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CROSS SECTIONS FOR PARTICLE-REARRANGEMENT IN ION-MOLECULE COLLISIONS I. HYDROGEN AND HELIUM SPECIES

November 1994

Akira ICHIHARA, Shigeo HAYAKAWA*, Masao SATAKA and Toshizo SHIRAI

日本原子力研究所
Japan Atomic Energy Research Institute

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Cross Sections for Particle-rearrangement in Ion-molecule Collisions I. Hydrogen and Helium Species

Akira ICHIHARA, Shigeo HAYAKAWA* , Masao SATAKA and Toshizo SHIRAI

Department of Reactor Engineering
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

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Experimental cross sections for particle-rearrangement in the ion-molecule collisions between primary plasma constituents have been collected for edge plasma studies. Total and partial cross sections are compiled in graphical forms. Brief comments on the cross-section measurements are given for each reaction. The literature has been surveyed through March 1994.

Keywords: Cross Section, Particle-rearrangement, H, D, H_2, HD, D_2, He

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* University of Osaka Prefecture

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イオン－分子間衝突での粒子組み替え反応断面積 I
水素及びヘリウム種

日本原子力研究所東海研究所原子炉工学部
市原　晃・早川　滋雄*・左高　正雄
白井　稔三

（1994年10月17日受理）

エッジプラズマのモデリング及び診断に必要なイオン－分子反応の断面積に関する実験データを収集した。1994年３月までの文献を対象として収集された反応の全および部分断面積を図にまとめた。

本報は、大阪府立大学への委託調査をふくむ。
東海研究所：〒319－11　茨城県那珂郡東海村白方字白根２－４
* 大阪府立大学総合科学部

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It has been widely known from recent experiments on tokamak plasmas that conditions of edge plasma affect crucially on the overall plasma performance[1]. The edge plasma is characterized by the temperature range of 1 to 200 eV and the particle densities in the range of 10^{12} - 10^{15} cm^{-3}. Because of the low temperatures, not only neutral particles but also molecular species exist and a variety of collision processes occur in the edge plasma. This makes the analysis of edge plasma very complex. Accurate knowledge of the cross sections for these collision processes gives the basis of the edge plasma modeling and diagnostics. Sufficient accumulation of reliable atomic and molecular data is, therefore, strongly required for the future development of the fusion reactor.

This report presents a compilation of the experimental total and partial (state-selective) cross sections for particle-rearrangement in the ion-molecule collisions. As a first step, hydrogen and helium species, which are the primary plasma constituents, are selected. All relevant papers published till March 1994 were collected and surveyed using bibliographic information in references [2-4]. Absolute total and partial cross sections are presently available for twenty-one and six collision systems, respectively. They are compiled in graphical forms together with the recommended data in Ref.[3] and analytical fits, when available. We cite the uncertainties of the data as given by the authors. A short review is given on the cross-section measurements.

It is well known in a theoretical description [5] in terms of the Langevin model that cross section for exothermic reaction varies inversely as the square root of the collision energy and its reaction rate constant is independent of the collision energy for reactions of the type $X^+ + YH \rightarrow XH^+ + Y$. The rate coefficients at thermal energies are available in a few comprehensive compilations.[6]

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[1] R.K. Janev, M.F.A. Harrison, and H.W. Drawin, Nucl. Fusion **29**, 109 (1989) and the related references therein.

[2] *An Index to the Literature on Atomic and Molecular Collision Data for Fusion Research*, CIAMDA80 and 87 (IAEA, Vienna, 1980 and 1987); *International Bulletin on Atomic and Molecular Data for Fusion*, Nos.33-41, edited by J.J. Smith, (IAEA, Vienna, 1986-1990);

ibid, Nos. 42–47, edited by J. Botero (IAEA, Vienna, 1991–1993).

[3] C.F. Barnett, *Atomic Data for Fusion Volume 1: Collisions of* H, H_2, He *and* Li *Atoms and Ions with Atoms and Molecules,* edited by H.T. Hunter, M.I. Kirkpatrick, I.Arvarez, C. Cisneros, and P.A. Phaneuf, Oak Ridge Natl. Lab. Rep. ORNL–6086/V1 (1990).

[4] P. Reinig, M. Zimmer and F. Linder, Nucl. Fusion Suppl. **2**, 95 (1992).

[5] G. Gioumousis and D.P. Stevenson, J. Chem. Phys. **29**, 294 (1958).

[6] Y. Ikezoe, S. Matsuoka, M. Takebe, and A. Viggiano, *Gas Phase Ion–Molecule Reaction Rate Constants Through 1986*, (Maruzen, Tokyo, 1987); V.G. Anicich and W.T. Huntress Jr., Astrophys. J. Suppl. Ser. **62**, 553(1986); D.L. Albritton, Atom. Data and Nucl. Data Tables **22**, 1 (1978).

2. Explanation of Figures

Figures. Cross section vs Energy

Ordinate: Cross section (in cm^2)

Abscissa: Collision energy (in eV/amu)

Experimental cross sections are shown by circles, triangles or squares in figures. The analytical curves are indicated by solid or dotted lines.

For the D_2^+(v=0–3) + H_2 → HD_2^+ + H reactions (Figs.32–35), collision energies defined in the analytical curves of Barnett ([3] in References for Introduction) are multiplied by a factor of 10 in order to obtain the reasonable agreement with the experimental cross sections. Similarly, the collision energies of Barnett for the HD^+(v=0–4) + He → HeH^+ + D (Figs. 42–46) reactions are multiplied by a factor of 3.

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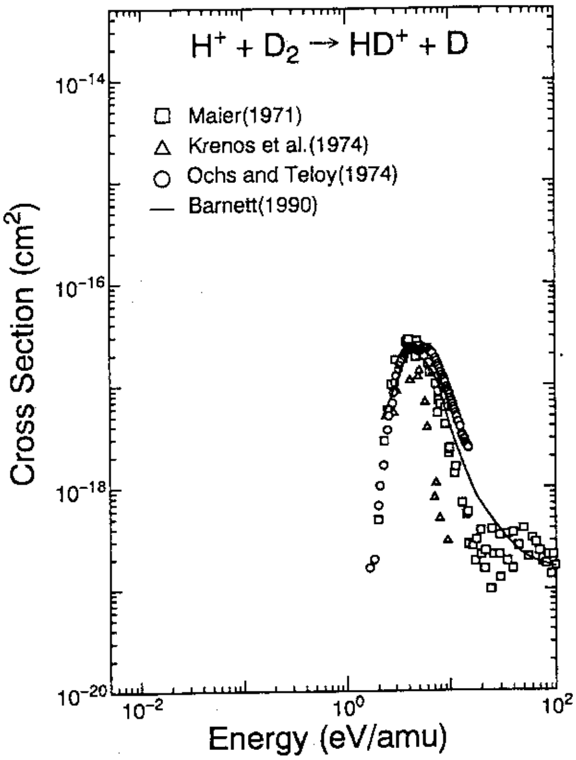
Fig.1



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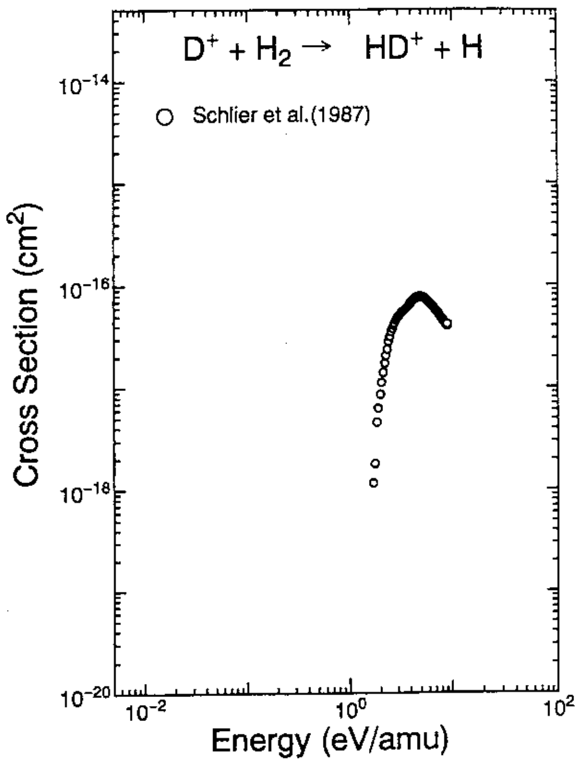

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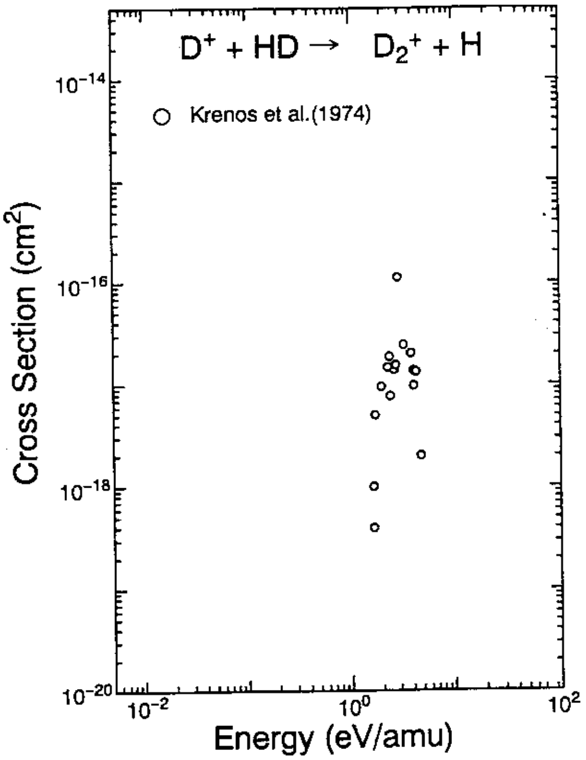

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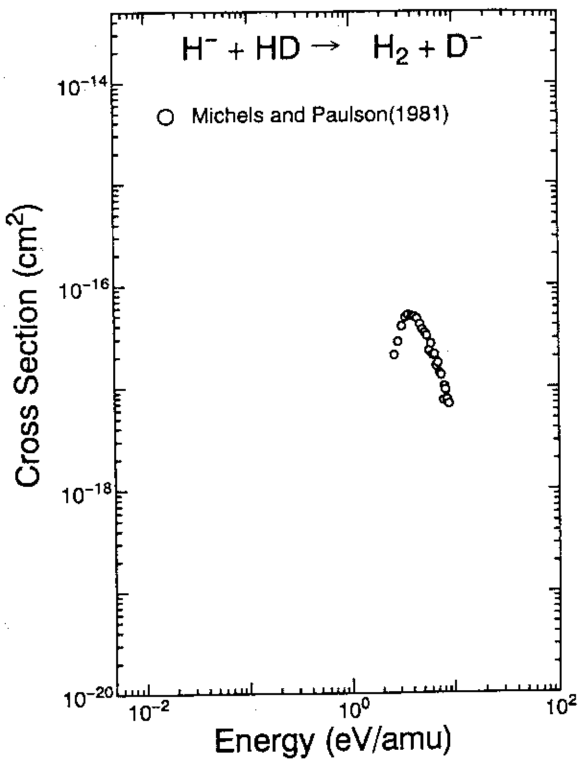

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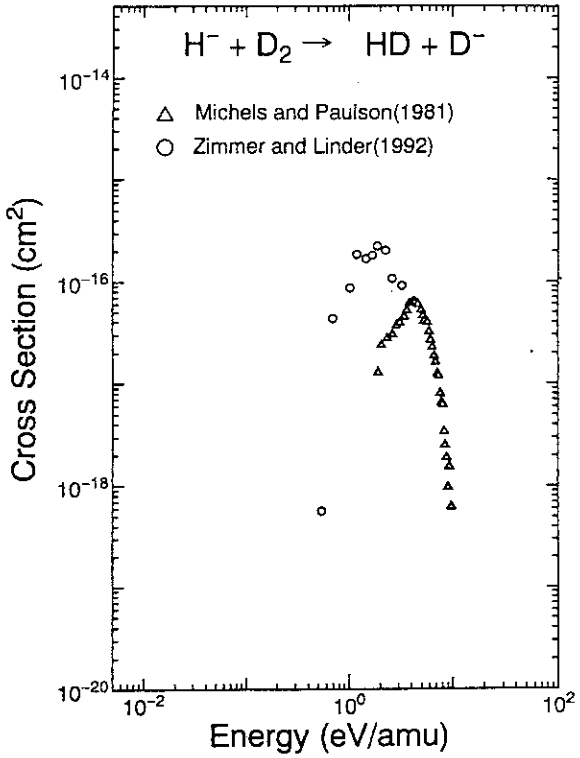

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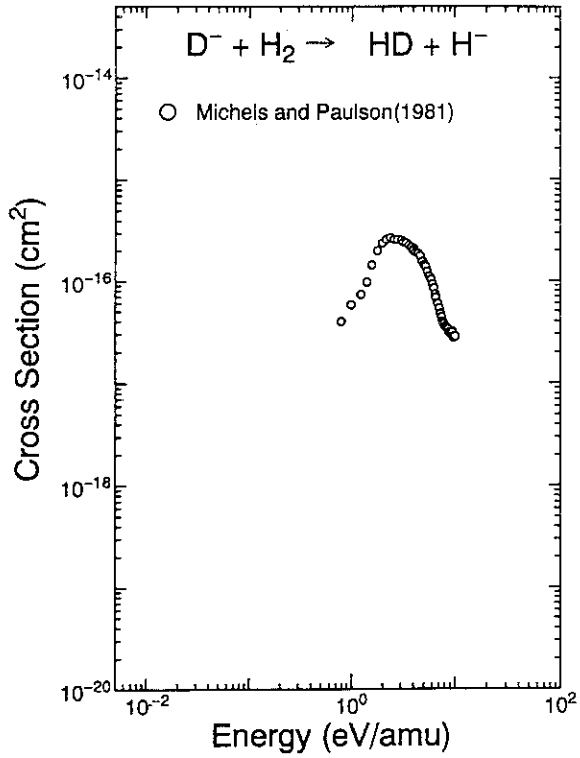

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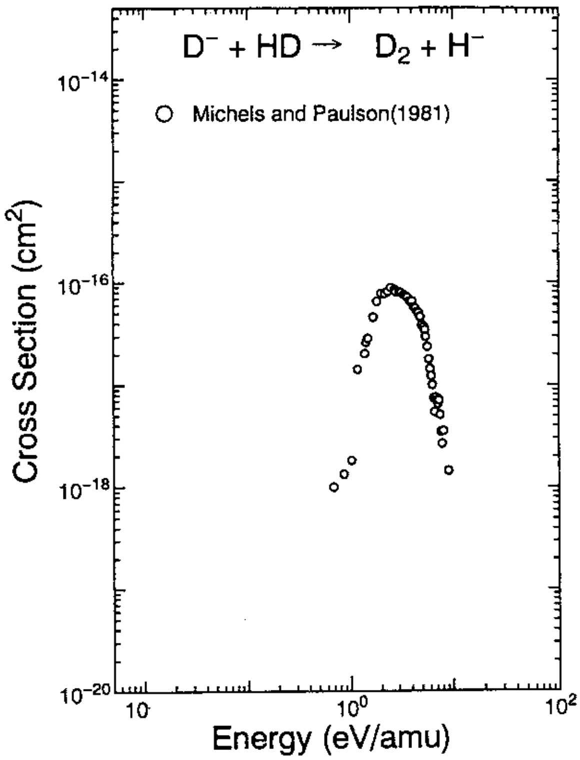

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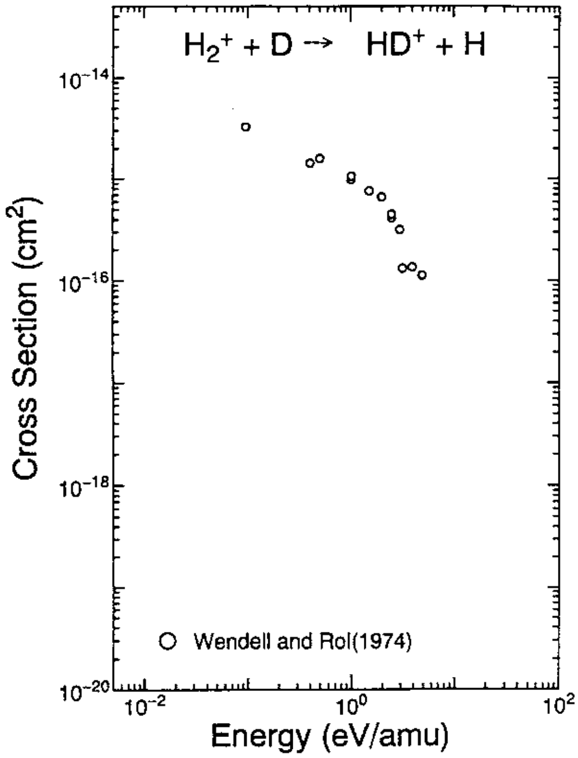

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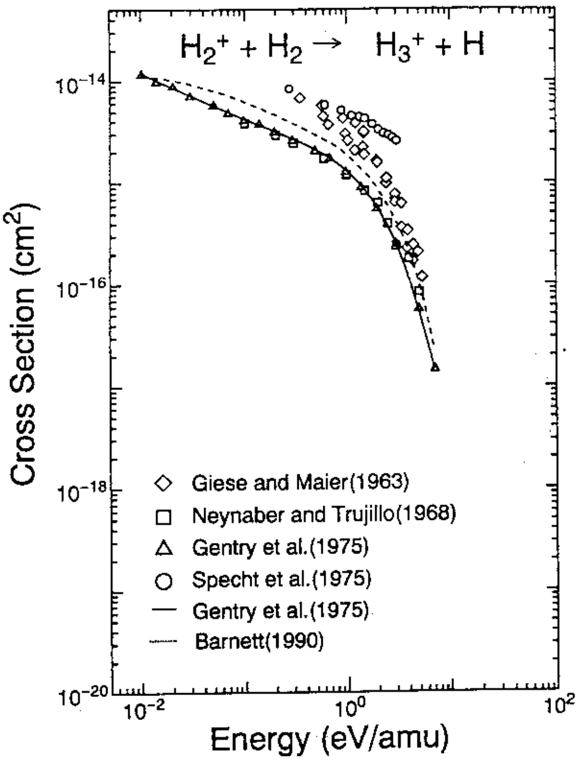

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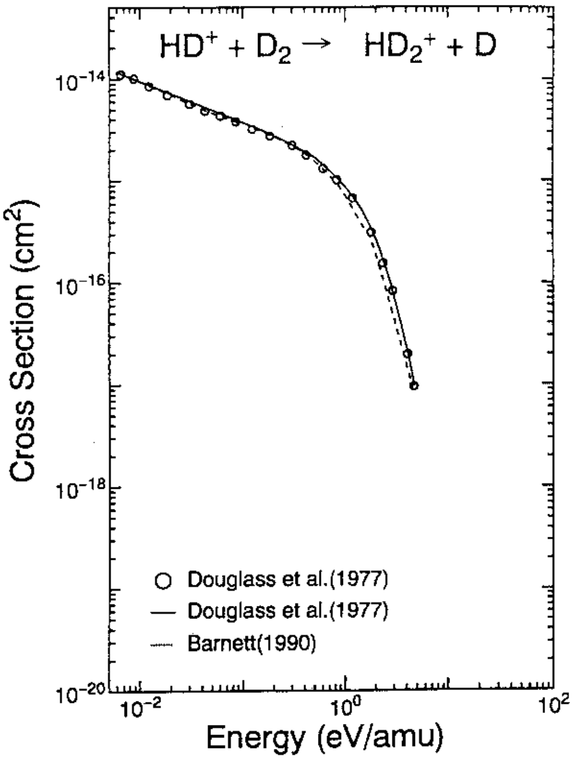

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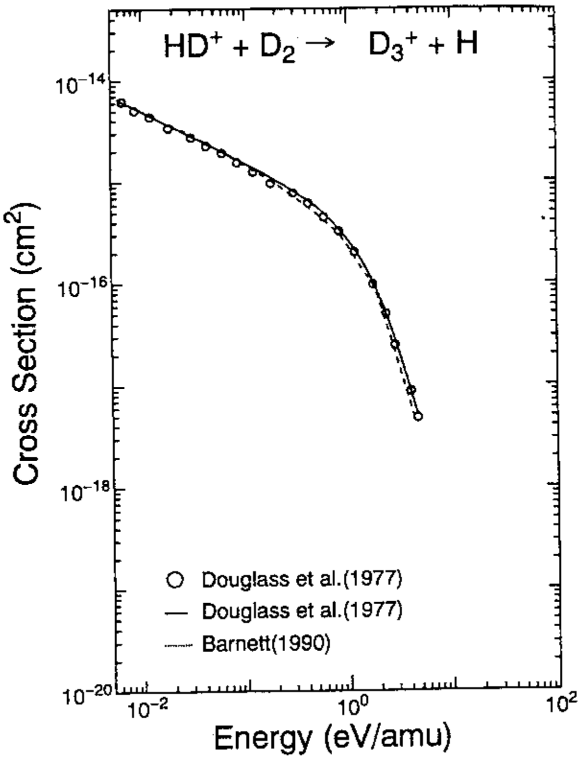

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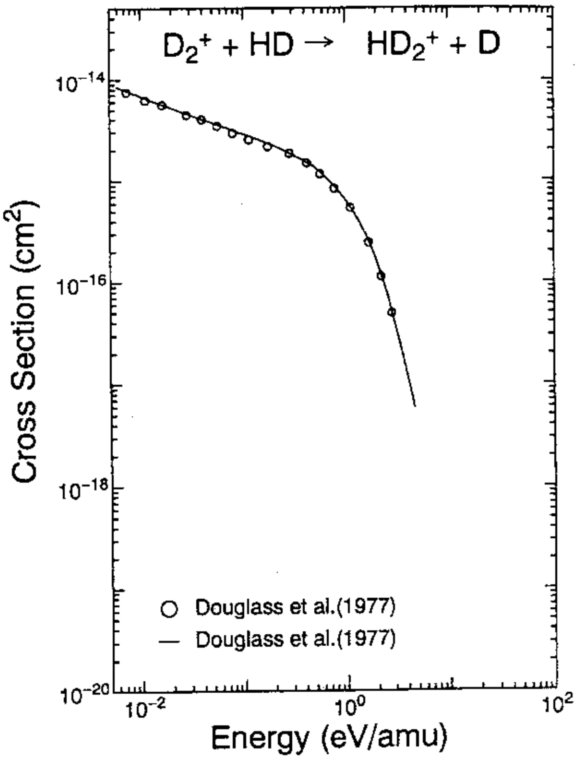

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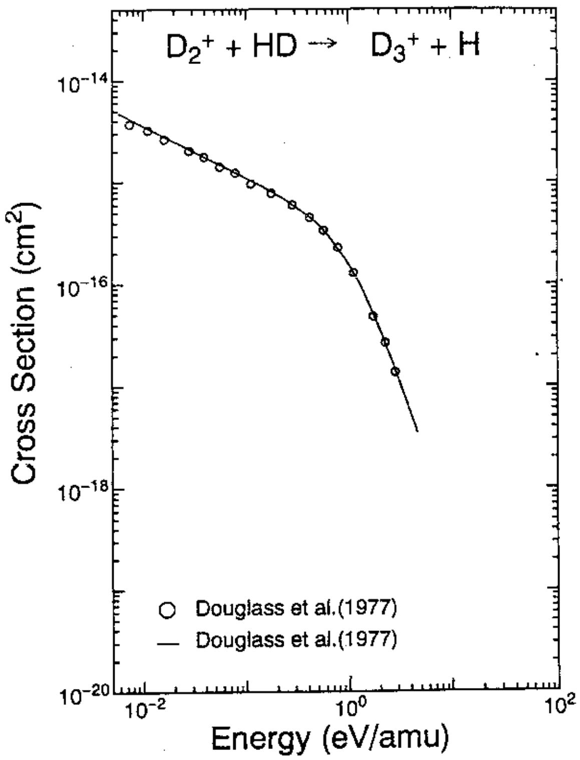

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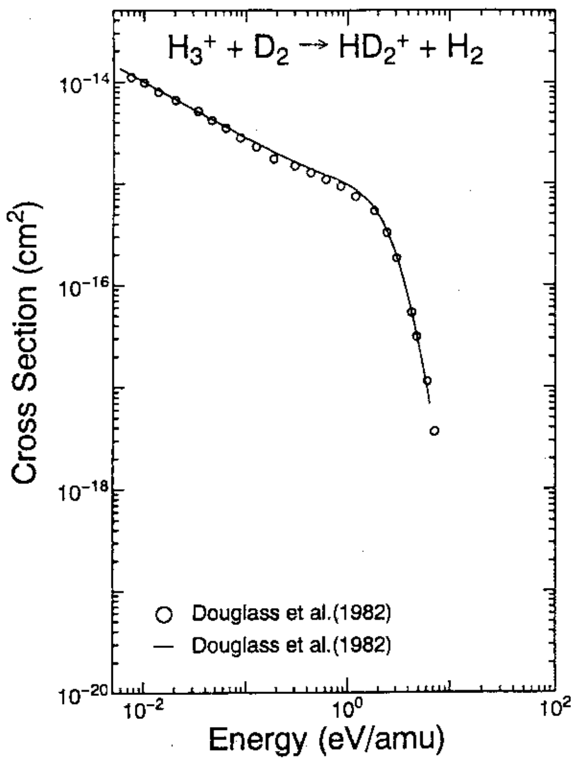

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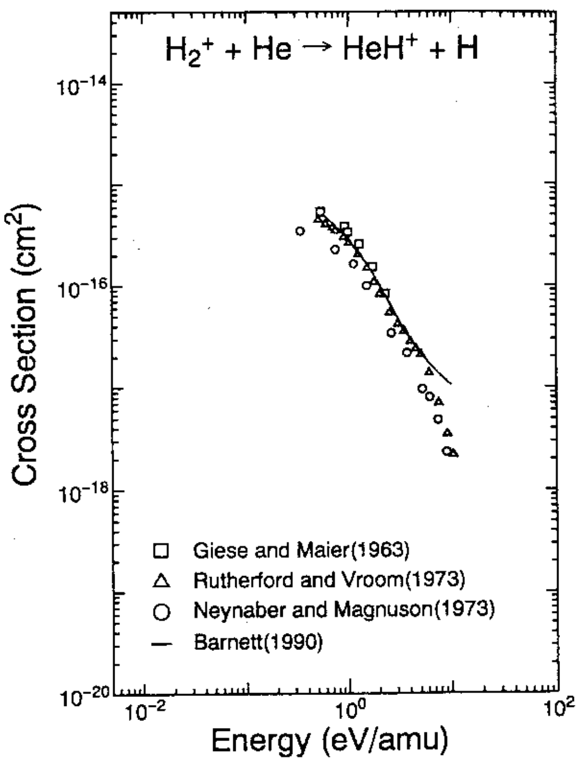

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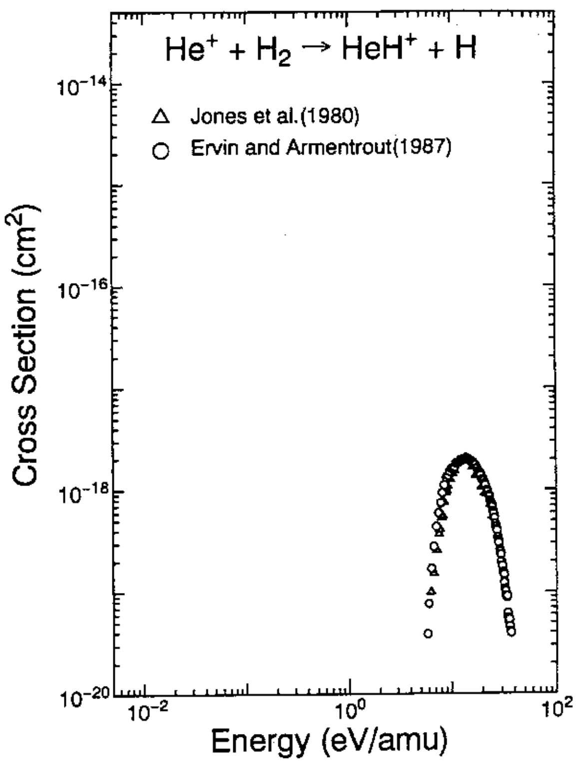

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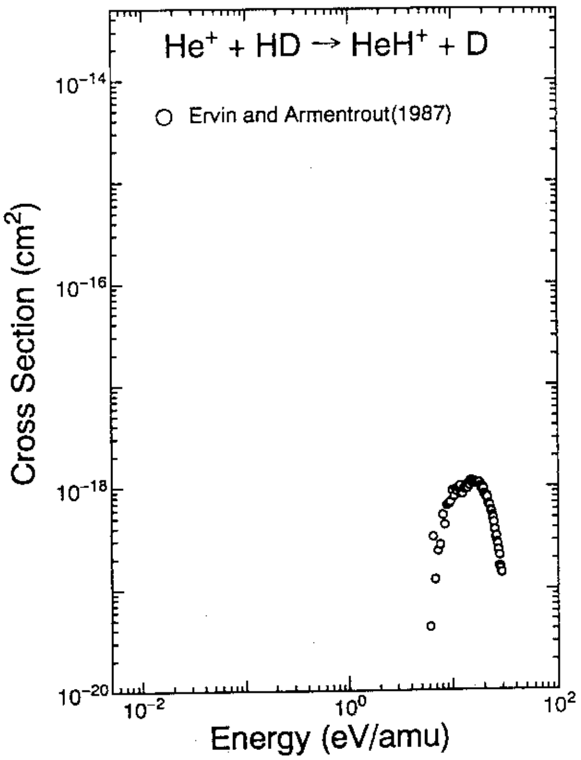

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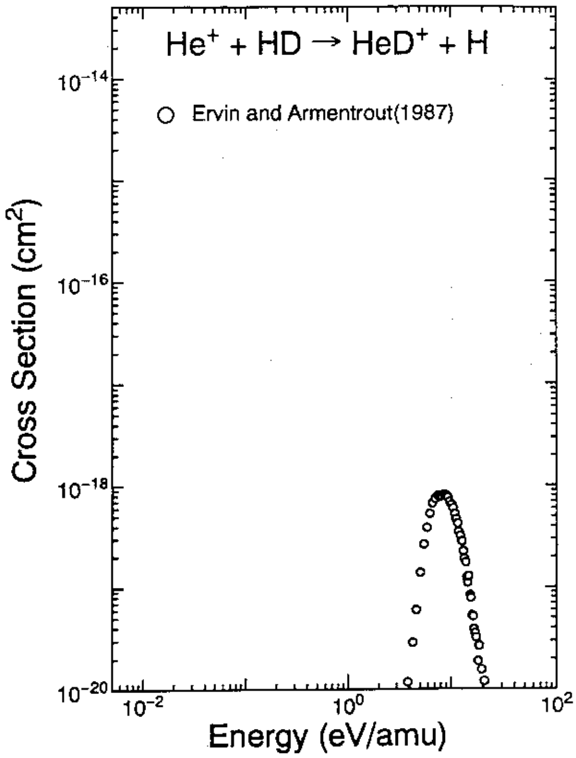

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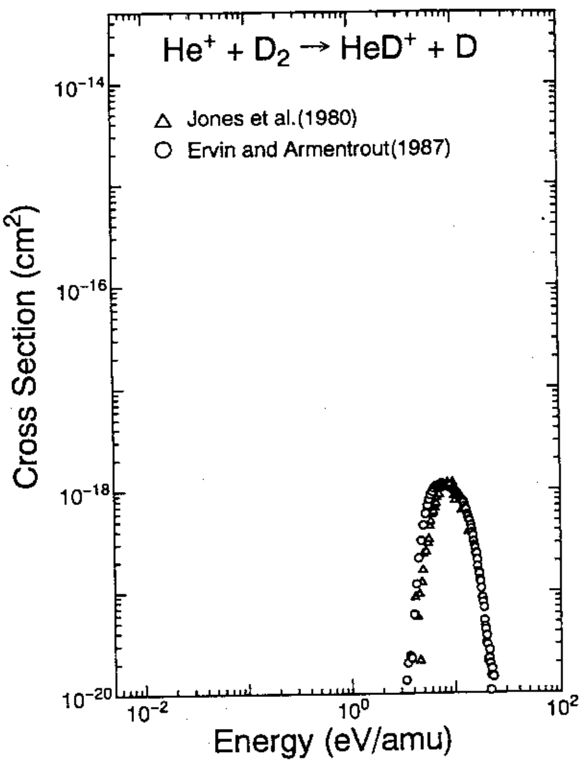

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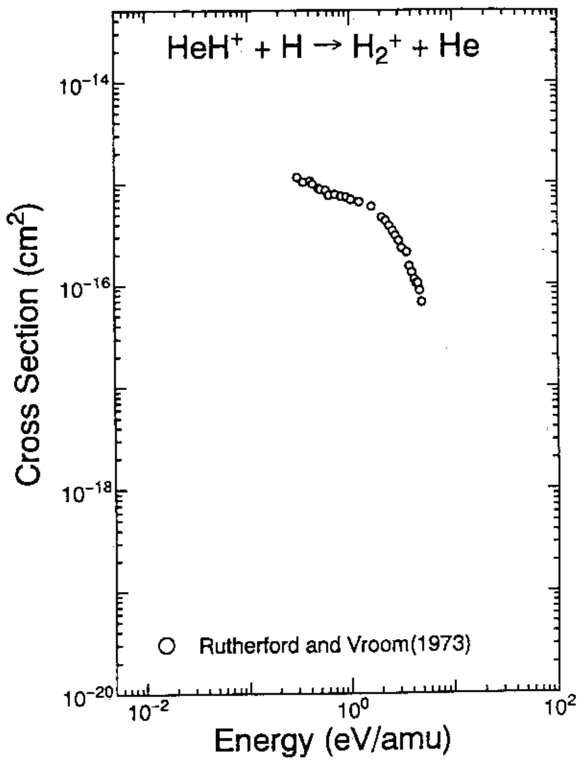

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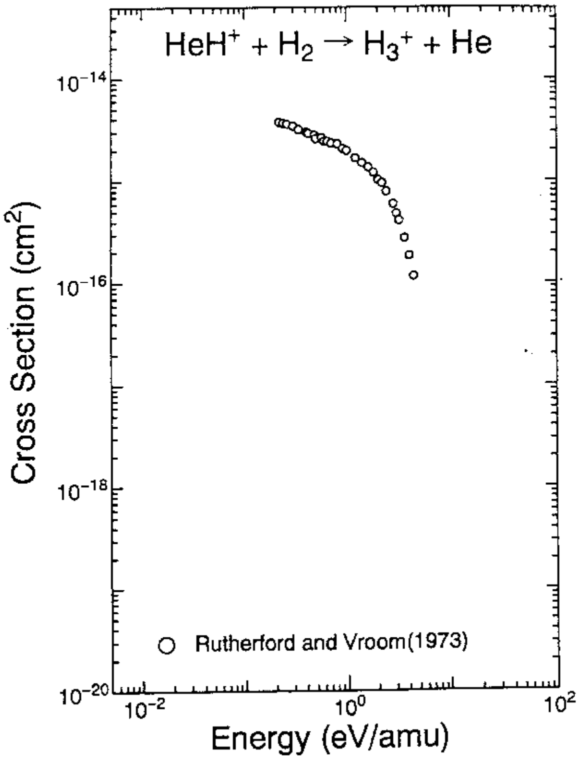

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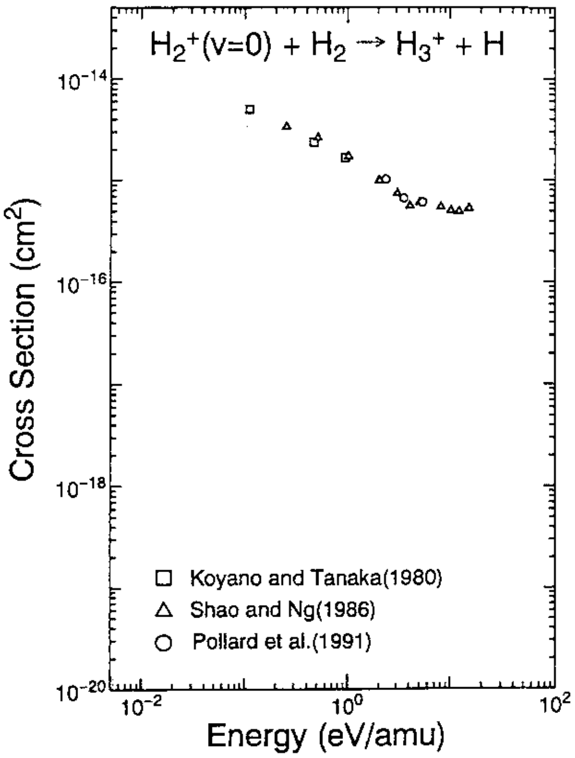

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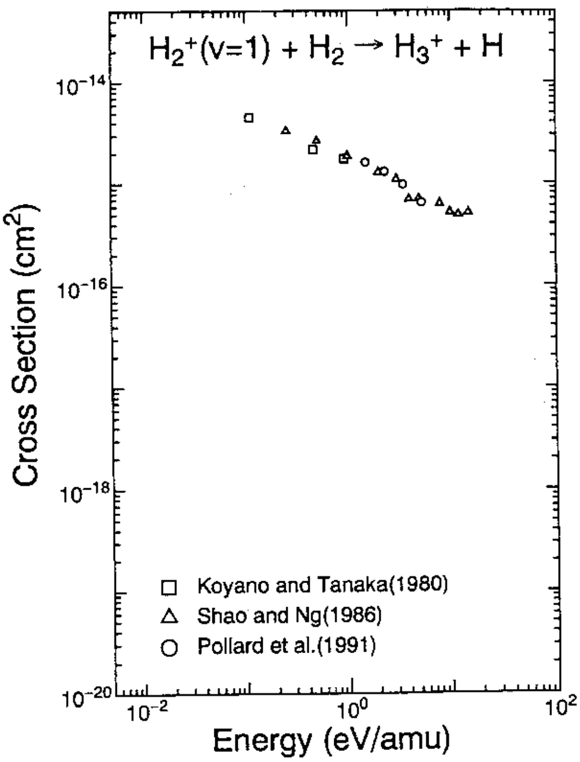

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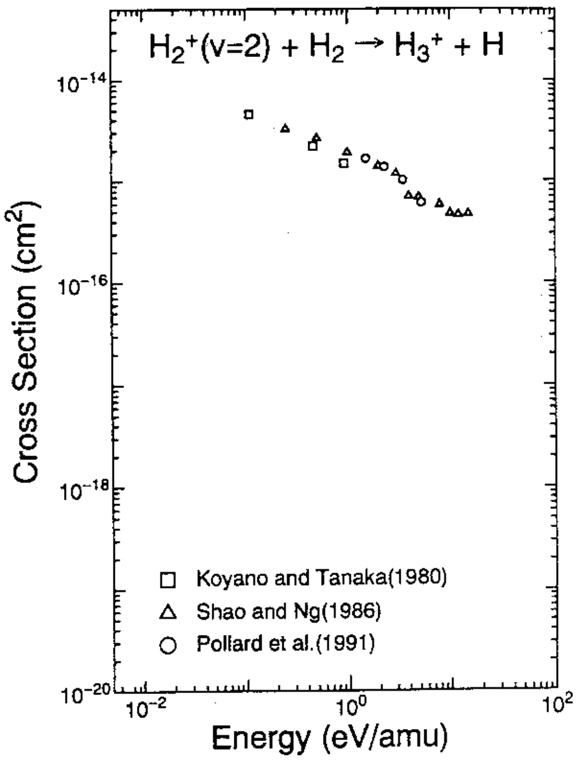

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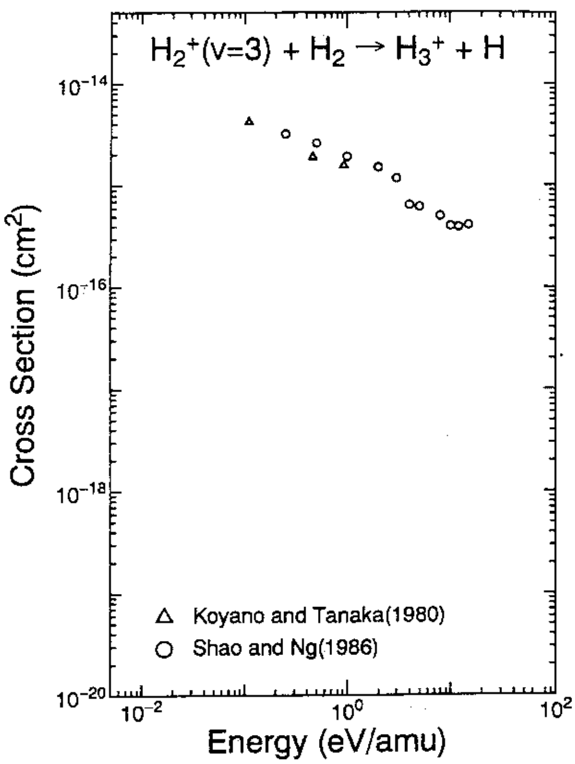

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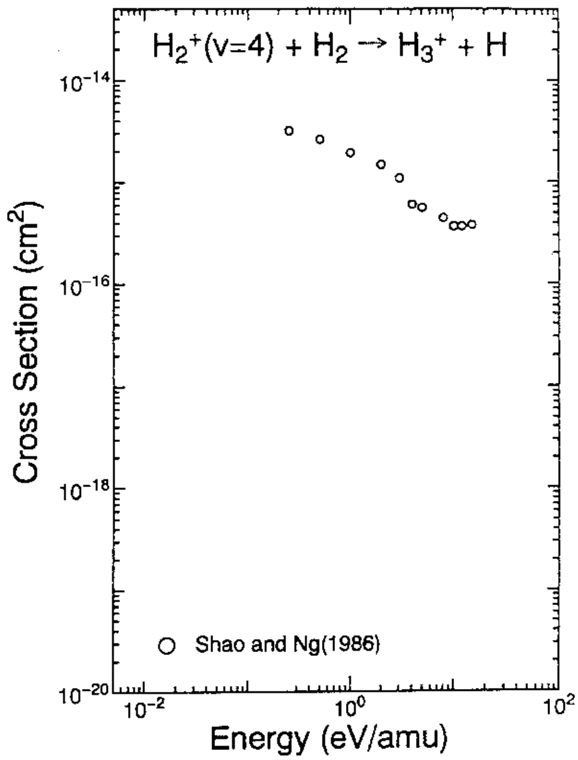

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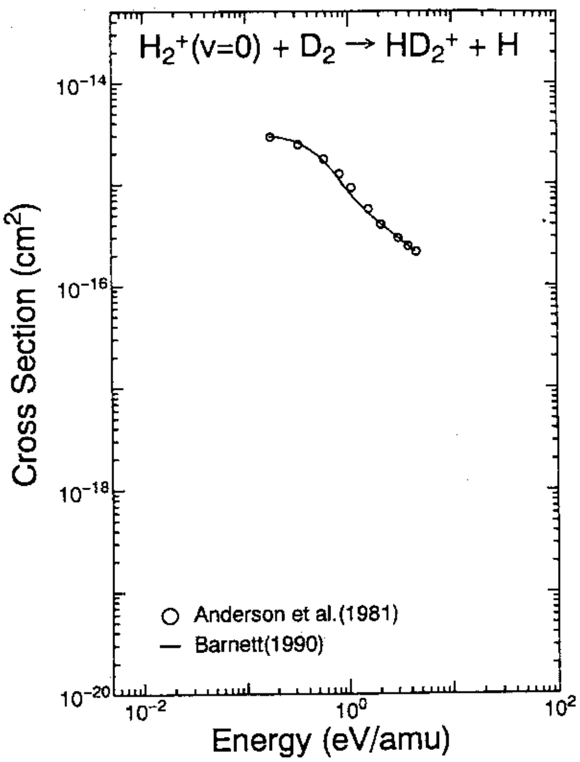

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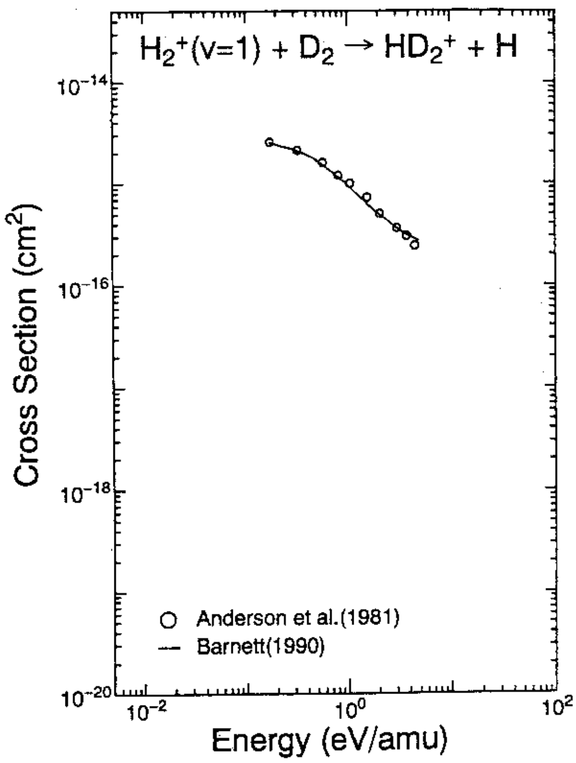

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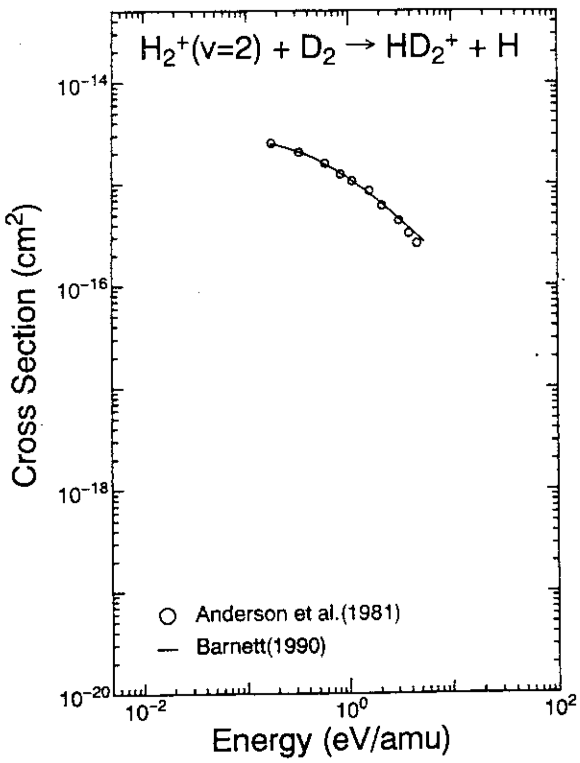

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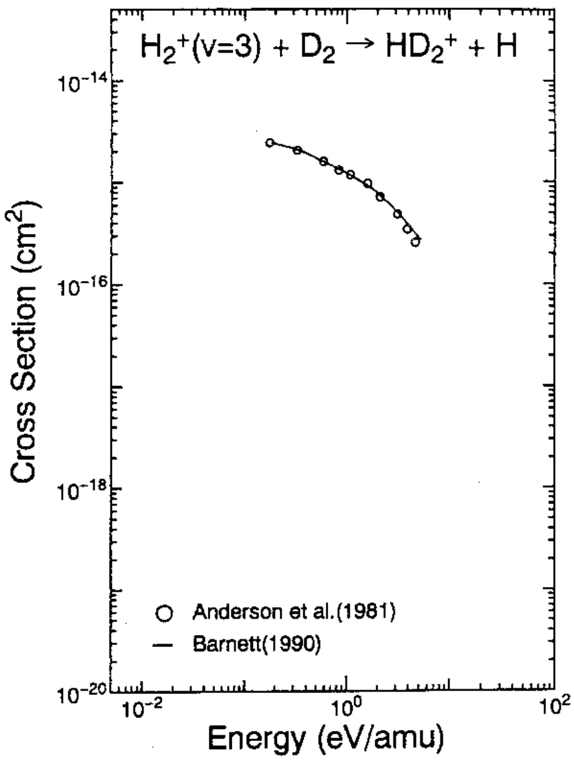

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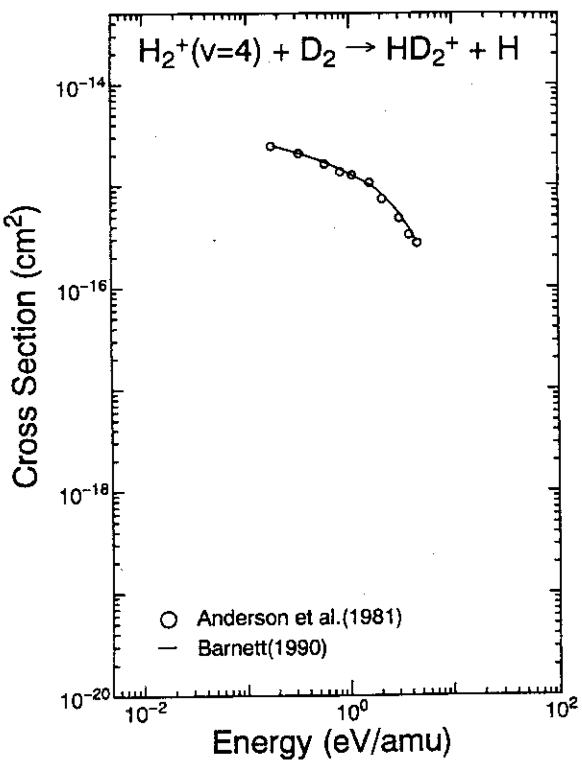

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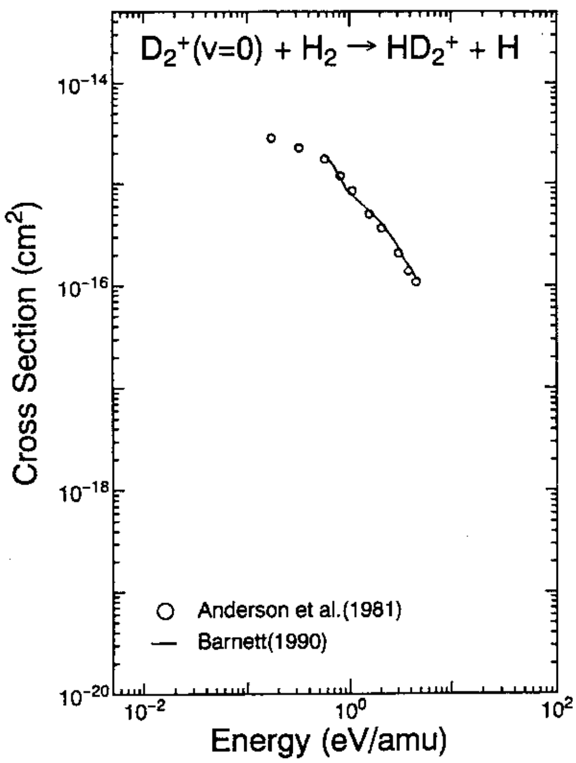

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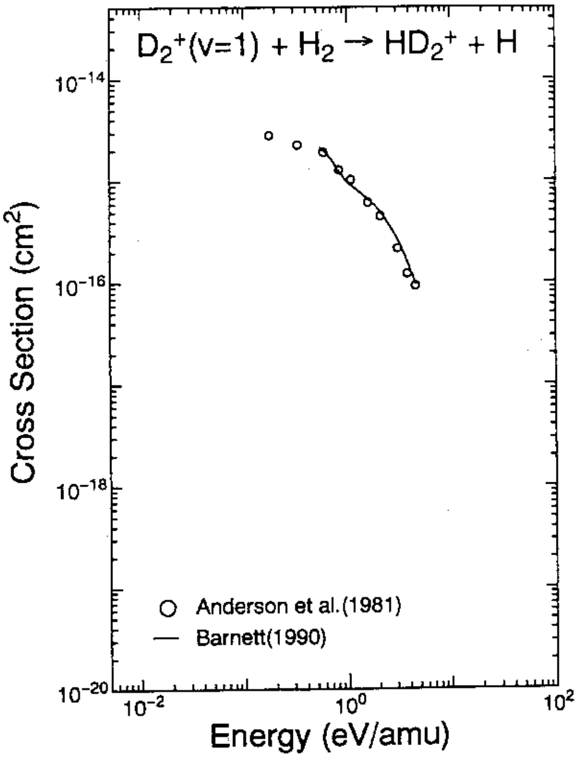

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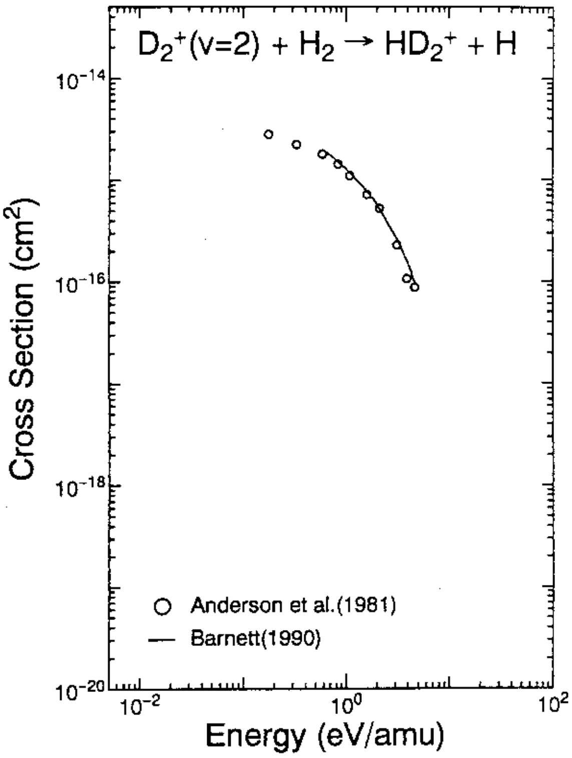

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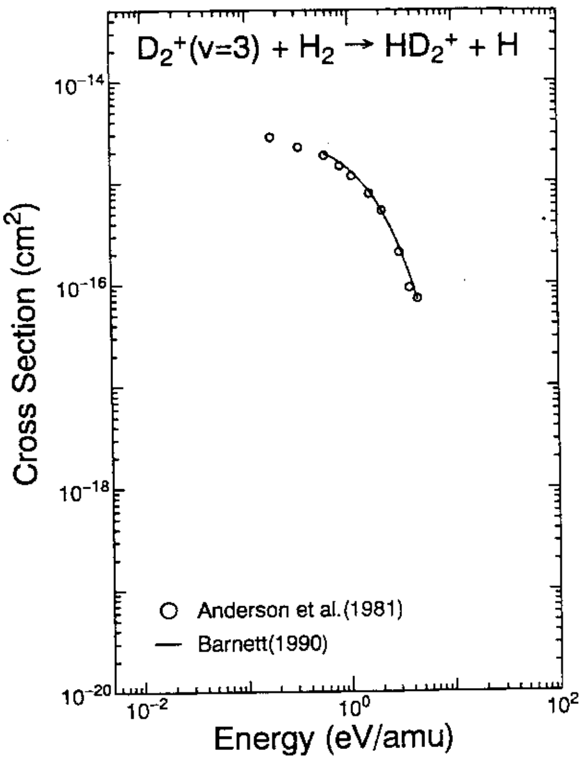

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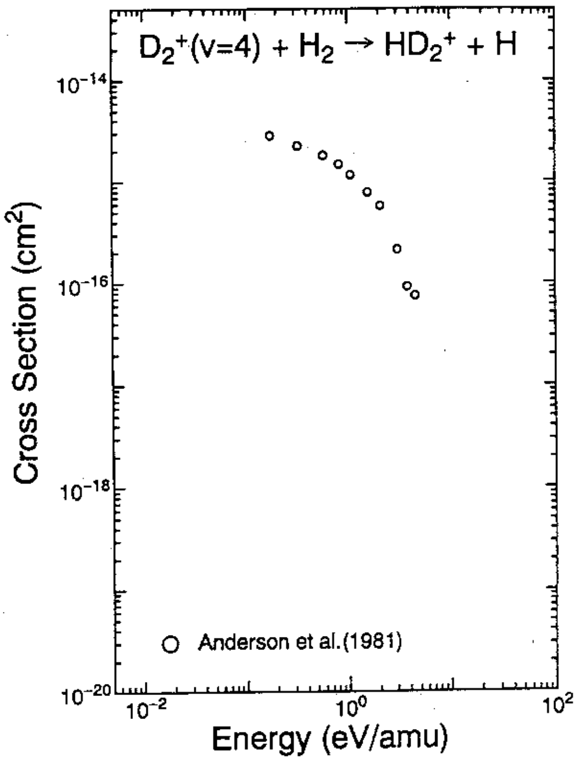

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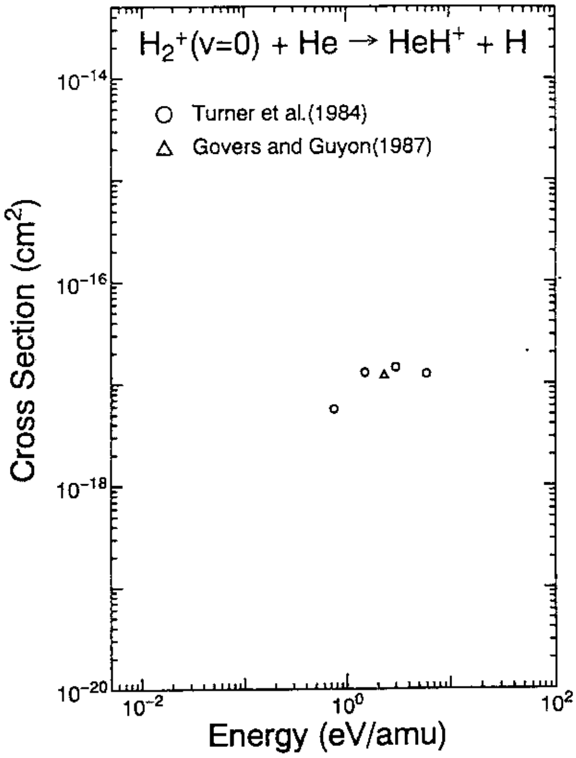

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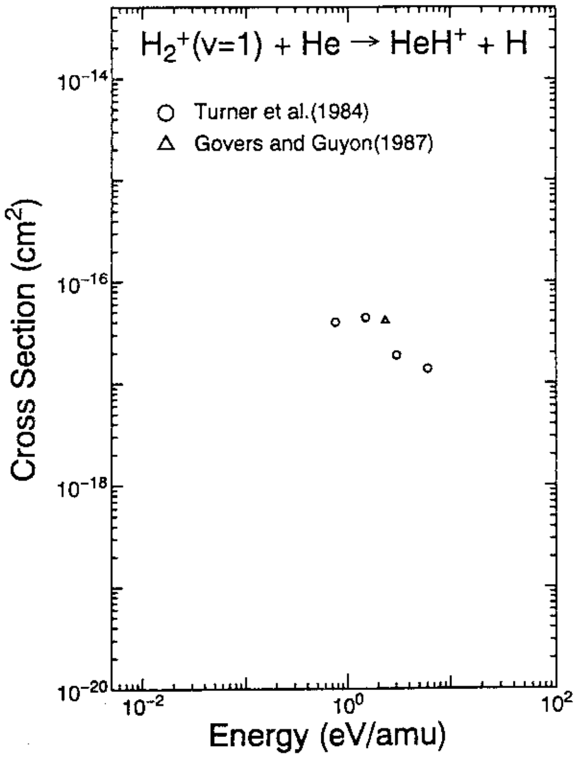

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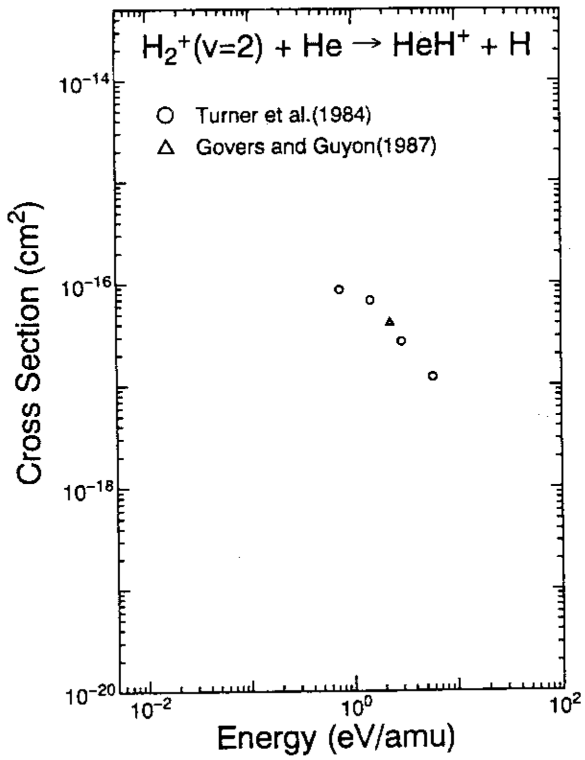

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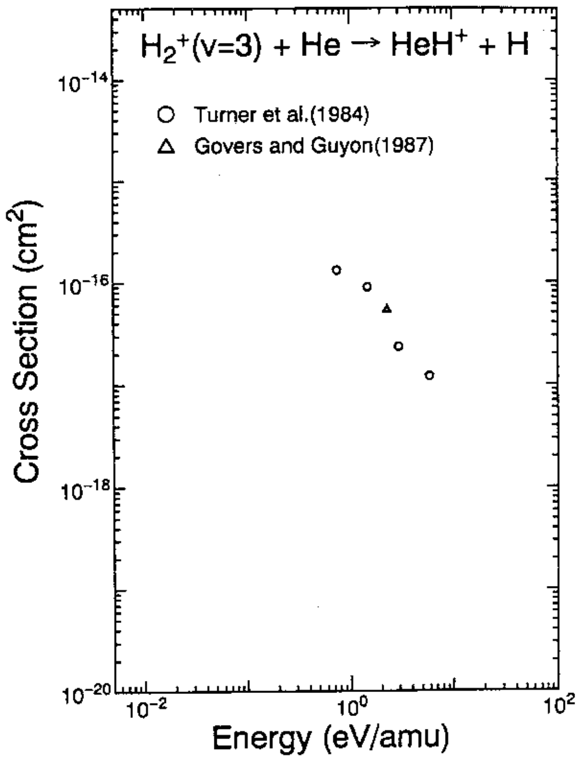

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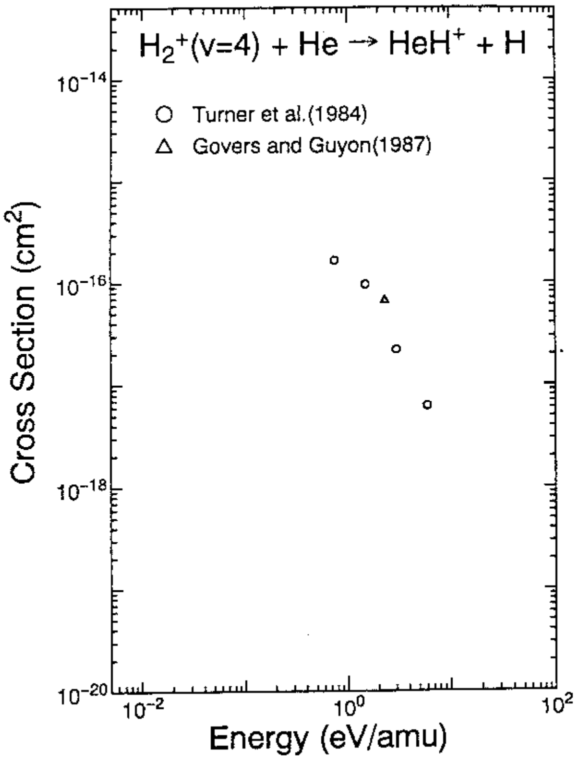

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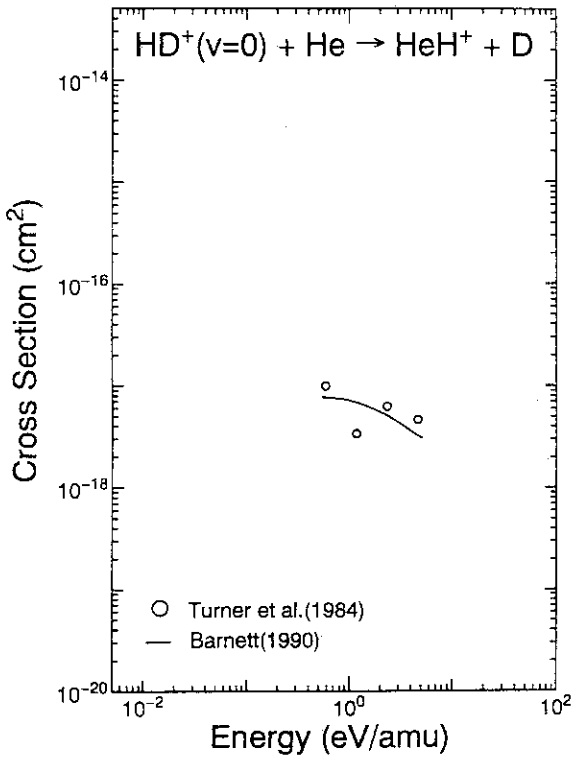

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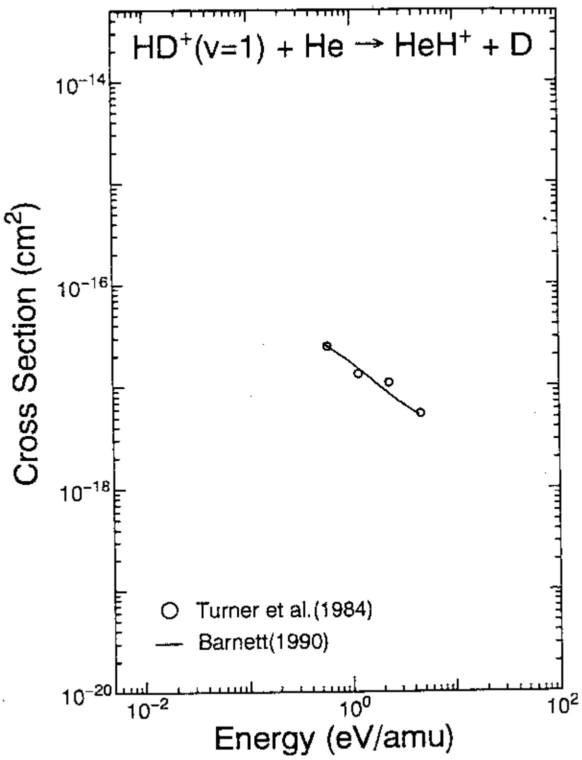

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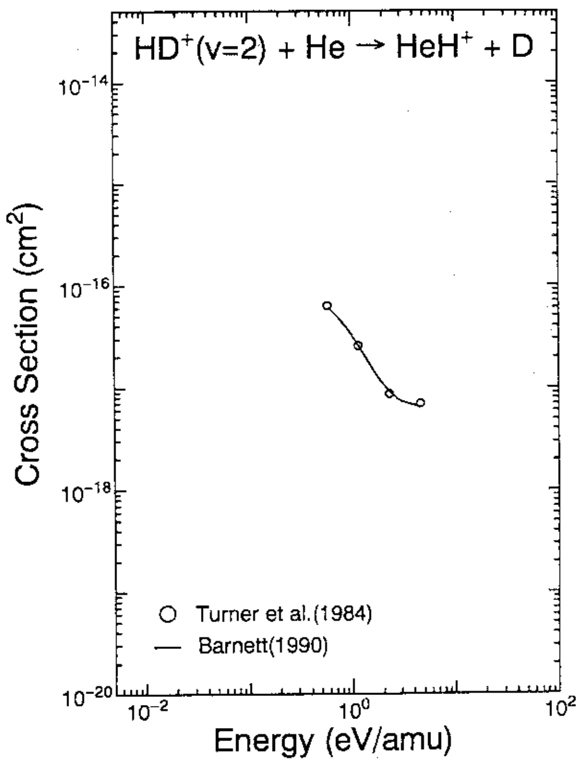

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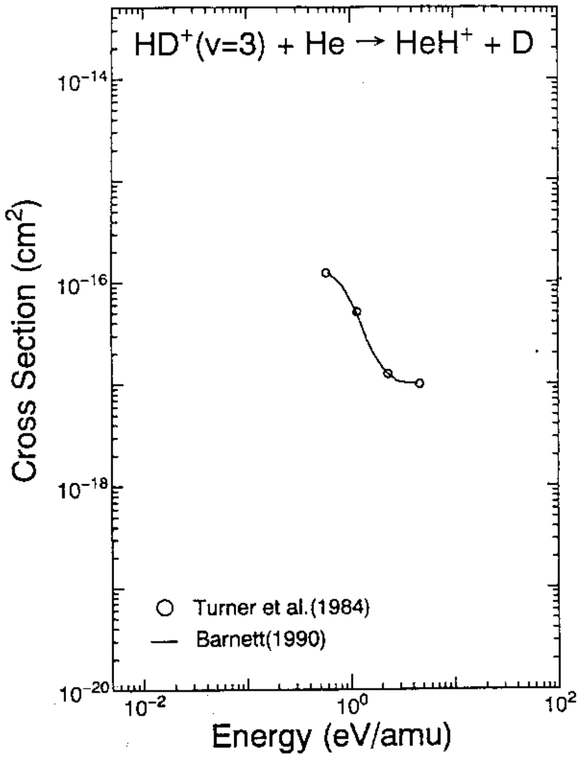

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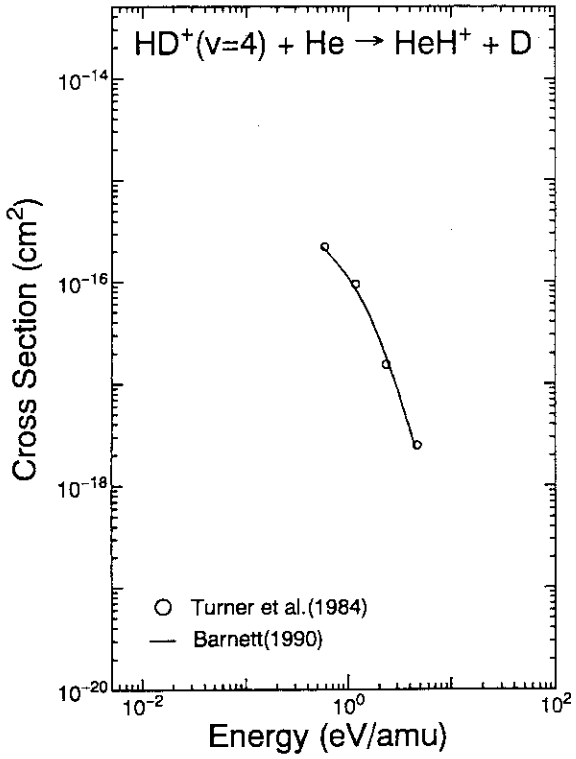

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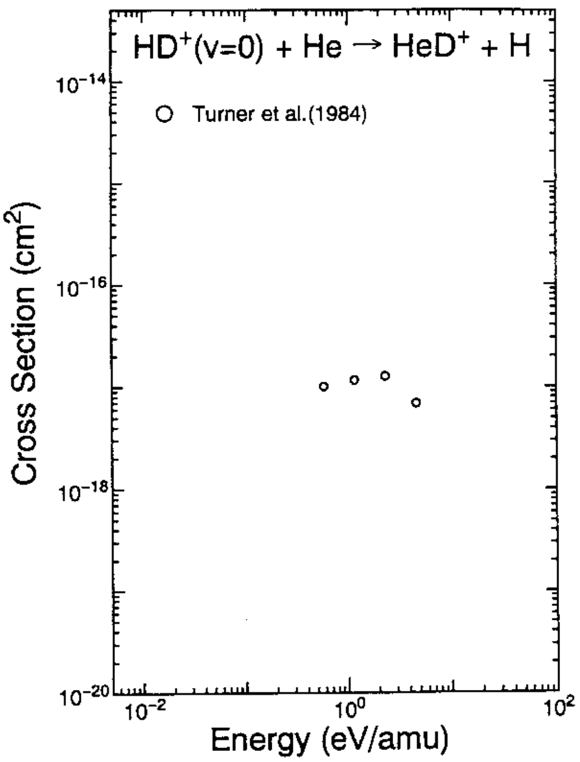

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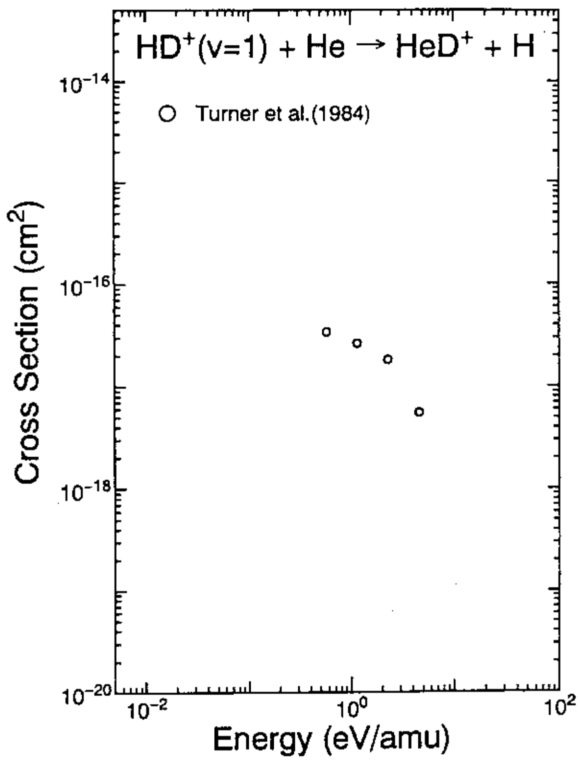

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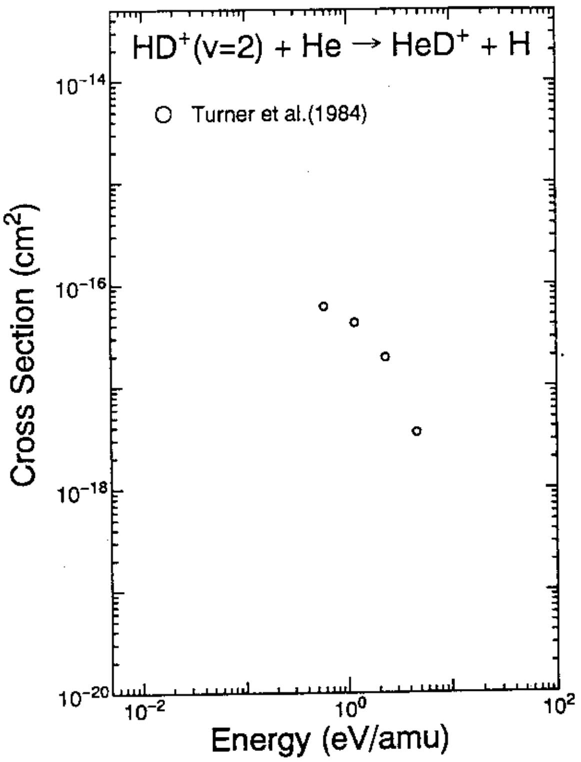

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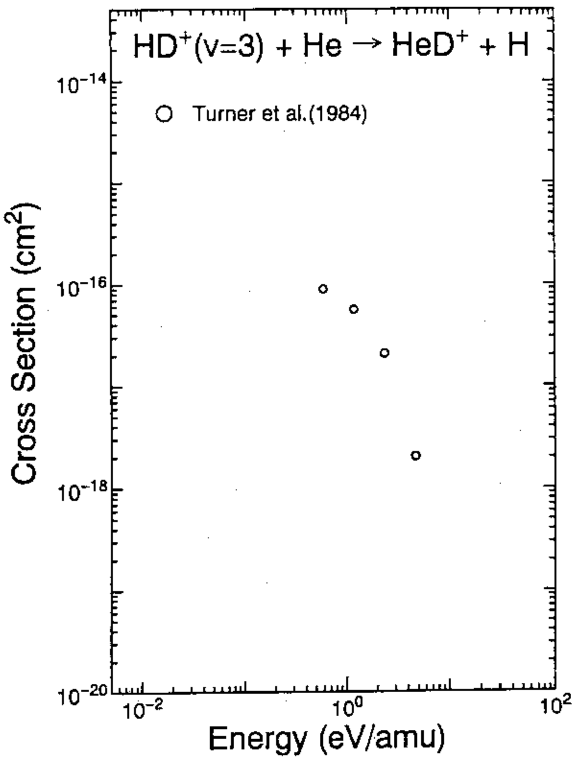

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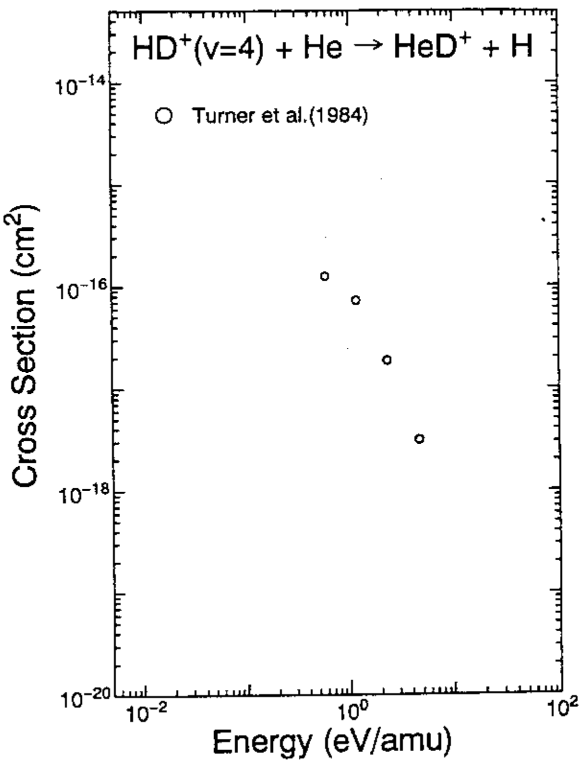

3. Brief Comments on Cross-Section Measurements

The measurements for total and state-selective cross sections are summarized in Tables I and II, respectively. Reaction systems, range of collision energies, experimental methods and range of absolute errors are listed with references.

For the measurements of total cross sections for ion-molecule reactions, widely used techniques are the tandem mass spectrometer (TMS) method and the guided beam (GB) technique. In the TMS method, a beam of mass-selected ions collides with a neutral target gas in a collision chamber, and the ionic products are analyzed in a second mass spectrometer. The GB technique was devised to overcome some disadvantages of the TMS method. A reduction of the number of excited ions in the primary beam and good definition of the kinetic energy are attained by the use of electric field to guide ions. Besides a collection and detection probability for the secondary ions approaches unity for all scattering angles in a broad energy band. Absolute measurement of total cross sections by means of the GB technique is considered to be more reliable than that by the TMS method.

In the merged beam (MB) technique, a fast beam of mass- and energy-selected neutral species, instead of a neutral gas in a collision chamber, is merged with a primary ion beam. This technique enables to determine total cross sections in a wide range of collision energies down to extremely low energies.

In the crossed beam (CB) technique, a target gas beam is crossed with a primary ion beam. The energy and angle distributions of the reaction products are measured using a rotatable detector with energy and mass analysis. It is now possible to carry out measurements down to energies of the order of 0.1 eV. However, absolute measurement is generally difficult, because it is not easy to determine collision volume accurately.

In most of the TMS experiments of total cross sections collected here, the primary ions are produced by electron impact. The beam may contain ions in excited states. In the MB experiments the neutral molecules are formed by means of electron transfer to corresponding ions produced by electron impact. The beam may contain molecules in excited vibrational and rotational states.

For the state-selective measurements collected here, reactants in a specific vibrational state are produced by photoionization of respective parent molecules.

3.1 Total Cross Sections

$$H^+ + D_2 \rightarrow HD^+ + D \text{ (Fig.1)}$$

Absolute cross section was measured by Maier[1] using a TMS apparatus. The values are estimated to be low by a factor of 4 or more, since a correction of secondary-ion-loss to the walls of the reaction chamber was not made. In the CB experiment of Krenos *et al.*[2], the collision volume (path length times number density) of the neutral gas beam was estimated by normalizing it to the experiment of Moran and Roberts[3] for the $H_2^+ + H_2 \rightarrow H_3^+ + H$ reaction. The number density for the D_2 beam was determined using an effusive flow relation. The total cross section was deduced from the measurement at 0° laboratory angle assuming that the angular distribution of the product ions for the $H^+ + D_2 \rightarrow HD^+ + D$ reaction is similar to that for the $H_2^+ + H_2 \rightarrow H_3^+ + H$ reaction. The absolute error of the total cross section is estimated to be a factor of 2 or 3. In the GB experiment of Ochs and Teloy[4], a good agreement with trajectory surface hopping calculation[4] is obtained. The estimated error of the absolute cross section is ±20%.

$$D^+ + H_2 \rightarrow HD^+ + H \text{ (Fig.2)}$$

The GB experiment was carried out by Schlier *et al.*[5] with an estimated error of ±10%.

$$D^+ + HD \rightarrow D_2^+ + H \text{ (Fig.3)}$$

In the CB experiment of Krenos *et al.*[2], total cross section was measured with an estimated error of a factor of 2 or 3.

$$H^- + HD \rightarrow H_2 + D^-,\ H^- + D_2 \rightarrow HD + D^-$$
$$D^- + H_2 \rightarrow HD + H^-,\ D^- + HD \rightarrow D_2 + H^- \text{ (Fig.4-7)}$$

Cross sections of these processes were measured by Michels and Paulson[6] using a TMS apparatus with an error of a factor of 2. Negative ions were produced by dissociative attachment of electron to NH_3 and H_2O. The energy spread of the reactant ion beam was 0.5 to 1.0 eV. The cross section for the $H^- + D_2 \rightarrow HD + D^-$ reaction was also measured by Zimmer and Linder[7] using a CB apparatus. The absolute value was determined by comparing the intensity of detected ions for the $H^- + D_2$ reaction with that for the elastic H^- + He scattering, whose absolute cross section is known both experimentally and theoretically. The estimated error is about 20% around the maximum of cross section and increases to about

30% at the higher energies. They determined the threshold energy of 0.42±0.06 eV, in contrast with about 1.3 eV in the TMS experiment[6]. The discrepancy between the CB and TMS cross sections below 3.0 eV is attributed to the transmission and collection efficiency problem of the TMS experiment.

$H_2^+ + D \rightarrow HD^+ + H$ (Fig.8)

The MB experiment was carried out by Wendell and Rol[8]. The D beam was formed by electron transfer to the D^+ ions produced in the arc source. The absolute values were determined by comparing the HD^+ count rate with the count rate of NaO^+ in the measurement of the $O_2^+ + Na \rightarrow NaO^+ + O$ reaction[9], the absolute cross section of which is known. They assumed that the collection efficiency of the HD^+ ion was the same as of the NaO^+ ion. The error of their measurement is estimated to be about ±60%.

$H_2^+ + H_2 \rightarrow H_3^+ + H$ (Fig.9)

In the TMS experiment of Giese and Maier[10], the primary ion energy was determined with an error of 0.1 eV, and the absolute cross section was measured with an estimated error of ±40%. Neynaber and Trujillo[11] measured the cross section using a MB apparatus. The H_2 beam was formed by electron transfer to the H_2^+ ion produced by electron impact. The absolute measurement was carried out at 1.0 eV and the cross section of 12×10^{-16} cm^2 was obtained with an estimated error of −26 to +37%. The normalization of relative cross sections was made with this absolute value. The error of the relative cross section is estimated to be −11% to +6% at 0.1 eV, and the standard deviation is about ±18% at 3 eV. A similar MB measurement was carried out by Gentry *et al.*[12]. They determined the absolute cross section of 12.91×10^{-16} cm^2 at 1.0 eV with an estimated standard deviation of 4.2%. Both the MB measurements agree well with each other. Specht *et al.*[13] measured the cross section using a beam−gas−mass−analysis apparatus. Their result is more than a factor of 3 larger than the MB measurements[11,12]. In the measurement of Specht *et al.* the H_2^+ ions were formed from the H_2 molecules by the impact of metastable He^* atoms. In parallel with this reaction electronically excited neutrals H^* and H_2^* were produced by the $He^* + H_2 \rightarrow H^* + H + He$ and $He^* + H_2 \rightarrow H_2^* + He$ reactions, respectively. The discrepancy is attributed that both reactions $H^* + H_2 \rightarrow H_3^+ + e$ and $H_2^* + H_2 \rightarrow H_3^+ + H + e$ are included in the experiment of Specht *et al.*

$$HD^+ + D_2 \rightarrow HD_2^+ + D,\ HD^+ + D_2 \rightarrow D_3^+ + H$$
$$D_2^+ + HD \rightarrow HD_2^+ + D,\ D_2^+ + HD \rightarrow D_3^+ + H \text{ (Figs.10–13)}$$

Cross sections for these reactions were measured by Douglass *et al.*[14] using a MB apparatus. The neutral D_2 and HD beams were obtained by electron transfer to the D_2^+ and HD^+ ions, after these D_2^+ and HD^+ ions were produced by electron impact. The absolute measurement was carried out at 0.1 eV and the relative cross sections were normalized to it. The errors of the absolute cross sections for the $HD^+ + D_2 \rightarrow HD_2^+ + D$ and the $HD^+ + D_2 \rightarrow D_3 + H$ reactions are estimated to be about 15%, and those for the $D_2^+ + HD \rightarrow HD_2^+ + D$ and $D_2^+ + HD \rightarrow D_3^+ + H$ reactions to be about 30%.

$$H_3^+ + D_2 \rightarrow HD_2^+ + H_2 \text{ (Fig.14)}$$

The MB experiment was performed by Douglass *et al.*[15]. The D_2 beam was formed from the parent D_2^+ ions through electron transfer. The absolute cross section was determined at 1.0 eV and the relative cross sections were normalized to it. The error of the absolute cross sections is estimated to be about 13%.

$$H_2^+ + He \rightarrow HeH^+ + H \text{ (Fig.15)}$$

In the TMS experiment of Giese and Maier[10], the primary ion energy was determined with an error of 0.1 eV, and the absolute cross section was measured with an estimated error of ±40%. In the CB experiment of Rutherford and Vroom[16], the neutral beam density was determined by using laws for effusion and the absolute cross section was measured with estimated errors of ±20% at high impact energies and of ±30% at the lowest energy. In the MB experiment of Neynaber and Magnuson[17], the absolute cross section of 2.3×10^{-16} cm^2 at 1.0 eV was obtained with an estimated error of +47% to −40%. The normalization of the relative cross sections was made with this absolute value. The errors of the relative cross sections are about ±15% for $E \leq 5$ eV and about ±20% for $E > 5$ eV.

$$He^+ + H_2 \rightarrow HeH^+ + H,\ He^+ + HD \rightarrow HeH^+ + D$$
$$He^+ + HD \rightarrow HeD^+ + H,\ He^+ + D_2 \rightarrow HeD^+ + D \text{ (Figs.16–19)}$$

The cross section measurement was carried out by Ervin and Armentrout[18] for those reactions using a GB apparatus with an estimated error of a factor of 2. The He^+ ions were produced by electron impact ionization with electron energies below the threshold for formation of metastable Rydberg states. Jones *et al.*[19] measured the relative cross sections for the $He^+ + H_2 \rightarrow HeH^+ + H$ and $He^+ + D_2 \rightarrow HeD^+ + D$ reactions using a TMS apparatus. Their cross sections were normalized at each peak to the GB measurement of Ervin and Armentrout[18].

$$HeH^+ + H \rightarrow H_2^+ + He \text{ (Fig.20)}$$

In the CB experiment of Rutherford and Vroom[16], the absolute cross section was measured with estimated errors of ±20% at high impact energies and of ±30% at the lowest energy.

$$HeH^+ + H_2 \rightarrow H_3^+ + He \text{ (Fig.21)}$$

The CB measurement was carried out by Rutherford and Vroom[20]. The neutral beam density was determined using laws for effusion. The maximum error of the absolute cross section is estimated to be ±20% at high impact energies and ±30% at the lowest collision energy.

3.2 State-Selective Cross Sections

$$H_2^+(v=0-4) + H_2 \rightarrow H_3^+ + H \text{ (Figs.22-26)}$$

Cross sections were measured by Koyano and Tanaka[21] with a threshold electron-secondary ion coincidence (TESICO)-BG apparatus. The relative cross sections were converted to the absolute values using the thermal rate constant of Theard and Huntress[22] in the case of v=0 at the room temperature ($k(v=0)=2.5 \times 10^{-9}$ cm^3 s^{-1}, corresponding to the cross section of 92×10^{-16} cm^2 at average collision energy of 0.033 eV). Shao and Ng[23] measured the absolute cross sections with a state-selective photoionization (SSPI)-GB apparatus. The error of the collision energy is estimated to be 0.1 eV. The standard deviations of the relative cross sections for v=0-4 are ≤10% and ≤20% at E=1-5 eV and 6-15 eV, respectively. Pollard *et al.*[24] measured the relative cross section using a resonantly enhanced multi-photon ionization (REMPI)-CB apparatus. The absolute values were determined with the results of Shao and Ng[23]. The error of the collision energy is estimated to be ±0.10 eV. A good agreement is obtained among the cross sections in these three measurements.

$$H_2^+(v=0-4) + D_2 \rightarrow HD_2^+ + H,\ D_2^+(v=0-4) + H_2 \rightarrow HD_2^+ + H$$

(Figs.27-36)

Anderson *et al.*[25] measured the absolute cross sections for these reaction systems using a SSPI-GB apparatus with an estimated error of ±25%.

$$H_2^+(v=0-4) + He \rightarrow HeH^+ + H,\ HD^+(v=0-4) + He \rightarrow HeH^+ + D$$

$$HD^+(v=0-4) + He \rightarrow HeD^+ + H$$ (Figs.37-51)

Cross sections for these reactions were measured by Turner *et al.*[26] using a SSPI-GB apparatus. Govers and Guyon[27] measured the cross sections for the $H_2^+(v=0-6) + He \rightarrow HeH^+ + H$ reactions with a threshold photo-electron photo-ion coincidence (TPEPICO)-CB apparatus. Their measurement was made at the energy of 3.1 eV, and the relative cross sections were normalized to the values of Chupka *et al.*[28,29]. The estimated error of the cross sections is about ±25%.

Table I. Measurements of Total Particle-Rearrangement Cross Sections

Reaction	Collision energy[a]	Method[b]	Absolute error	Reference
$H^+ + D_2 \rightarrow HD^+ + D$	1.3 -100	TMS	factor of 4	1
	2.9 - 9.4	CB	factor of 2–3	2
	2.5 - 15	GB	±20%	4
$D^+ + H_2 \rightarrow HD^+ + H$	0. - 9	GB	±10%	5
$D^+ + HD \rightarrow D_2^+ + H$	1.7 - 4.8	CB	factor of 2–3	2
$H^- + HD \rightarrow H_2 + D^-$	0.7 - 13	TMS	factor of 2	6
$H^- + D_2 \rightarrow HD + D^-$	0.6 - 13	TMS	factor of 2	6
	0.4 - 4	CB	±30%	7
$D^- + H_2 \rightarrow HD + H^-$	0.5 - 10	TMS	factor of 2	6
$D^- + HD \rightarrow D_2 + H^-$	0.4 - 8	TMS	factor of 2	6
$H_2^+ + D \rightarrow HD^+ + H$	0.05 - 5	MB	±60%	8
$H_2^+ + H_2 \rightarrow H_3^+ + H$	0.3 - 5	TMS	±40%	10
	0.1 - 5	MB	−26% to 37% at 1eV	11
	0.01 - 7	MB	−2.2 to 1.8%	12
	0.2 - 3			13
$HD^+ + D_2 \rightarrow HD_2^+ + D$	0.006- 4.7	MB	±15%	14
$HD^+ + D_2 \rightarrow D_3^+ + H$	0.006- 4.7	MB	±15%	14
$D_2^+ + HD \rightarrow HD_2^+ + D$	0.006- 4.7	MB	±30%	14
$D_2^+ + HD \rightarrow D_3^+ + H$	0.006- 4.7	MB	±30%	14
$H_3^+ + D_2 \rightarrow HD_2^+ + H_2$	0.006- 6.4	MB	±13%	15
$H_2^+ + He \rightarrow HeH^+ + H$	0.53 - 2.3	TMS	±40%	10
	0.5 - 10.5	CB	±30%	16
	0.04 - 9	MB	−40 to 47% at 1 eV	17
$He^+ + H_2 \rightarrow HeH^+ + H$	0.08 - 37	GB	factor of 2	18
	0.08 - 23	TMS		19
$He^+ + HD \rightarrow HeH^+ + D$	0.06 - 29	GB	factor of 2	18
$He^+ + HD \rightarrow HeD^+ + H$	0.06 - 29	GB	factor of 2	18
$He^+ + D_2 \rightarrow HeD^+ + D$	0.05 - 25	GB	factor of 2	18
	0.05 - 13	TMS		19
$HeH^+ + H \rightarrow H_2^+ + He$	0.24 - 4.8	CB	±30%	16
$HeH^+ + H_2 \rightarrow H_3^+ + He$	0.21 - 4.2	CB	±30%	20

a) Relative collision energy is given in eV/amu.

b) Abbreviations are defined as follows:

TMS – tandem mass spectrometer (beam–gas)
CB – crossed beam
GB – guided beam
MB – merged beam

Table II. Measurements of State-Selective Particle-Rearrangement Cross Sections

Reaction	Collision energy[a]	Method[b]	Absolute error	Reference
H_2^+(v=0–3) + H_2				
→ H_3^+ + H	0.11 - 0.93	TESICO-BG		21
(v=0–4)	0.04 - 15	SSPI-GB	±20%	23
(v=0–2)	1.5 - 5.3	REMPI-CB		24
H_2^+(v=0–4)+ D_2				
→ HD_2^+ + H	0.17 - 4.6	SSPI-GB	±25%	25
D_2^+(v=0–4)+ H_2				
→ HD_2^+ + H	0.17 - 4.6	SSPI-GB	±25%	25
H_2^+(v=0–4)+ He				
→ HeH^+ + H	0.75 - 6	SSPI-GB		26
(v=0–6)	2.3	TPEPICO-CB	±25%	27
HD^+(v=0–4)+ He				
→ HeH^+ + D	0.6 - 4.7	SSPI-GB		26
HD^+(v=0–4)+ He				
→ HeD^+ + H	0.6 - 4.7	SSPI-GB		26

a) Relative collision energy is given in eV/amu.

b) Abbreviations are defined as follows:

TESICO – threshold electron–secondary ion coincidence
SSPI – state selective photoionization
REMPI – resonantly enhanced multi–photon ionization
TPEPICO – threshold photo–electron photo–ion coincidence
BG – beam gas
GB – guided beam
CB – crossed beam

4. Analytical Fits

Empirical analytical fits were carried out by Gentry *et al.*[12] and Douglass *et al.*[14,15] to their experimental cross sections. The analytical formula is expressed as

$$\log_{10}\sigma = (b_1+b_2\log_{10}E_0)F(-y)+(b_3+b_4\log_{10}E_0)F(y), \qquad (1)$$

$$F(y)=e^y/(1+e^y),$$

with $y=(\log_{10}E_0-b_5)b_6^2$ and $E_0=b_0E$,

where σ is the cross section in 10^{-16} cm^2 and E the collision energy in eV/amu. In Table III fit parameters $\{b_i\}$ to be used with Eq.(1) are presented.

Table III. Fit Parameters for Cross Sections

Reaction	b_0	b_1	b_2	b_3	b_4	b_5	b_6
$H_2^+ + H_2 \rightarrow H_3^+ + H$ [a]	1.0	1.07254	-.5	1.43575	-4.41373	.83887	1.5410
$HD^+ + D_2 \rightarrow HD_2^+ + D$ [b]	1.714	1.2438	-.4146	-1.6950	-8.1470	1.4972	1.5638
$HD^+ + D_2 \rightarrow D_3^+ + H$ [b]	1.714	.7703	-.5242	-.2259	-2.8924	.8912	1.6515
$D_2^+ + HD \rightarrow HD_2^+ + D$ [b]	1.714	1.0719	-.4249	1.0529	-6.1341	1.1622	1.4880
$D_2^+ + HD \rightarrow D_3^+ + H$ [b]	1.714	.6294	-.5232	-.0260	-2.1136	.5060	1.7555
$H_3^+ + D_2 \rightarrow HD_2^+ + H_2$ [c]	1.714	.99985	-.56766	3.46514	-5.20255	.86080	1.9482

a) Reference 12.

b) Reference 14.

c) Reference 15.

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