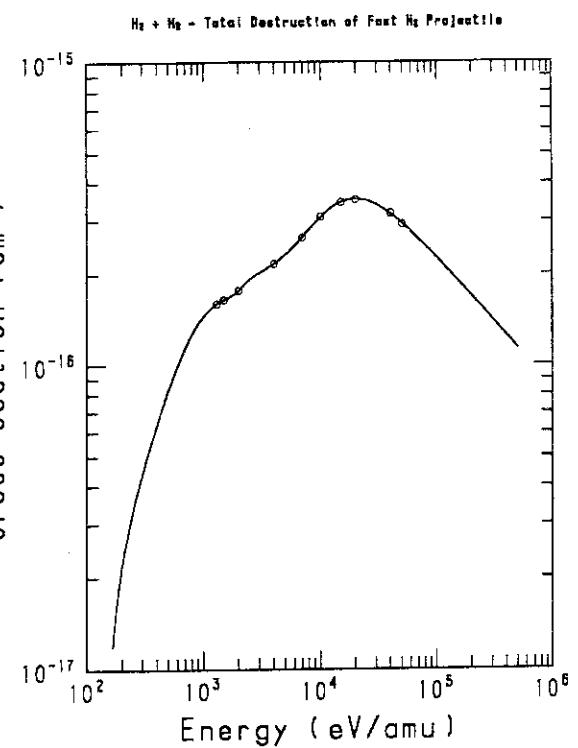
GRAPH 24



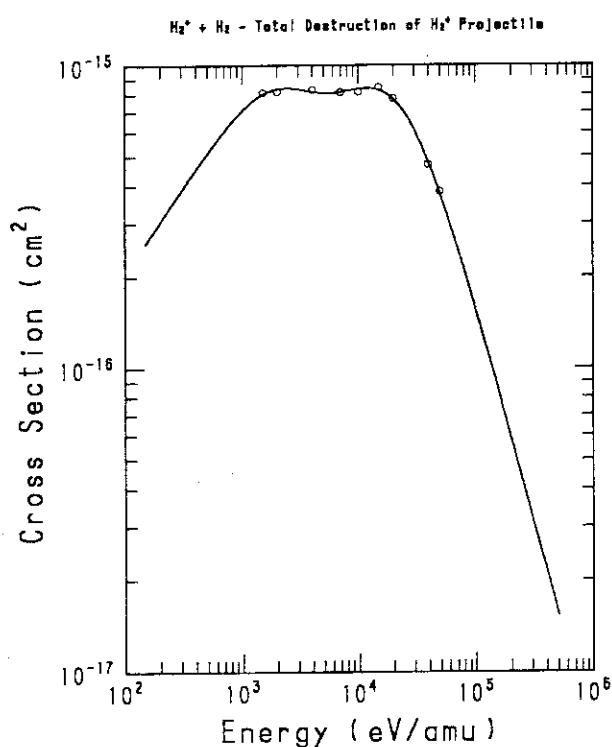
GRAPH 25



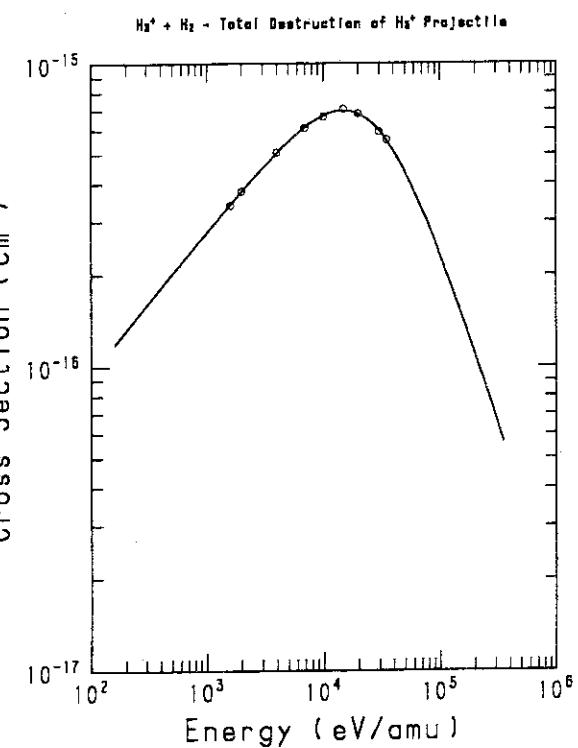
GRAPH 26



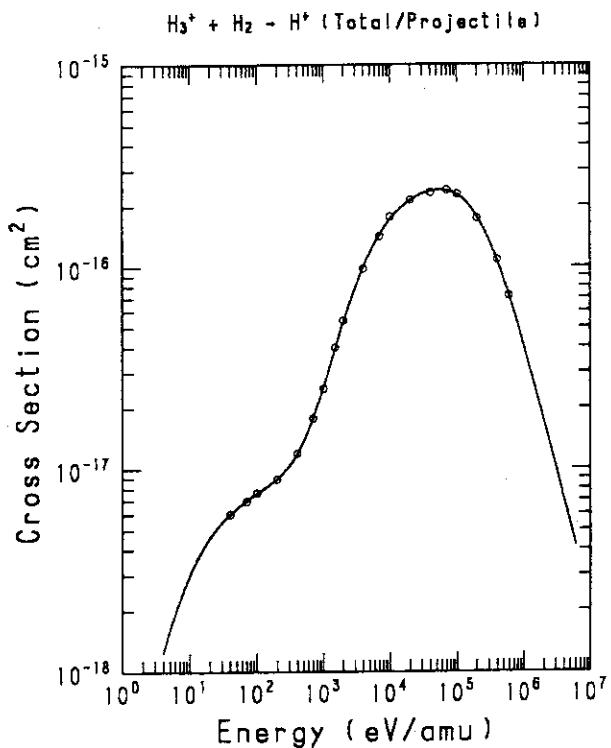
GRAPH 27



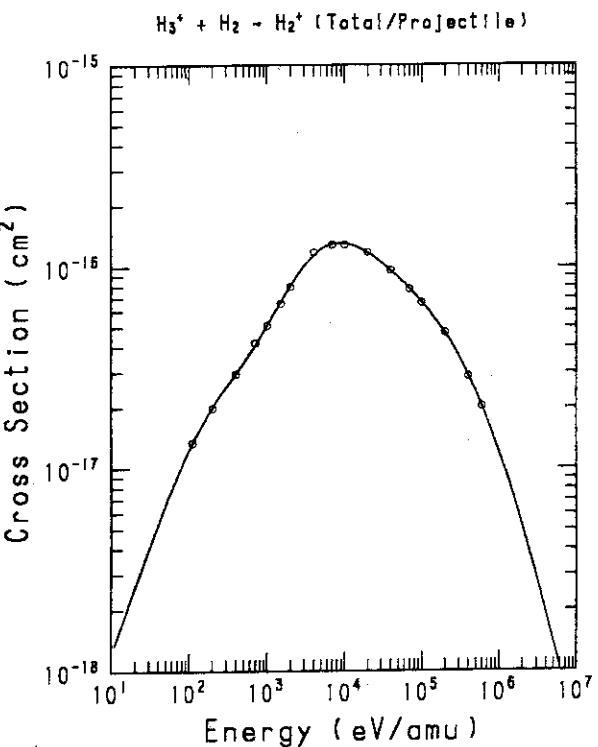
GRAPH 28



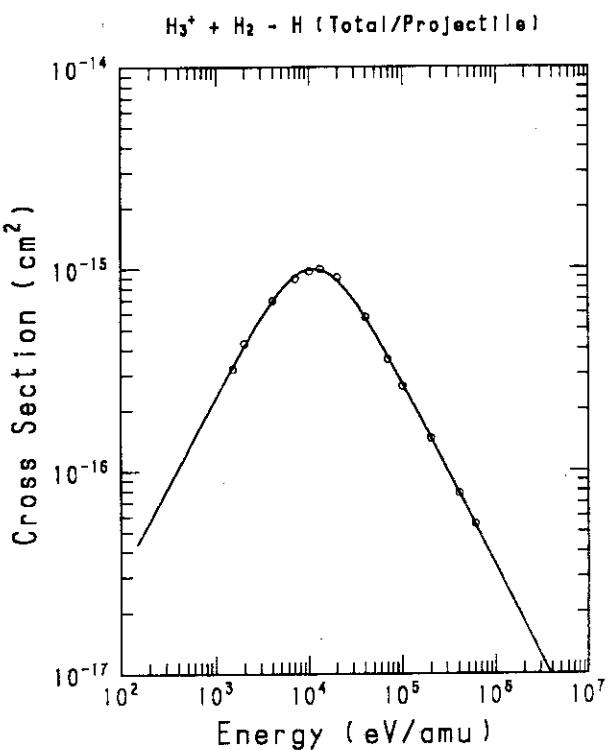
GRAPH 29



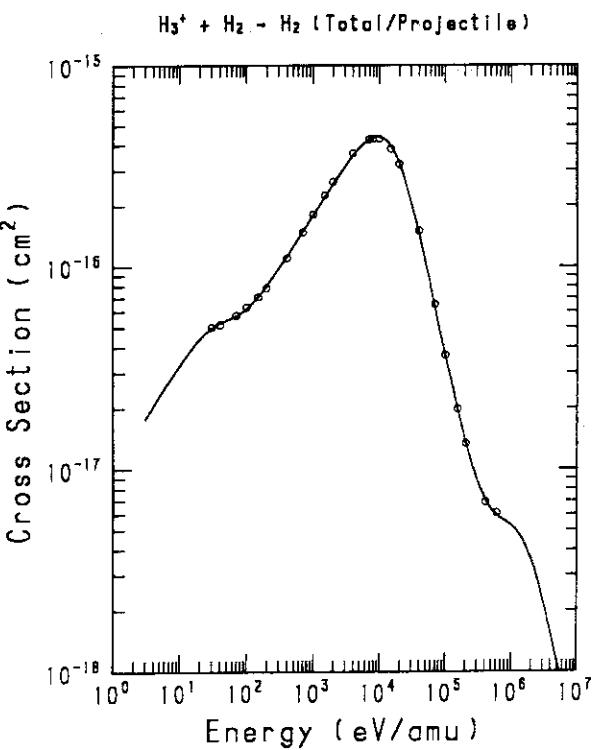
GRAPH 30



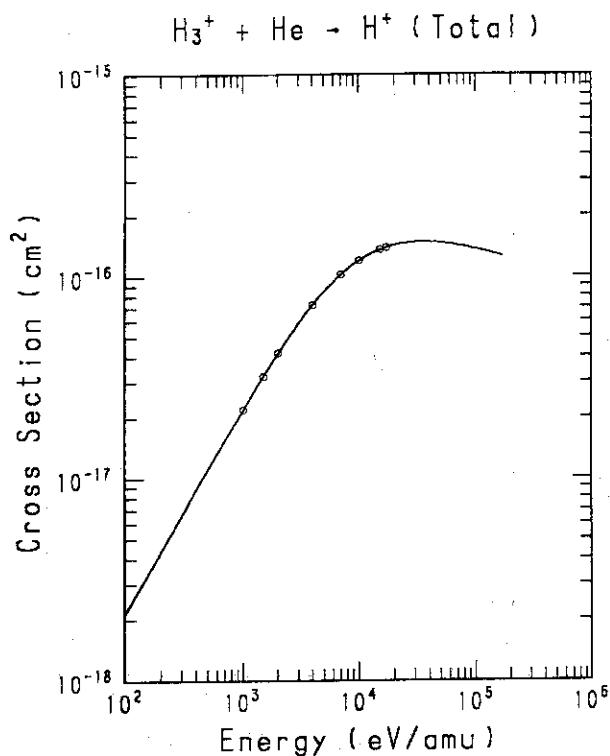
GRAPH 31



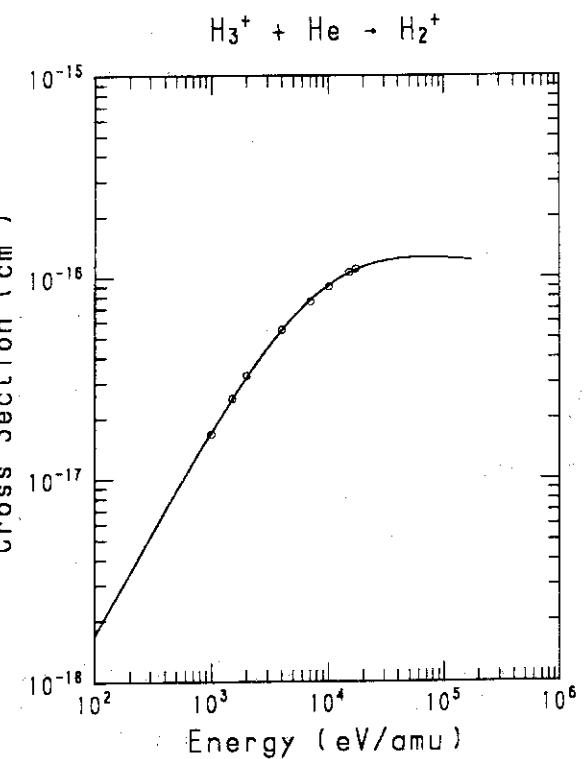
GRAPH 32



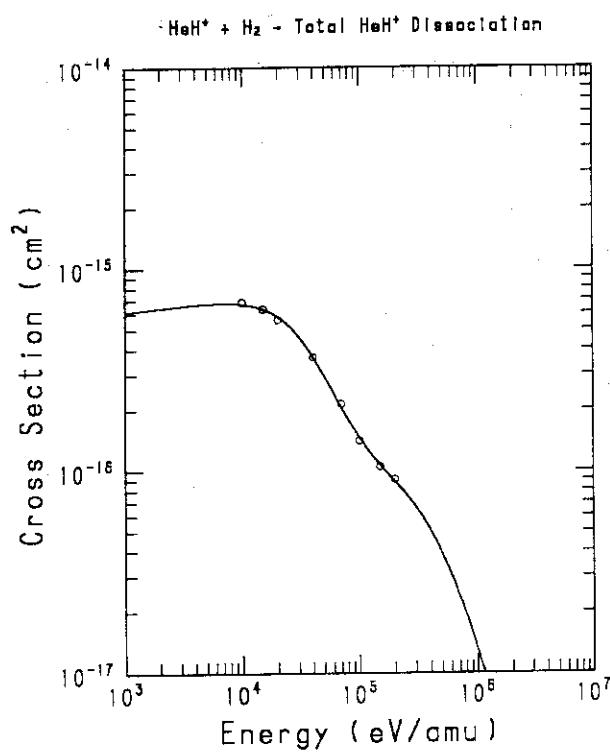
GRAPH 33



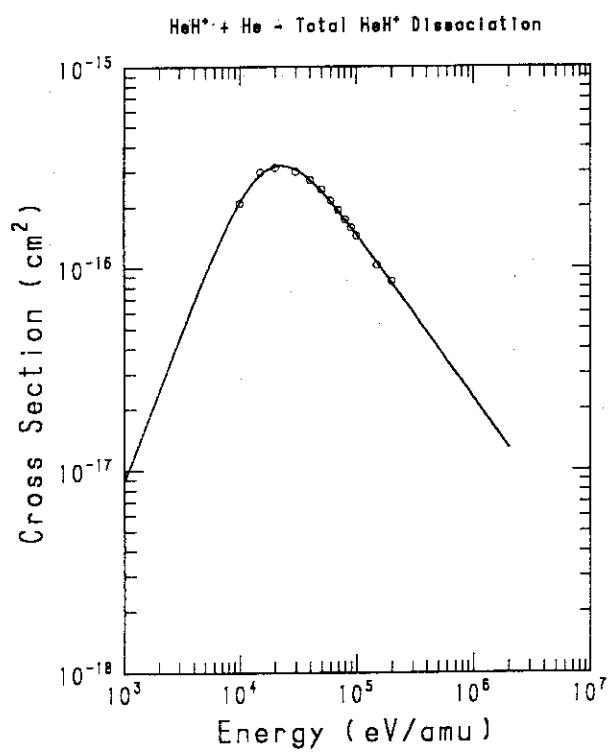
GRAPH 34



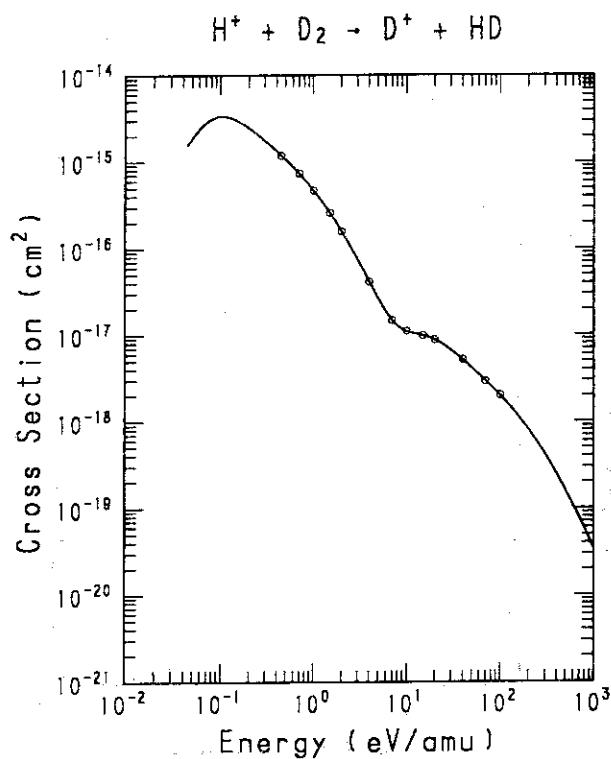
GRAPH 35



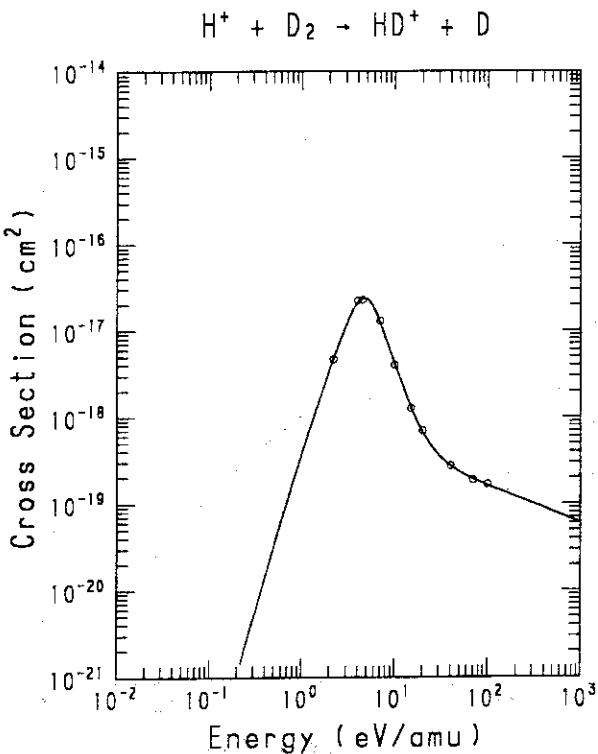
GRAPH 36



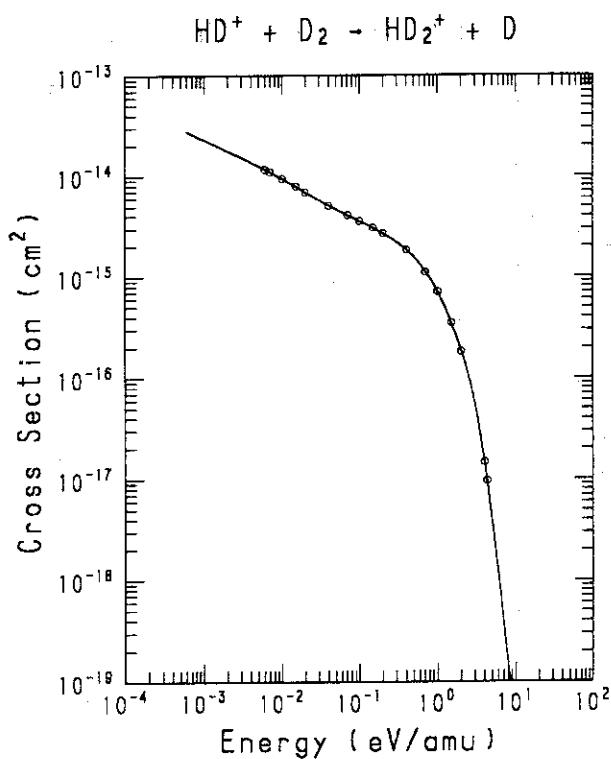
GRAPH 37



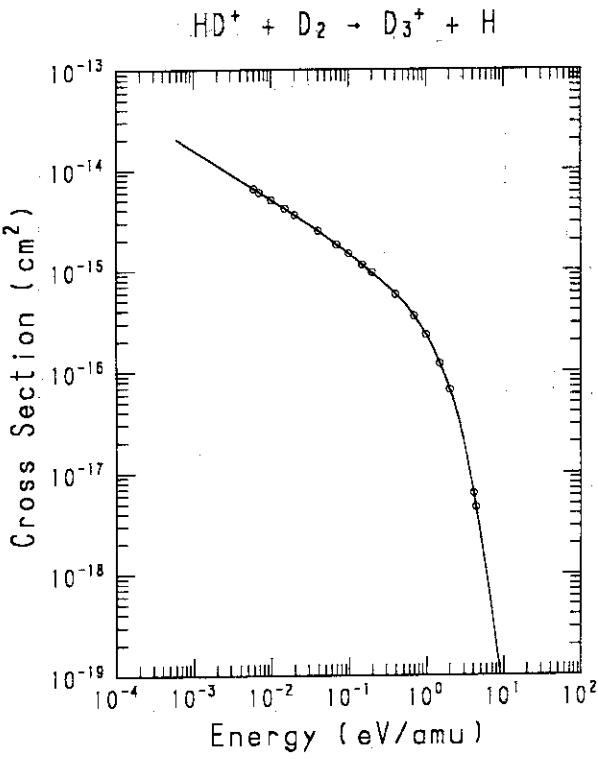
GRAPH 38



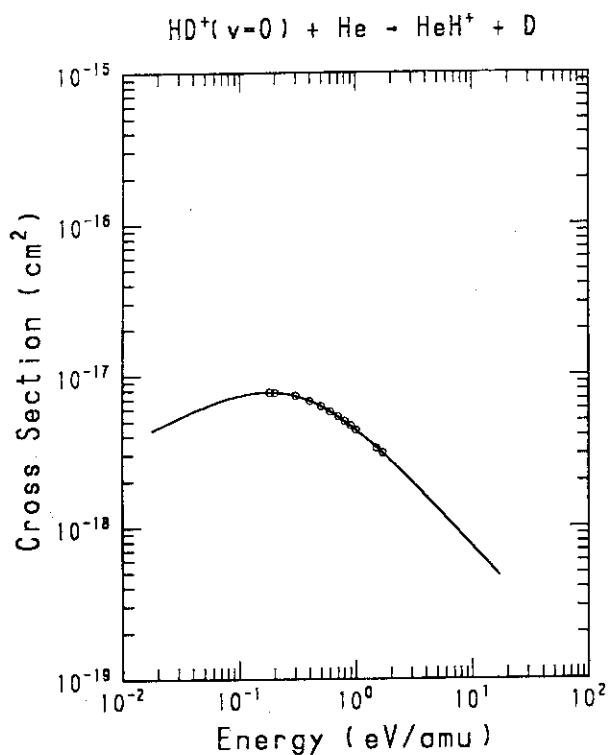
GRAPH 39



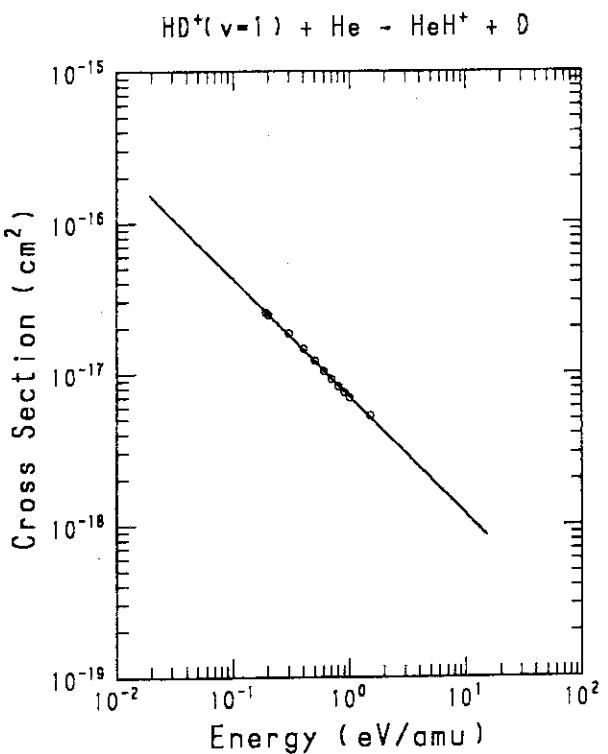
GRAPH 40



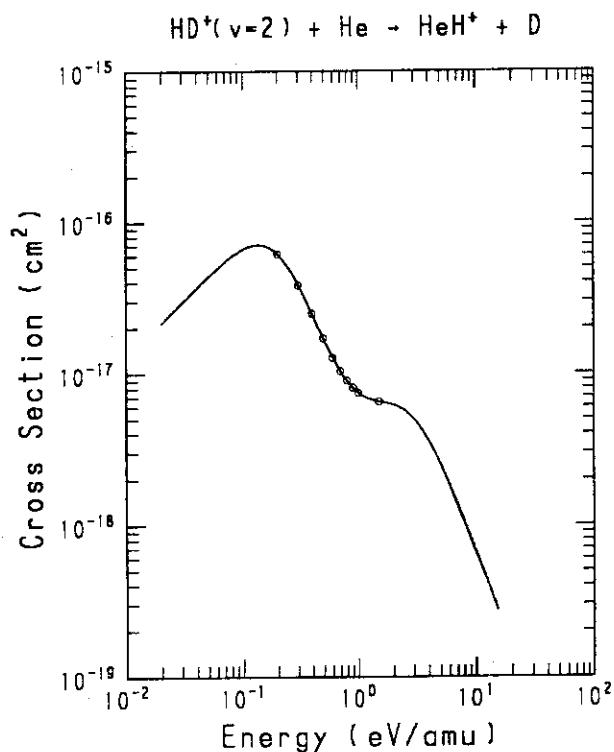
GRAPH 41



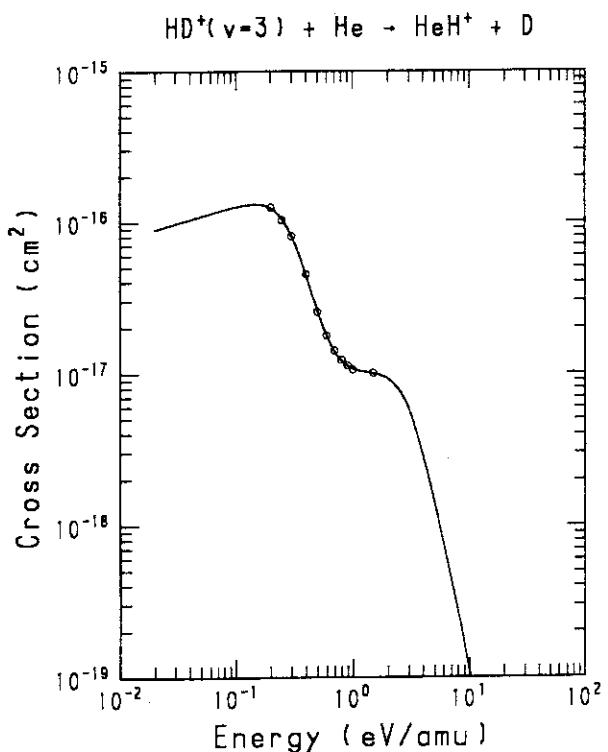
GRAPH 42



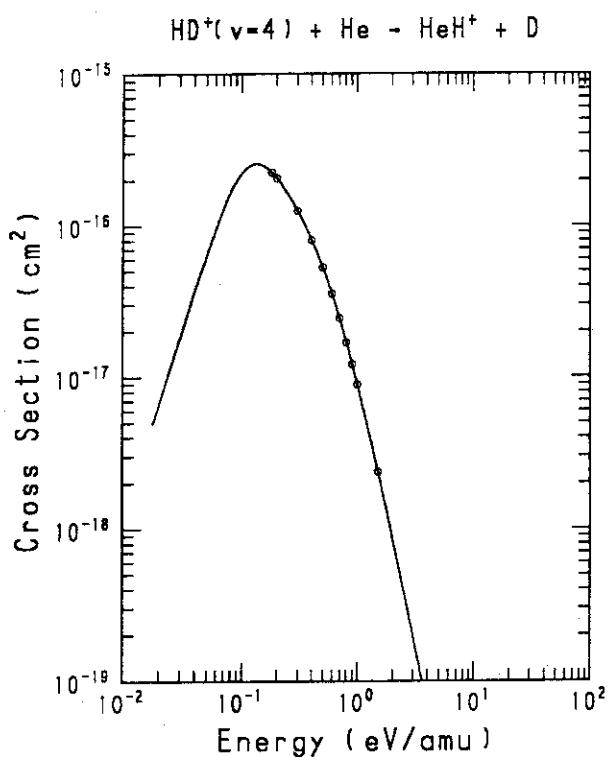
GRAPH 43



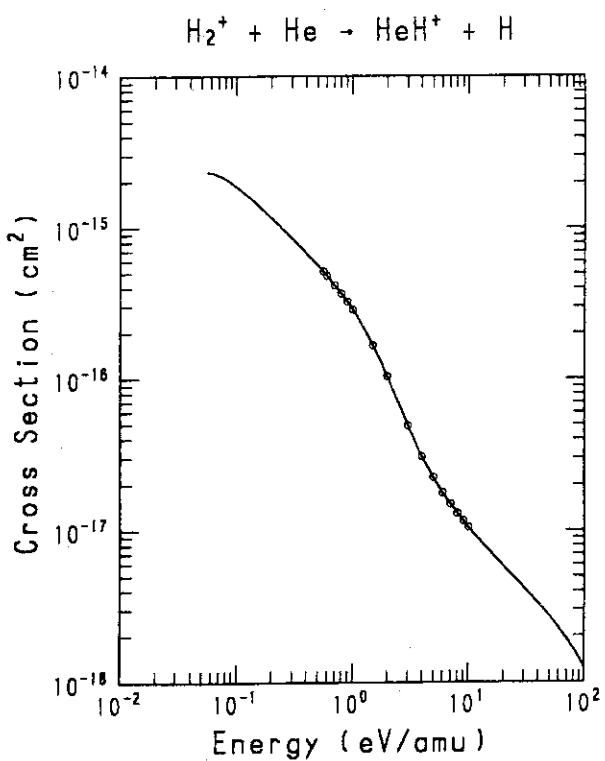
GRAPH 44



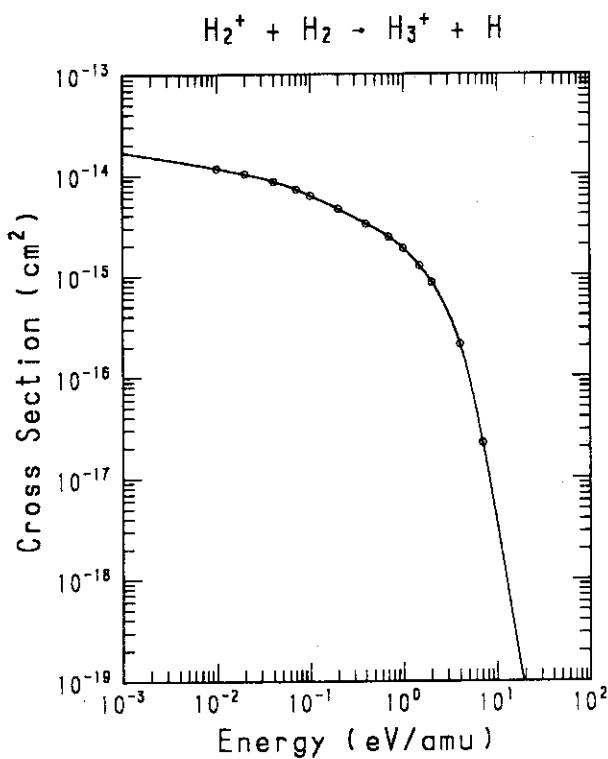
GRAPH 45



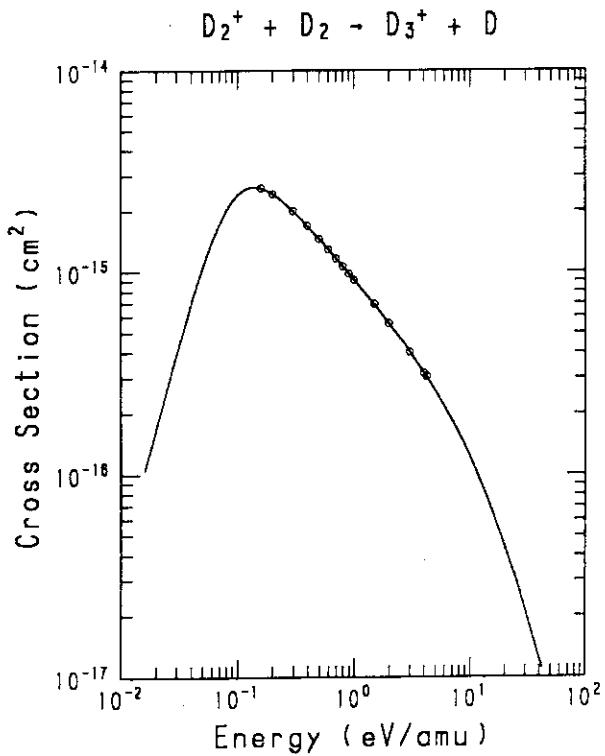
GRAPH 46



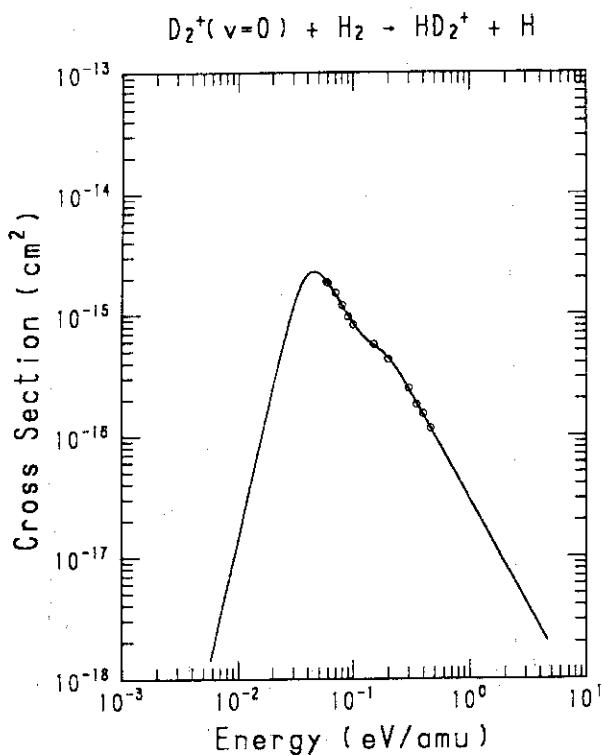
GRAPH 47



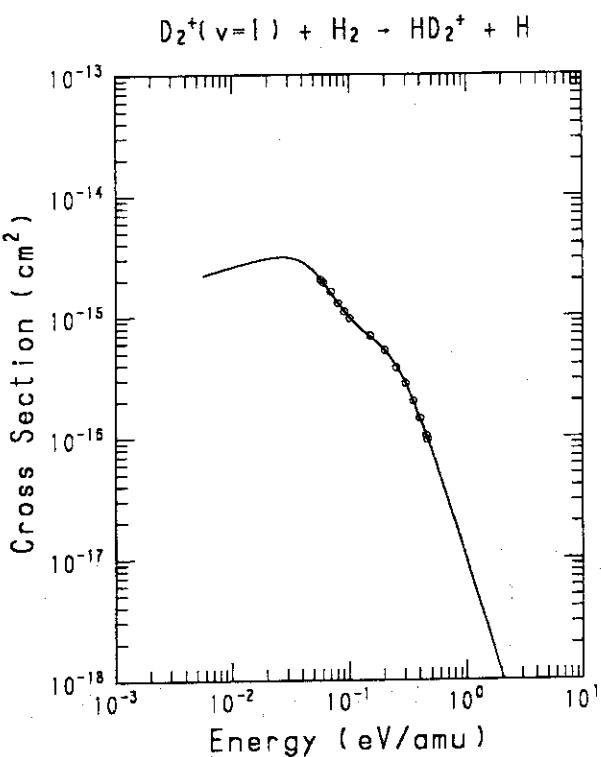
GRAPH 48



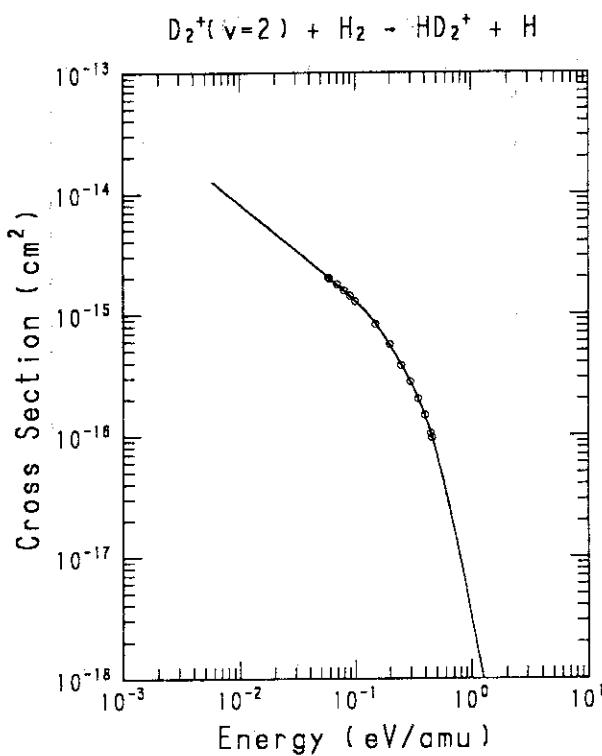
GRAPH 49



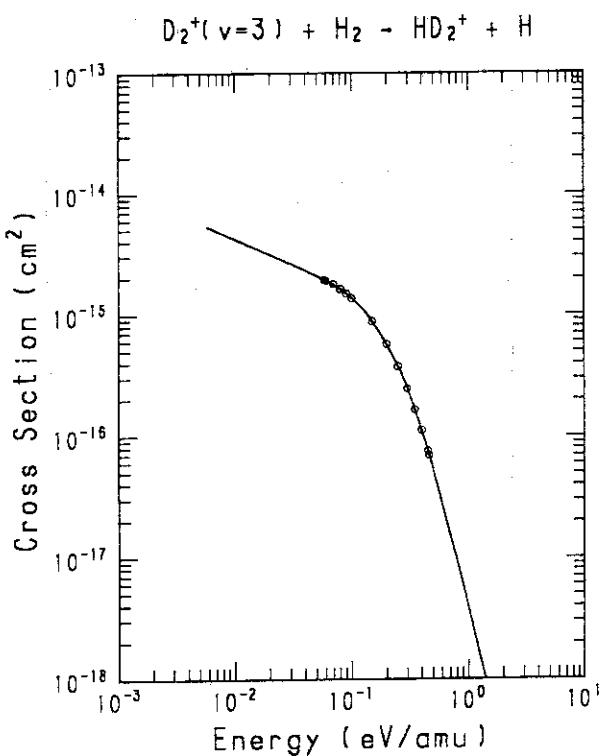
GRAPH 50



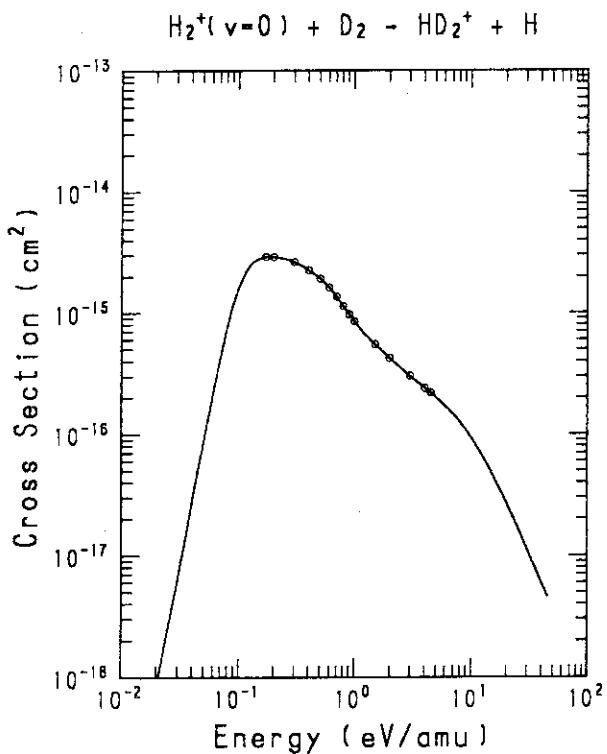
GRAPH 51



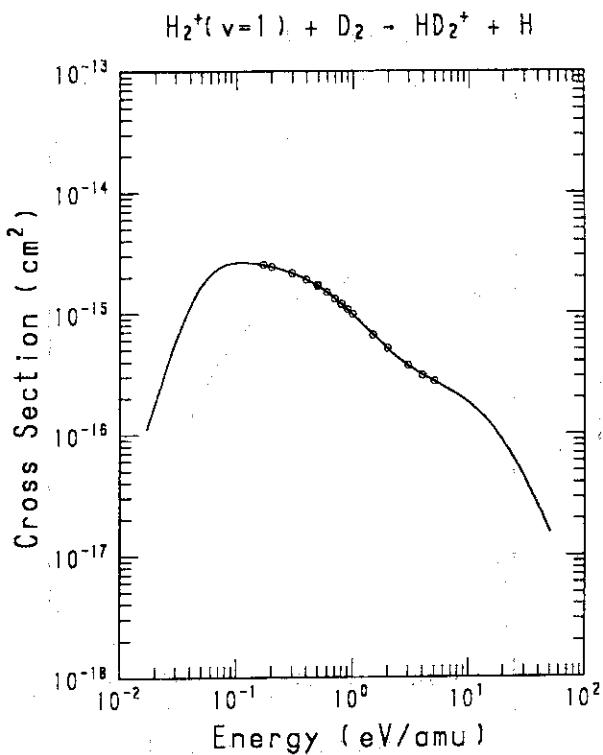
GRAPH 52



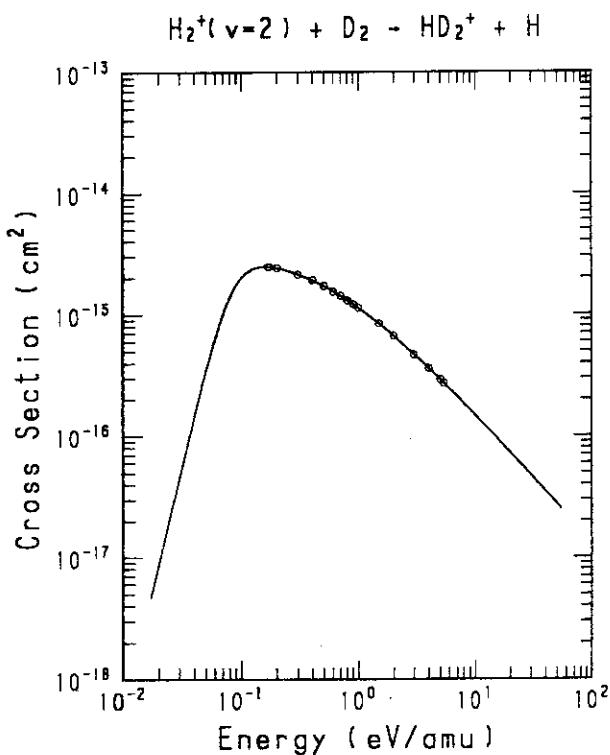
GRAPH 53



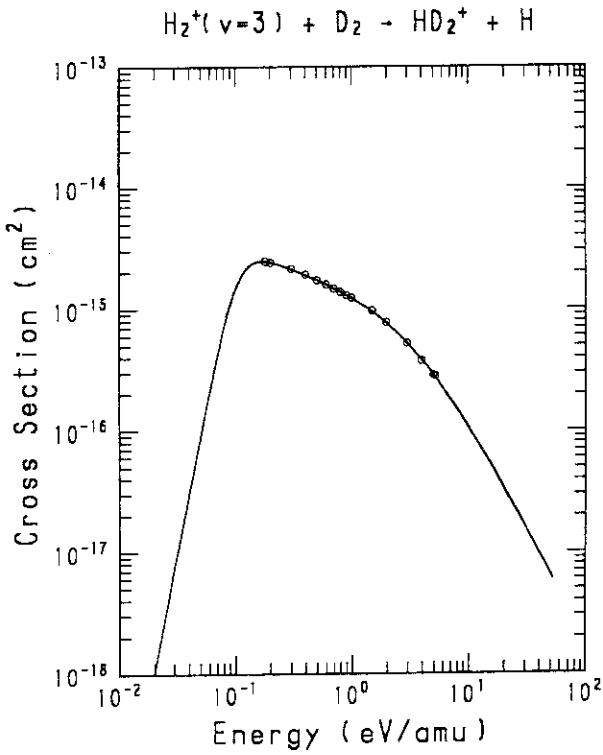
GRAPH 54



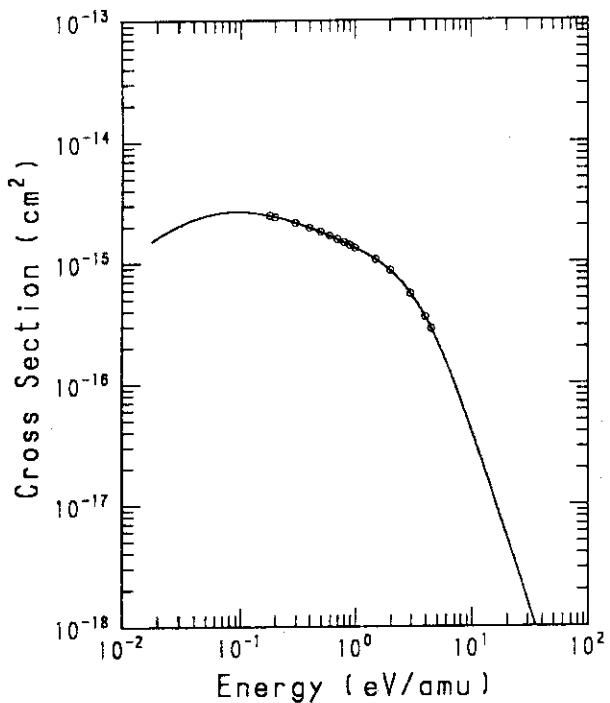
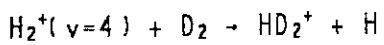
GRAPH 55



GRAPH 56



GRAPH 57



## Appendix

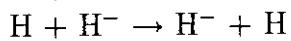
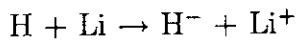
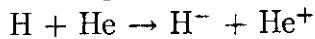
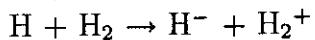
### List of Reactions Treated in Previous Reports

In this appendix reactions treated in part I-III of the present series of reports (Refs. 9-11 on pages 2 and 3) are given.

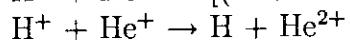
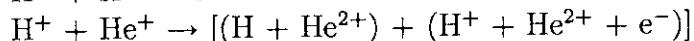
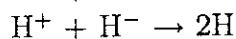
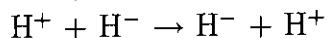
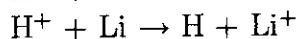
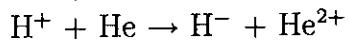
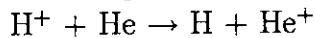
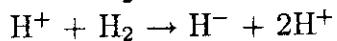
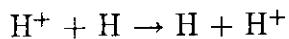
#### Reactions Treated in Part I

##### Electron Capture Collisions

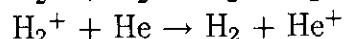
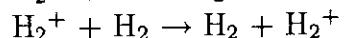
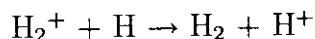
###### Electron capture by neutral H



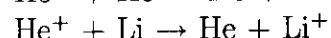
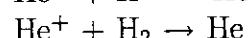
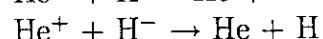
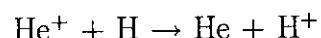
###### Electron capture by $H^+$

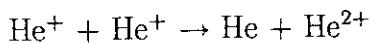


###### Electron capture by $H_2^+$

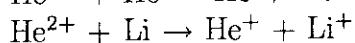
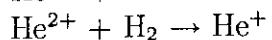
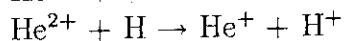
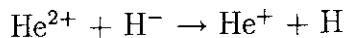
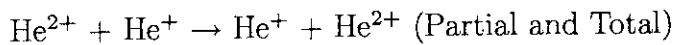


###### Electron capture by $He^+$



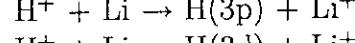
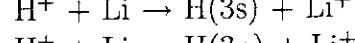
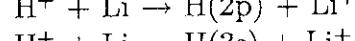
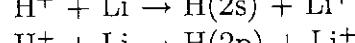
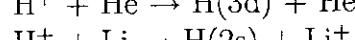
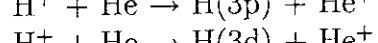
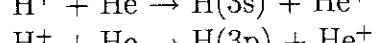
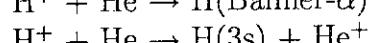
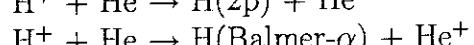
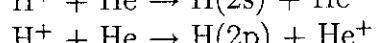
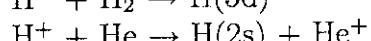
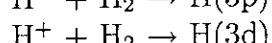
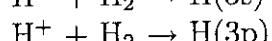
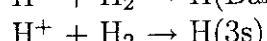
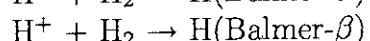
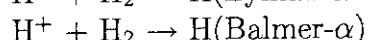
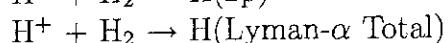
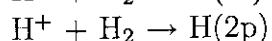
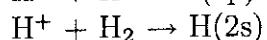
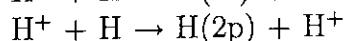
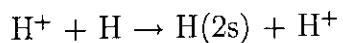


### **Electron capture by $\text{He}^{2+}$**

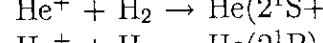
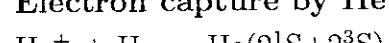


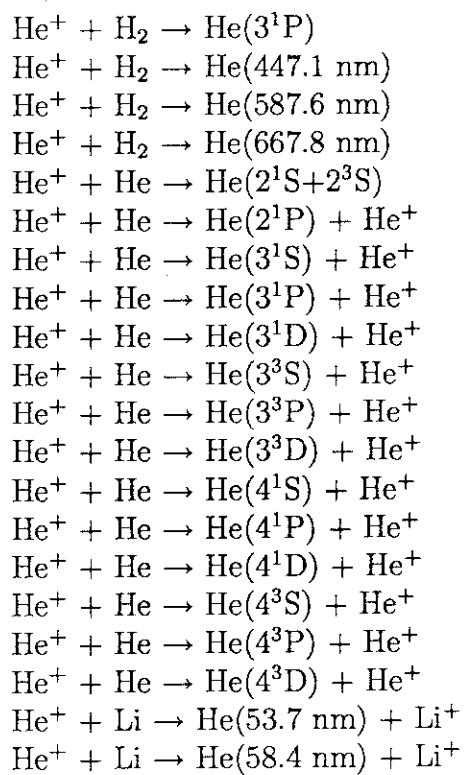
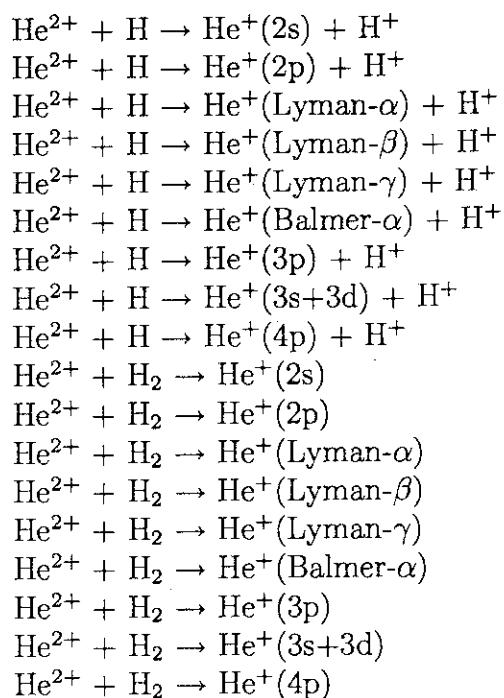
### **Electron Capture into Excited States**

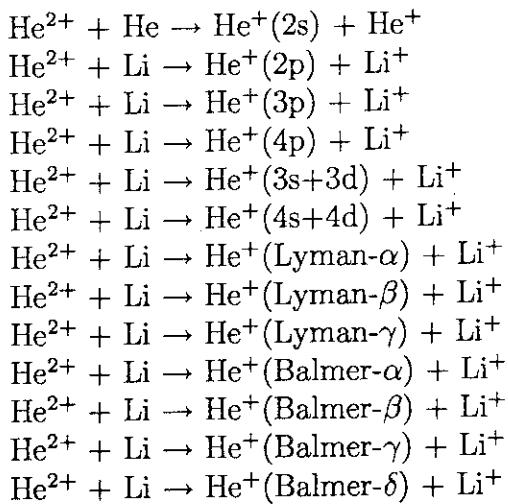
#### **Electron capture by $\text{H}^+$**



#### **Electron capture by $\text{He}^+$**



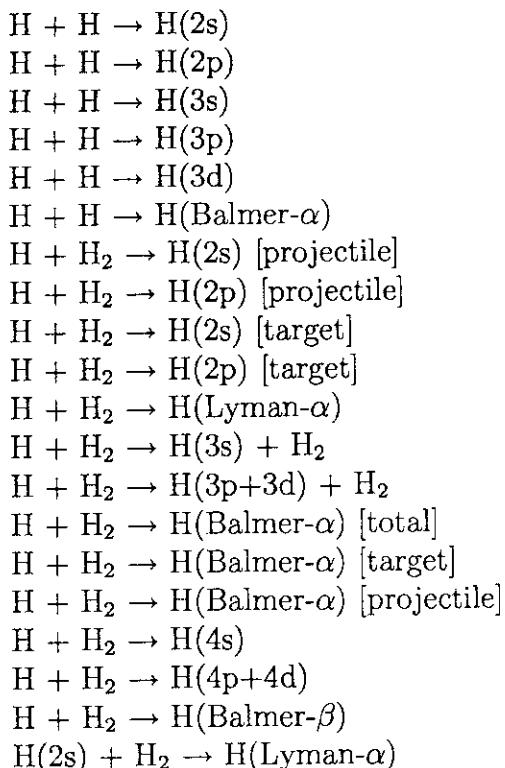
**Electron capture by  $\text{He}^{2+}$** 



## Reactions Treated in Part II

### Excitation and Spectral Line Emission

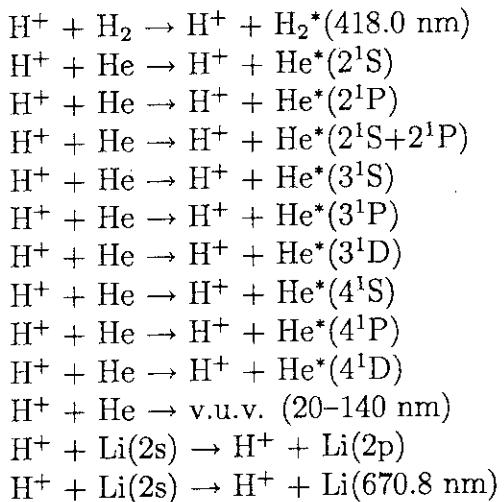
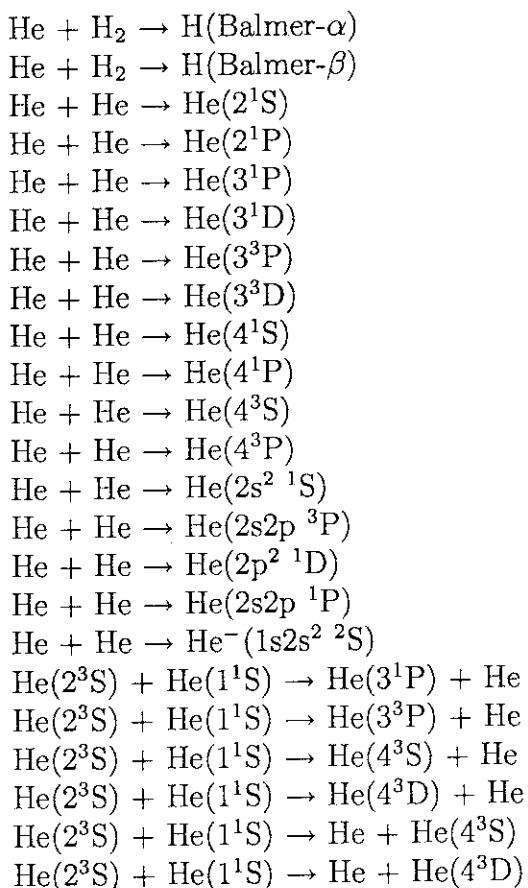
#### Collision by neutral H

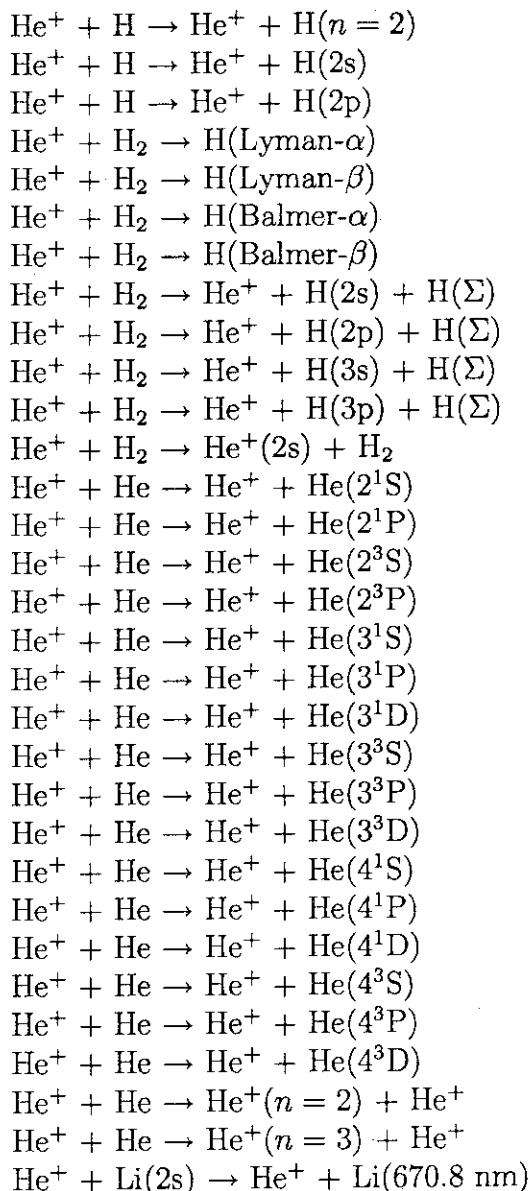
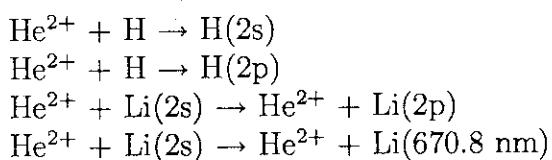


$H(2s) + H_2 \rightarrow H(\text{Balmer-}\alpha)$   
 $H(2s) + H_2 \rightarrow H(3s)$   
 $H(2s) + He \rightarrow H(\text{Lyman-}\alpha)$   
 $H(2s) + He \rightarrow H(3s)$   
 $H(2s) + He \rightarrow H(\text{Balmer-}\alpha)$   
 $H + He \rightarrow H(\text{Lyman-}\alpha)$   
 $H + He \rightarrow H(2s)$   
 $H + He \rightarrow H(2p)$   
 $H + He \rightarrow H(3s)$   
 $H + He \rightarrow H(3p)$   
 $H + He \rightarrow H(3d)$   
 $H + He \rightarrow H(3p+3d)$   
 $H + He \rightarrow H(\text{Balmer-}\alpha)$   
 $H + He \rightarrow H(\text{Balmer-}\beta)$   
 $H + He \rightarrow H(4s)$   
 $H + He \rightarrow H(4p+4d)$   
 $H + He \rightarrow He(3^1P)$   
 $H + He \rightarrow He(3^3P)$   
 $H + He \rightarrow He(3^3D)$   
 $H + He \rightarrow He(4^1S)$   
 $H + He \rightarrow He(4^1P)$   
 $H + He \rightarrow He(4^1D)$   
 $H + He \rightarrow He(4^3S)$   
 $H + He \rightarrow He(4^3P)$   
 $H + He \rightarrow He(4^3D)$

### Collision by $H^+$

$H^+ + H \rightarrow H^+ + H(2s)$   
 $H^+ + H \rightarrow H^+ + H(2p)$   
 $H^+ + H \rightarrow H^+ + H(n = 2)$   
 $H^+ + H \rightarrow H^+ + H(n = 3)$   
 $H^+ + H \rightarrow H^+ + H(n = 4)$   
 $H^+ + H_2 \rightarrow H^+ + H(2s) + H$   
 $H^+ + H_2 \rightarrow H^+ + H(2p) + H$   
 $H^+ + H_2 \rightarrow H^+ + H(3p) + H$   
 $H^+ + H_2 \rightarrow H(\text{Lyman-}\alpha)$   
 $H^+ + H_2 \rightarrow H(\text{Balmer-}\alpha)$   
 $H^+ + H_2 \rightarrow H(\text{Balmer-}\beta)$   
 $H^+ + H_2 \rightarrow H(\text{Balmer-}\gamma)$   
 $H^+ + H_2 \rightarrow H^+ + H_2^*(160.6 \text{ nm})$

**Collision by neutral He**

**Collision by He<sup>+</sup>****Collision by He<sup>2+</sup>**

## Reactions Treated in Part III

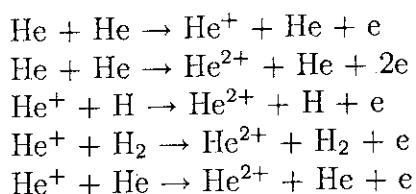
### Ionization and Production of Charged Particles

$\text{H} + \text{H}_2 \rightarrow$  Total Slow Positive Ion Production  
 $\text{H} + \text{H}_2 \rightarrow$  Total Slow Electron Production  
 $\text{H} + \text{H}_2 \rightarrow \text{H} + \text{H}_2^+ + \text{e}$   
 $\text{H}^+ + \text{H} \rightarrow \text{H}^+ + \text{H}^+ + \text{e}$   
 $\text{H}^+ + \text{H}^- \rightarrow \text{H}_2^+ + \text{e}$   
 $\text{H}^+ + \text{H}_2 \rightarrow$  Total Slow Electron Production  
 $\text{H}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2^+ + \text{e}$   
 $\text{H}^+ + \text{H}_2 \rightarrow$  Total Production of  $\text{H}_2^+$   
 $\text{H}^+ + \text{H}_2 \rightarrow$  Total Production of  $\text{H}^+$   
 $\text{H}^+ + \text{He} \rightarrow$  Electrons and  $\text{H}^-$   
 $\text{H}^+ + \text{He} \rightarrow \text{H}^+ + \text{He}^+ + \text{e}$   
 $\text{H}^+ + \text{He} \rightarrow (\text{H} + \text{He}^+) \text{ or } (\text{H}^+ + \text{He}^+ + \text{e})$   
 $\text{H}^+ + \text{He} \rightarrow \text{H}^+ + \text{He}^{2+} + 2\text{e}$   
 $\text{H}^+ + \text{He} \rightarrow (\text{H}^- + \text{He}^{2+}) \text{ or } (\text{H}^+ + \text{He}^{2+} + 2\text{e})$   
 $\text{H}^+ + \text{He}^+ \rightarrow \text{H}^+ + \text{He}^{2+} + \text{e}$   
 $\text{H}^+ + \text{He}^+ \rightarrow (\text{H}^+ + \text{He}^{2+} + \text{e}) \text{ or } (\text{H}^0 + \text{He}^{2+})$   
 $\text{H}^+ + \text{Li} \rightarrow \text{H}^+ + \text{Li}^+ + \text{e}$   
 $\text{He}(2^1\text{S}) + \text{H} \rightarrow \text{He} + \text{H}^+ + \text{e}$   
 $\text{He}(2^1\text{S}) + \text{H} \rightarrow \text{HeH}^+ + \text{e}$   
 $\text{He}(2^1\text{S}) + \text{H} \rightarrow (\text{He} + \text{H}^+ + \text{e}) \text{ or } (\text{HeH}^+ + \text{e})$   
 $\text{He}(2^3\text{S}) + \text{H} \rightarrow \text{He} + \text{H}^+ + \text{e}$   
 $\text{He}(2^3\text{S}) + \text{H} \rightarrow \text{HeH}^+ + \text{e}$   
 $\text{He}(2^3\text{S}) + \text{H} \rightarrow (\text{He} + \text{H}^+ + \text{e}) \text{ or } (\text{HeH}^+ + \text{e})$   
 $\text{He}(2^3\text{S}) + \text{H}_2 \rightarrow$  Total Ionization  
 $\text{He}(2^3\text{S}) + \text{H}_2 \rightarrow$  Rearrangement Ionization  
 $\text{He}(2^1\text{S}) + \text{H}_2 \rightarrow$  Total Ionization  
 $\text{He}(2^1\text{S}) + \text{H}_2 \rightarrow$  Rearrangement Ionization  
 $\text{He} + \text{H}_2 \rightarrow$  Total Slow Positive Ion Production  
 $\text{He} + \text{H}_2 \rightarrow$  Total Slow Electron Production  
 $\text{He} + \text{H}_2 \rightarrow \text{He} + \text{H}_2^+ + \text{e}$   
 $\text{He} + \text{H}_2 \rightarrow$  Total  $\text{H}^+$  Production  
 $\text{He} + \text{He} \rightarrow$  Total Slow Positive Ion Production  
 $\text{He} + \text{He} \rightarrow$  Total Slow Electron Production  
 $\text{He} + \text{He} \rightarrow \text{He} + \text{He}^+ + \text{e}$   
 $\text{He} + \text{He} \rightarrow \text{He} + \text{He}^{2+} + 2\text{e}$   
 $\text{He}^+ + \text{He}^+ \rightarrow \text{He}^+ + \text{He}^{2+} + \text{e}$

$\text{He}^+ + \text{He}^+ \rightarrow (\text{He} + \text{He}^{2+})$  or  $(\text{He}^+ + \text{He}^{2+} + e)$   
 $\text{He}^+ + \text{H} \rightarrow \text{He}^+ + \text{H}^+ + e$   
 $\text{He}^+ + \text{H}_2 \rightarrow$  Total Slow Positive Ion Production  
 $\text{He}^+ + \text{H}_2 \rightarrow$  Total Slow Electron Production  
 $\text{He}^+ + \text{H}_2 \rightarrow (\text{He} + \text{H}_2^+)$  or  $(\text{He}^+ + \text{H}_2^+ + e)$   
 $\text{He}^+ + \text{H}_2 \rightarrow$  Total  $\text{H}^+$  Production  
 $\text{He}^+ + \text{H}_2 \rightarrow \text{He}^+ + 2\text{H}^+ + 2e$   
 $\text{He}^+ + \text{He} \rightarrow$  Total Slow Positive Ion Production  
 $\text{He}^+ + \text{He} \rightarrow$  Total Slow Electron Production  
 $\text{He}^+ + \text{He} \rightarrow \text{He}^+ + \text{He}^+ + e$   
 $\text{He}^+ + \text{He} \rightarrow \text{He}^+ + \text{He}^{2+} + 2e$   
 $\text{He}^+ + \text{Li} \rightarrow \text{He}^+ + \text{Li}^+ + e$   
 $\text{He}^{2+} + \text{H} \rightarrow \text{He}^{2+} + \text{H}^+ + e$   
 $\text{He}^{2+} + \text{H}_2 \rightarrow$  Total Slow Positive Ion Production  
 $\text{He}^{2+} + \text{H}_2 \rightarrow$  Total Slow Electron Production  
 $\text{He}^{2+} + \text{H}_2 \rightarrow$  Total  $\text{H}_2^+$  Production  
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{H}_2^+$  Production by Single Ionization  
 $\text{He}^{2+} + \text{H}_2 \rightarrow$  Total  $\text{H}^+$  Production  
 $\text{He}^{2+} + \text{H}_2 \rightarrow \text{H}^+$  Production by Ionization Collisions  
 $\text{He}^{2+} + \text{He} \rightarrow$  Total Slow Positive Ion Production  
 $\text{He}^{2+} + \text{He} \rightarrow$  Total Slow Electron Production  
 $\text{He}^{2+} + \text{He} \rightarrow \text{He}^{2+} + \text{He}^+ + e$   
 $\text{He}^{2+} + \text{He} \rightarrow \text{He}^{2+} + \text{He}^{2+} + 2e$   
 $\text{He}^{2+} + \text{Li} \rightarrow \text{He}^{2+} + \text{Li}^+ + e$

### Projectile Electron Loss or Stripping Collisions

$\text{H} + \text{H} \rightarrow \text{H}^+ + \text{H} + e$   
 $\text{H}(2s) + \text{H}(1s) \rightarrow \text{H}^+ + \text{H} + e$   
 $\text{H} + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2 + e$   
 $\text{H}(2s) + \text{H}_2 \rightarrow \text{H}^+ + \text{H}_2 + e$   
 $\text{H} + \text{He} \rightarrow \text{H}^+ + \text{He} + e$   
 $\text{H}(2s) + \text{He} \rightarrow \text{H}^+ + \text{He} + e$   
 $\text{He} + \text{H} \rightarrow \text{He}^+ + \text{H} + e$   
 $\text{He} + \text{H}_2 \rightarrow \text{He}^+ + \text{H}_2 + e$   
 $\text{He} + \text{H}_2 \rightarrow \text{He}^{2+} + \text{H}_2 + 2e$   
 $\text{He}^* + \text{H}_2 \rightarrow \text{He}$  or  $\text{He}^+$   
 $\text{He}^* + \text{H}_2 \rightarrow \text{He}^+ + \text{H}_2 + e$   
 $\text{He}^* + \text{H}_2 \rightarrow \text{He} + \text{H}_2$



### Electron Detachment Collisions

