

## **ANALYTIC CROSS SECTIONS FOR COLLISIONS OF $H^+$ , $H_2^+$ , $H_3^+$ , $H$ , $H_2$ , AND $H^-$ WITH HYDROGEN MOLECULES**

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Analytic expressions fitted to cross section data on collisions of  $H^+$ ,  $H_2^+$ ,  $H_3^+$ ,  $H$ ,  $H_2$ , and  $H^-$  with  $H_2$  are given. The data used are those recommended by Phelps [J. Chem. Phys. Ref. Data **19**, 653 (1990)] and additional experimental data, when available, up to a projectile energy of about 100 keV, including new kinds of reactions not treated by Phelps. The analytic expressions are of the semiempirical functional forms proposed by Green and McNeal [J. Geophys. Res. **76**, 133 (1971)] and modifications of these, thus making it possible not only to interpolate but also to extrapolate the data to some extent. © 2000 Academic Press

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## INTRODUCTION

Data on cross sections of collision processes between hydrogen ions, atoms, and molecules with hydrogen molecules are important in thermonuclear fusion research in relation to edge plasma as well as in the study of hydrogen thyra-trons, ion sources, and other devices. Comprehensive reviews of these processes were given by Barnett et al. [1], Tawara et al. [2], Janev et al. [3], and Phelps [4]. Consulting earlier reviews as well as original papers on experimental and theoretical works, Phelps [4] gave recommended data on cross sections for many different processes such as momentum transfer, excitations, ionization, etc., for  $\text{H}^+$ ,  $\text{H}_2^+$ ,  $\text{H}_3^+$ ,  $\text{H}$ ,  $\text{H}_2$ , and  $\text{H}^-$  in collisions with  $\text{H}_2$ . The purpose of the present paper is to give analytic expressions fitted to Phelps' recommended data [4] and additional experimental data [5] published later.

Forty-nine collision processes in the energy range from 0.1 to 10 keV were treated by Phelps [4]. Among these processes, 14 were considered also by Barnett et al. [1]. Little difference is seen between the recommended cross sections of Refs. [1] and [4] except for the charge transfer process in  $\text{H}_2^+$  collisions with  $\text{H}_2$  (Graph 12). For this latter process we have also adopted Phelps' recommendation, which is based on Ref. [2] and gives the trend of decreasing cross section with decreasing energy at energies below 5 keV. Reference [1] includes, in particular, the processes accompanied by electronic transitions at relatively high energies above 1 keV. Analytic cross sections fitted to the recommended data of processes included in Ref. [1] are available in a series of publications by Ito et al. [6–9].

Phelps' recommended data for dissociative collisions between  $\text{H}_3^+$  and  $\text{H}_2$  are considerably smaller than the recent experimental results of Peco and Champion [5] obtained by the crossed-beam technique in the energy range below 400 eV. We have adopted the latter results in the present compilation (Graphs 18–21), because the results of Peco and Champion for the  $\text{H}_3^+$  destruction cross section join smoothly with those reported by Williams et al. [10] in the energy range above 2.5 keV, as shown in Graph 51. The data for the dissociative collisions at high energies in Graphs 18–21 have been taken from McClure [11] as in Ref. [4].

For fast  $\text{H}_2^+$  production in  $\text{H}_3^+$  collisions with  $\text{H}_2$  (Graph 19), the cross section measured by Peco and Champion [5] increases with decreasing collision energy down to 55 eV. Considering that the threshold energy of the process is 15.5 eV, however, the extrapolated cross section has been made to fall off at energies below 55 eV. This also applies to the cross section for fast  $\text{H}$  production in  $\text{H}_3^+$  collisions with  $\text{H}_2$  (Graph 20), because fast  $\text{H}$  is produced together with fast  $\text{H}_2^+$  simply through dissociation of  $\text{H}_3^+$  at low energies below 125 eV. In the energy range above 125 eV, on the other hand, dissociative charge transfer becomes more dominant in this process. The corresponding cross sections, not available from the literature, have been estimated so as to be consistent with the results of McClure [11] at high energies.

Phelps' recommended data are confined to the energy region up to 10 keV. To extend the applicable energy region of the present recommendations by analytic expressions, we have also used additional data, when available, between 10

and 100 keV from the original experimental papers cited by Phelps. In doing so, we have found errors in his compilation of all inelastic data in  $H_3^+$  collision with  $H_2$  and have revised them by reanalyzing the data originally published (Graphs 22–24). We have also revised Phelps' recommended data for double electron loss collisions between  $H^-$  and  $H_2$  according to the measurements of Williams [12] and Geddes et al. [13] (Graph 49). In the present compilation, fast  $H_2$  production in the symmetrical  $H_2^+ + H_2$  collisions (Graph 50), which shows a similar energy dependence for the cross section as for slow  $H_2^+$  production (Graph 12), and four additional dissociative reactions in  $H_3^+$  collisions with  $H_2$  (Graphs 51–54) observed by Peco and Champion [5] have been included.

The list of the cross sections considered is given in Table A, where the number given with each reaction is the same as the corresponding Graph number.

### Analytic Expressions

The functional forms used for the analytic expressions are those semiempirically developed by Green and McNeal [14] and modifications of them such as used in our previous work [6–9]. The relevant basic relations and definitions are as follows:

$$f_1(x; c_1, c_2) = \sigma_0 c_1 (x/E_R)^{c_2} \quad (i)$$

$$f_2(x; c_1, c_2, c_3, c_4) = f_1(x; c_1, c_2) / [1 + (x/c_3)^{c_2+c_4}] \quad (ii)$$

$$f_3(x; c_1, c_2, c_3, c_4, c_5, c_6) = f_1(x; c_1, c_2) / [1 + (x/c_3)^{c_2+c_4} + (x/c_5)^{c_2+c_6}] \quad (iii)$$

$$f_4(x; c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8) = f_1(x; c_1, c_2) [1 + (x/c_3)^{c_4-c_2}] / [1 + (x/c_5)^{c_4+c_6} + (x/c_7)^{c_4+c_8}] \quad (iv)$$

$$\sigma_0 = 1 \times 10^{-16} \text{ cm}^2 \quad (v)$$

$$E_R = 1.361 \times 10^{-2} \text{ keV (Rydberg constant)} \quad (vi)$$

$$E_1 = E - E_{th} \quad (vii)$$

$$E = \text{incident projectile energy in keV} \quad (viii)$$

$$E_{th} = \text{threshold energy of reaction in keV.} \quad (ix)$$

The symbols  $x$  and  $c_i$  ( $i = 1, 2, \dots, 8$ ) denote dummy parameters. Depending on the formula to be chosen from Eqs. (1)–(14) below, the value of  $E_1$  or  $E_1/a_i$  ( $i = 6, 8, 10$  or  $12$ ) is put into  $x$ , and  $a_1, a_2$ , etc., are put into  $c_i$ .

The cross sections for the individual collisional processes are given by the following set of analytic expressions, according to the correlation between the “No.” and “Eq.” columns in Table I (read across two facing pages):

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) \quad (1)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + a_5 f_2(E_1/a_6; a_1, a_2, a_3, a_4) \quad (2)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_2(E_1; a_5, a_6, a_7, a_8) \quad (3)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_2(E_1; a_5, a_6, a_7, a_8) + a_9 f_2(E_1/a_{10}; a_5, a_6, a_7, a_8) \quad (4)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_2(E_1; a_5, a_6, a_7, a_8) + f_2(E_1; a_9, a_{10}, a_{11}, a_{12}) \quad (5)$$

$$\sigma = f_3(E_1; a_1, a_2, a_3, a_4, a_5, a_6) \quad (6)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_3(E_1; a_5, a_2, a_6, a_7, a_8, a_4) \quad (7)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_3(E_1; a_5, a_2, a_6, a_7, a_8, a_9) \quad (8)$$

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + f_3(E_1; a_5, a_6, a_7, a_8, a_9, a_4) \quad (9)$$

$$\sigma = f_3(E_1; a_1, a_2, a_3, a_4, a_5, a_6) + a_7 f_3(E_1/a_8; a_1, a_2, a_3, a_4, a_5, a_6) \quad (10)$$

$$\sigma = f_3(E_1; a_1, a_2, a_3, a_4, a_5, a_6) + f_2(E_1; a_7, a_8, a_9, a_{10}) \quad (11)$$

$$\sigma = f_3(E_1; a_1, a_2, a_3, a_4, a_5, a_6) + f_2(E_1; a_7, a_8, a_9, a_{10}) + a_{11} f_2(E_1/a_{12}; a_7, a_8, a_9, a_{10}) \quad (12)$$

$$\sigma = f_3(E_1; a_1, a_2, a_3, a_4, a_5, a_6) + f_3(E_1; a_7, a_8, a_9, a_{10}, a_{11}, a_{12}) \quad (13)$$

$$\sigma = f_4(E_1; a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8). \quad (14)$$

The use of such expressions allows one not only to interpolate but also to extrapolate the data to some extent, in contrast to polynomial fits, which frequently show physically unreasonable behavior just outside the energy range of the available data.

The number of adjustable parameters used in the analytic expressions is between 4 and 12 according to the type of the function. The values of the adjustable parameters have been determined by least-squares fits to the data except for some values that were chosen to guarantee reasonable behavior outside the energy range of the available data. The values determined are given in the last six columns of Table I.

The analytic expressions obtained are compared with the recommended and experimental data in the set of Graphs, which show that agreement is quite good. The root-mean-square (rms) and the maximum deviations of the expressions

**TABLE A**  
Collisional Cross Sections Represented by Analytic Expressions and Shown in Graphs 1-54

<b>H<sup>+</sup> collisions with H<sub>2</sub> (H<sup>+</sup> + H<sub>2</sub>)</b>	
1 Rotational excitation for $J = 0 \rightarrow 2$ :	$H^+ + H_2 (J = 0) \rightarrow H_2 (J = 2)$
2 Rotational excitation for $J = 1 \rightarrow 3$ :	$H^+ + H_2 (J = 1) \rightarrow H_2 (J = 3)$
3 Vibrational excitation for $v = 0 \rightarrow 1$ :	$H^+ + H_2 (v = 0) \rightarrow H_2 (v = 1)$
4 Vibrational excitation for $v = 0 \rightarrow 2$ :	$H^+ + H_2 (v = 0) \rightarrow H_2 (v = 2)$
5 Vibrational excitation for $v = 0 \rightarrow 3$ :	$H^+ + H_2 (v = 0) \rightarrow H_2 (v = 3)$
6 Rearrangement or charge transfer to fast H:	$H^+ + H_2 \rightarrow \text{fast H}$
7 Ly- $\alpha$ excitation:	$H^+ + H_2 \rightarrow \text{Ly-}\alpha \text{ (Total)}$
8 H $\alpha$ excitation:	$H^+ + H_2 \rightarrow \text{H}\alpha \text{ (Total)}$
9 Electron production:	$H^+ + H_2 \rightarrow e \text{ (Total)}$
10 Momentum transfer:	$H^+ + H_2 \rightarrow \text{Momentum Transfer}$
<b>H<sub>2</sub><sup>+</sup> collisions with H<sub>2</sub> (H<sub>2</sub><sup>+</sup> + H<sub>2</sub>)</b>	
11 H <sub>3</sub> <sup>+</sup> formation:	$H_2^+ + H_2 \rightarrow H_3^+ + H$
12 Slow H <sub>2</sub> <sup>+</sup> formation:	$H_2^+ + H_2 \rightarrow \text{slow } H_2^+ \text{ (Charge Transfer at } E \leq 3\text{keV)}$
13 Vibrational excitation for $v = 0 \rightarrow 1$ :	$H_2^+ + H_2 (v = 0) \rightarrow H_2 (v = 1)$
14 Dissociation to fast H <sup>+</sup> :	$H_2^+ + H_2 \rightarrow \text{fast } H^+$
15 Ly- $\alpha$ excitation:	$H_2^+ + H_2 \rightarrow \text{Ly-}\alpha \text{ (Total)}$
16 H $\alpha$ excitation:	$H_2^+ + H_2 \rightarrow \text{H}\alpha \text{ (Total)}$
17 Electron production:	$H_2^+ + H_2 \rightarrow e \text{ (Total)}$
<b>H<sub>3</sub><sup>+</sup> collisions with H<sub>2</sub> (H<sub>3</sub><sup>+</sup> + H<sub>2</sub>)</b>	
18 Dissociation to fast H <sup>+</sup> :	$H_3^+ + H_2 \rightarrow \text{fast } H^+$
19 Dissociation to fast H <sub>2</sub> <sup>+</sup> :	$H_3^+ + H_2 \rightarrow \text{fast } H_2^+$
20 Charge transfer to form fast H:	$H_3^+ + H_2 \rightarrow \text{fast H}$
21 Charge transfer to form fast H <sub>2</sub> :	$H_3^+ + H_2 \rightarrow \text{fast } H_2$
22 Ly- $\alpha$ excitation:	$H_3^+ + H_2 \rightarrow \text{Ly-}\alpha \text{ (Total)}$
23 H $\alpha$ excitation:	$H_3^+ + H_2 \rightarrow \text{H}\alpha \text{ (Total)}$
24 Electron production:	$H_3^+ + H_2 \rightarrow e \text{ (Total)}$
25 Momentum transfer:	$H_3^+ + H_2 \rightarrow \text{Momentum Transfer}$
<b>H collisions with H<sub>2</sub> (H + H<sub>2</sub>)</b>	
26 Rotational excitation for $J = 0 \rightarrow 2$ :	$H + H_2 (J = 0) \rightarrow H_2 (J = 2)$
27 Rotational excitation for $J = 1 \rightarrow 3$ :	$H + H_2 (J = 1) \rightarrow H_2 (J = 3)$
28 Vibrational excitation for $v = 0 \rightarrow 1$ :	$H + H_2 (v = 0) \rightarrow H_2 (v = 1)$
29 Production of fast H <sup>-</sup> :	$H + H_2 \rightarrow \text{fast } H^-$
30 Production of slow H <sub>2</sub> <sup>+</sup> :	$H + H_2 \rightarrow \text{slow } H_2^+$
31 Production of fast H <sup>+</sup> :	$H + H_2 \rightarrow \text{fast } H^+$
32 Ly- $\alpha$ excitation:	$H + H_2 \rightarrow \text{Ly-}\alpha \text{ (Total)}$
33 H $\alpha$ excitation:	$H + H_2 \rightarrow \text{H}\alpha \text{ (Total)}$
34 H $\beta$ excitation:	$H + H_2 \rightarrow \text{H}\beta \text{ (Total)}$
35 Electron production:	$H + H_2 \rightarrow e \text{ (Total)}$
36 Momentum transfer:	$H + H_2 \rightarrow \text{Momentum Transfer}$
<b>H<sub>2</sub> collisions with H<sub>2</sub> (H<sub>2</sub> + H<sub>2</sub>)</b>	
37 Fast H <sub>2</sub> destruction:	$H_2 + H_2 \rightarrow \text{fast } H_2 \text{ Destruction}$
38 Production of fast H <sub>2</sub> <sup>+</sup> :	$H_2 + H_2 \rightarrow \text{fast } H_2^+$
39 Rotational excitation for $J_1, J_2 = 0, 0 \rightarrow 0, 2$ :	$H_2 (J = 0) + H_2 (J = 0) \rightarrow H_2 (J = 0) + H_2 (J = 2)$
40 Rotational excitation for $J_1, J_2 = 0, 0 \rightarrow 2, 2$ :	$H_2 (J = 0) + H_2 (J = 0) \rightarrow H_2 (J = 2) + H_2 (J = 2)$
41 Rotational excitation for $J_1, J_2 = 0, 0 \rightarrow 0, 4$ :	$H_2 (J = 0) + H_2 (J = 0) \rightarrow H_2 (J = 0) + H_2 (J = 4)$
42 Vibrational excitation for $v = 0 \rightarrow 1$ :	$H_2 + H_2 (v = 0) \rightarrow H_2 (v = 1)$
43 Production of fast H <sup>+</sup> :	$H_2 + H_2 \rightarrow \text{fast } H^+$
44 H $\alpha$ excitation:	$H_2 + H_2 \rightarrow \text{H}\alpha \text{ (Total)}$
45 Ionization:	$H_2 + H_2 \rightarrow \text{fast } H_2^+ \text{ or fast } H^+$
46 Momentum transfer:	$H_2 + H_2 \rightarrow \text{Momentum Transfer}$
<b>H<sup>-</sup> collisions with H<sub>2</sub> (H<sup>-</sup> + H<sub>2</sub>)</b>	
47 Detachment to form an electron and fast H:	$H^- + H_2 \rightarrow e + \text{fast H}$
48 Momentum transfer:	$H^- + H_2 \rightarrow \text{Momentum Transfer}$
49 Production of fast H <sup>+</sup> :	$H^- + H_2 \rightarrow \text{fast } H^+$
<b>Additional data</b>	
50 Fast H <sub>2</sub> formation in collisions of H <sub>2</sub> <sup>+</sup> with H <sub>2</sub> :	$H_2^+ + H_2 \rightarrow \text{fast } H_2 \text{ (Charge Transfer at } E \leq 3\text{keV)}$
51 H <sub>3</sub> <sup>+</sup> destruction in collisions with H <sub>2</sub> :	$H_3^+ + H_2 \rightarrow H_3^+ \text{ Destruction}$
52 Production of slow H <sub>3</sub> <sup>+</sup> in collisions of H <sub>3</sub> <sup>+</sup> with H <sub>2</sub> :	$H_3^+ + H_2 \rightarrow \text{slow } H_3^+$
53 Production of slow H <sup>+</sup> in collisions of H <sub>3</sub> <sup>+</sup> with H <sub>2</sub> :	$H_3^+ + H_2 \rightarrow \text{slow } H_3^{*+} \rightarrow \text{slow } H^+$
54 Production of slow H <sub>2</sub> <sup>+</sup> in collisions of H <sub>3</sub> <sup>+</sup> with H <sub>2</sub> :	$H_3^+ + H_2 \rightarrow \text{slow } H_3^{*+} \rightarrow \text{slow } H_2^+ \text{ (Dissociative Charge Transfer at } E > 125\text{eV)}$

*Note.* "Total" means total emission from the projectile and the target. In the last two reaction formulas, the symbol \* means the excited state.

from the data are given in the fifth and the sixth column of Table I. For the processes for which the data have been taken only or mostly from Phelps' recommendation, the rms deviation is generally smaller than about 5%. Large deviations are due to experimental uncertainties rather than the errors of fitting as can typically be seen, for example, from Graph 18.

### Example of Use of Table I

As an illustration, we calculate the cross section for Ly- $\alpha$  excitation in collisions of  $H^+$  with  $H_2$  at incident energy  $E = 0.500$  keV (Reaction No. 7). From Table I, we find that the cross section is given by Eq. (2) as

$$\sigma = f_2(E_1; a_1, a_2, a_3, a_4) + a_5 f_2(E_1/a_6; a_1, a_2, a_3, a_4).$$

The coefficients  $a_1$  to  $a_6$  are listed in Table I together with the threshold energy  $E_{th}$ . Using basic relation (vii), we have  $E_1 = E - E_{th} = 0.475$  keV. Substituting basic relation (i) into (ii) and using (v) and (vi), we find for the terms in Eq. (2)

$$\begin{aligned} f_2(E_1; a_1, a_2, a_3, a_4) &= 10^{-16} \times 3.2 \times 10^{-5} \left( \frac{0.475}{0.01361} \right)^{2.228} / \\ &\quad \left[ 1 + \left( \frac{0.475}{0.83} \right)^{2.228+0.428} \right] \\ &= 8.762 \times 10^{-18} / 1.227 \\ &= 7.14 \times 10^{-18} \end{aligned}$$

and

$$\begin{aligned} f_2(E_1/a_6; a_1, a_2, a_3, a_4) &= 10^{-16} \times 3.2 \times 10^{-5} \left( \frac{0.475}{9.44 \times 0.01361} \right)^{2.228} / \\ &\quad \left[ 1 + \left( \frac{0.475}{9.44 \times 0.83} \right)^{2.228+0.428} \right] \\ &= 5.893 \times 10^{-20} / 1.001 \\ &= 5.89 \times 10^{-20}. \end{aligned}$$

Hence, the fitted cross section is

$$\begin{aligned} \sigma &= 7.14 \times 10^{-18} + 3.12 \times 5.89 \times 10^{-20} \\ &= 7.32 \times 10^{-18} \text{ (cm}^2\text{)}, \end{aligned}$$

which agrees with Graph 7.

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*Notes added after completion of this work.* It has come to our attention that Krstić and Schultz [15] have recently performed fully quantum-mechanical calculations in infinite order sudden approximation on the cross sections for vibrational excitation and momentum transfer in  $H^+$  collisions with  $H_2$  (Graphs 3–5 and 10) and H collisions with  $H_2$  (Graphs 28 and 36) in the energy range from 0.15 to 150 eV. Their results show an oscillatory structure or a narrow peak of the cross section at energies near the threshold on the respective cross section curve for vibrational excitation, while Phelps' recommended cross section decreases monotonically with decreasing energy. This discrepancy stems from the fact that Phelps did not have actual data in this energy region and had based his recommended values on extrapolation. As far as the cross sections for vibrational excitation in  $H^+$  collisions with  $H_2$  (Graphs 3–5) are concerned, the sets of results agree well with each other at energies above 6 eV, except for excitation to the third excited vibrational state, for which the cross section of Krstić and Schultz is larger than that of Phelps by about 40%. For excitation to the first excited vibrational state in H collisions with  $H_2$  (Graph 28), on the other hand, we see considerable discrepancies between these two data sets; that is, the new data are lower by about a factor of four than Phelps', which had been simply taken from the corresponding data set for  $H^+$  collisions with  $H_2$  at high energies. For momentum transfer, the results of Krstić and Schultz are in approximate agreement with Phelps' recommended data at low collision energies, though the former are a little smaller than Phelps' in  $H^+$  collisions with  $H_2$ , and larger than Phelps' in H collisions with  $H_2$ . However, their results become smaller by a factor up to about 10 than Phelps' with increasing energy. A similar situation had been noted by Phelps [4] during his data assessment, where he found that the cross sections inferred from his procedure were about an order of magnitude larger than a calculation at 38 eV and suggested that more work in the energy range from 1 eV to 1 keV would be important.

In the present work we have aimed at providing users with analytic fits to Phelps' recommended data sets and new experimental data. Therefore, we do not include the analytic fits to the single theoretical data sets of Krstić and Schultz, but the results of fits to these data sets are available upon request to one of the present authors (T.S.).

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**EXPLANATION OF TABLE****TABLE I. Energy Ranges of Data, Fitting Errors, and Parameters of the Analytic Expressions**

No.	Number label identifying a particular reaction process in the same sequence as in Table A and in the Graphs.
Process	The relevant reaction process.
$E_{min}$	Minimum energy (in keV) of the recommended data.
$E_{max}$	Maximum energy (in keV) of the recommended data.
$\delta_{rms}$	Root-mean-square relative deviation (in %) of the analytic expression from the data.
$\delta_{max}$	Maximum relative deviation (in %) of the analytic expression from the data.
$E_{\delta_{max}}$	Energy (in keV) at which the relative deviation takes on the value $\delta_{max}$ .
Eq.	The identifying number of the equation to be used for deriving the cross sections.
$n$	Number of applicable fit parameters.
$E_{th}$	Threshold energy of the reaction (in keV); values are often the ones adjusted to give good fits to data rather than the actual threshold energy.
$a_i$ ( $i = 1, 2, \dots, 12$ )	Fit parameters.

The notation 1.23–1 means  $1.23 \times 10^{-1}$ .

**EXPLANATION OF GRAPHS****GRAPHS. Cross Section vs Projectile Energy**

Graphs are numbered in the same sequence as in Table A and Table I.

Ordinate	Cross section in $\text{cm}^2$ .
Abscissa	Laboratory energy in eV of the projectile for $\text{H}_2$ at rest.
Solid line	Recommended data from the analytic formula of the present work.
Circles	Phelps' recommended data (Ref. [4]).
Pentagons	Experimental data in the energy range above 10 keV from the same sources as used by Phelps.
Other symbols	Experimental or theoretical data from other sources as explained in the legend.

TABLE I. Energy Ranges of Data, Fitting Errors, and Parameters of the Analytic Expressions

See page 7 for Explanation of Tables

No.	Process	$E_{min}$	$E_{max}$	$\delta_{rms}$	$\delta_{max}$	$E_{\delta_{max}}$
1	$H^+ + H_2(J=0) \rightarrow H_2(J=2)$ (Rotational Excitation)	1.00–4	3.16–1	2.3	4.7	3.16–4
2	$H^+ + H_2(J=1) \rightarrow H_2(J=3)$	1.33–4	2.37–1	2.4	6.1	1.33–1
3	$H^+ + H_2(v=0) \rightarrow H_2(v=1)$ (Vibrational Excitation)	1.00–3	1.00+1	1.7	4.2	7.50–3
4	$H^+ + H_2(v=0) \rightarrow H_2(v=2)$	1.78–3	1.00+1	2.7	7.3	3.16–3
5	$H^+ + H_2(v=0) \rightarrow H_2(v=3)$	2.37–3	3.16	2.1	4.5	1.00–1
6	$H^+ + H_2 \rightarrow \text{fast H}$	3.16–3	1.00+2	1.3	2.8	3.16–1
7	$H^+ + H_2 \rightarrow \text{Ly } \alpha$ (Total)	7.50–2	2.46+1	6.6	2.3+1	7.50–2
8	$H^+ + H_2 \rightarrow \text{H}\alpha$ (Total)	1.00–1	1.00+2	5.0	1.6+1	2.00+1
9	$H^+ + H_2 \rightarrow e$ (Total)	7.50–2	1.00+2	1.9	5.5	1.00–1
10	$H^+ + H_2 \rightarrow \text{Momentum Transfer}$	1.00–4	1.00+1	4.9	1.1+1	1.00–1
11	$H_2^+ + H_2 \rightarrow H_3^+ + H$	1.00–4	1.78–2	1.2	2.1	1.00–4
12	$H_2^+ + H_2 \rightarrow \text{slow } H_2^+$ (Charge Transfer at $E \leq 3\text{keV}$ )	1.00–4	4.67+1	2.0	5.2	1.78–3
13	$H_2^+(v=0) + H_2 \rightarrow H_2^+(v=1)$	1.78–3	1.00+1	1.5	4.9	1.33–2
14	$H_2^+ + H_2 \rightarrow \text{fast } H^+$	5.62–3	9.90+1	2.2	4.1	1.33–1
15	$H_2^+ + H_2 \rightarrow \text{Ly } \alpha$ (Total)	1.78–1	2.49+1	2.6	7.7	7.50
16	$H_2^+ + H_2 \rightarrow \text{H}\alpha$ (Total)	7.50–1	1.00+2	1.1	2.2	1.33
17	$H_2^+ + H_2 \rightarrow e$ (Total)	3.16–2	1.00+2	6.8	1.9+1	4.22–2
18	$H_3^+ + H_2 \rightarrow \text{fast } H^+$	1.48–2	1.15+2	1.8+1	6.0+1	1.48–2
19	$H_3^+ + H_2 \rightarrow \text{fast } H_2^+$	5.40–2	1.17+2	1.0+1	2.2+1	2.46–1
20	$H_3^+ + H_2 \rightarrow \text{fast H}$	5.40–2	1.19+2	5.9	1.4+1	5.4–2
21	$H_3^+ + H_2 \rightarrow \text{fast } H_2$	5.40–2	1.18+2	3.9	1.3+1	1.98–1
22	$H_3^+ + H_2 \rightarrow \text{Ly } \alpha$ (Total)	7.50–2	1.00+1	2.3	7.2	7.07–1
23	$H_3^+ + H_2 \rightarrow \text{H}\alpha$ (Total)	7.50–2	1.00+2	1.7	3.4	2.00+1
24	$H_3^+ + H_2 \rightarrow e$ (Total)	7.50–2	1.00+2	3.9	9.8	6.00
25	$H_3^+ + H_2 \rightarrow \text{Momentum Transfer}$	1.00–4	1.00+1	5.6	3.1+1	5.62
26	$H + H_2(J=0) \rightarrow H_2(J=2)$	1.00–4	1.00+1	4.7	1.3+1	7.50–4
27	$H + H_2(J=1) \rightarrow H_2(J=3)$	1.00–4	1.00+1	4.4	8.6	1.78–3



TABLE I. Energy Ranges of Data, Fitting Errors, and Parameters of the Analytic Expressions

See page 7 for Explanation of Tables

No.	Eq.	$n$	$E_{\text{th}}$	$a_1$ $a_7$	$a_2$ $a_8$	$a_3$ $a_9$	$a_4$ $a_{10}$	$a_5$ $a_{11}$	$a_6$ $a_{12}$
1	9	9	9.0–5	1.13+2 2.96–3	5.4–1 1.113	7.0–5 1.307–2	3.459	7.0+1	2.6–1
2	9	9	1.2–4	1.14+3 2.2–3	1.0 1.058	9.15–5 1.189–2	3.588	8.1+1	4.4–1
3	6	6	5.0–4	6.18	1.523	1.786–2	1.48–1	7.27–2	1.164
4	6	6	1.3–3	1.375	1.21	3.8–2	6.59–1	8.39–2	1.482
5	6	6	2.1–3	5.258–1	9.673–1	3.965–2	9.83–1	1.36–1	1.88
6	8	9	2.5–3	2.12+2 1.42–1	1.721 9.34	6.7–4 2.997	3.239–1	4.34–3	1.296
7	2	6	2.5–2	3.2–5	2.228	8.3–1	4.28–1	3.12	9.44
8	2	6	3.0–2	9.8–5	1.272	1.88	1.747	7.58	1.326+1
9	1	4	2.0–2	1.864–4	1.216	5.31+1	8.97–1		
10	1	4	0.0	5.74	–5.765–1	2.79–2	1.737		
11	6	6	0.0	6.05	–5.247–1	4.088–3	2.872	7.3–3	6.99
12	5	12	0.0	8.07 4.65–3	6.85–1 1.201–1	6.43–3 4.85–5	3.95 1.67	2.58+2 1.49+1	2.85 1.09
13	6	6	1.0–3	1.838	1.875	1.459–2	1.89–1	6.87–2	9.51–1
14	4	10	5.0–3	6.34+1 1.554+1	1.78 3.903	1.38–3 1.735	4.06–1 1.02+1	1.63–1	3.27–1
15	6	6	9.0–2	3.22–4	2.007	4.35–1	–2.55–1	4.0+1	1.0
16	6	6	4.0–1	3.26–4	1.195	2.09	–2.53–1	2.88+1	1.62
17	6	6	3.0–2	1.086–3	1.153	1.24+1	–4.44–1	5.96+1	1.0
18	3	8	1.1–2	6.67–1 1.1+1	1.35 –1.0–1	4.42–2	7.1–1	6.7–5	1.54
19	3	8	1.55–2	5.03–1 9.4+1	1.0 1.35	2.5–2	2.0	1.17–1	3.18–1
20	3	8	1.55–2	5.89–1 4.64+1	1.0 1.1	2.5–2	1.5	4.05–2	7.59–1
21	3	8	0.0	3.78+1 4.89+1	1.0 1.69	2.0–3	2.5–1	4.14–2	6.25–1
22	2	6	6.2–2	1.098–2	6.644–1	1.519	1.89	1.17+2	3.06+3
23	2	6	6.2–2	5.33–3	5.27–1	7.46–1	9.66–1	1.312+1	2.48+2
24	2	6	3.6–2	2.63–3	9.31–1	4.05–1	1.0	1.26+2	2.13+2
25	14	8	0.0	1.16 8.67–2	–8.12–1 2.18	4.29–4	–1.38–1	1.28–2	1.33
26	14	8	0.0	7.54–1 3.74–3	9.57–1 1.005	3.98–4	3.69	1.235–3	–2.97–1
27	14	8	0.0	7.81–1 3.72–3	1.03 9.91–1	5.41–4	3.98	1.342–3	–3.46–1

TABLE I. Energy Ranges of Data, Fitting Errors, and Parameters of the Analytic Expressions

See page 7 for Explanation of Tables

No.	Process	$E_{min}$	$E_{max}$	$\delta_{rms}$	$\delta_{max}$	$E_{\delta_{max}}$
28	$H + H_2(v=0) \rightarrow H_2(v=1)$	1.00-3	1.00+1	2.2	5.3	3.16
29	$H + H_2 \rightarrow \text{fast } H^-$	2.37-2	9.11+1	3.6	8.8	1.00
30	$H + H_2 \rightarrow \text{slow } H_2^+$	2.37-2	2.53+1	2.9	7.1	2.53+1
31	$H + H_2 \rightarrow \text{fast } H^+$	5.62-2	1.12+2	4.7	2.0+1	7.50-2
32	$H + H_2 \rightarrow \text{Ly } \alpha \text{ (Total)}$	2.37-2	2.50+1	3.9	1.1+1	3.16-2
33	$H + H_2 \rightarrow H\alpha \text{ (Total)}$	3.16-2	1.00+2	6.5	2.3+1	4.22-2
34	$H + H_2 \rightarrow H\beta \text{ (Total)}$	1.00-1	1.00+1	2.9	7.1	1.33-1
35	$H + H_2 \rightarrow e \text{ (Total)}$	4.22-2	2.84+1	4.7	1.1+1	1.00+1
36	$H + H_2 \rightarrow \text{Momentum Transfer}$	1.00-4	1.00+1	1.5	5.0	3.16
37	$H_2 + H_2 \rightarrow \text{fast } H_2 \text{ Destruction}$	1.78-2	1.00+2	2.8	9.2	3.16-2
38	$H_2 + H_2 \rightarrow \text{fast } H_2^+$	4.21-2	9.90+1	3.4	8.1	7.50-2
39	$H_2(J=0) + H_2(J=0) \rightarrow H_2(J=0) + H_2(J=2)$	1.00-4	7.50-1	3.2	1.3+1	7.50-1
40	$H_2(J=0) + H_2(J=0) \rightarrow H_2(J=2) + H_2(J=2)$	2.37-4	1.78	1.9	4.2	7.50-4
41	$H_2(J=0) + H_2(J=0) \rightarrow H_2(J=0) + H_2(J=4)$	7.50-4	4.22-1	1.6	5.9	4.21-2
42	$H_2 + H_2(v=0) \rightarrow H_2(v=1)$	2.37-3	1.00+1	2.2	6.6	3.16-3
43	$H_2 + H_2 \rightarrow \text{fast } H^+$	1.78-1	9.95+1	4.8	9.8	7.50
44	$H_2 + H_2 \rightarrow H\alpha \text{ (Total)}$	1.78-2	1.00+2	2.1	7.1	6.00+1
45	$H_2 + H_2 \rightarrow \text{fast } H_2^+ \text{ or fast } H^+ \text{ (Ionization)}$	4.21-2	9.90+1	2.9	6.8	7.50-2
46	$H_2 + H_2 \rightarrow \text{Momentum Transfer}$	1.00-4	1.00+1	1.2	3.6	1.78
47	$H^- + H_2 \rightarrow e + \text{fast } H$	2.37-3	5.00+1	6.4	2.1+1	1.0+1
48	$H^- + H_2 \rightarrow \text{Momentum Transfer}$	1.00-4	1.00+1	2.6	6.5	4.21-1
49	$H^- + H_2 \rightarrow \text{fast } H^+$	1.00	3.00+2	9.0	2.1+1	3.00
50	$H_2^+ + H_2 \rightarrow \text{fast } H_2 \text{ (Charge Transfer at } E \leq 3\text{keV)}$	1.00-4	1.2+2	2.1	7.2	3.32
51	$H_3^+ + H_2 \rightarrow H_3^+ \text{ Destruction}$	5.40-2	1.00+2	4.1	1.4+1	1.98-1
52	$H_3^+ + H_2 \rightarrow \text{slow } H_3^+$	8.41-3	5.13-2	1.2+1	2.8+1	4.16-2
53	$H_3^+ + H_2 \rightarrow \text{slow } H_3^{+*} \rightarrow \text{slow } H^+$	8.41-3	3.13-1	3.4	8.9	1.88-2
54	$H_3^+ + H_2 \rightarrow \text{slow } H_3^{+*} \rightarrow \text{slow } H_2^+$	1.67-2	3.13-1	9.4	2.7+1	1.88-2

TABLE I. Energy Ranges of Data, Fitting Errors, and Parameters of the Analytic Expressions

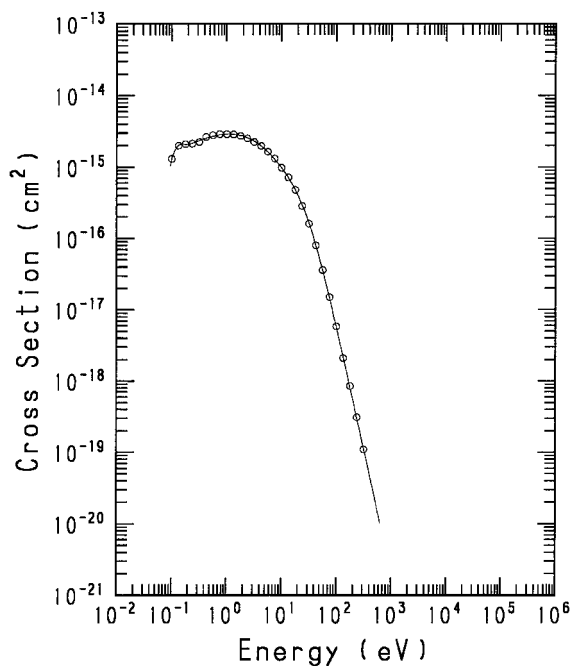
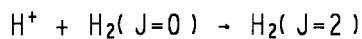
See page 7 for Explanation of Tables

No.	Eq.	$n$	$E_{\text{th}}$	$a_1$ $a_7$	$a_2$ $a_8$	$a_3$ $a_9$	$a_4$ $a_{10}$	$a_5$ $a_{11}$	$a_6$ $a_{12}$
28	6	6	9.0–4	1.602+1	1.082	5.96–3	2.7–2	4.37–2	1.005
29	13	12	2.1–2	9.73–3	2.38	1.39–2	–5.51–1	7.7–2	2.12
				1.97–6	2.051	5.5	6.62–1	2.02+1	3.62
30	11	10	2.1–2	9.69–3	2.4	1.36–2	–5.52–1	7.91–2	2.27
				1.05–4	1.538	8.35	2.6–2		
31	2	6	2.0–2	2.53–4	1.728	2.164	7.74–1	1.639	1.43+1
32	2	6	2.0–2	7.64–2	1.097	1.77–1	3.66–1	5.49–1	4.0
33	12	12	2.3–2	4.06–4	2.214	2.23–1	–1.1–1	6.41–1	1.34
				2.67–11	3.33	1.09+1	4.97–1	1.79	2.0+1
34	1	4	7.0–2	1.211–3	1.012	8.47–1	6.74–1		
35	2	6	3.2–2	4.21–4	1.64	2.35	4.68–1	2.79	1.25+1
36	6	6	0.0	2.97+1	4.095–3	1.11–4	5.55–1	6.0–3	1.607
37	10	8	1.1–2	4.69–3	2.946	4.36–2	–9.01–1	1.52–1	5.01–1
				2.6	3.229+1				
38	10	8	3.2–2	1.879–3	2.497	6.62–2	–4.67–1	3.58–1	5.0–1
				7.67	2.01+2				
39	6	6	6.0–5	3.25+1	1.073	3.65–3	6.24–1	7.68–3	1.678
40	6	6	9.0–5	2.47+1	1.746	7.94–3	8.42–1	2.106–2	1.98
41	6	6	9.0–5	2.54+1	2.81	3.76–3	–2.48–1	8.63–3	1.73
42	6	6	1.2–3	1.041+1	3.214	8.1–3	–3.22–1	1.44–2	6.2–1
43	2	6	2.0–2	1.307–5	1.586	1.066+1	2.03	2.73	4.71
44	7	8	1.1–2	1.07–8	2.211	2.31+1	8.38–1	4.79–3	2.044–2
				–3.58–1	2.4–1				
45	7	8	2.9–2	1.06–10	2.914	2.97+1	2.79	1.023–3	6.15–2
				–5.035–1	4.95				
46	6	6	0.0	1.018+1	–1.413–1	6.53–3	1.083	5.88–2	2.234
47	11	10	2.25–3	4.19–2	1.89	1.78–1	–2.3–1	1.04	8.7–1
				1.65+1	1.088	5.33–3	1.66–1		
48	6	6	0.0	6.36	–3.37–1	5.5–3	8.3–1	2.6–2	1.766
49	6	6	0.0	1.75–8	3.88	9.06–1	–2.74–1	3.19	1.19
50	12	12	0.0	2.29+2	2.78	4.75–3	1.248–1	2.14–1	2.33
				7.96	6.82–1	6.59–3	4.51	1.67–1	1.164+4
51	3	8	1.55–2	3.2+2	1.0	3.7–4	2.5–1	1.17–1	5.37–1
				7.68+1	1.59				
52	1	4	0.0	6.0	–5.0–1	1.322–2	4.26		
53	3	8	1.1–2	2.1	3.91–1	1.535–2	2.84	1.48–1	3.0–1
				1.4	2.5–1				
54	3	8	1.55–2	2.8–1	4.4	1.61–2	1.8	2.11–1	5.24–1
				8.4–1	2.5–1				

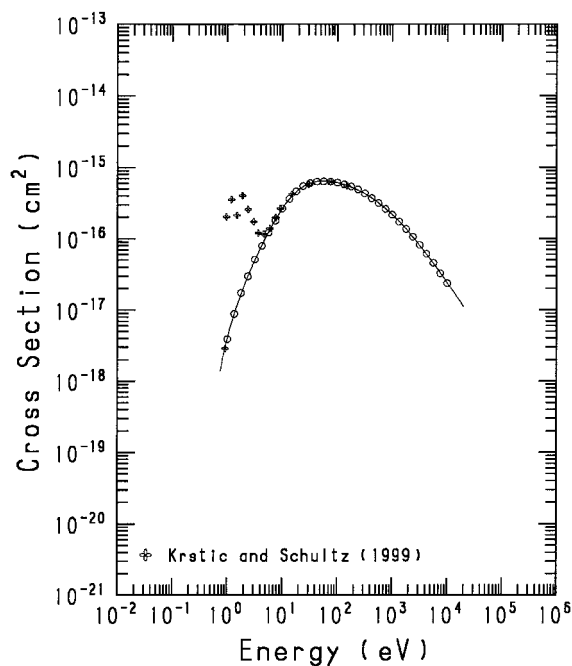
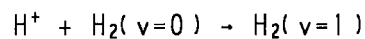
## GRAPHS. Cross Section vs Projectile Energy

See page 7 for Explanation of Graphs

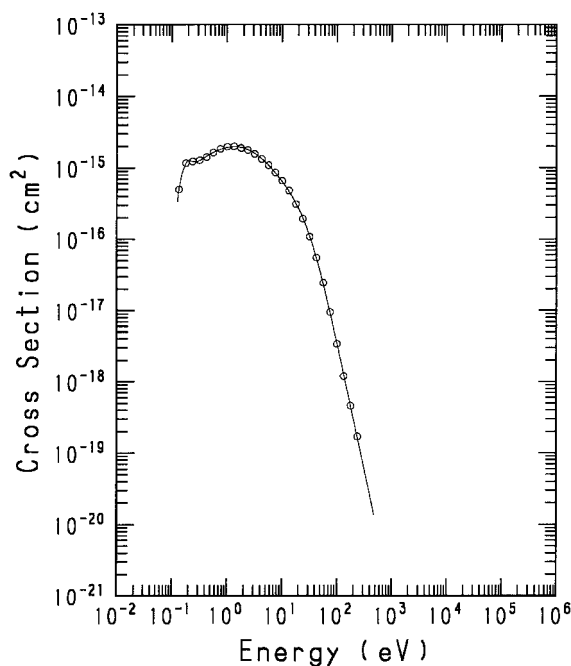
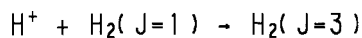
GRAPH 1



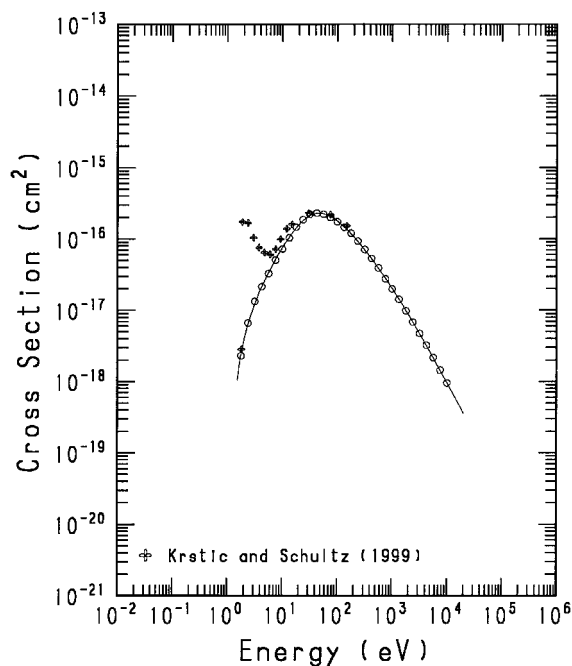
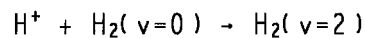
GRAPH 3



GRAPH 2



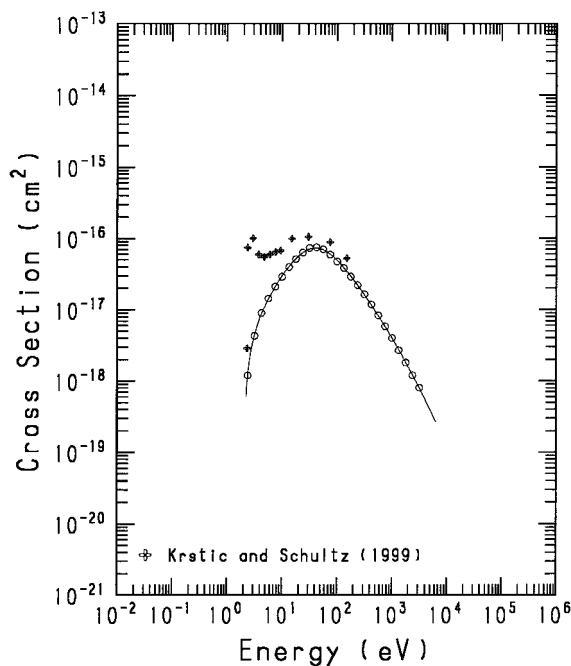
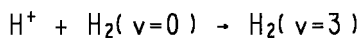
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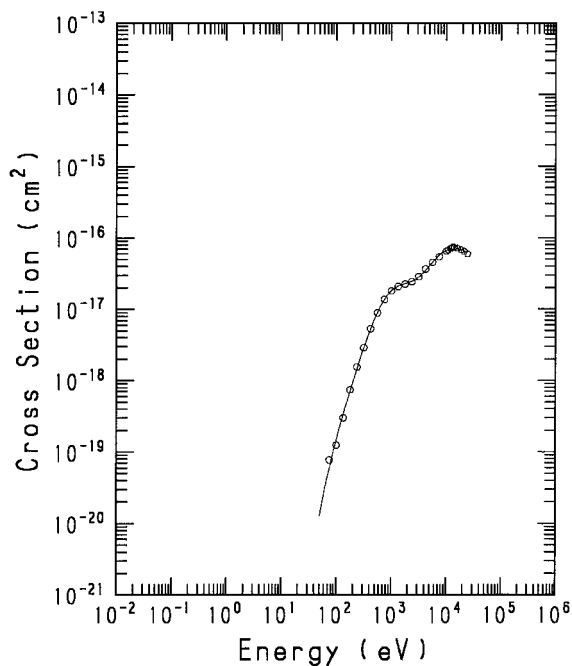
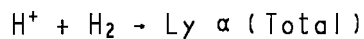
## GRAPHS. Cross Section vs Projectile Energy

See page 7 for Explanation of Graphs

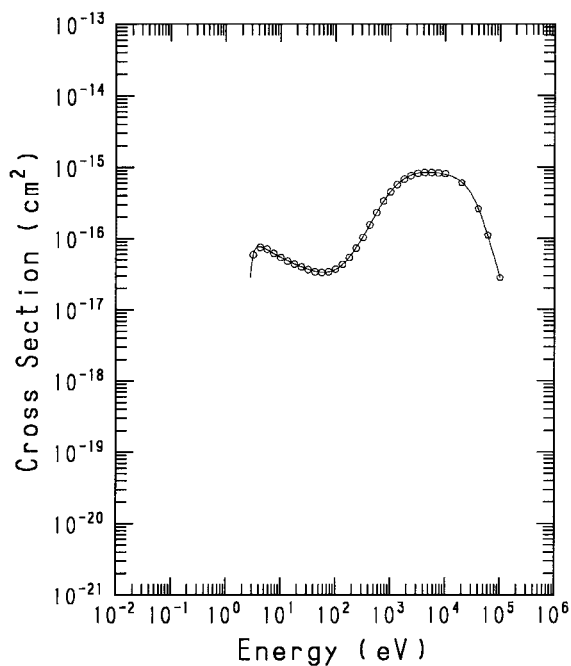
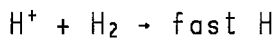
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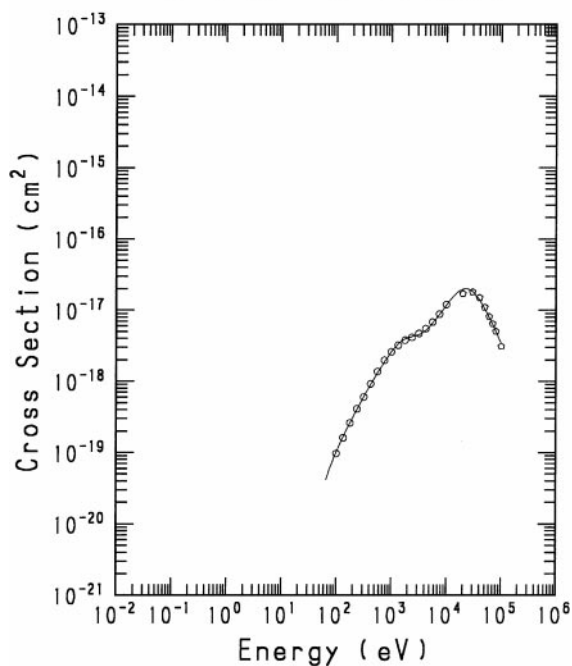
GRAPH 7



GRAPH 6



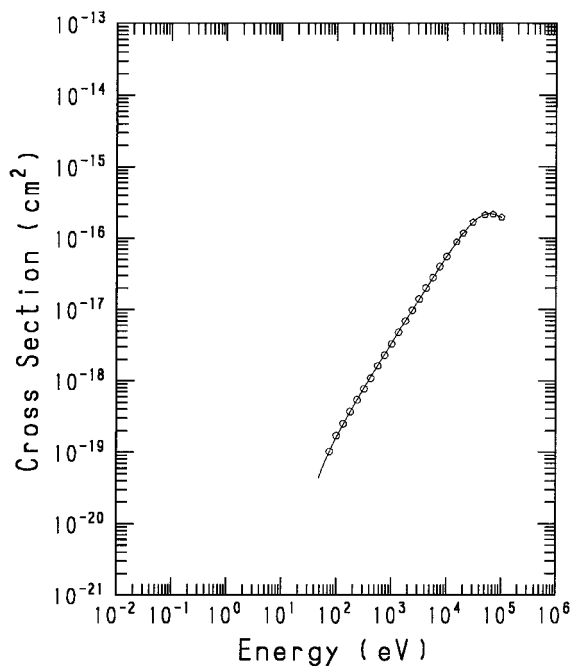
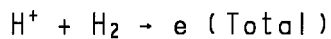
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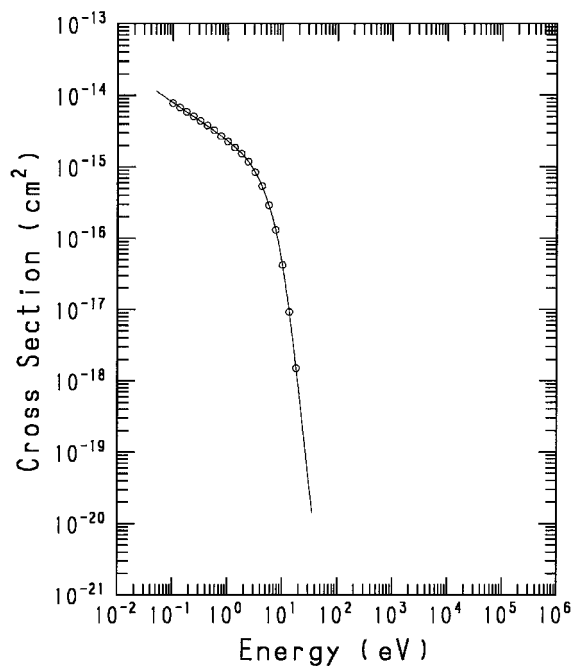
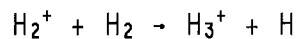
## GRAPHS. Cross Section vs Projectile Energy

See page 7 for Explanation of Graphs

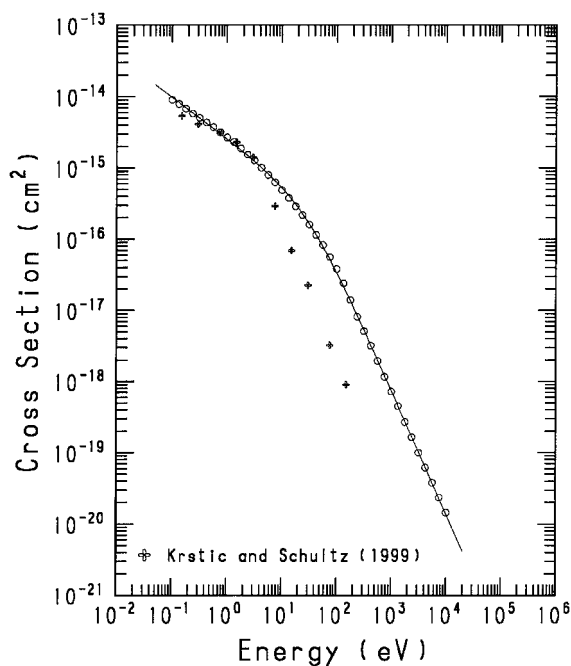
GRAPH 9



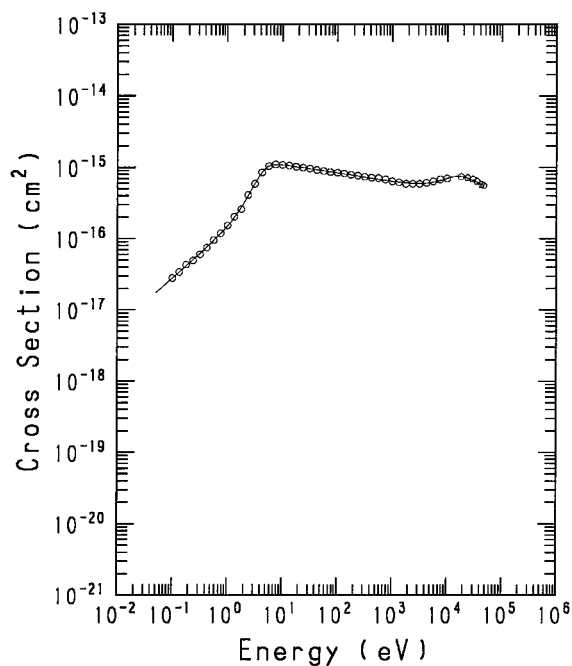
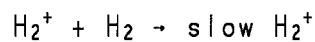
GRAPH 11



GRAPH 10



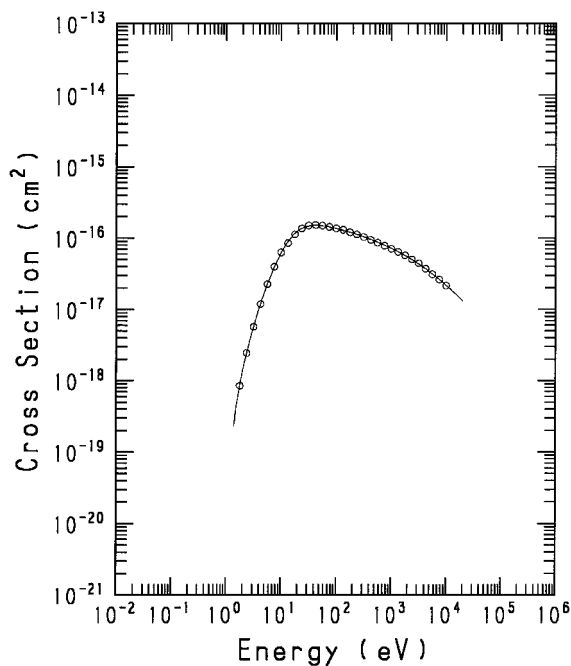
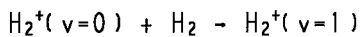
GRAPH 12



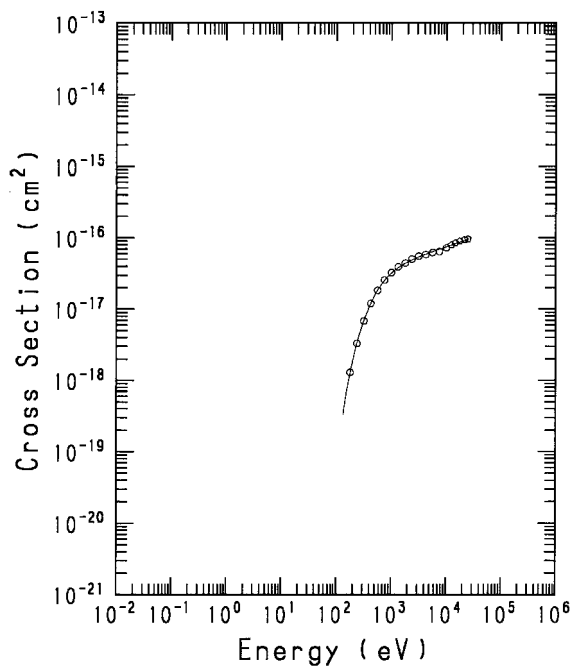
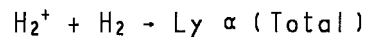
## GRAPHS. Cross Section vs Projectile Energy

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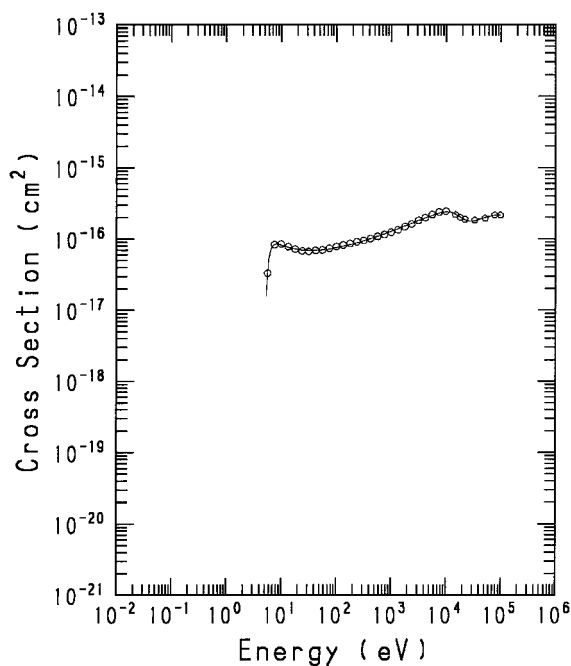
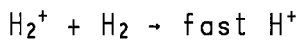
GRAPH 13



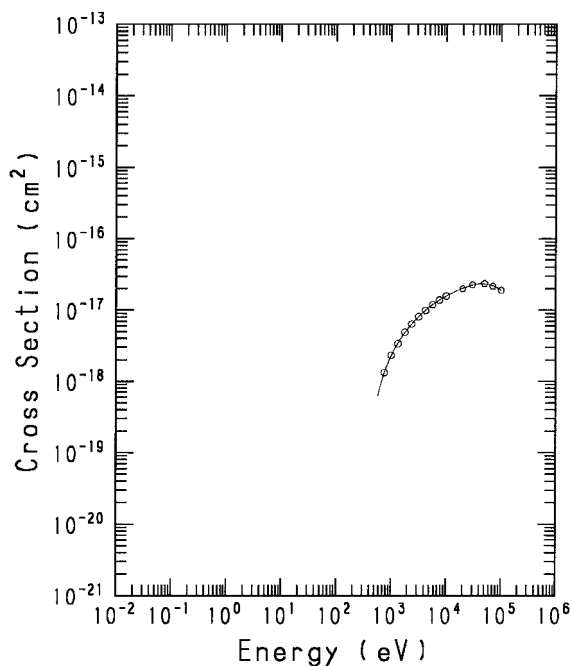
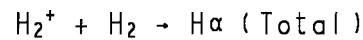
GRAPH 15



GRAPH 14



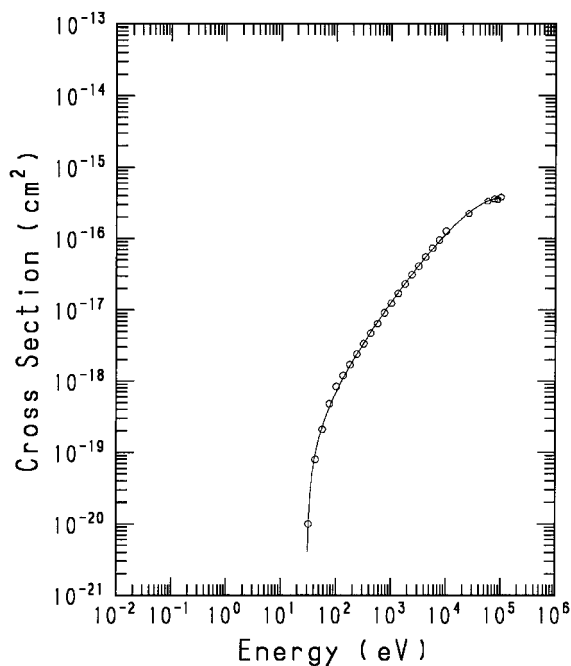
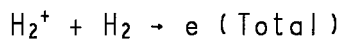
GRAPH 16



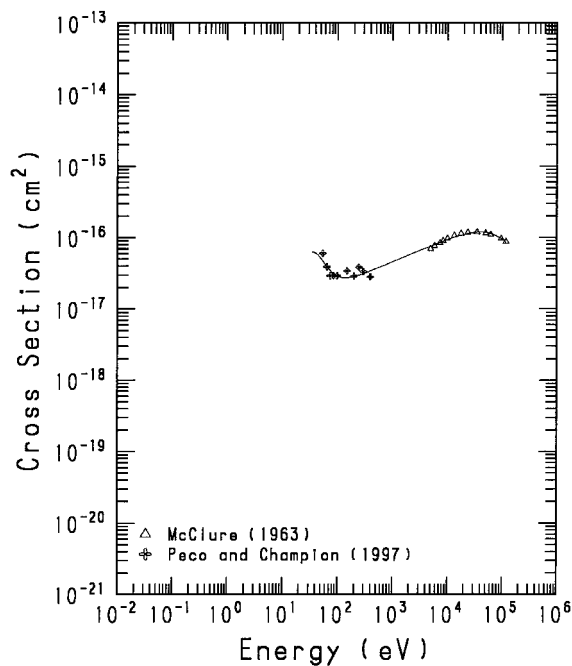
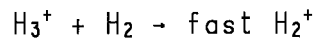
## GRAPHS. Cross Section vs Projectile Energy

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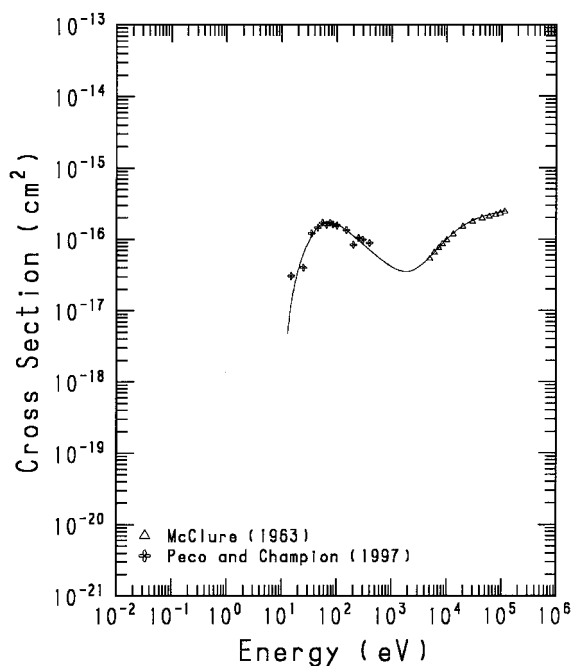
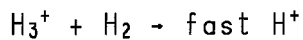
GRAPH 17



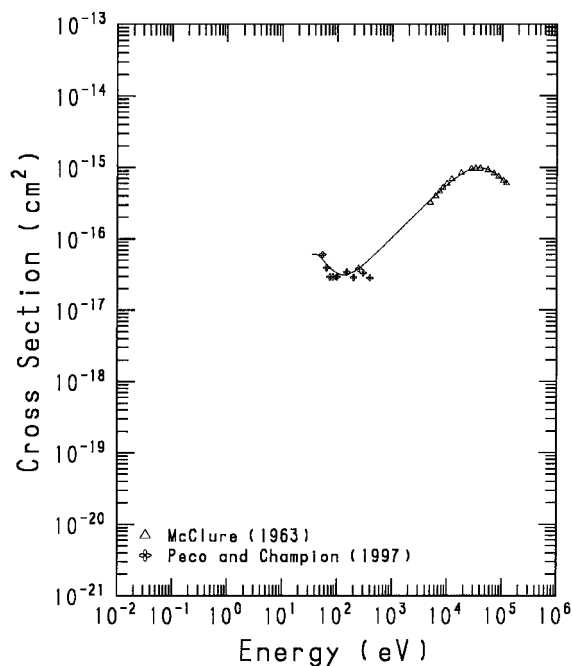
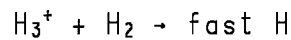
GRAPH 19



GRAPH 18



GRAPH 20

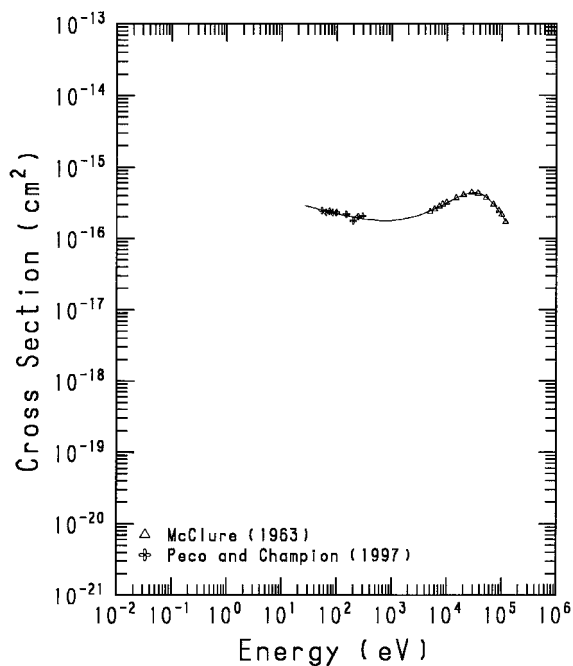




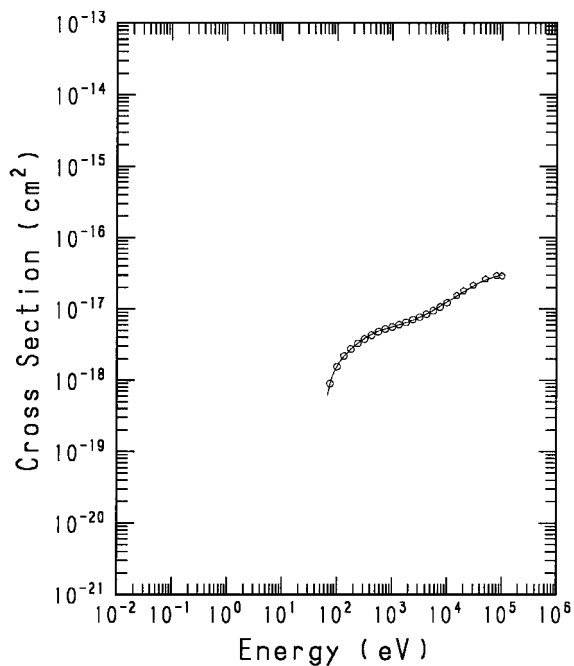
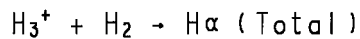
## GRAPHS. Cross Section vs Projectile Energy

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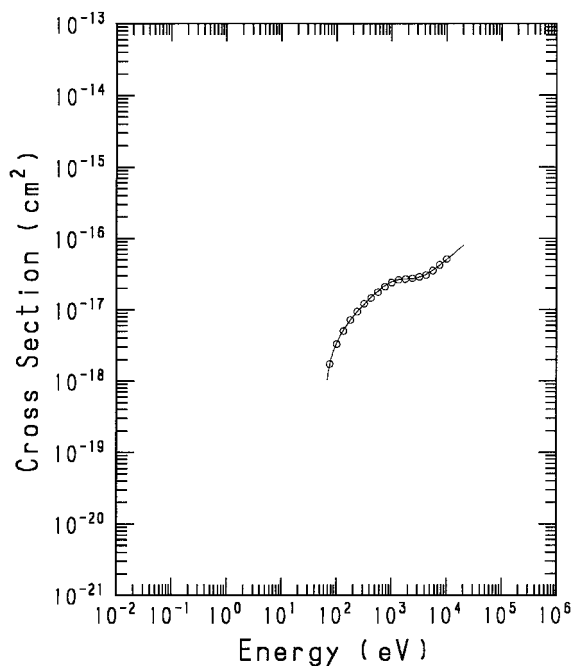
GRAPH 21



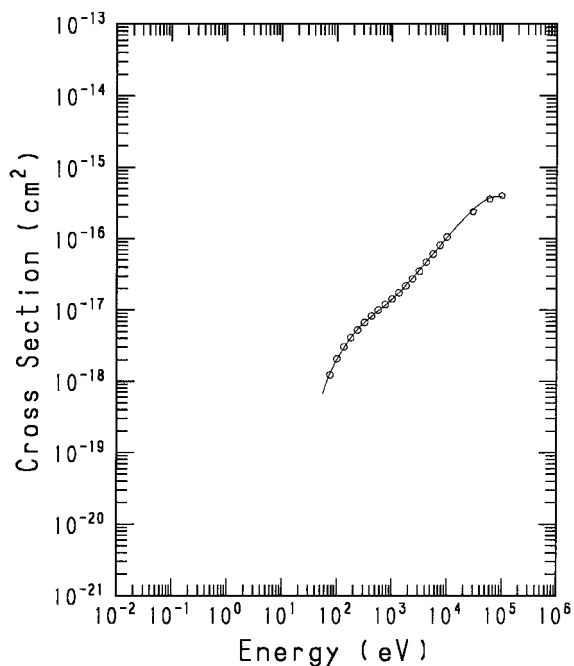
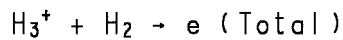
GRAPH 23



GRAPH 22



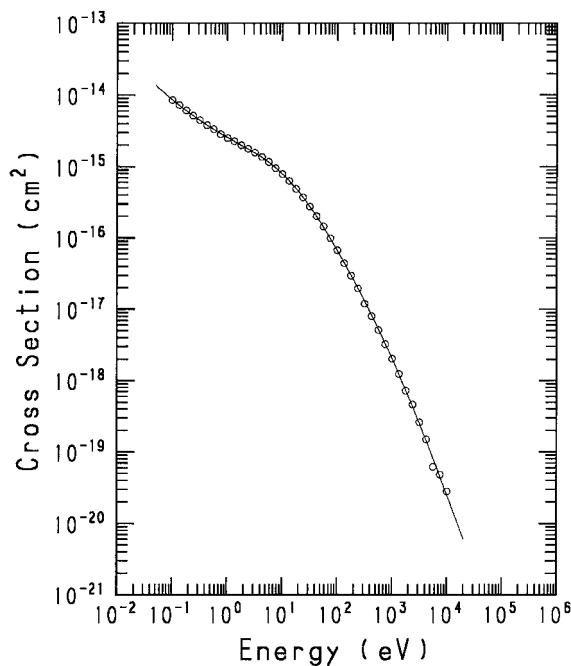
GRAPH 24



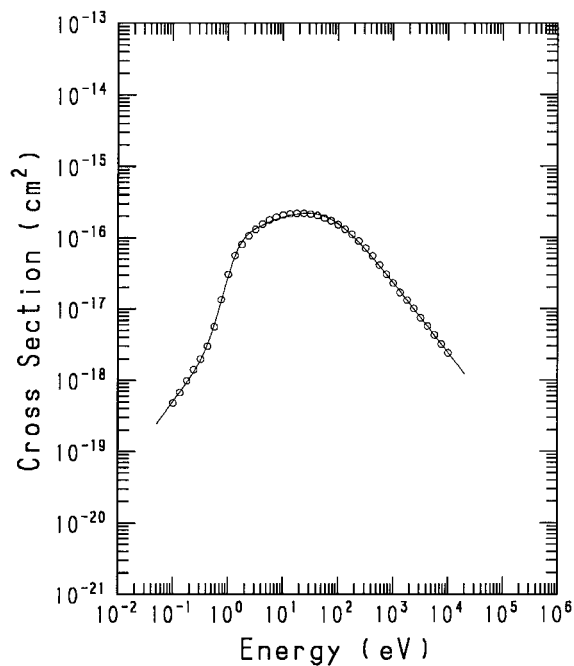
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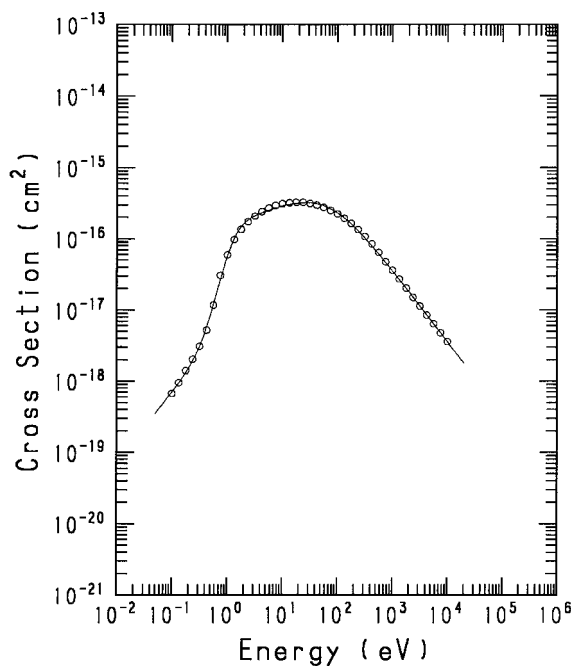
GRAPH 25

 $\text{H}_3^+ + \text{H}_2 \rightarrow \text{Momentum Transfer}$ 

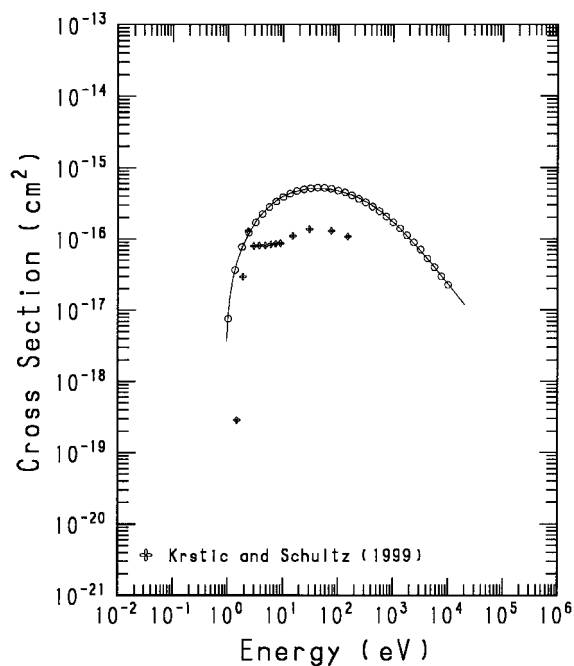
GRAPH 27

 $\text{H} + \text{H}_2(\text{J}=1) \rightarrow \text{H}_2(\text{J}=3)$ 

GRAPH 26

 $\text{H} + \text{H}_2(\text{J}=0) \rightarrow \text{H}_2(\text{J}=2)$ 

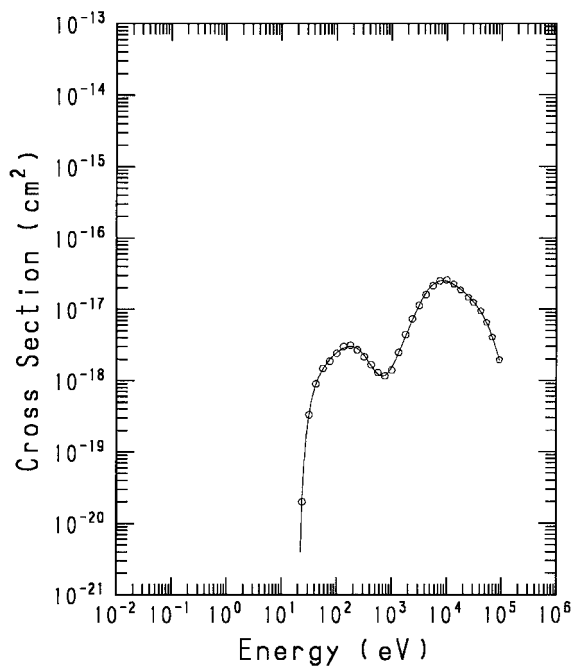
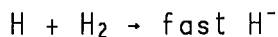
GRAPH 28

 $\text{H} + \text{H}_2(\text{v}=0) \rightarrow \text{H}_2(\text{v}=1)$ 

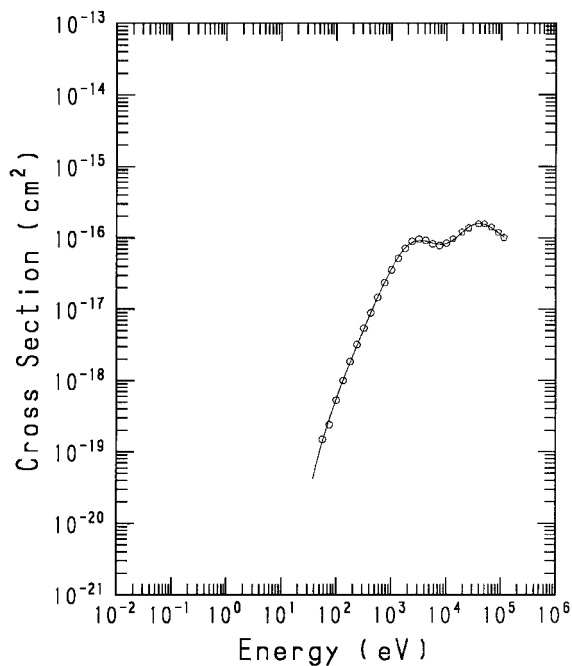
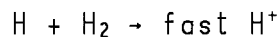
## GRAPHS. Cross Section vs Projectile Energy

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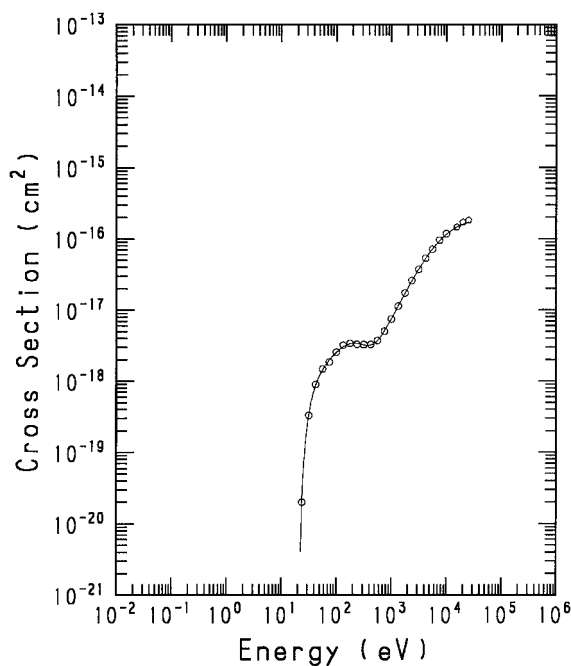
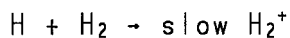
GRAPH 29



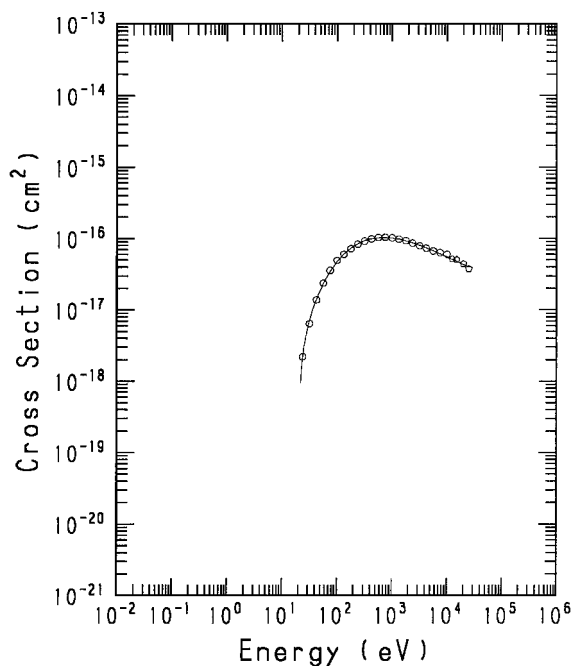
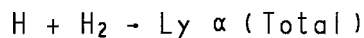
GRAPH 31



GRAPH 30



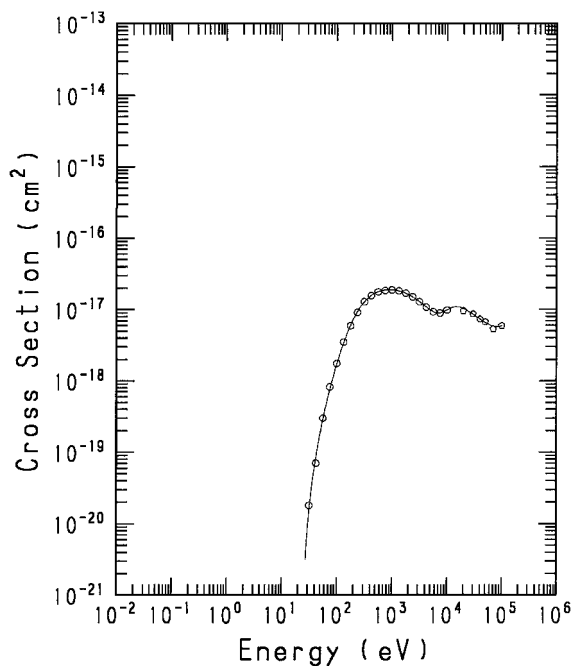
GRAPH 32



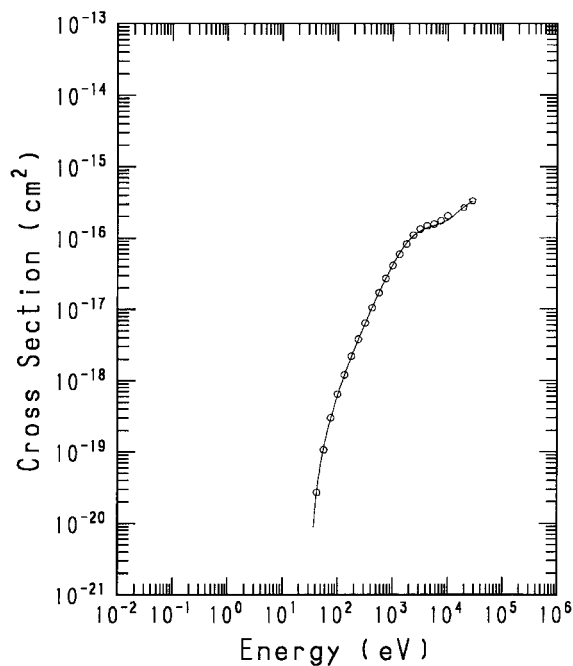
## GRAPHS. Cross Section vs Projectile Energy

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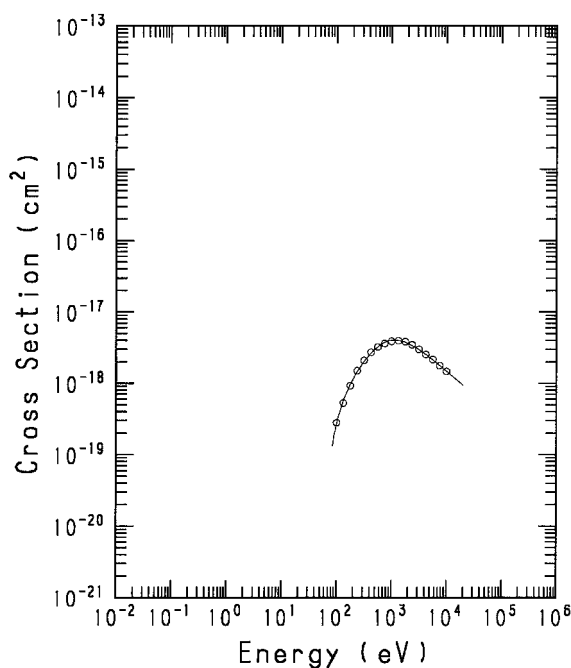
GRAPH 33

 $H + H_2 \rightarrow H\alpha$  (Total)

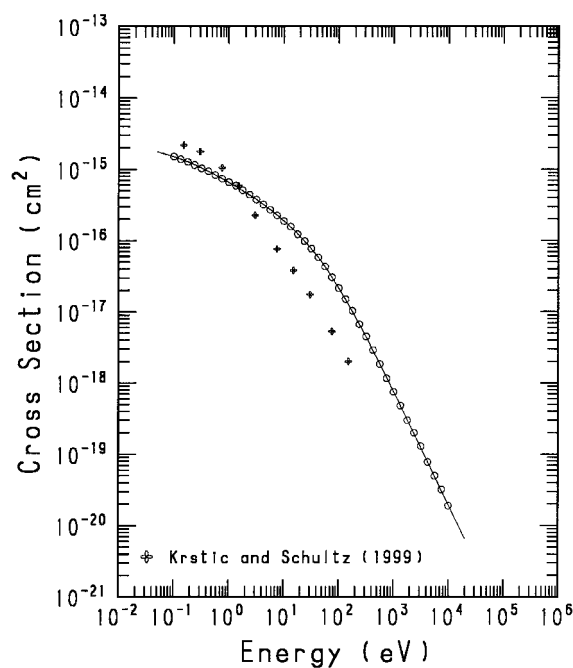
GRAPH 35

 $H + H_2 \rightarrow e$  (Total)

GRAPH 34

 $H + H_2 \rightarrow H\beta$  (Total)

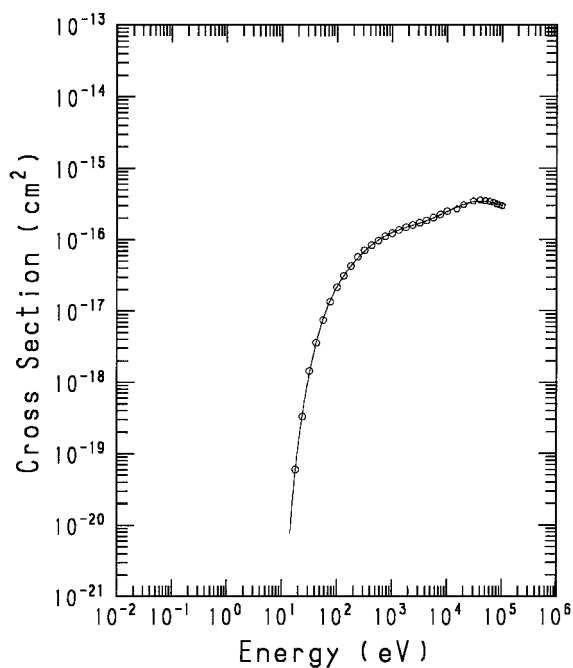
GRAPH 36

 $H + H_2 \rightarrow$  Momentum Transfer

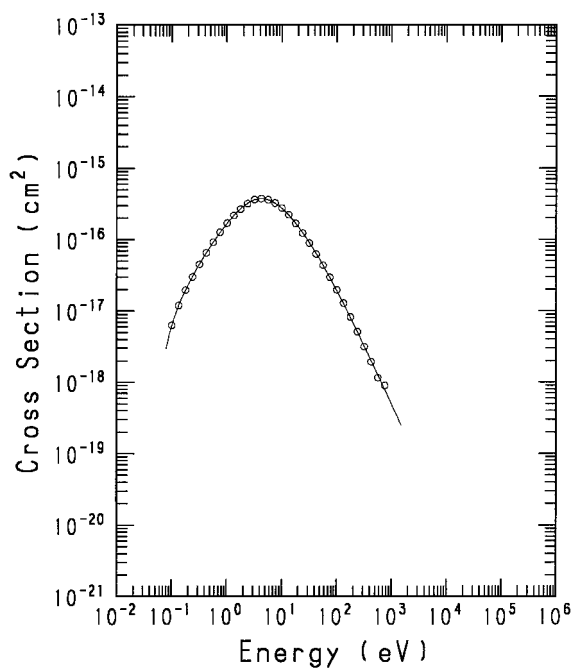
## GRAPHS. Cross Section vs Projectile Energy

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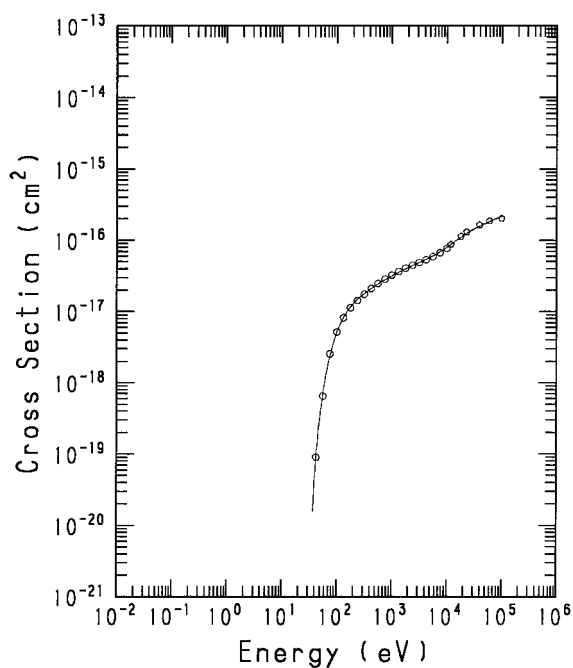
GRAPH 37

 $\text{H}_2 + \text{H}_2 \rightarrow \text{fast H}_2 \text{ Destruction}$ 

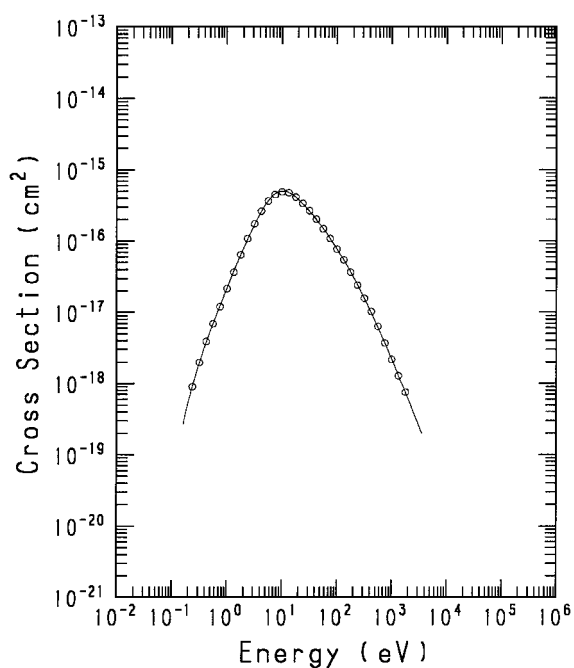
GRAPH 39

 $\text{H}_2(\text{J}=0) + \text{H}_2(\text{J}=0) \rightarrow \text{H}_2(\text{J}=0) + \text{H}_2(\text{J}=2)$ 

GRAPH 38

 $\text{H}_2 + \text{H}_2 \rightarrow \text{fast H}_2^+$ 

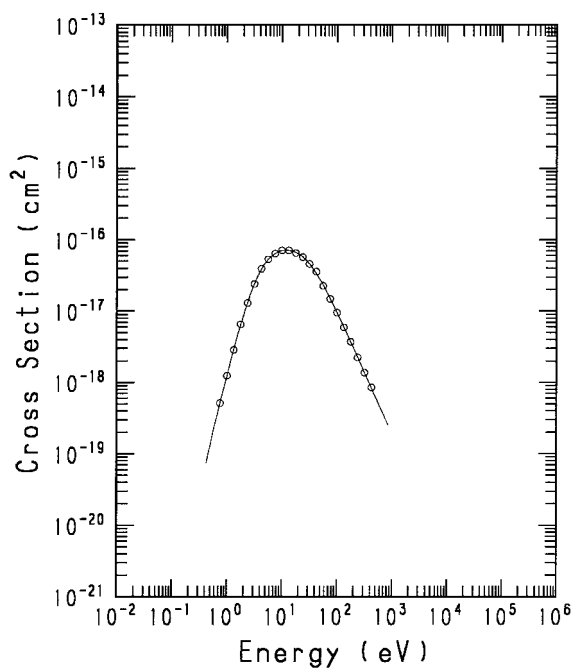
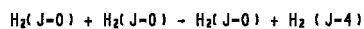
GRAPH 40

 $\text{H}_2(\text{J}=0) + \text{H}_2(\text{J}=0) \rightarrow \text{H}_2(\text{J}=2) + \text{H}_2(\text{J}=2)$ 

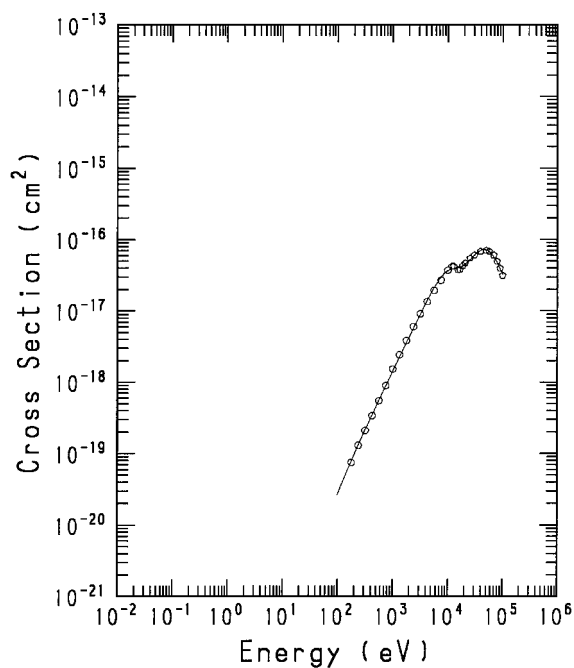
## GRAPHS. Cross Section vs Projectile Energy

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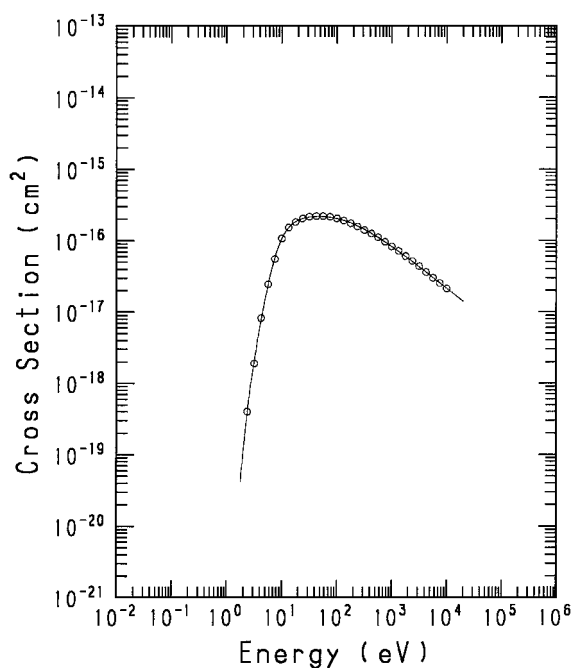
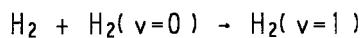
GRAPH 41



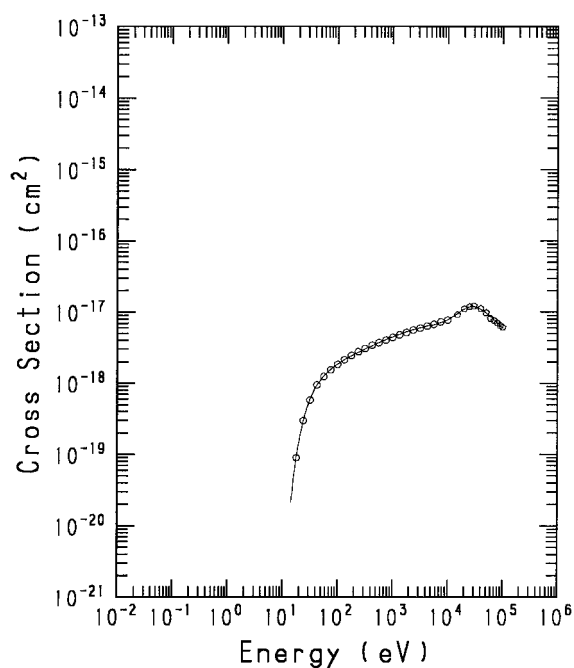
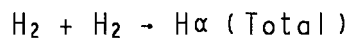
GRAPH 43



GRAPH 42



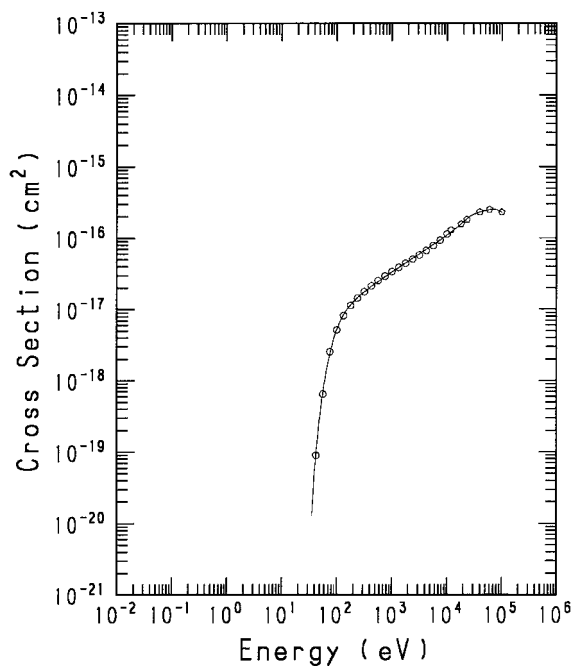
GRAPH 44



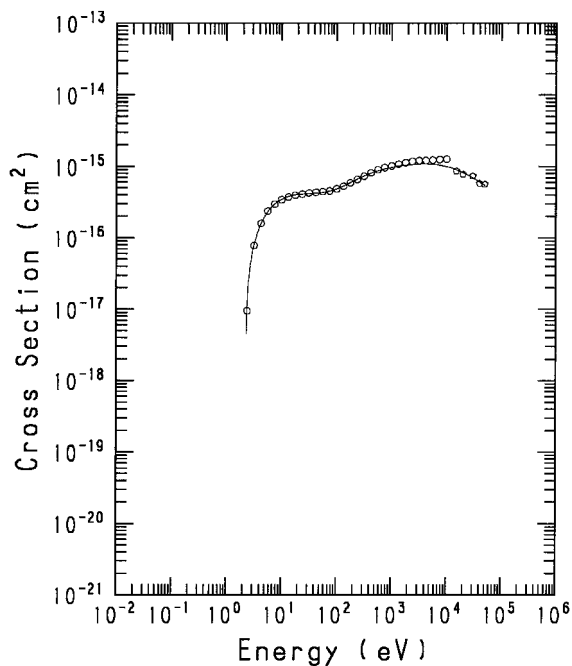
## GRAPHS. Cross Section vs Projectile Energy

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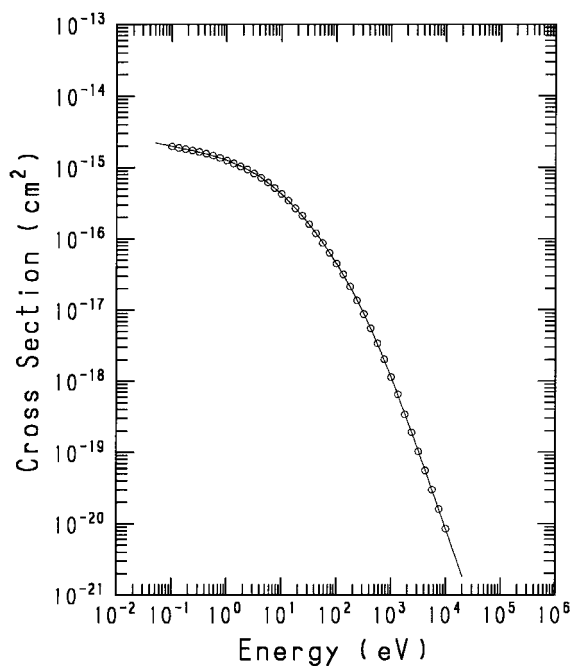
GRAPH 45

 $\text{H}_2 + \text{H}_2 \rightarrow \text{fast H}_2^+ \text{ or fast H}^+$ 

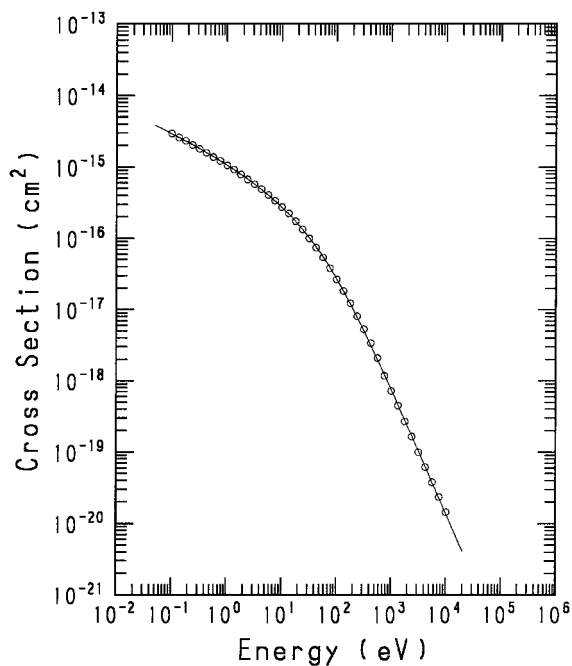
GRAPH 47

 $\text{H}^- + \text{H}_2 \rightarrow \text{e} + \text{fast H}$ 

GRAPH 46

 $\text{H}_2 + \text{H}_2 \rightarrow \text{Momentum Transfer}$ 

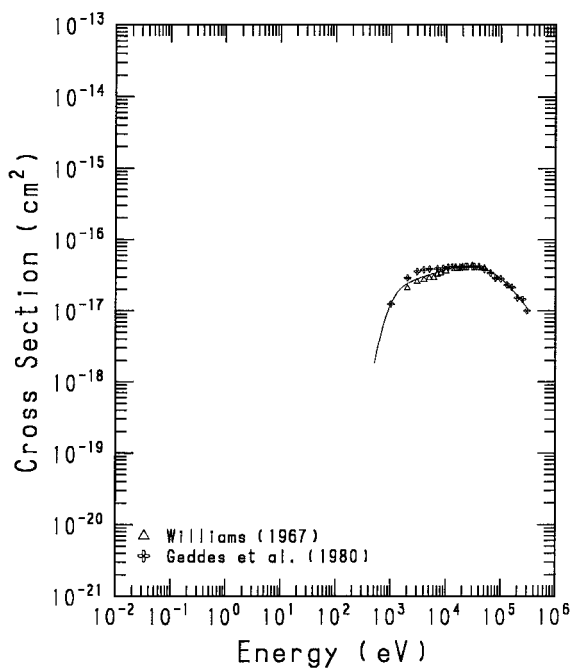
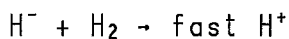
GRAPH 48

 $\text{H}^- + \text{H}_2 \rightarrow \text{Momentum Transfer}$ 

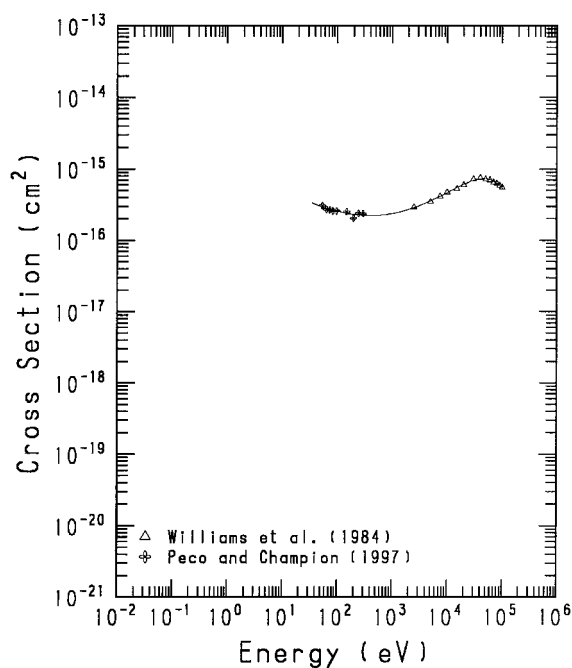
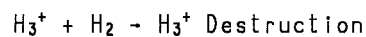
## GRAPHS. Cross Section vs Projectile Energy

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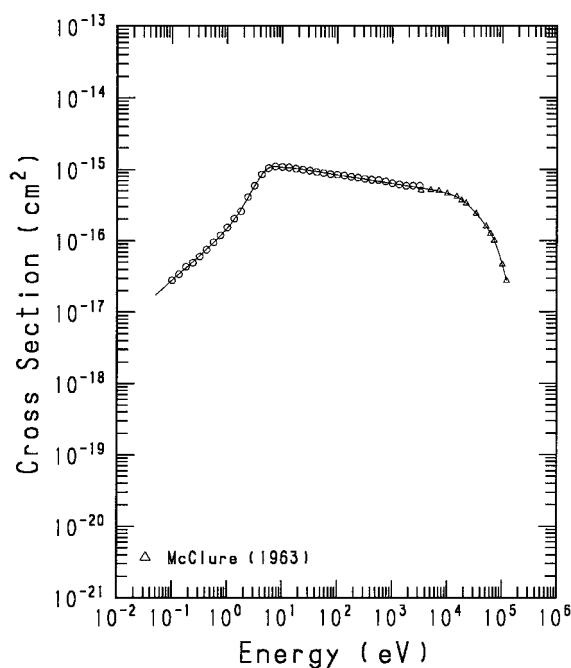
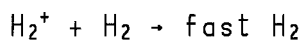
GRAPH 49



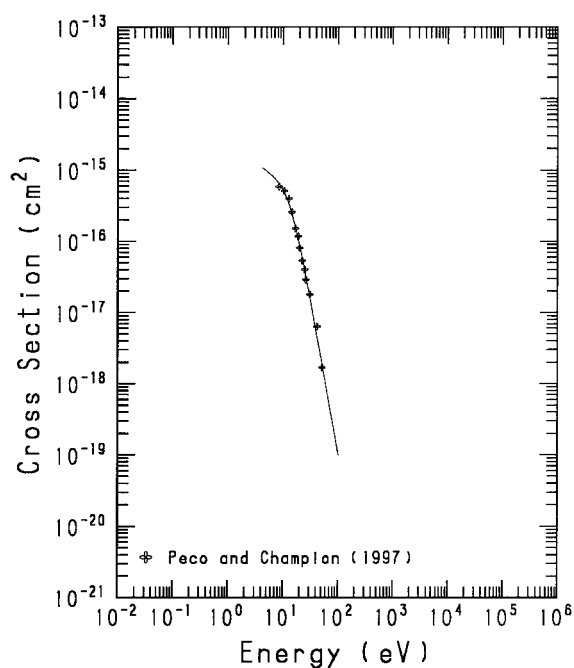
GRAPH 51



GRAPH 50



GRAPH 52

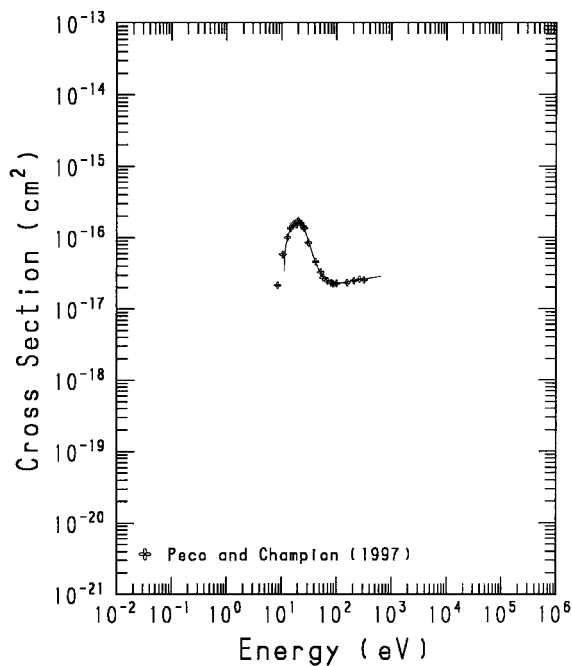
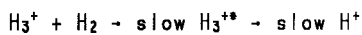




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GRAPH 53



GRAPH 54

