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Total and Partial Cross Sections of Electron Transfer Processes for Be^{q+} and B^{q+} Ions in Collisions with H, H_2 and He Gas Targets
– Status in 1991 –

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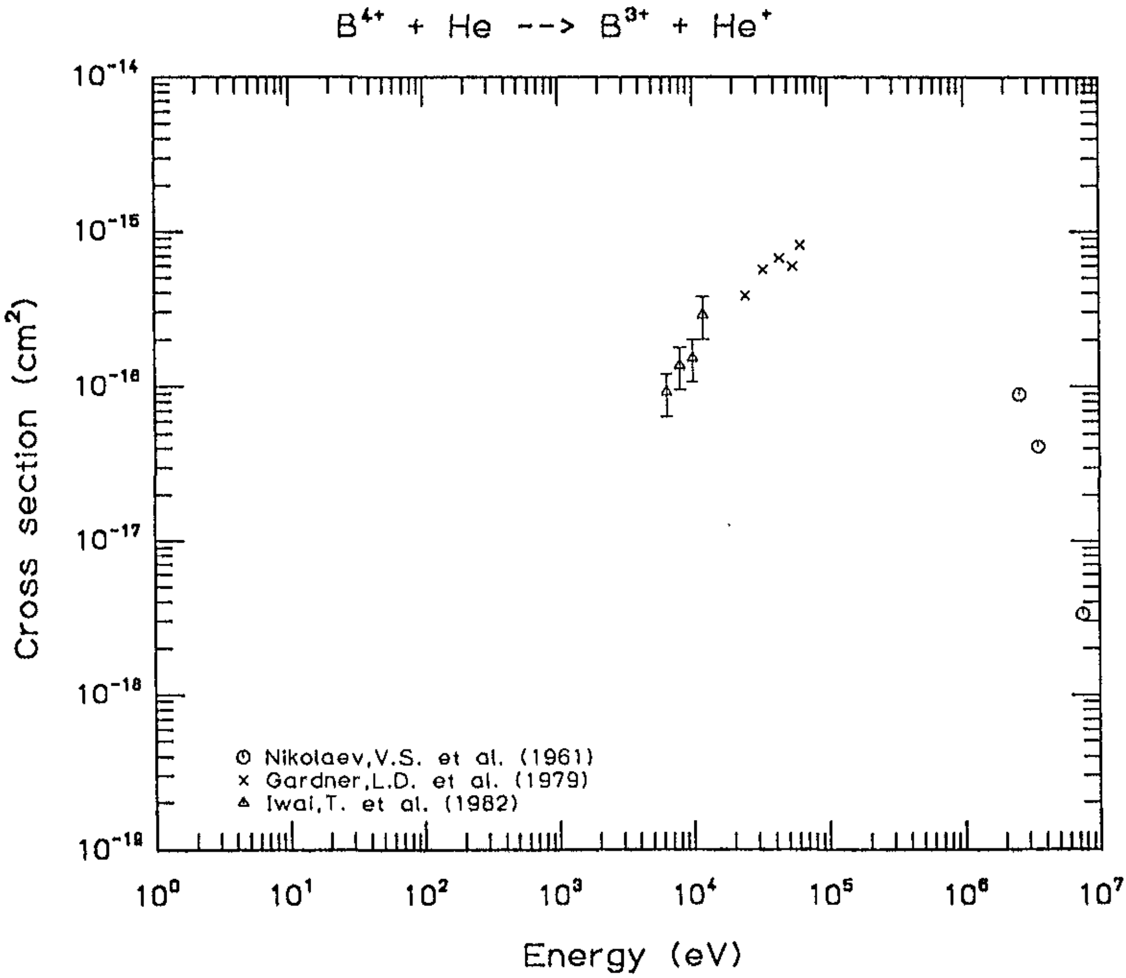

Total and partial cross sections of electron transfer processes for Be^{q+} and B^{q+} ions in collisions with H, H_2 and He gas targets -status in 1991-

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Abstract

A review is given on data of total and partial cross sections of electron transfer for Be^{q+} and B^{q+} ions in collisions with the important constituent targets in plasma devices such as H, H_2 and He. A short comment on electron transfer data in relation to recent observations of photons from Be^{q+} ions at JET tokamak is also given.

Keywords: charge trnasfer, n-ℓ distribusion, plasma, Be^{q+}, B^{q+}, H, H_2, He,

1. Introduction

Very recently Be and B have been experimentally confirmed to be most promising materials for the plasma-facing inner-wall of the plasma devices as they are of low-Z and thus could reduce significantly the radiation loss from high temperature plasmas and also as they could enhance their stabilities.

To optically diagnose such high temperature plasmas in fusion devices, data are needed of electron transfer cross sections involving these highly ionized ions of the wall materials under the operating conditions of the devices such as neutral beam injection.

In this report we try to summarize the present status of the data for the following electron transfer processes of these ions with different charge under collisions with the most common constituents in plasma devices, namely H, H_2 and He :

$$Be^{q+} + H\ (H_2,\ He) \rightarrow Be^{(q-1)+}(nl) + H^+\ (H_2^+,\ He^+) \qquad (1)$$

$$B^{q+} + H\ (H_2,\ He) \rightarrow B^{(q-1)+}(nl) + H^+\ (H_2^+,\ He^+) \qquad (2)$$

where q ranges from 1 to Z, the atomic number of the ions, and (nl) the principal and azimuthal quantum number, respectively. It is also known that, in two electron targets (H_2 and He), two electron transfer processes might occur generally with much lower probabilities, compared with the single electron transfer processes mentioned above. At higher energies the ionization processes without any electron transfer come into play a role but are not treated here. Some related data for total cross sections for electron transfer processes of various ions have been already compiled for H and H_2 as well as for He.[1,2] As found in the following list of references at the end of the paper, the data presently available for Be^{q+} and B^{q+} ions are very limited. Experimental data are available only for total cross sections. In particular, even total cross section data for Be ions are very scarce. Indeed no single experimental data have been reported for partial cross sections closely related with the optical transitions applicable to plasma diagnostics and at the moment we have to rely upon the theoretical calculations of partial cross sections for electron transfer of these ions.

Table 1 summarizes the present situation of such data, theoretical as well as experimental, for Be^{q+} and B^{q+} ions in collisions with H, H_2 and He targets.

Table 1 Status for electron transfer data of Be^{q+} and B^{q+} ions in collisions with H, H_2 and He targets

	q	H	H_2	He
Be	1			
	2	t	T^*	
	3	p	T^*	t T
	4	p	T^*	t T
B	1	T	T	T^*
	2	T	T	T
	3	t T	T	p T
	4	T	T	T
	5	p T	T	t T^*

Note

1) T indicates experimental data for total cross sections available.
2) T^* indicates very few data available.
3) p and t indicate theoretical partial and total cross sections available.
4) Blank spaces indicate no data available.
5) No experimental data are available for partial cross section at all up to now !

2. General features of electron transfer cross sections for Be^{q+} and B^{q+} ions

2.1. Total cross sections

It is well known[4,5] that total cross sections for electron transfer of ions with low atomic number decrease drastically as the collision energy decreases below low keV region down to 10 eV/amu. This is because only a few electronic states of the incident ions are available for the transferring electron from target. Indeed for most of both Be^{q+} and B^{q+} ions in collisions with targets of few electrons such as H, He, the total cross sections decrease sharply at the eV/amu region. This is in contrast to highly charged ions with higher atomic number such as Ne^{q+} or Ar^{q+} ions, where the electron transfer cross sections are usually large and constant up to a few 10 keV/amu, roughly independent of the collision energy, because a large number of the electronic excited states are available for an electron to be transferred from target atoms into the incident ions.

2.2. n-distributions

Theoretical calculations of total cross sections are generally in good agreement with each other but sometimes partial cross sections, not only l-distributions but even n-distributions, disagree significantly with each other. For example, theoretical total cross sections for B^{5+} + H collisions by Ryufuku,[6] Fritsch and Lin[7] and Bendahman et al.[8] indeed agree with each other within 10-20 % in the overlapped energy range but, as shown in **Fig.1**, the calculated results of n-distributions by Fritsch and Lin show the dominance at n=4 by a factor of 10 over that at n=3 at low energies (< 1 keV/amu) and still by a factor of two at 10-20 keV/amu which seems to be in good agreement with those by Bendahman et al. However, the calculations by Ryufuku indicate the intensities for n=3 and n=4 are comparable over the energy range 10-200 keV/amu. On the other hand, two calculations by Fyufuku and Fritsch and Lin for the n-distributions in Be^{4+} ions in collisions with H atoms are in good agreement with each other, as seen in **Fig.1**.

It is clear that the n-distributions for both Be^{4+} and B^{5+} ions become less selective at high energies (100 keV/amu), as expected.

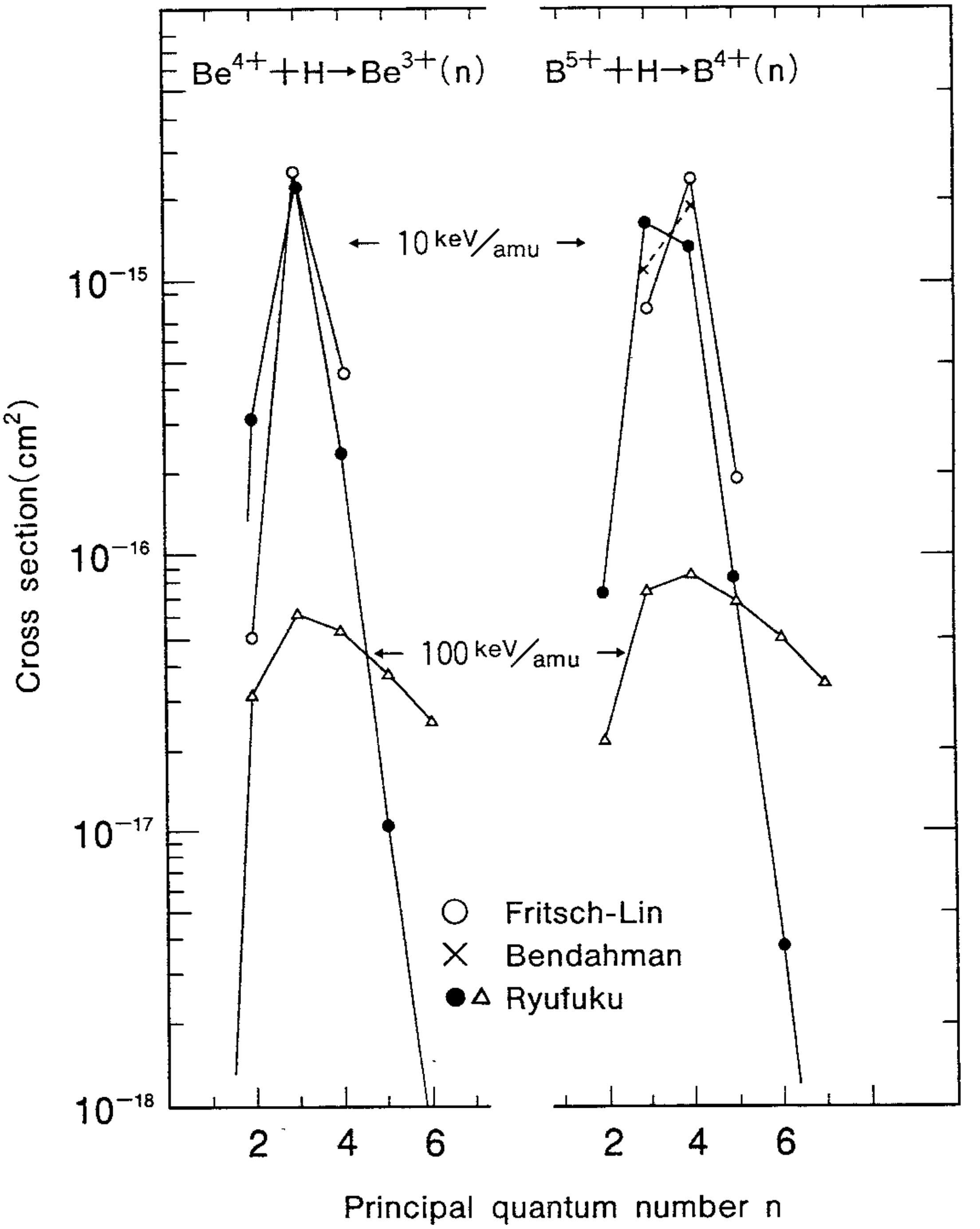

Fig.1 Comparison of n-distributions calculated by Ryufuku[6], Fritsch and Lin[7] and Bendahman et al.[8] for Be^{4+} + H and B^{5+} + H collisions

3. Some remarks on recent observation of Be^{q+} ion lines at JET

Though experiments on electron transfer involving Be^{q+} and B^{q+} ions are limited, recent observations of photons from Be ions at JET tokamak[9)] is very interesting in relation to the investigations of electron transfer processes. The most dominant state for electron transfer to $Be^{3+}(1s)$ ions from the ground state $H(n_0=1)$ target is calculated to be n=2 by Shimakura[10)] based upon molecular orbital expansion method :

$$Be^{3+}(1s) + H(n_0=1s) \rightarrow Be^{2+}(1s2l) + H^+. \qquad (3)$$

Indeed, as seen in **Fig.2** in the observations of a limiter region at JET, the line at 100.26 A˚ corresponding to $Be^{2+}(1s2p)\ ^1P$ state electron-captured into $Be^{3+}(1s)$ ions is found to be the most intense and the photon intensities from $Be^{2+}(1snp)$ ions are found to decrease with increasing n, indicating that most of atomic hydrogens in the region are in the ground state. On the other hand, a spectrum observed at the inner-wall shows another enhancement of the intensity of photons at n=5 corresponding to $Be^{2+}(1s5p)$ state. This enhancement is understood from the fact that the following collision due to the presence of the metastable atomic hydrogens in $n_0=2$ state, $H(n_0=2)$, results in the most dominant electronic state at n=5 (see below) :

$$Be^{3+}(1s) + H(n_0=2) \rightarrow Be^{2+}(1s5l) + H^+, \qquad (4)$$

suggesting that a plenty of atomic hydrogens near the inner-wall might be in higher excited states. This enhancement is understood to be due to the fact that the cross sections estimated for $H(n_0=2)$ atoms are larger than those for $H(n_0=1)$ atoms, in particular at low energies, and show weak energy dependence (see later discussion).

Similar singular structures in photon spectrum from $Ar^{16+}(1snl)$ ions have been previously observed in Alcator tokamak by Rice et al.[11)] Such a shift of the most dominant state of electron transfer for atomic hydrogen targets in different electronic states has been discussed already and easily could be explained qualitatively through the classical over-barrier model. For example, this classical model predicts that in Be^{3+} + H(1s) collisions the most dominant state for electron transfer is n=2, meanwhile that in Be^{3+} + $H(n_0=2)$ collisions is n=5, as observed in JET experiments.

The following expression from the classical over-barrier model can be used to

$$Be^{3+}(1s) + H(n_0) \rightarrow Be^{2+}(1snl) + H^{+}$$

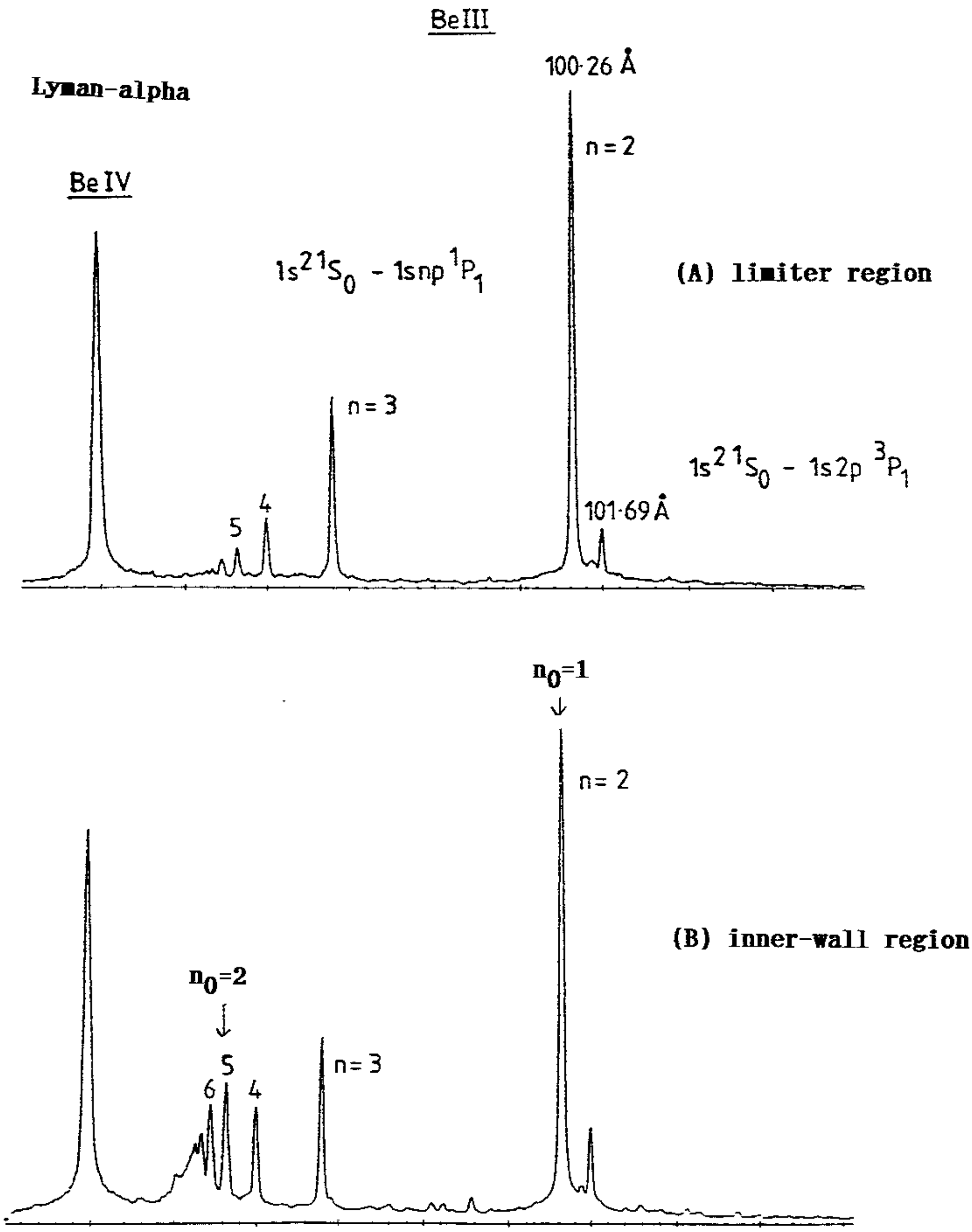

Fig.2 XUV spectra from $Be^{3+} + H \rightarrow Be^{2+} + H^{+}$ in JET plasmas. (A) plasmas contact with the outer limiter. (B) plasmas contact with the inner-wall. Note the enhancement of n=5 line in (B). Also note that plasmas were operated with deuterium (D_2) gas instead of hydrogen (H_2) gas.[9]

know the most dominant state n in electron transfer into the incident ions[12,13] :

$$[n] = (Z_1/Z_2)[\{Z_2 + 2*(Z_1*Z_2)^{1/2}\}/\{Z_1 + 2*(Z_1*Z_2)^{1/2}\}]^{1/2} \qquad (5)$$

where $Z_i = n_g(I_i/13.6)^{1/2}$ (i=1 and 2, corresponding to the incident ion and target atom, respectively) and I_i is the ionization potential of ions or atoms in eV and n_g is the principal quantum number of their ground state (for atomic hydrogens, $n_g = 1$).

It should be also pointed out that the cross sections of Be^{3+} ions for the ground state $H(n_0=1)$ targets are calculated by Shimakura to increase relatively sharply as the collision energy increases at low keV/amu energy region, meanwhile those for the excited state $H(n_0=2)$ targets are calculated by the classical over-barrier model to be about 100 $A^{\cdot 2}$, more than order of magnitude larger than those for $H(n_0=1)$, and might be nearly constant over the energy range of our interest.

Another important situation in JET observations is the need of data for the electron transfer into high n state of the ions which results in the emission of visible lights, much easier access to diagnostics. As seen in spectra of JET (**Fig.3**), the transition (n=6 -> n=5) at 4658.54 A˙ in Be^{3+}(1snl) ions resulting from bare Be^{4+} ions are clearly seen and found to be enhanced when the neutral beams are injected into plasmas for heating. The most theoretical calculations have shown that the cross sections for high n states decrease sharply with increasing n. For example, the cross sections into n=6 state for Be^{4+} ions in collisions with $H(n_0=1)$ targets are estimated to be smaller by three orders of magnitude than those for n=3 states at low energies which are calculated to be the most dominant (also see **Fig.1** shown above) :

$$Be^{4+} + H(n_0=1) \rightarrow Be^{3+}(3l) + H^{+}. \qquad (6)$$

Precise calculations of the cross sections for the electron transfer into such highly excited states, as performed by Ryufuku[6] and Fritsch and Lin,[7] need to include a large number of the basis set of the electronic states of ions. It is known that the calculated cross sections are very sensitive to the choice of the electronic states to be included, thus hindering to obtain precise values. Similarly the cross sections for B^{5+} ions in collisions with atomic hydrogens have been calculated by Fritsch and Lin[7] to be the largest for B^{4+}(n=4) up to 20 keV/amu energy region :

$$B^{5+} + H(n_0=1) \rightarrow B^{4+}(4l) + H^+, \quad (7)$$

with a small contribution of n=3 states.
If there are hydrogen atoms in the excited state, $H(n_0=2)$, the electron capture to B^{5+} ions is expected to occur dominantly into n=7 state of B^{4+} ions :

$$B^{5+} + H(n_0=2) \rightarrow B^{4+}(7l) + H^+. \quad (8)$$

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$$Be^{4+} + H \rightarrow Be^{3+}(nl) + H^{+}$$

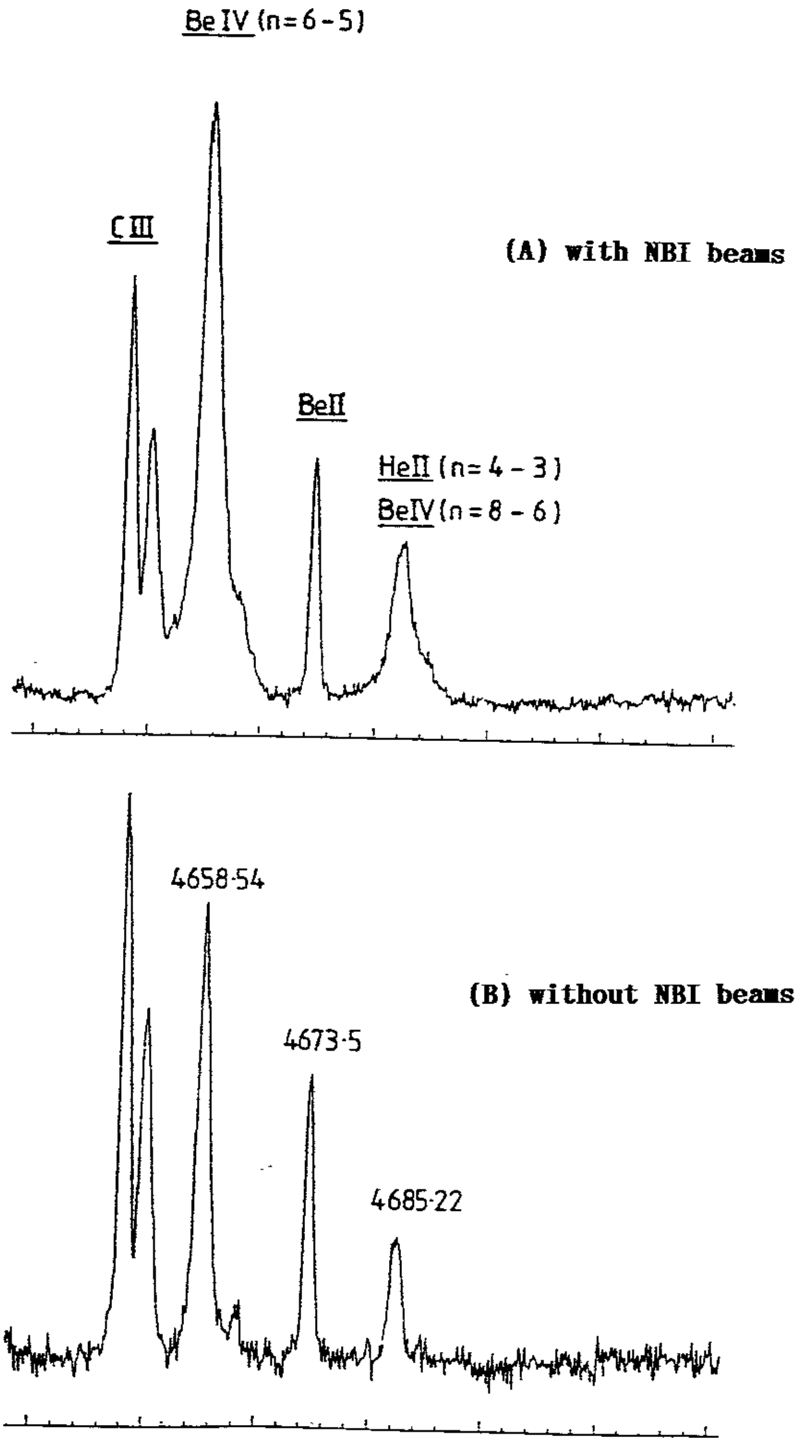

Fig.3 Visible spectra from JET. (A) with NBI heating beams. (B) without NBI heating beams. Note the enhancement of Be IV n=6->5 transition line at 4658.54 A˚ with NBI beams in (A).[9]

Urgent data needs

Looking into the discussion above and data available presently (shown in a series of figures in the next section), the following data for electron transfer into Be^{q+} and B^{q+} ions in collisions with H, H_2 and He targets have to be determined experimentally as well as theoretically :

1) confirmation of some calculated partial cross sections
2) more systematic measurements and calculations of total as well as partial cross sections for the ground state atomic hydrogens
3) similar cross sections for the excited state atomic hydrogen targets ($n \geq 1$)
4) measurements and calculations of the cross sections over a wide range of the collision energy up to a few 100 keV/amu

It should be noted that such data are necessary not only for highly charged (large-q) ions relevant to high temperature plasma region but also for relatively low charge (low-q) ions relevant to low temperature edge plasma region.

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Data for Be^{q+} and B^{q+} ions

A series of data related to total and partial cross sections presently available for Be^{q+} and B^{q+} ions are summarized in the following figures. In choosing data, our emphasis is kept on the partial cross sections as they are the most relevant to plasma diagnostics through photon observations. In most of theoretical references which are included in each section, only total cross sections have been given and a few of them are included here if they cover a wide range of the collision energy range where no experiment has been performed. The curves in total cross sections are based upon our empirical formula given in IPPJ-AM-15 (Institute of Plasma Physics, Nagoya University, 1980).

$Be^{q+} + H$

$Be^{+} + H$

Up to now no experimental and theoretical work has been reported yet.

Be^{2+} + H (Figs.4-7)

Only a single theoretical calculation for partial cross sections resulting into $Be^{+}(1s^{2}2s)$ and $Be^{+}(1s^{2}2p)$ has been reported by Wetmore et al. using the perturbed stationary state method, indicating that the capture into 2s state is dominant below 5 keV/amu and at 10 keV/amu the transfer into other states (possibly 31 states) becomes important. However, the Landau-Zener calculation for electron capture into 2s state by Bates and Moisewitsch and also the two state calculation by Bates et al. show quite different energy dependence, compared with those by Wetmore et al.

But no experimental data have been reported yet.

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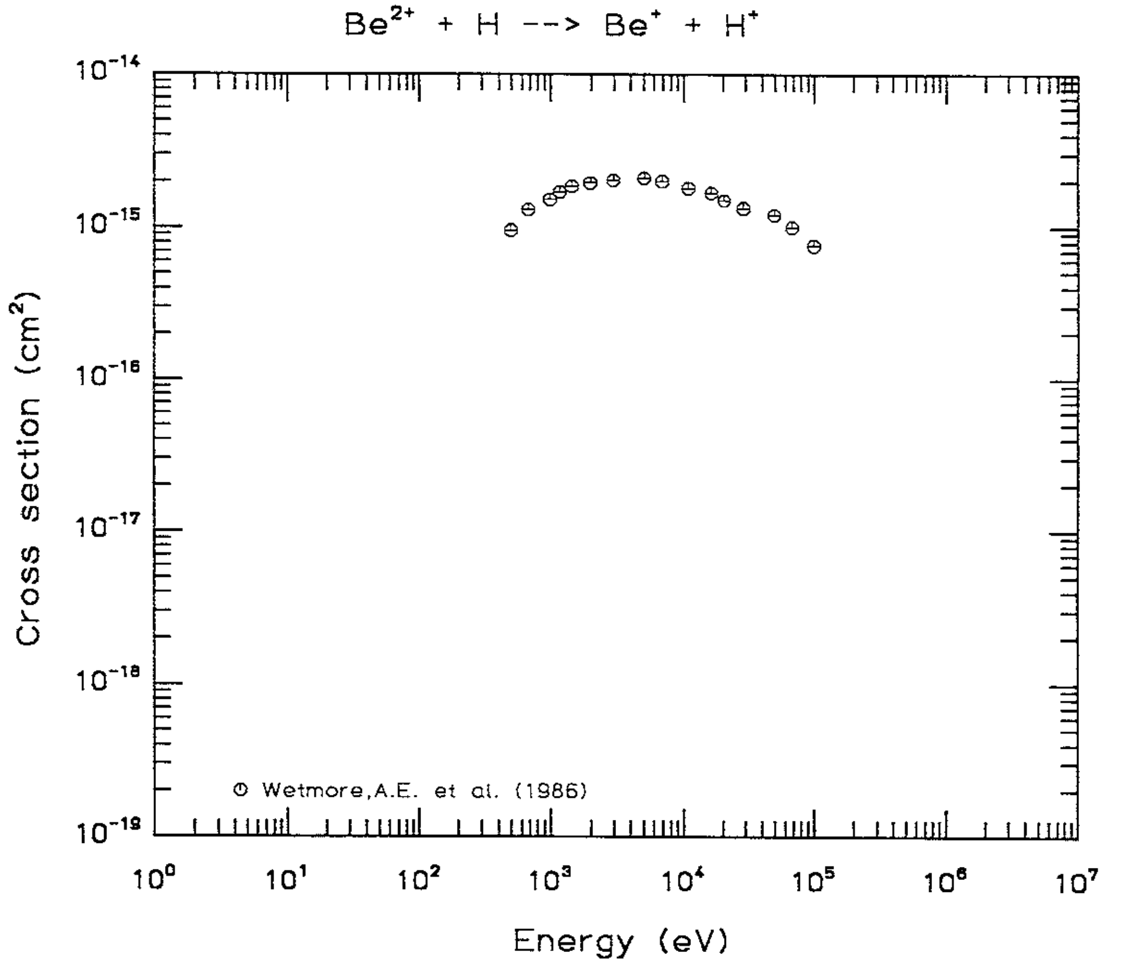

Fig.4 Partial cross sections into $Be^{+}(2s)$ in Be^{2+} + H collisions

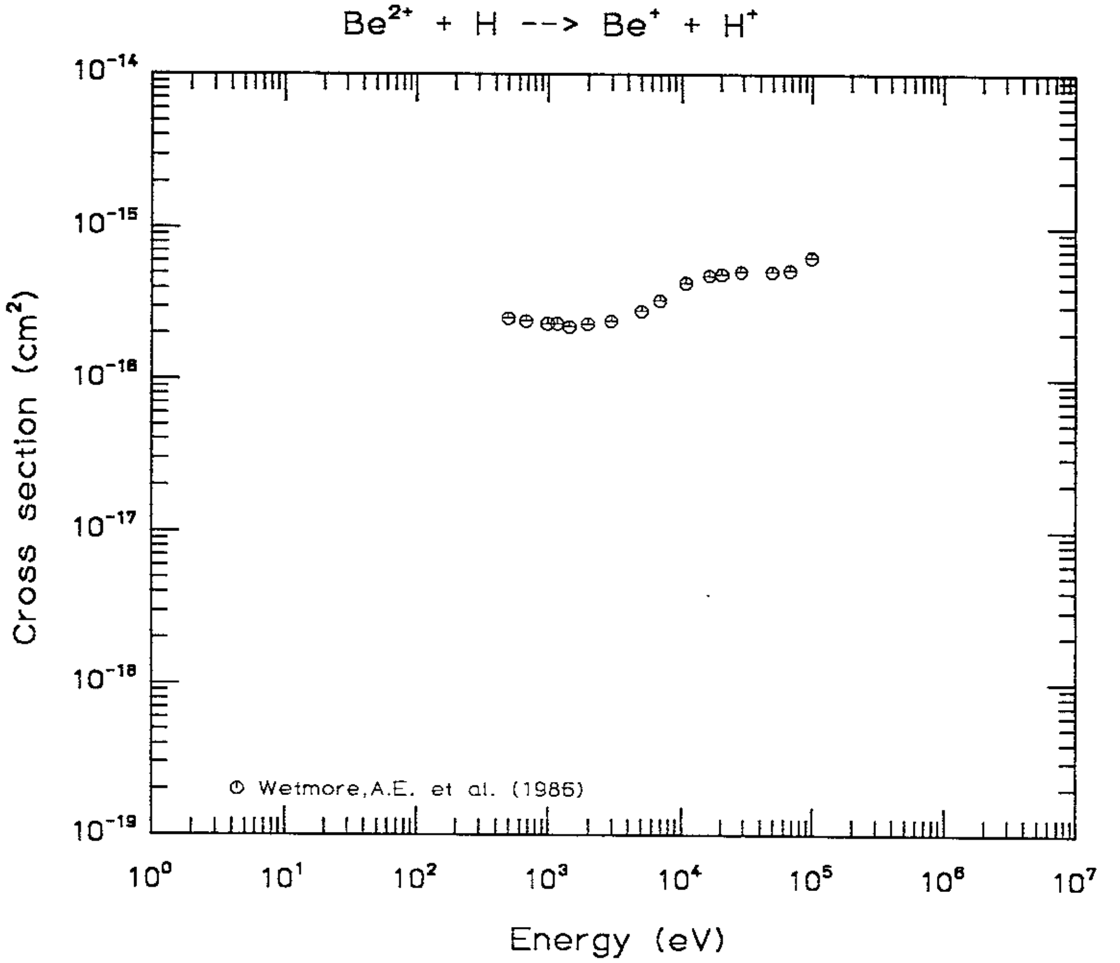

Fig.5 Partial cross sections into $Be^{+}(2p)$ in Be^{2+} + H collisions

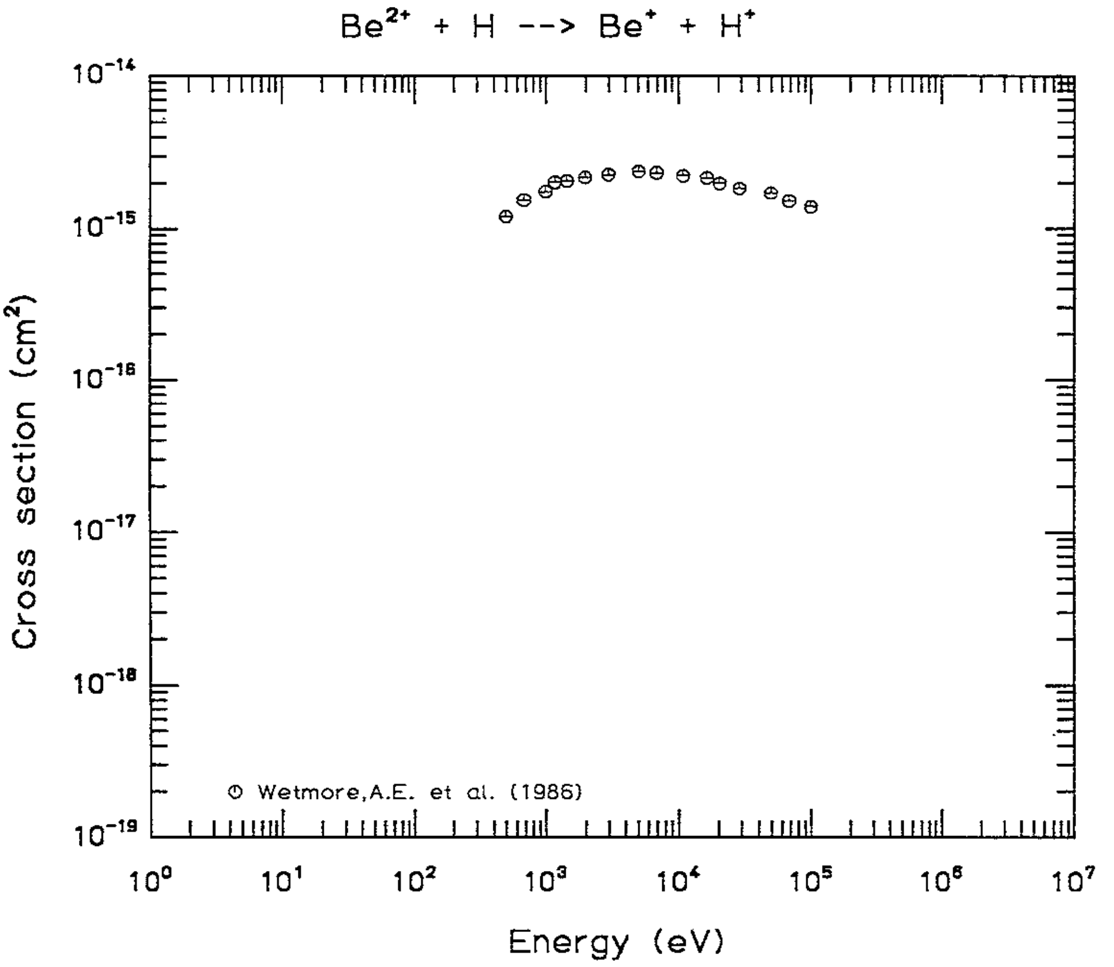

Fig.6 Partial cross sections into $Be^{+}(n=2)$ in Be^{2+} + H collisions

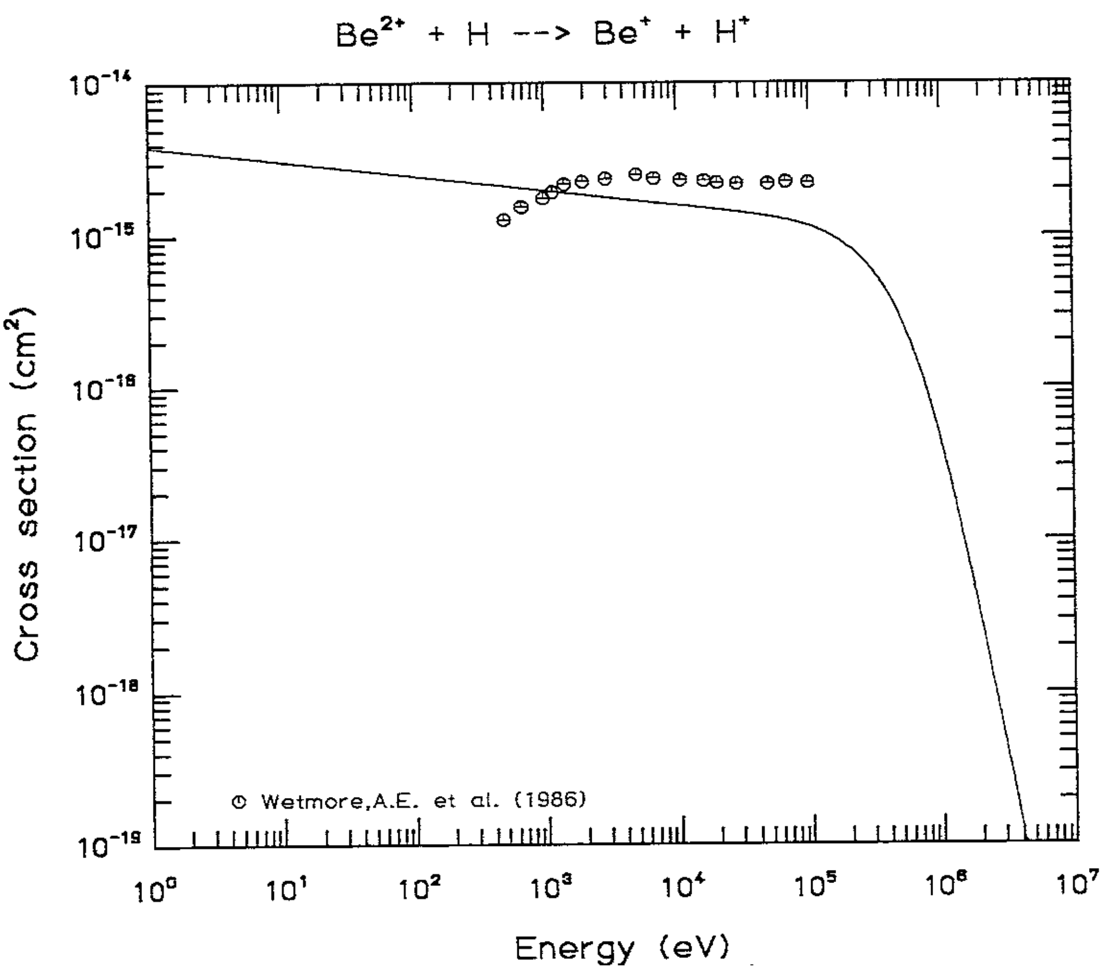

Fig.7 Total cross sections into Be^{+} in Be^{2+} + H collisions

Be^{3+} + H (Figs.8-15)

Partial as well as total cross sections have been calculated using molecular basis method by Shimakura, who has shown that the most dominant capturing state at low energy region is Be^{2+}(1s2l) states. Dalgarno and Butler calculated the rate coefficients for low temperature region. However, no experimental results have been reported yet.

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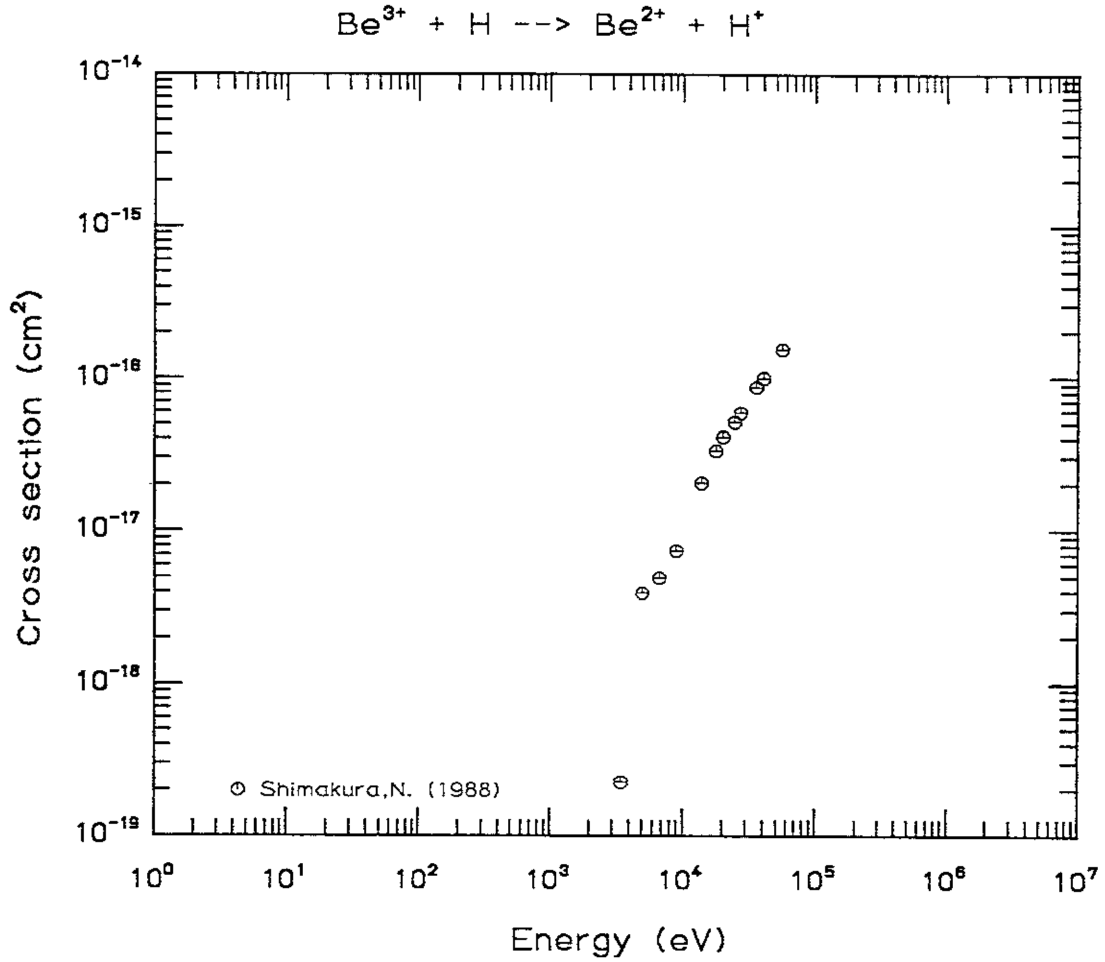

Fig.8 Partial cross sections into $Be^{2+}(2s)$ in Be^{3+} + H collisions

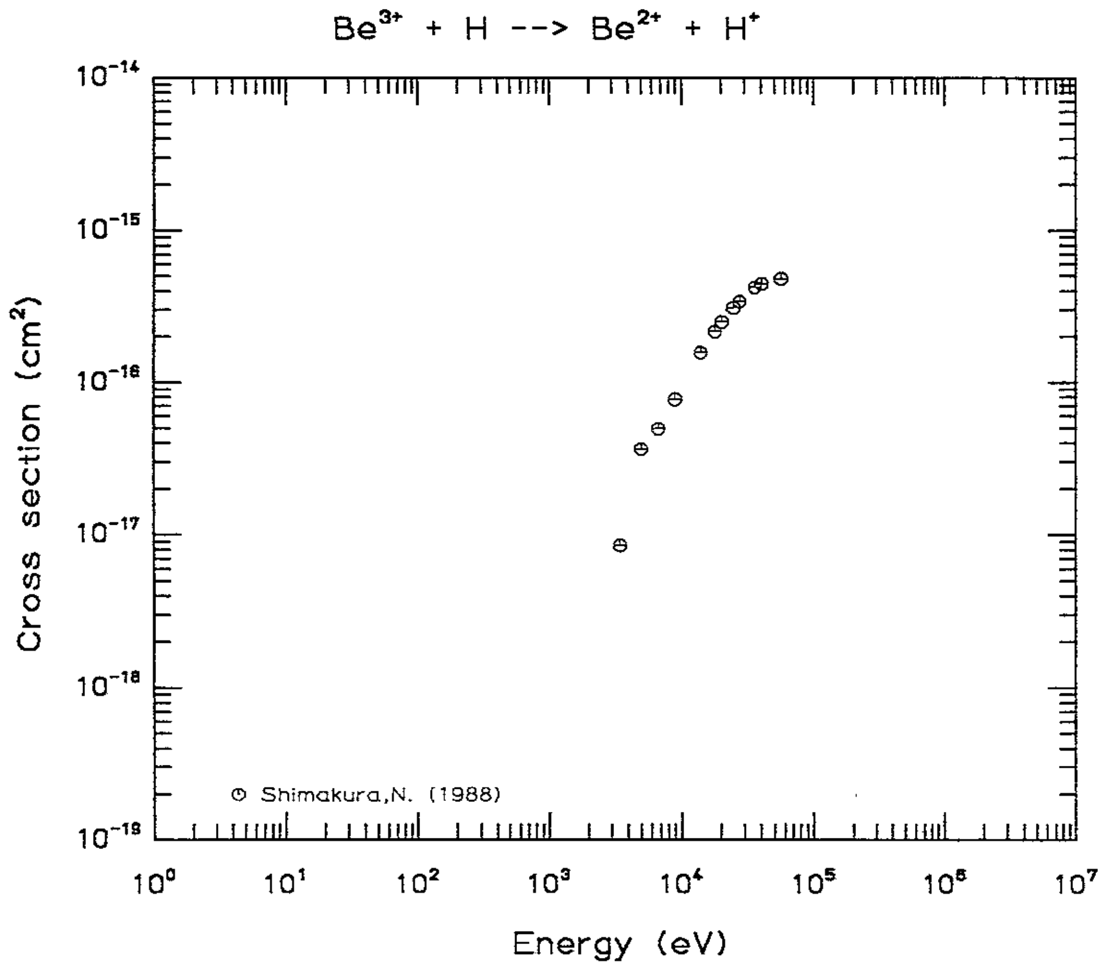

Fig.9 Partial cross sections into $Be^{2+}(2p)$ in Be^{3+} + H collisions

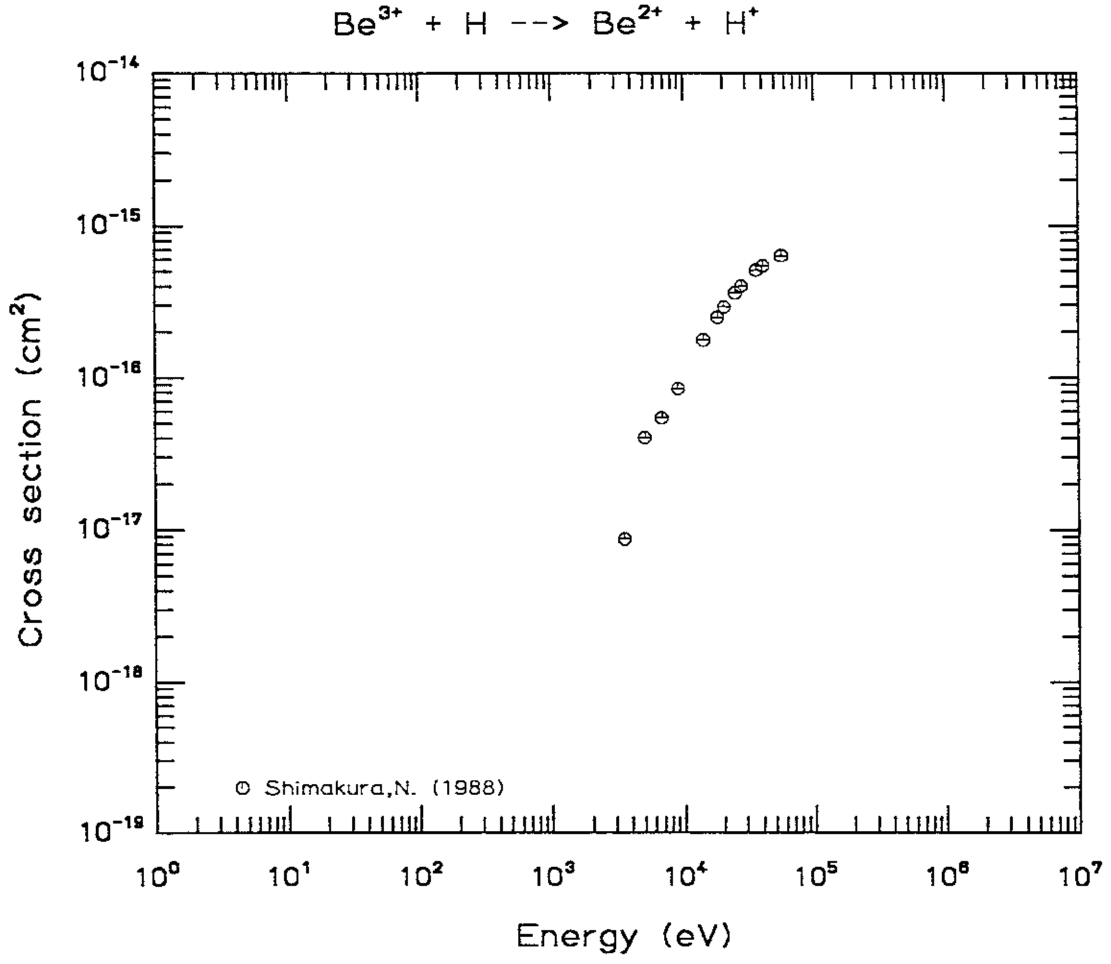

Fig.10 Partial cross sections into $Be^{2+}(n=2)$ in Be^{3+} + H collisions

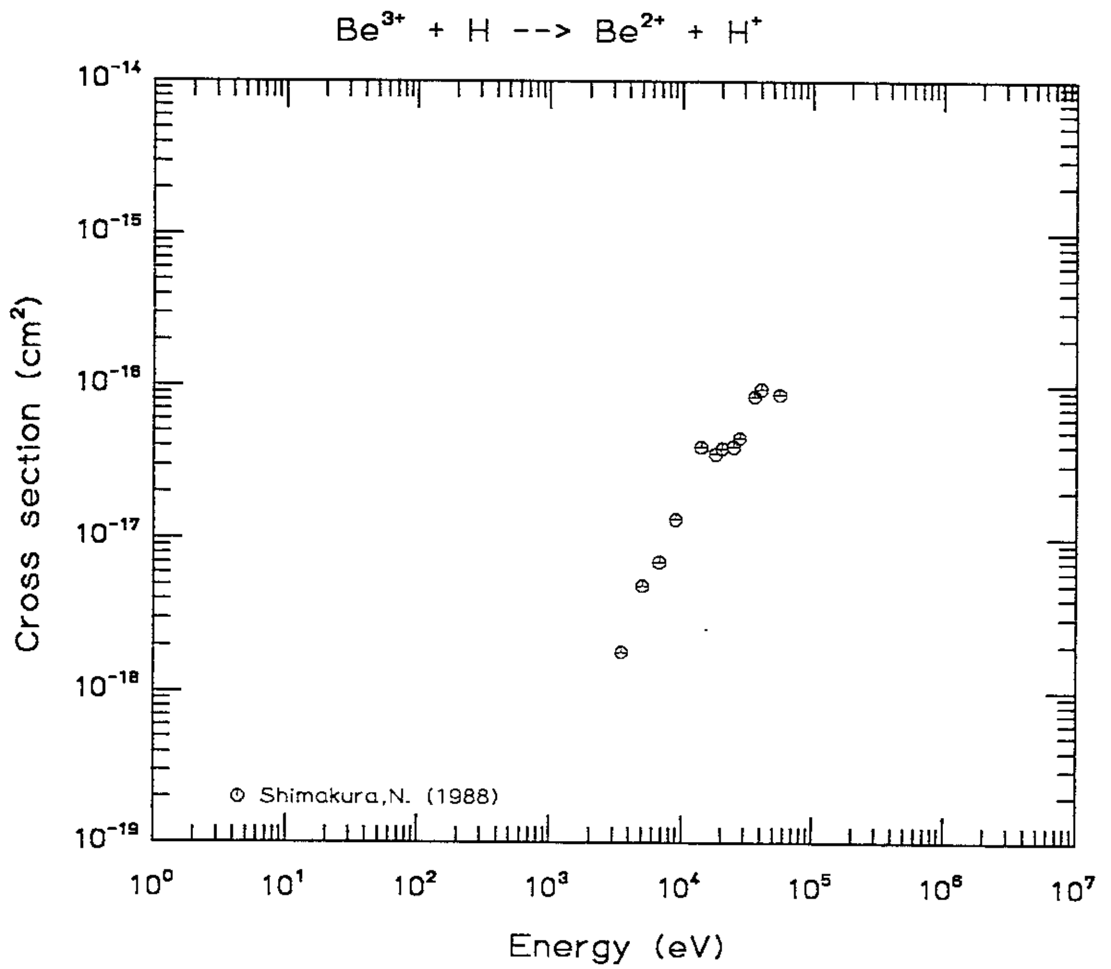

Fig.11 Partial cross sections into $Be^{2+}(3s)$ in Be^{3+} + H collisions

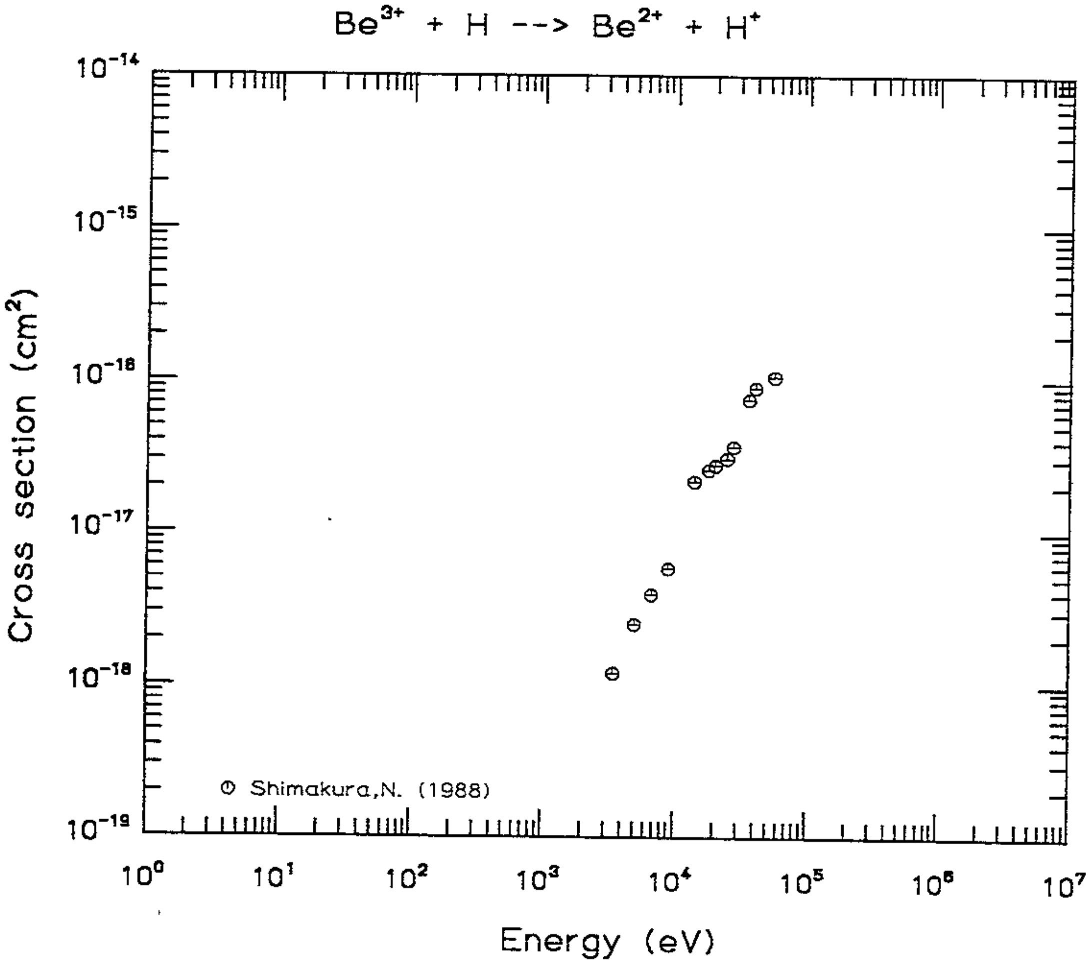

Fig.12 Partial cross sections into $Be^{2+}(3p)$ in Be^{3+} + H collisions

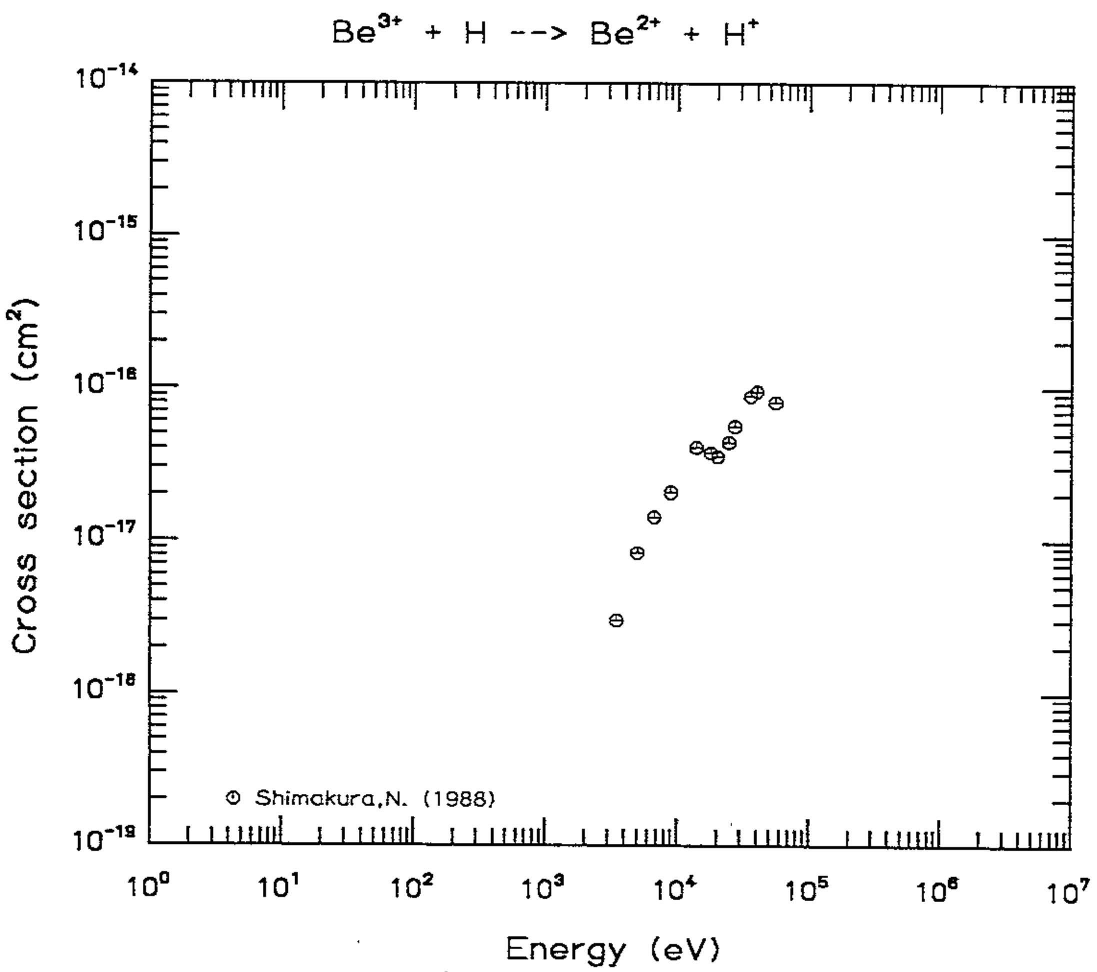

Fig.13 Partial cross sections into $Be^{2+}(3d)$ in Be^{3+} + H collisions

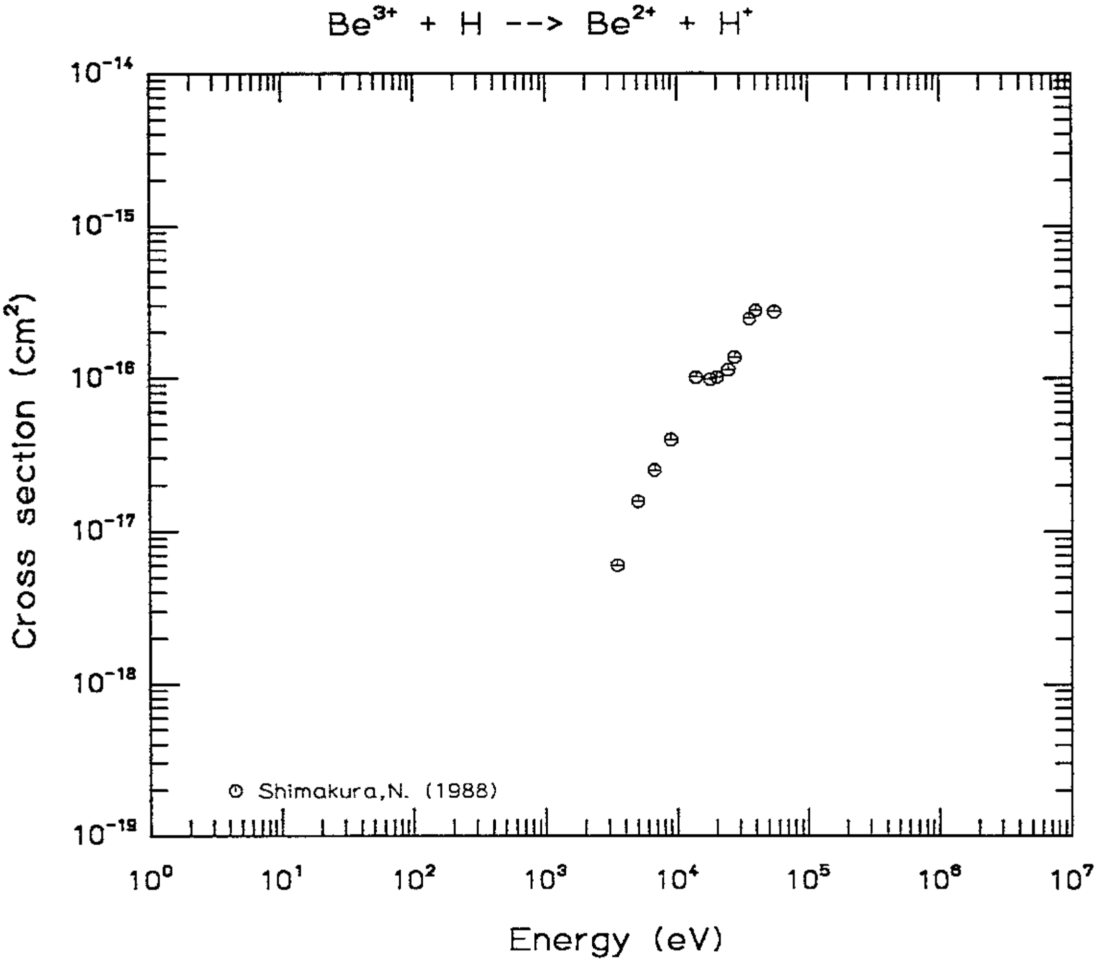

Fig.14 Partial cross sections into Be^{2+}(n=3) in Be^{3+} + H collisions

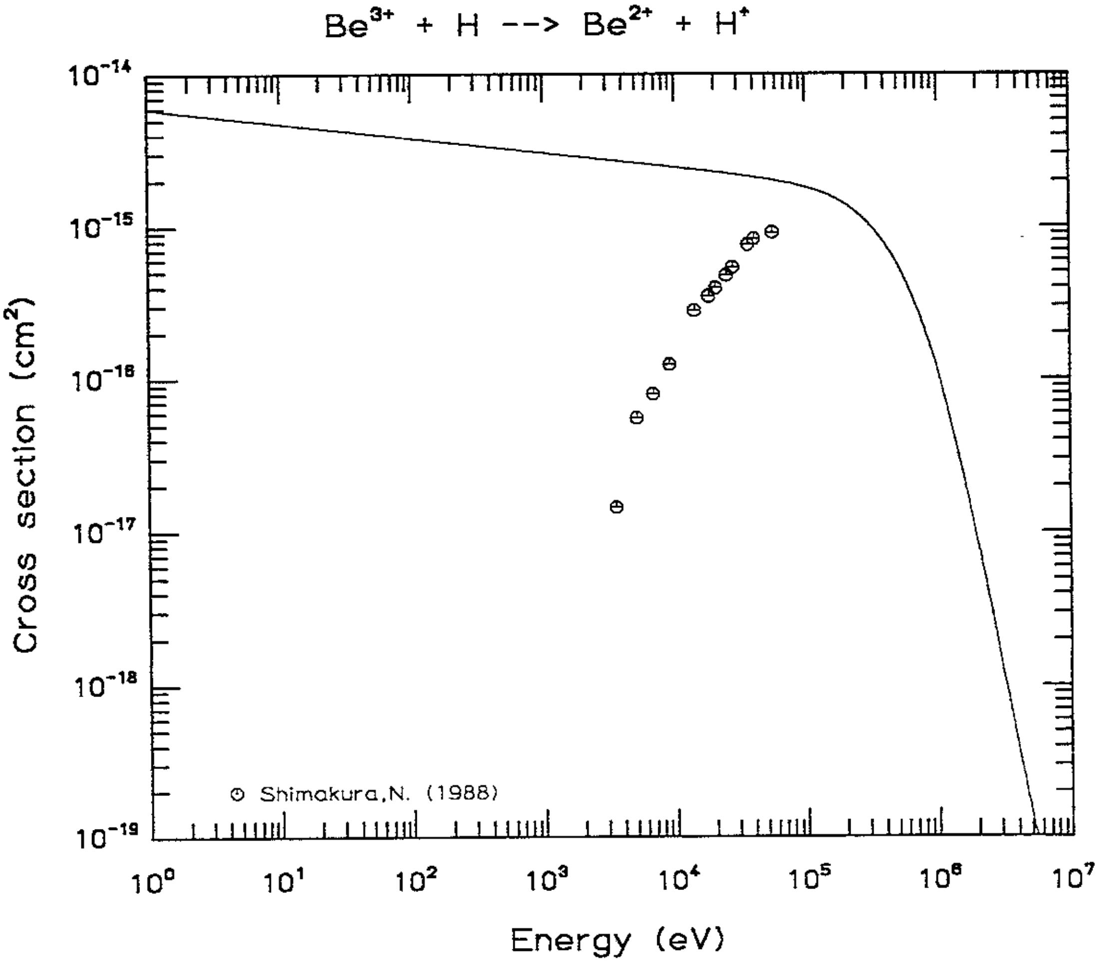

Fig.15 Total cross sections into Be^{2+} in Be^{3+} + H collisions

Be^{4+} + H (Figs.16-41)

No experimental cross sections have been reported yet. Because this is one of the simplest collision system, a number of theoretical calculations of total cross sections have been reported using various models. Systematic calculations for partial as well as total cross sections have been performed by Ryufuku using UDWA (unitarized distorted wave approximation) and Fritsch and Lin using atomic basis method. Total cross sections have also been calculated by Bransden et al., with the partial cross sections for different n-states (n=1-5) and those at single nl=51 states. Similar calculation of partial cross sections at a single collision energy of 100 keV/amu has been performed by Golden et al. Harel and Salin have also calculated the partial cross sections for nl=31 states. It should be noted that the calculation by Wada and Murai shows some oscillation at low energies which is not predicted in other calculations. Chan and Eichler have calculated total cross sections in collisions with the metastable hydrogen atoms, H(2s), at high energies (10-1000 keV/amu) and found different dependence on target electronic states from that at lower energies. In contrast to the results at low energies with the enhancement of more than order of magnitude in H(n_0=2) targets described in section 3, the calculated cross sections for H(n_0=2) targets at the energy range above a few tens of keV/amu are found to be smaller (0.25 at 50 keV/amu to 0.12 at 5 MeV/amu) than those for H(n_0=1) targets because the 2s wave function has smaller momentum than the 1s wave function.

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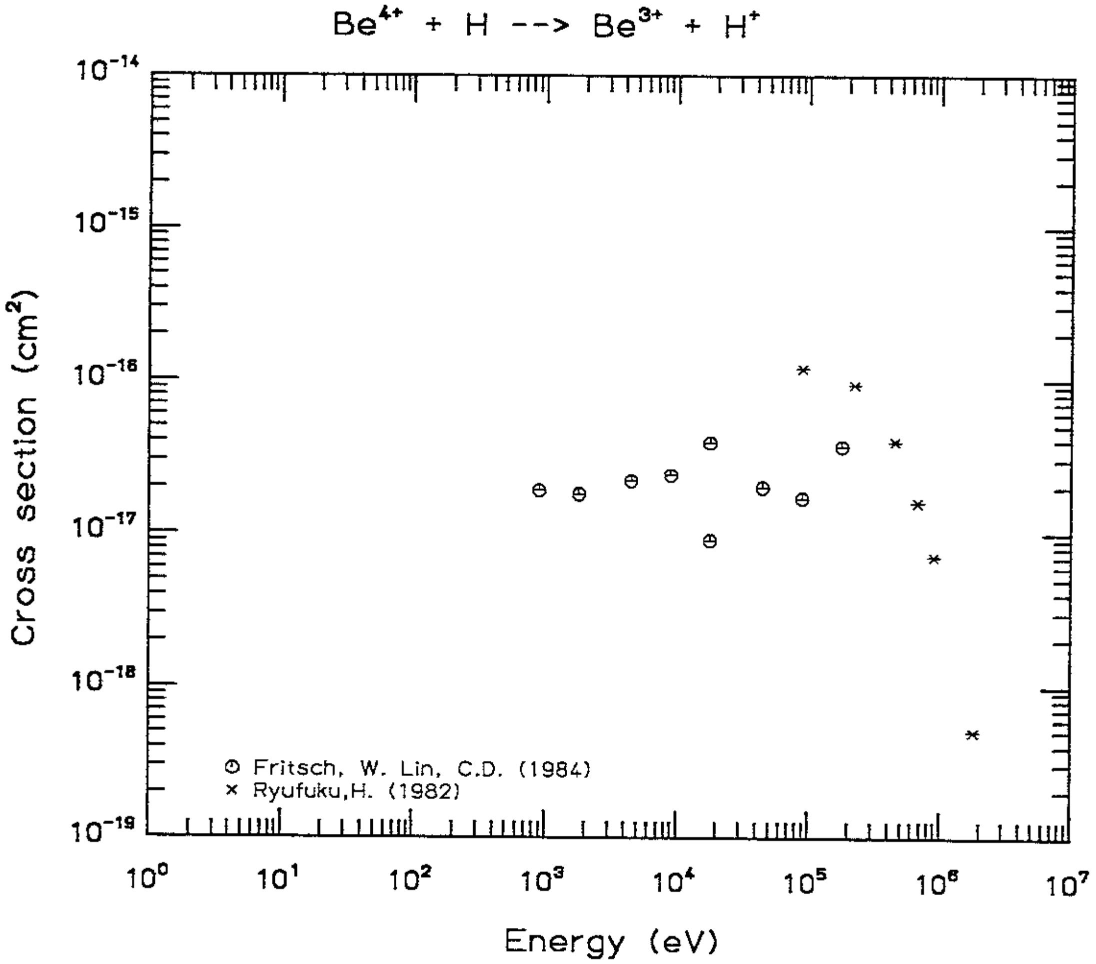

Fig.16 Partial cross sections into Be^{3+}(2s) in Be^{4+} + H collisions

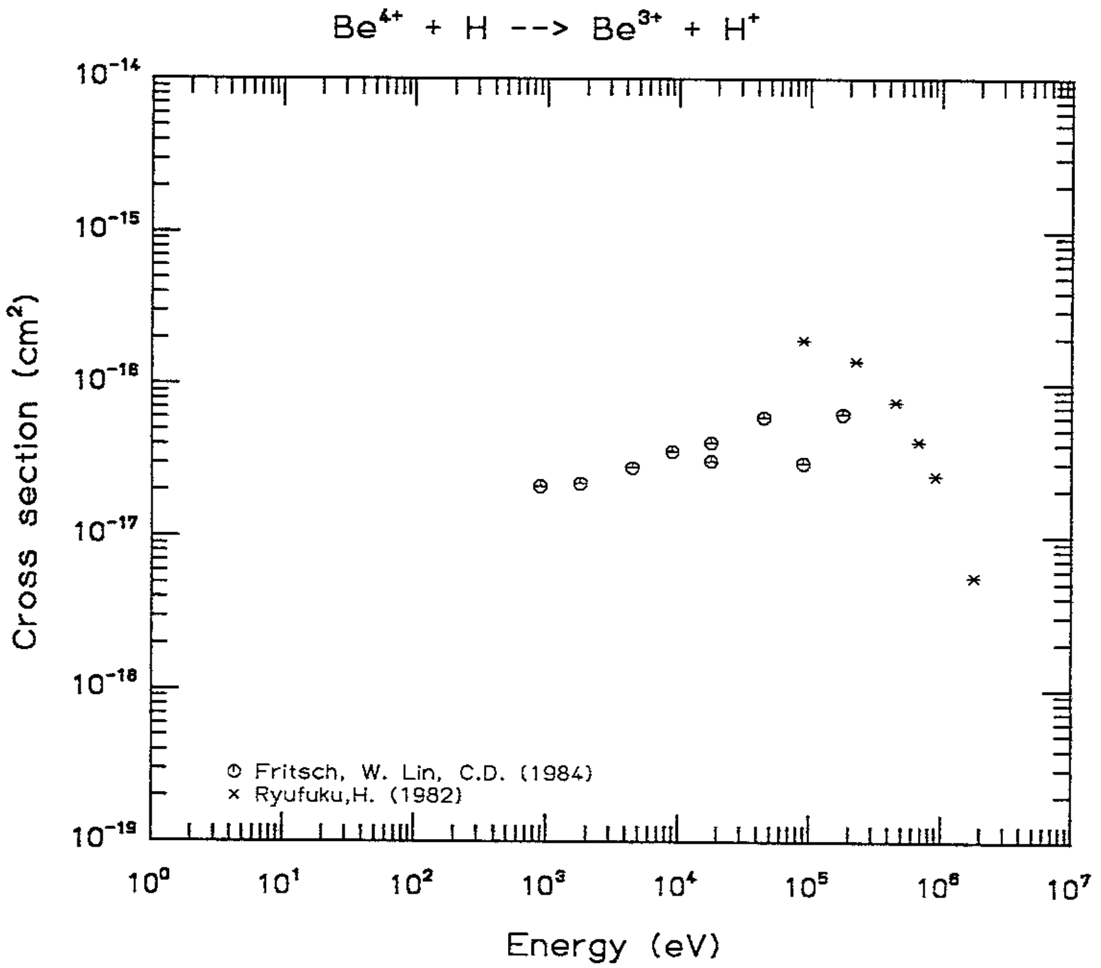

Fig.17 Partial cross sections into Be^{3+}(2p) in Be^{4+} + H collisions

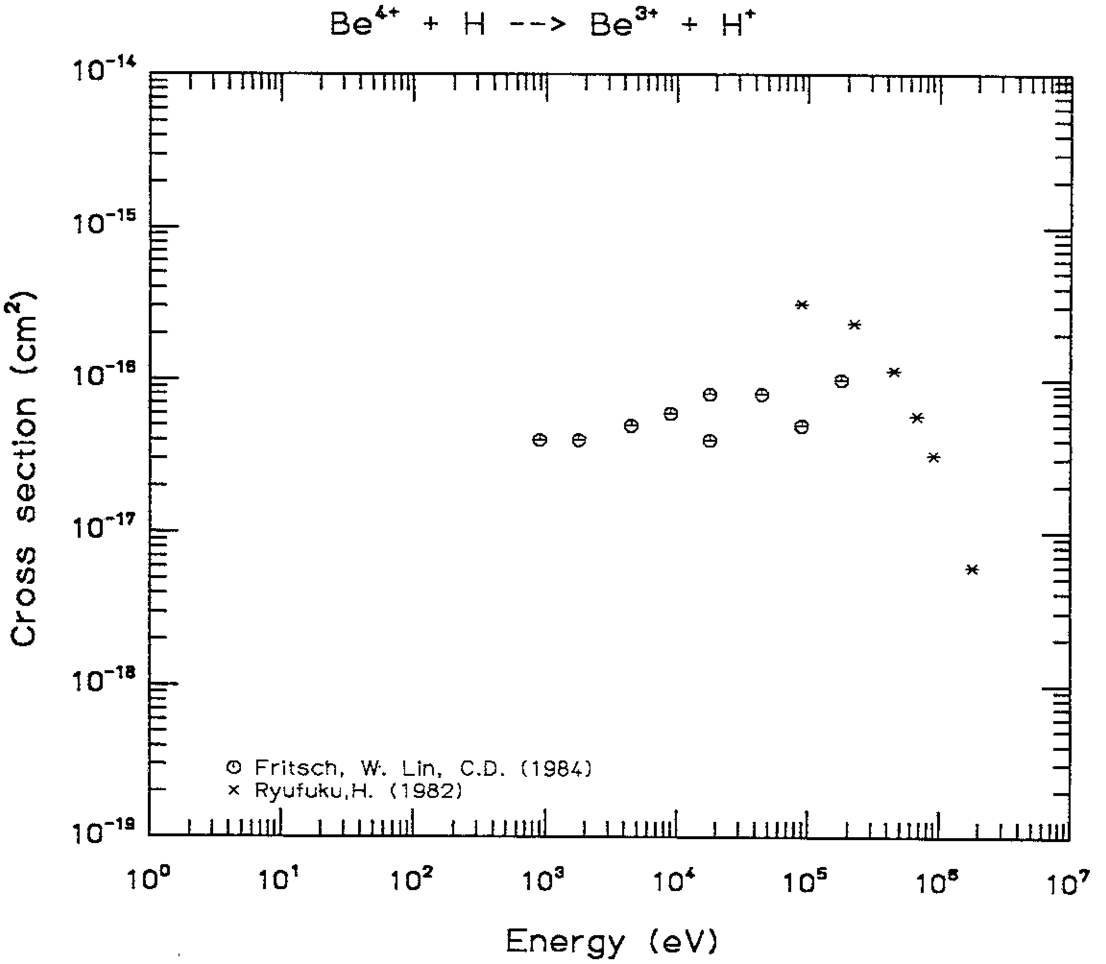

Fig.18 Partial cross sections into Be^{3+}(n=2) in Be^{4+} + H collisions

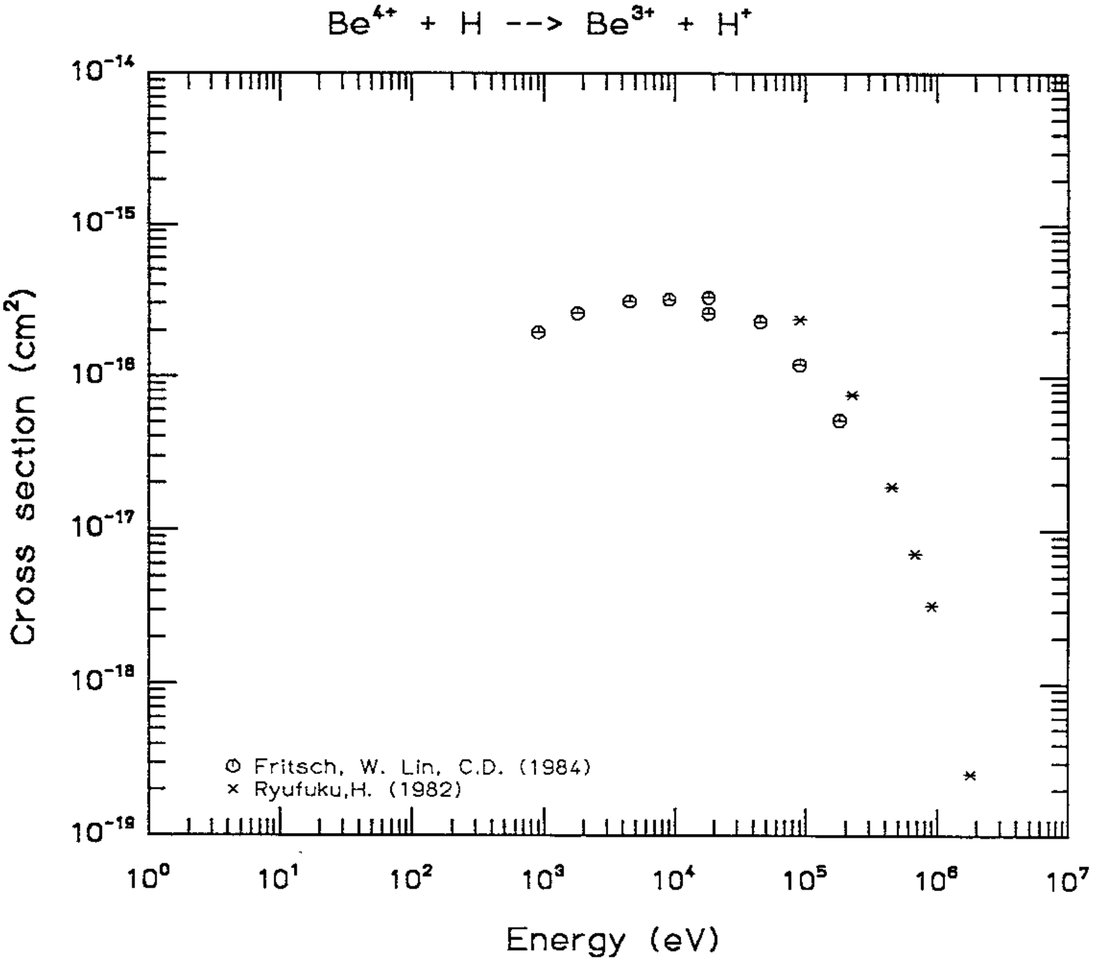

Fig.19 Partial cross sections into Be^{3+}(3s) in Be^{4+} + H collisions

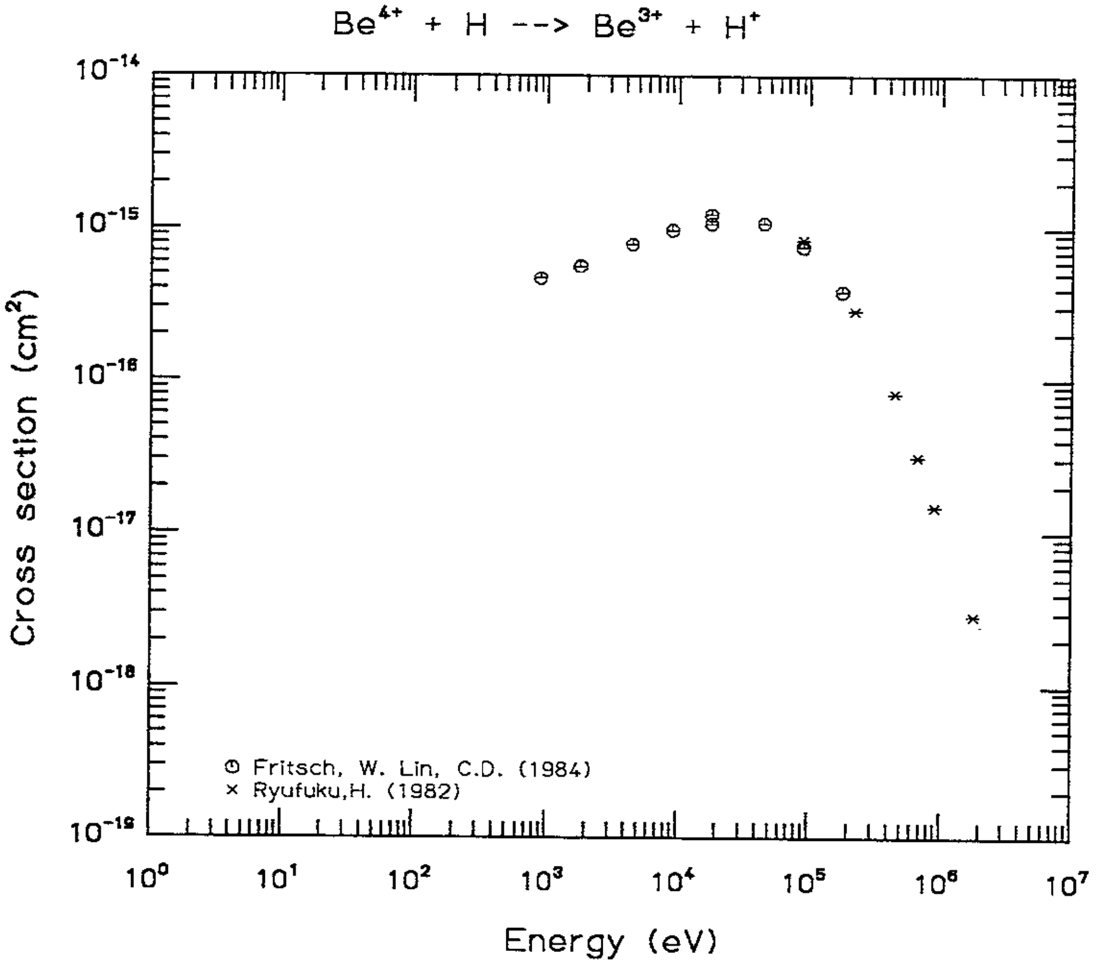

Fig.20 Partial cross sections into $Be^{3+}(3p)$ in Be^{4+} + H collisions

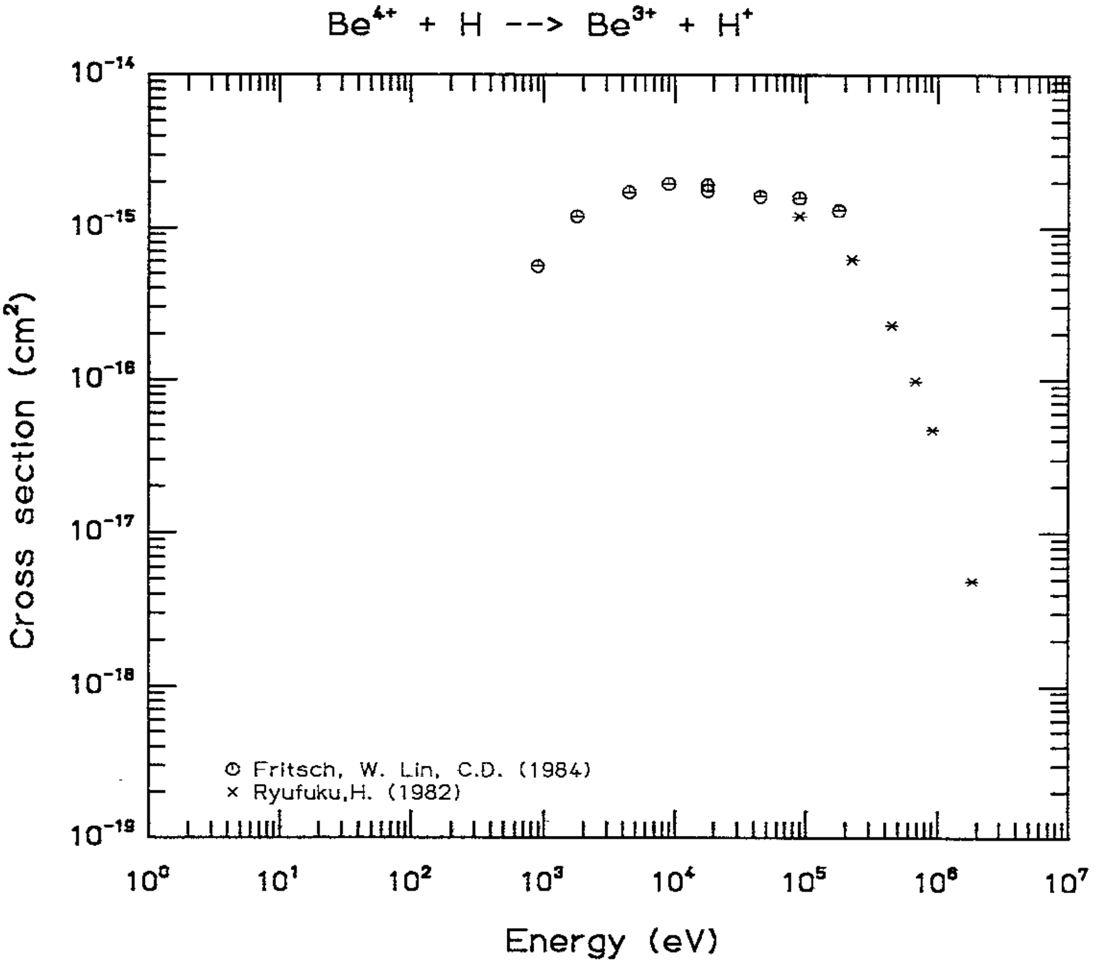

Fig.21 Partial cross sections into $Be^{3+}(3d)$ in Be^{4+} + H collisions

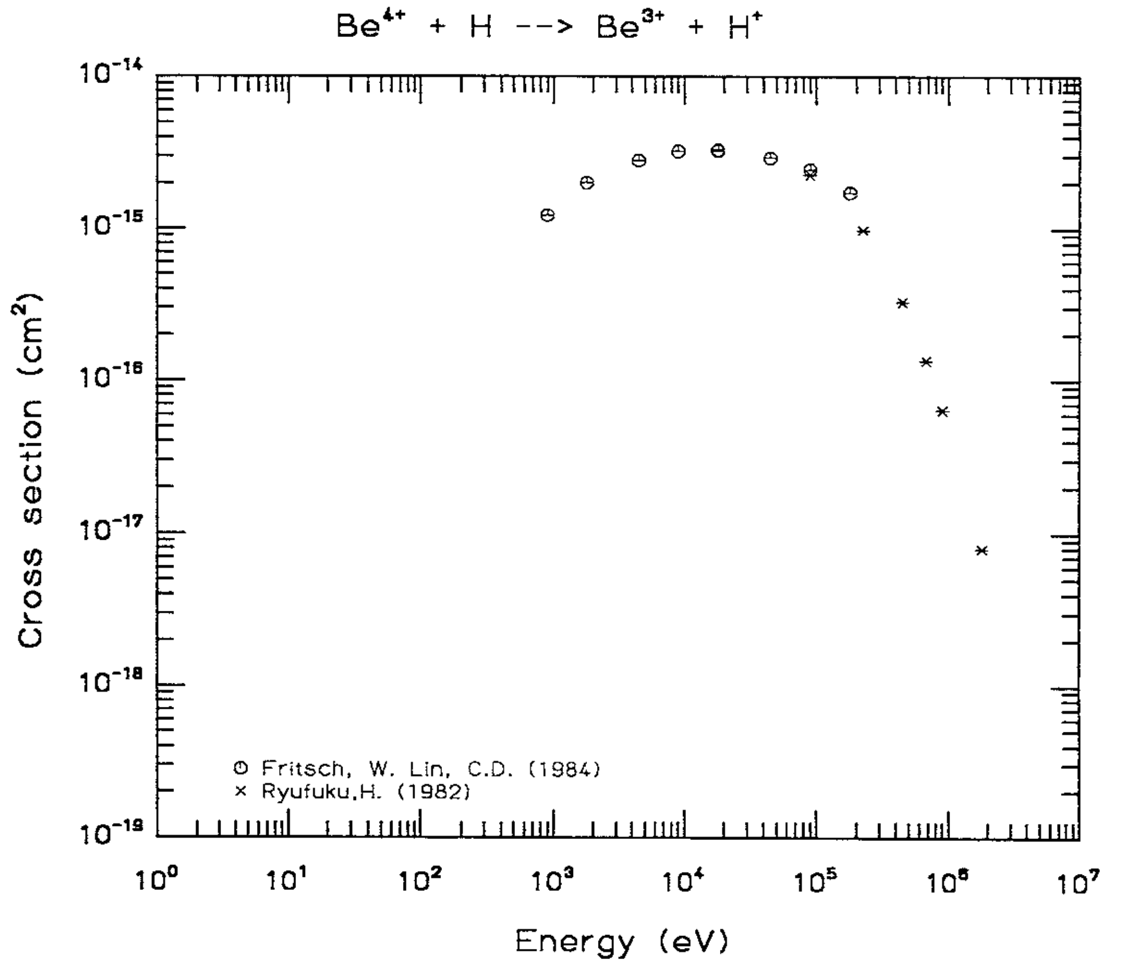

Fig.22 Partial cross sections into Be^{3+}(n=3) in Be^{4+} + H collisions

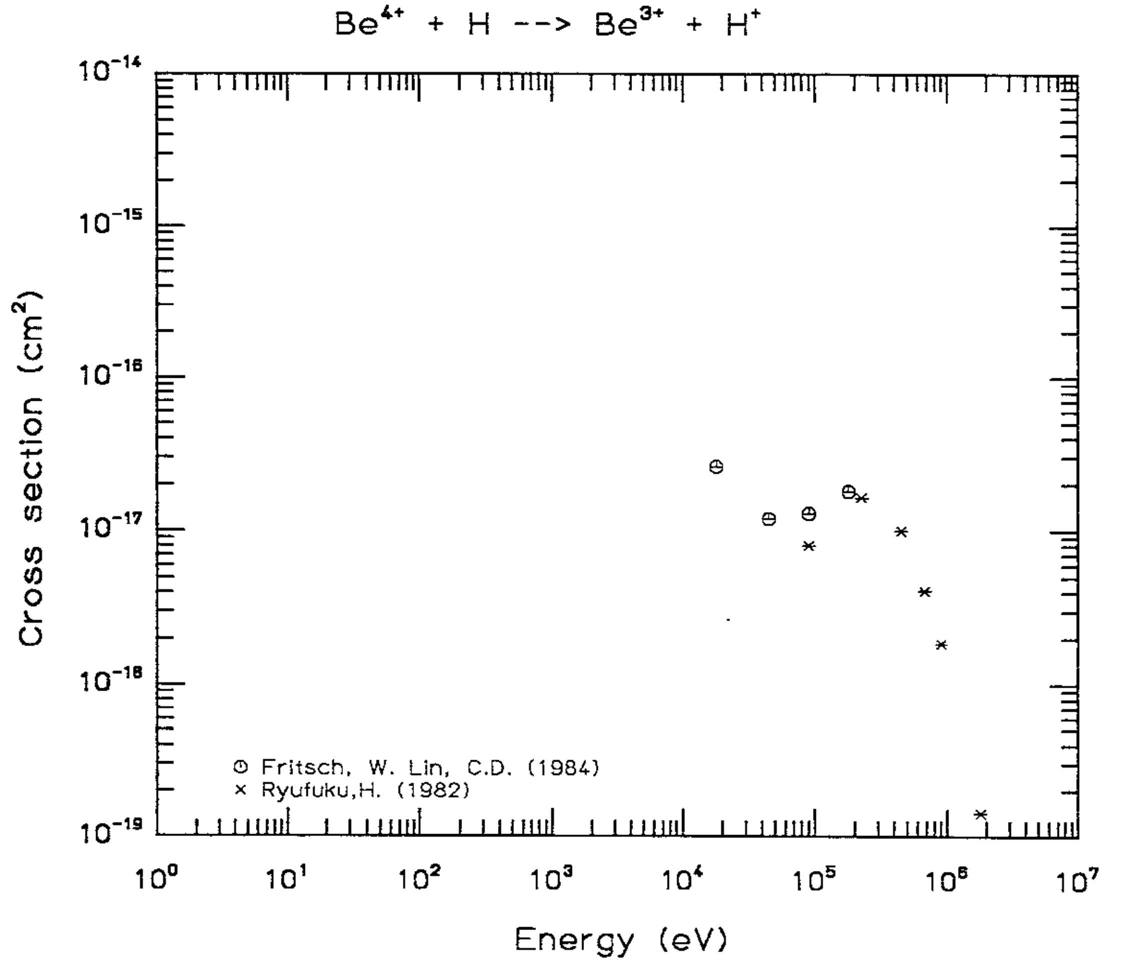

Fig.23 Partial cross sections into Be^{3+}(4s) in Be^{4+} + H collisions

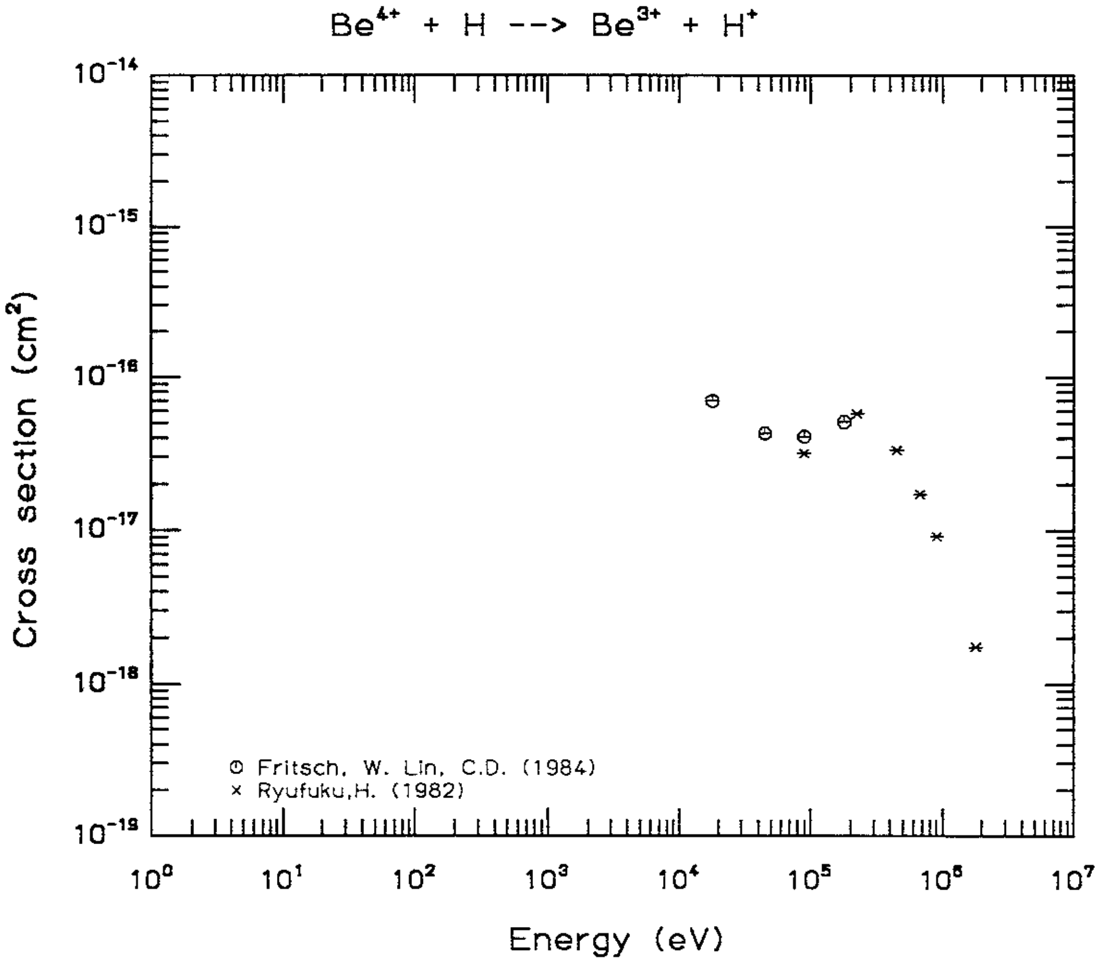

Fig.24 Partial cross sections into $Be^{3+}(4p)$ in Be^{4+} + H collisions

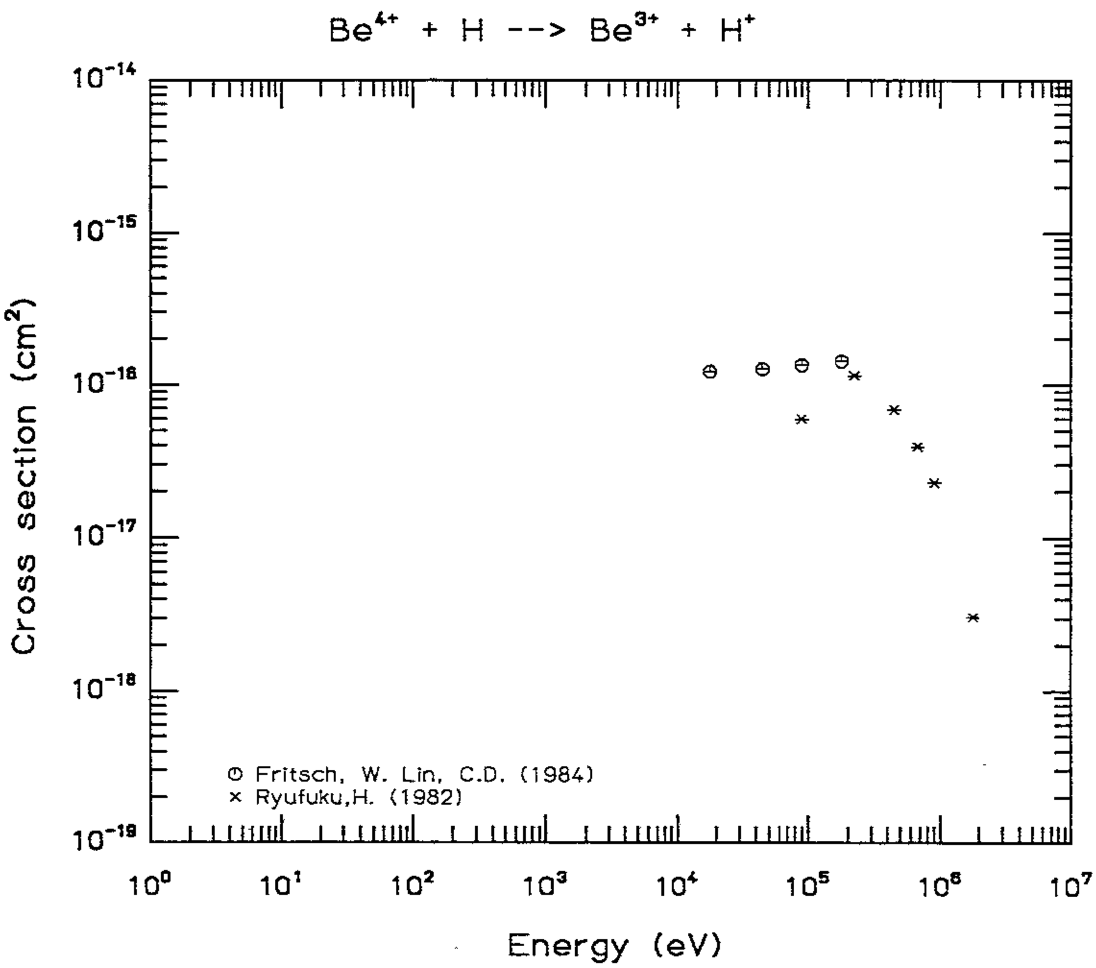

Fig.25 Partial cross sections into $Be^{3+}(4d)$ in Be^{4+} + H collisions

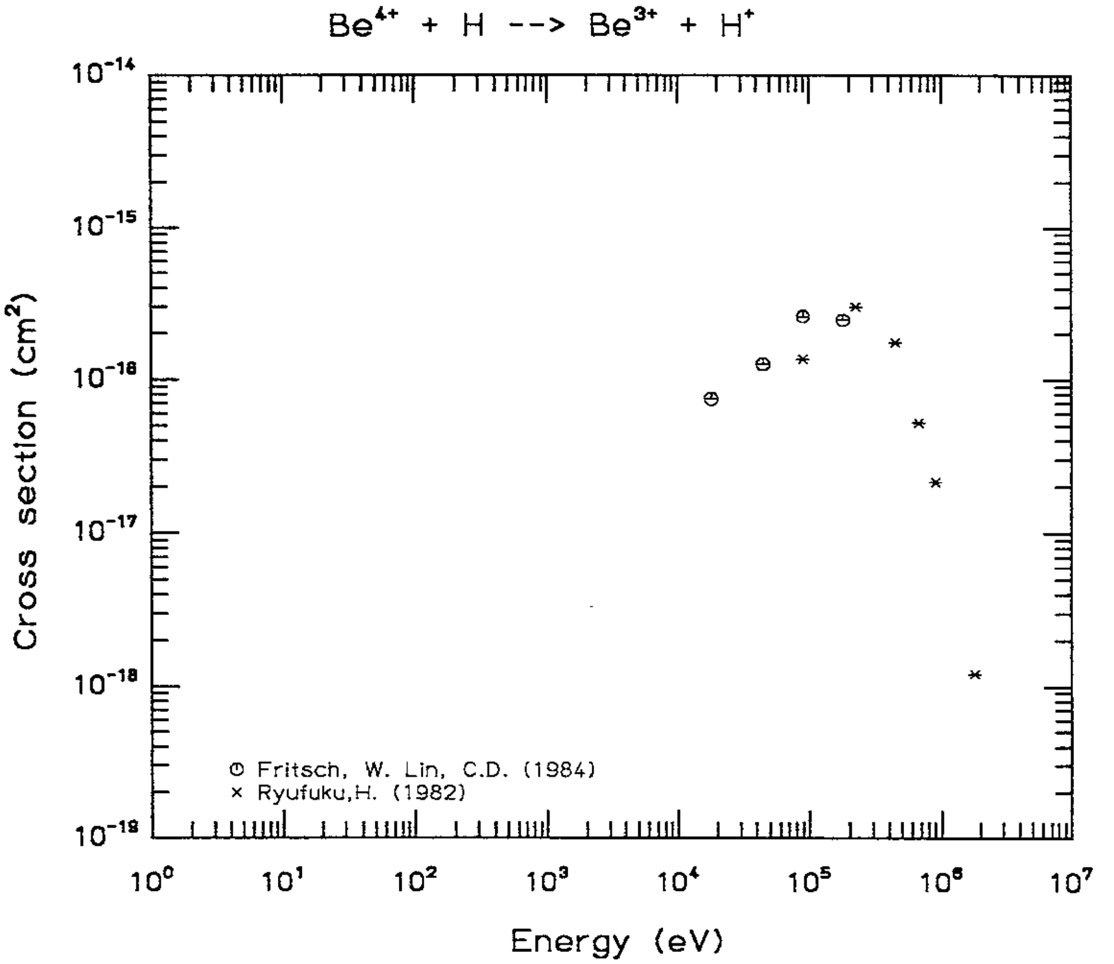

Fig.26 Partial cross sections into Be^{3+}(4f) in Be^{4+} + H collisions

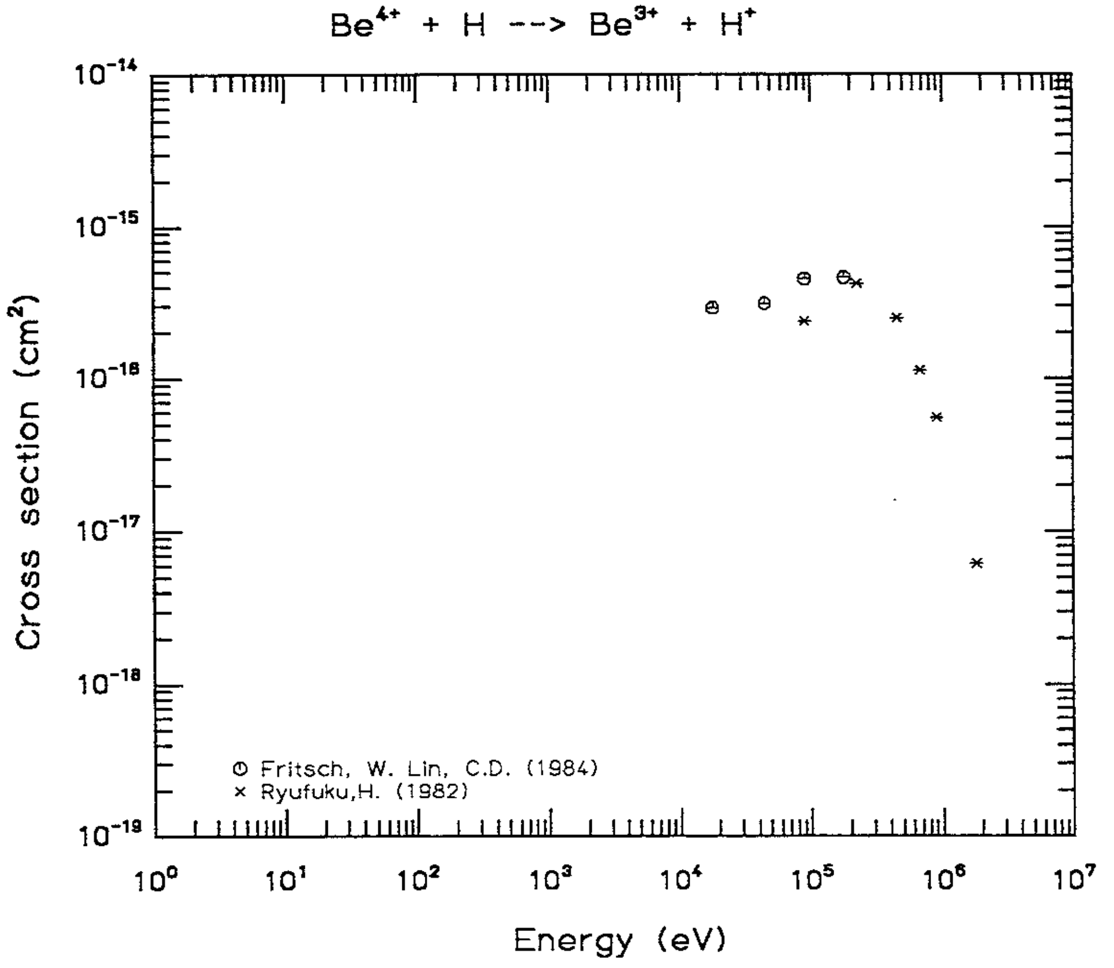

Fig.27 Partial cross sections into Be^{3+}(n=4) in Be^{4+} + H collisions

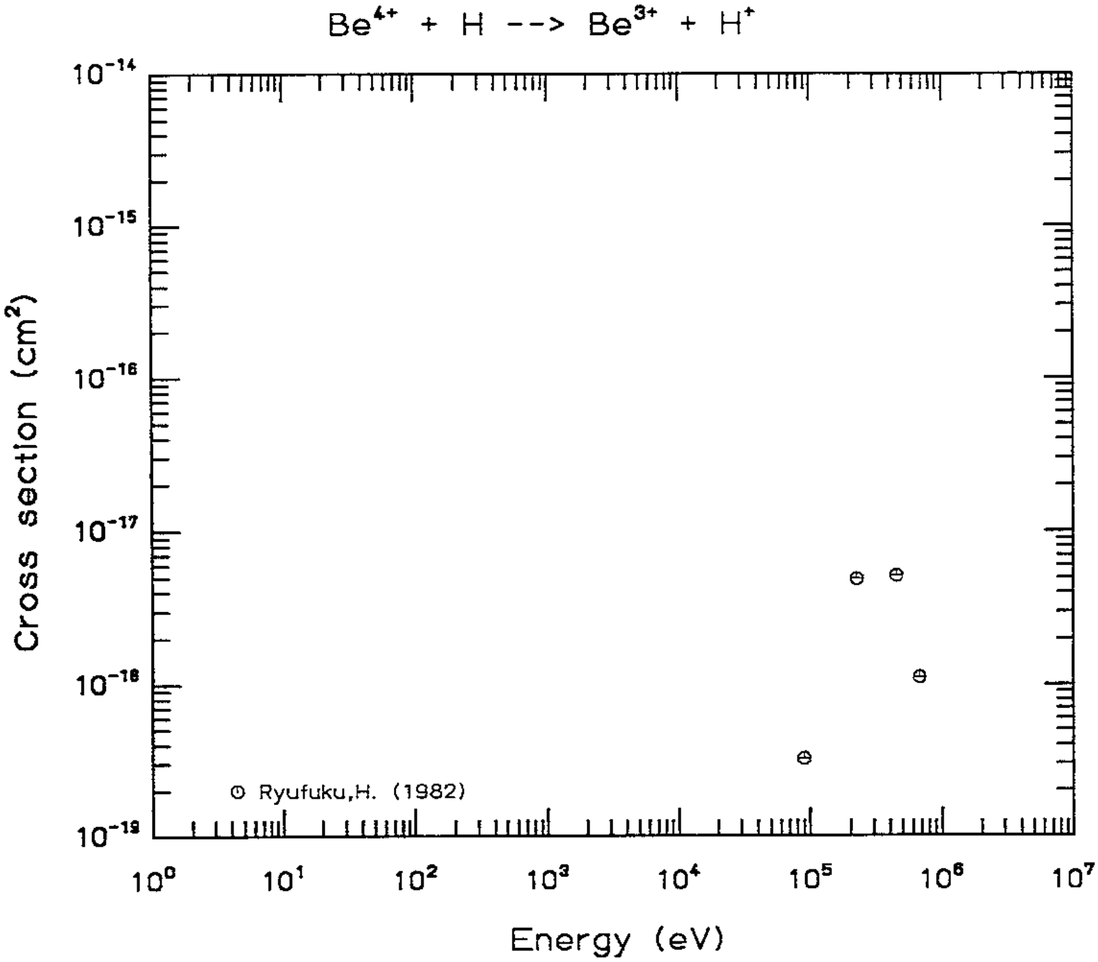

Fig.28 Partial cross sections into Be^{3+}(5s) in Be^{4+} + H collisions

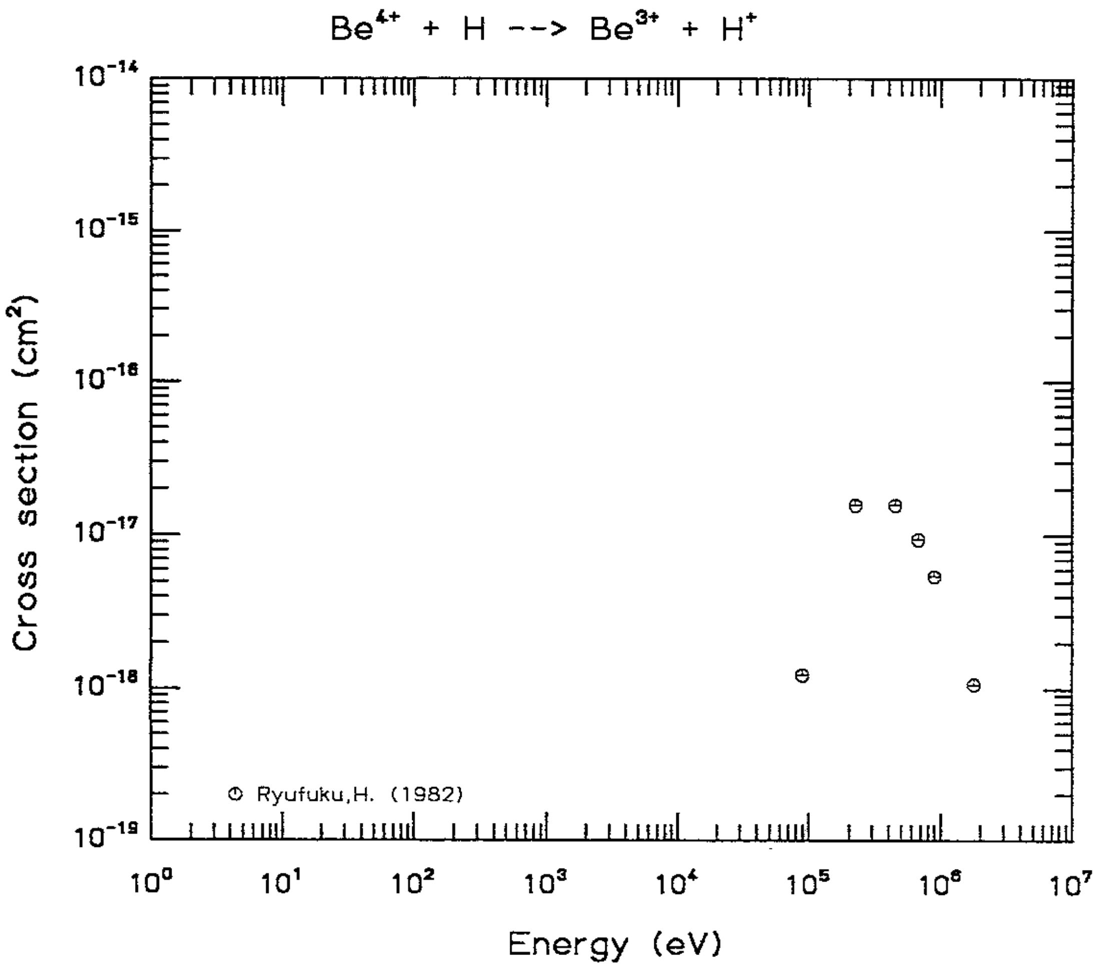

Fig.29 Partial cross sections into Be^{3+}(5p) in Be^{4+} + H collisions

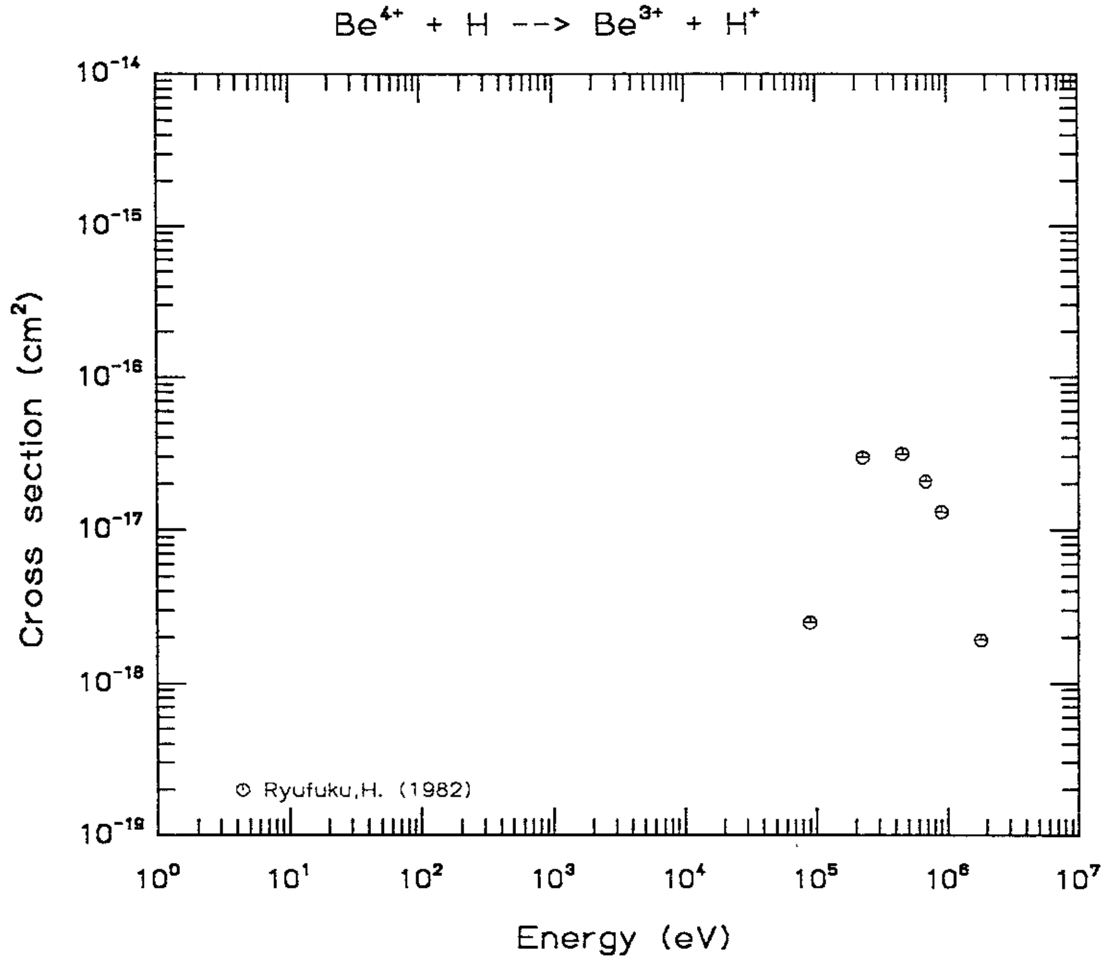

Fig.30 Partial cross sections into Be^{3+}(5d) in Be^{4+} + H collisions

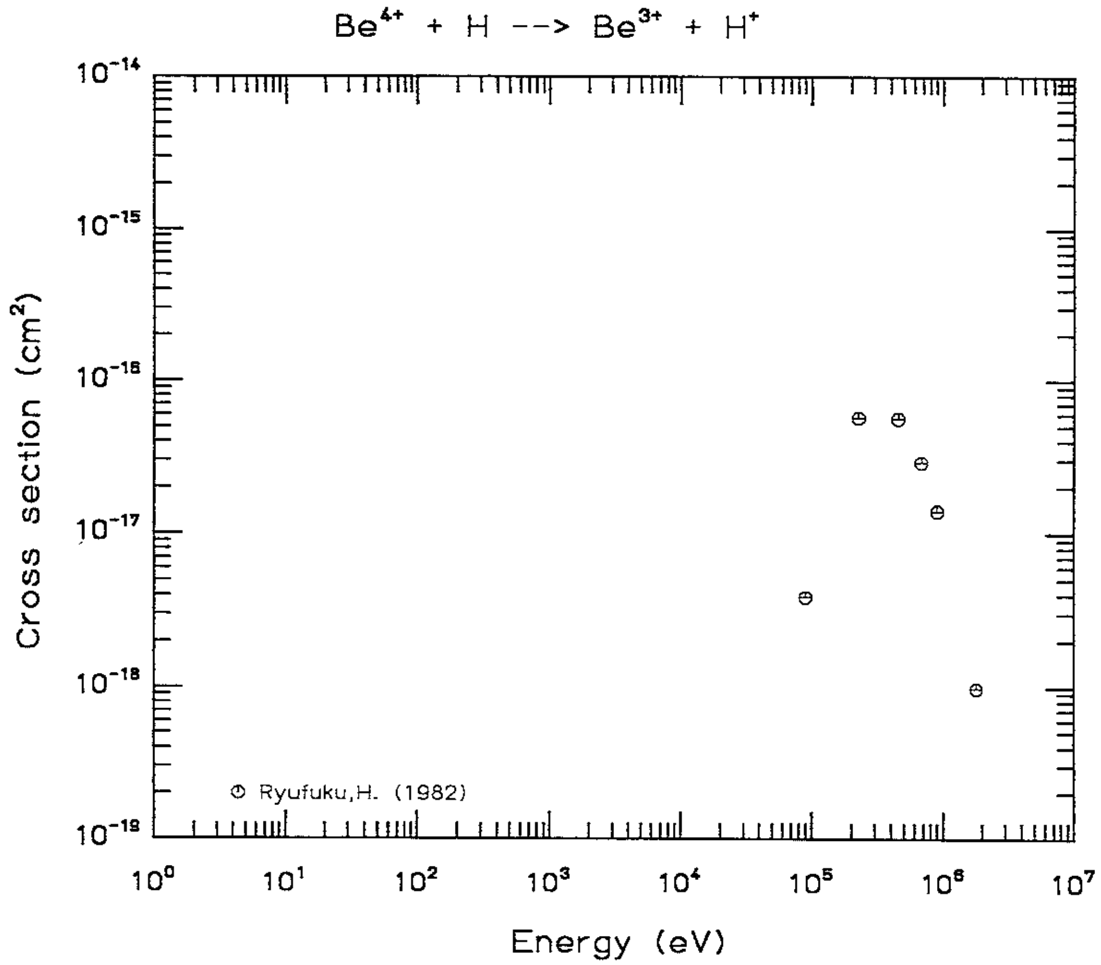

Fig.31 Partial cross sections into Be^{3+}(5f) in Be^{4+} + H collisions

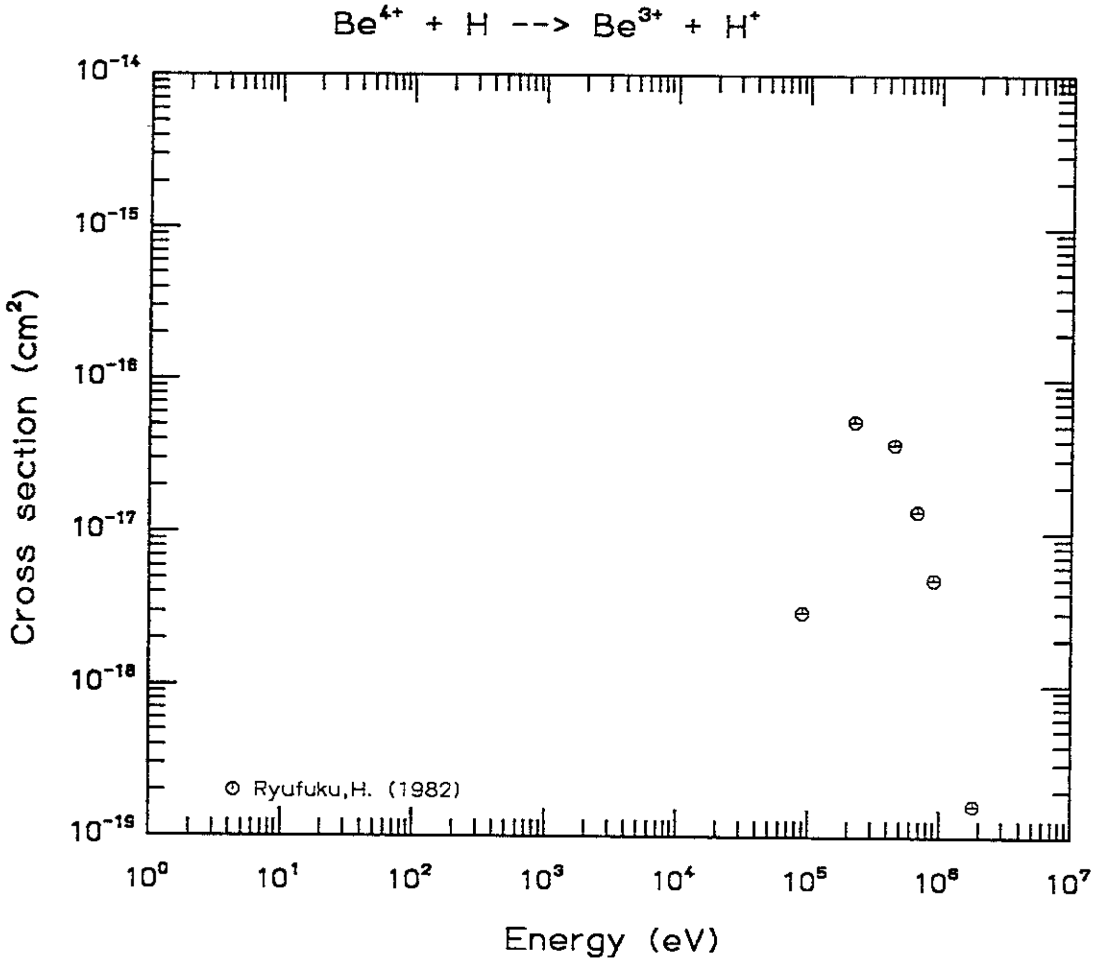

Fig.32 Partial cross sections into Be^{3+}(5g) in Be^{4+} + H collisions

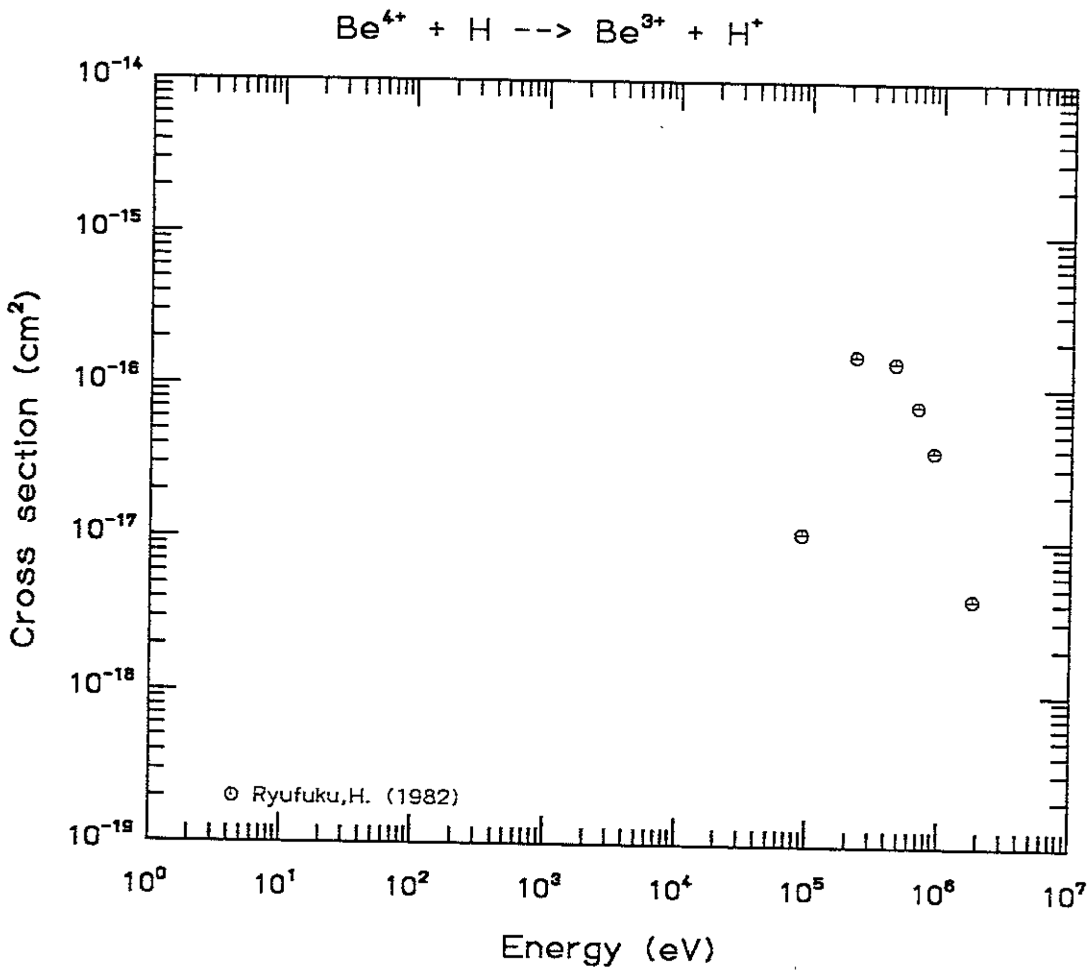

Fig.33 Partial cross sections into Be^{3+}(n=5) in Be^{4+} + H collisions

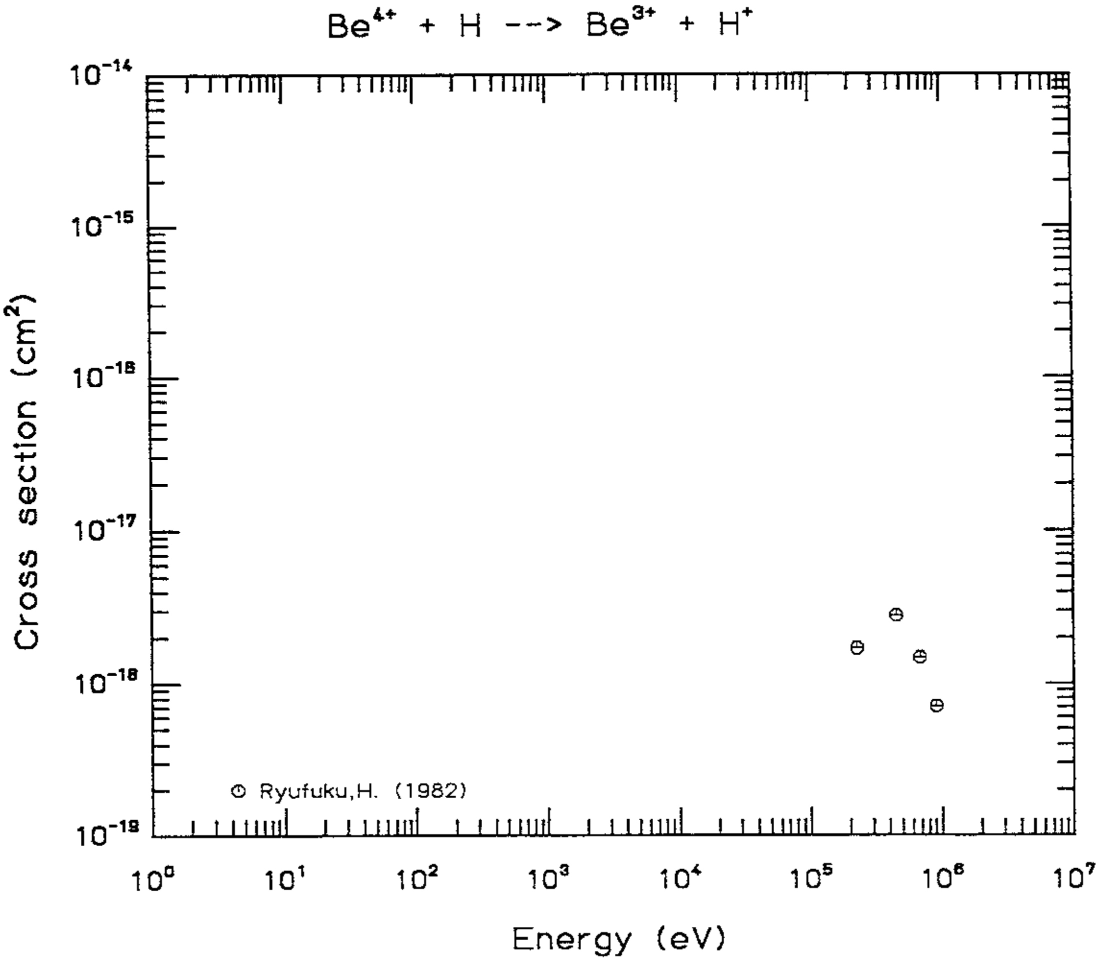

Fig.34 Partial cross sections into $Be^{3+}(6s)$ in Be^{4+} + H collisions

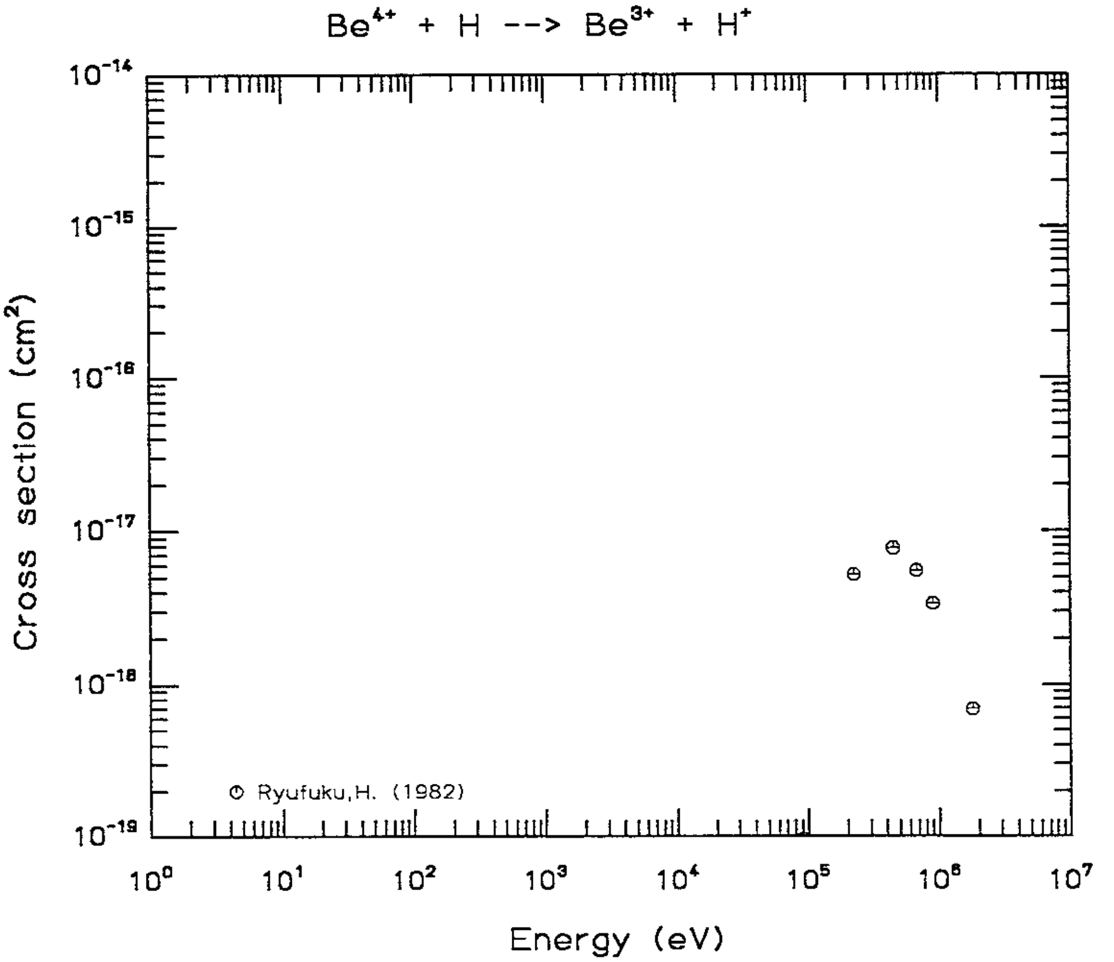

Fig.35 Partial cross sections into $Be^{3+}(6p)$ in Be^{4+} + H collisions

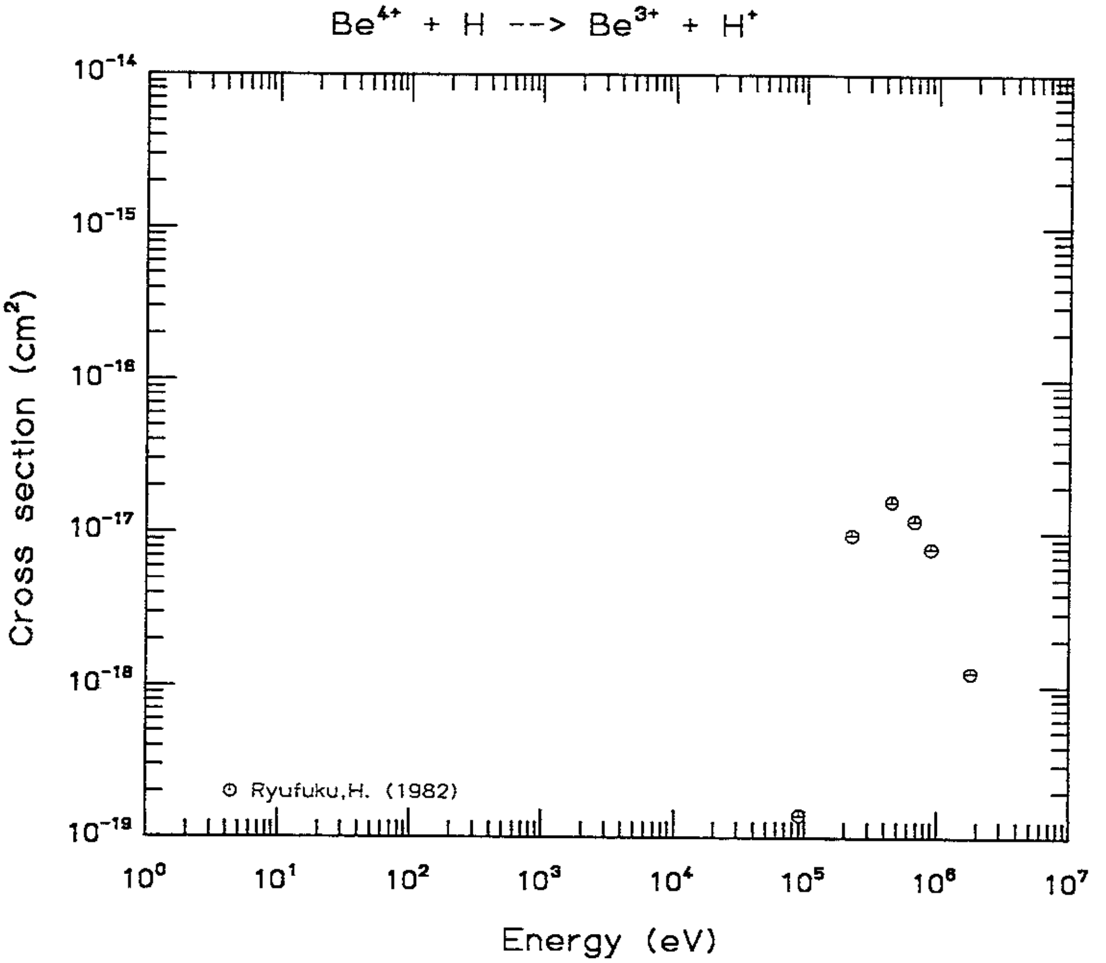

Fig.36 Partial cross sections into Be^{3+}(6d) in Be^{4+} + H collisions

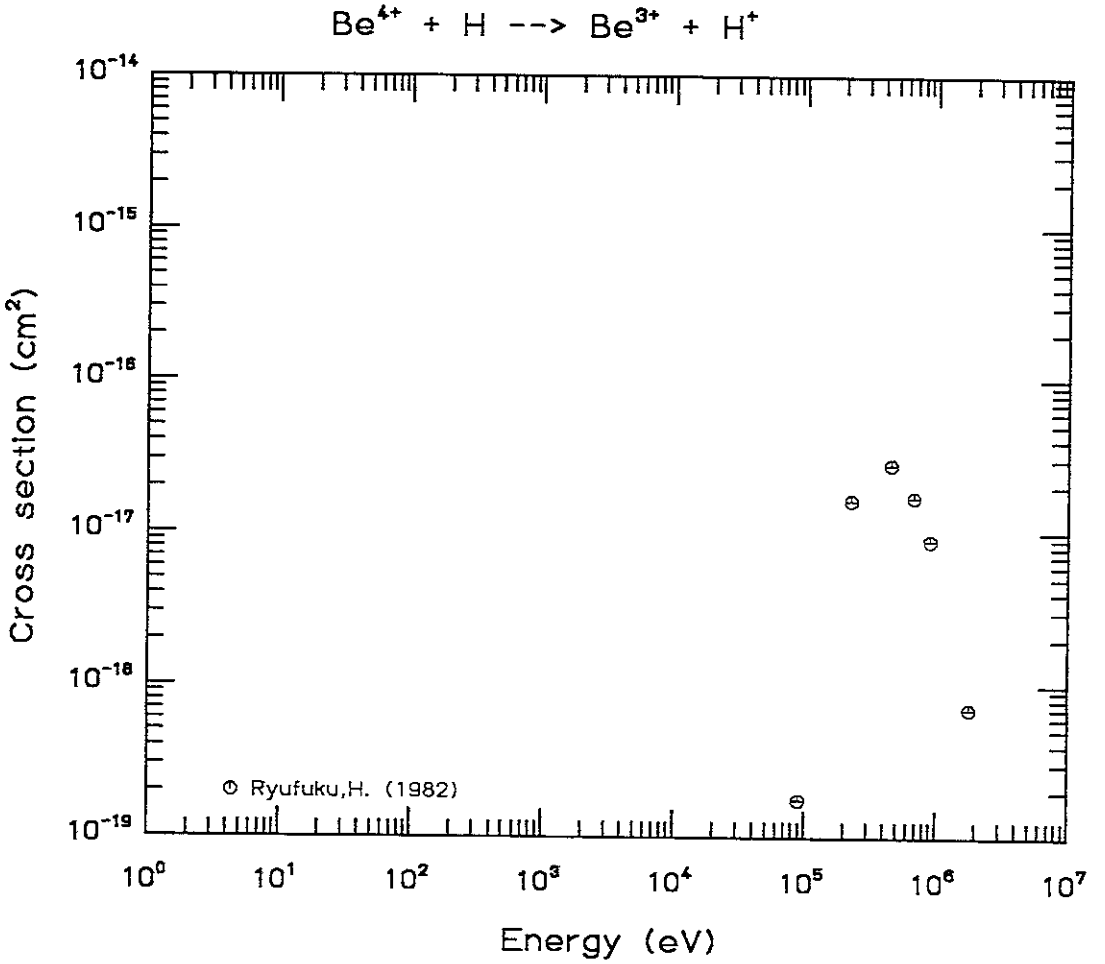

Fig.37 Partial cross sections into Be^{3+}(6f) in Be^{4+} + H collisions

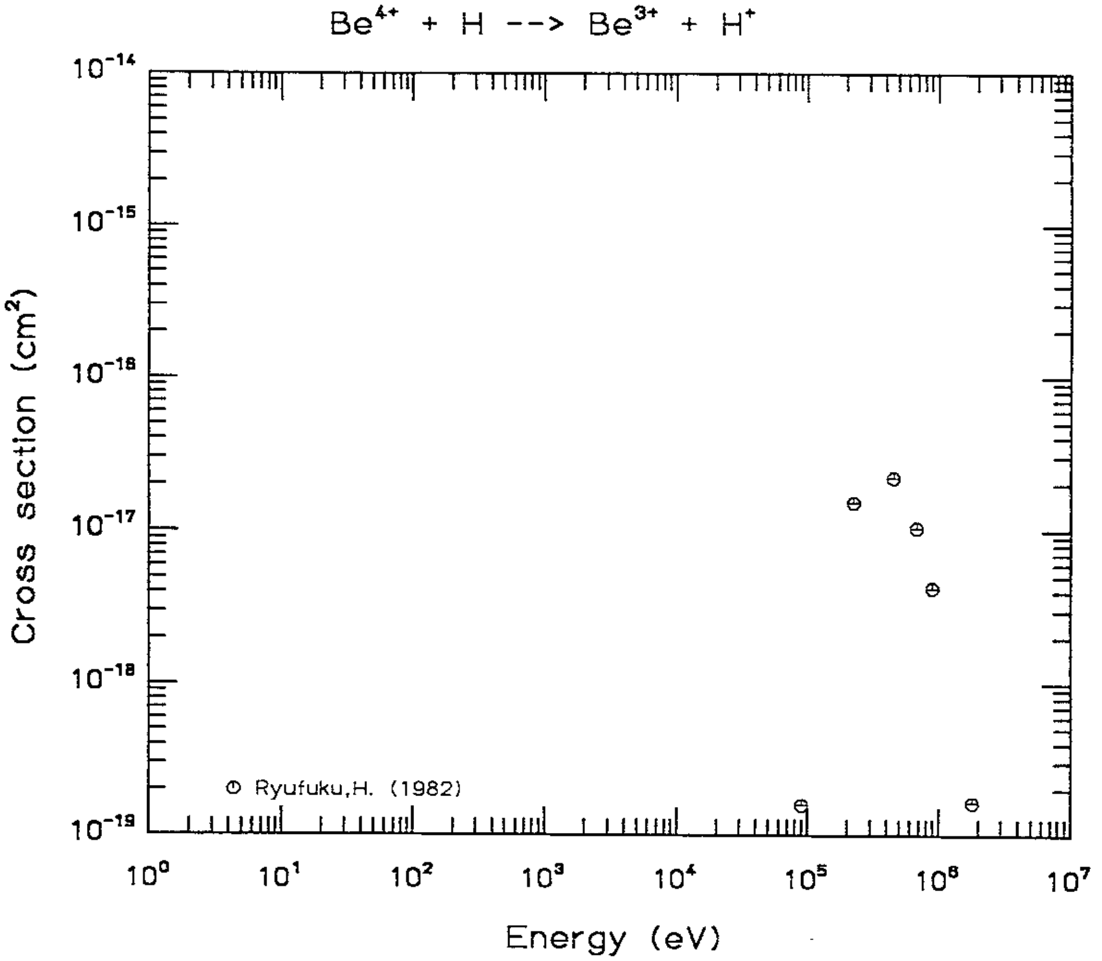

Fig.38 Partial cross sections into Be^{3+}(6g) in Be^{4+} + H collisions

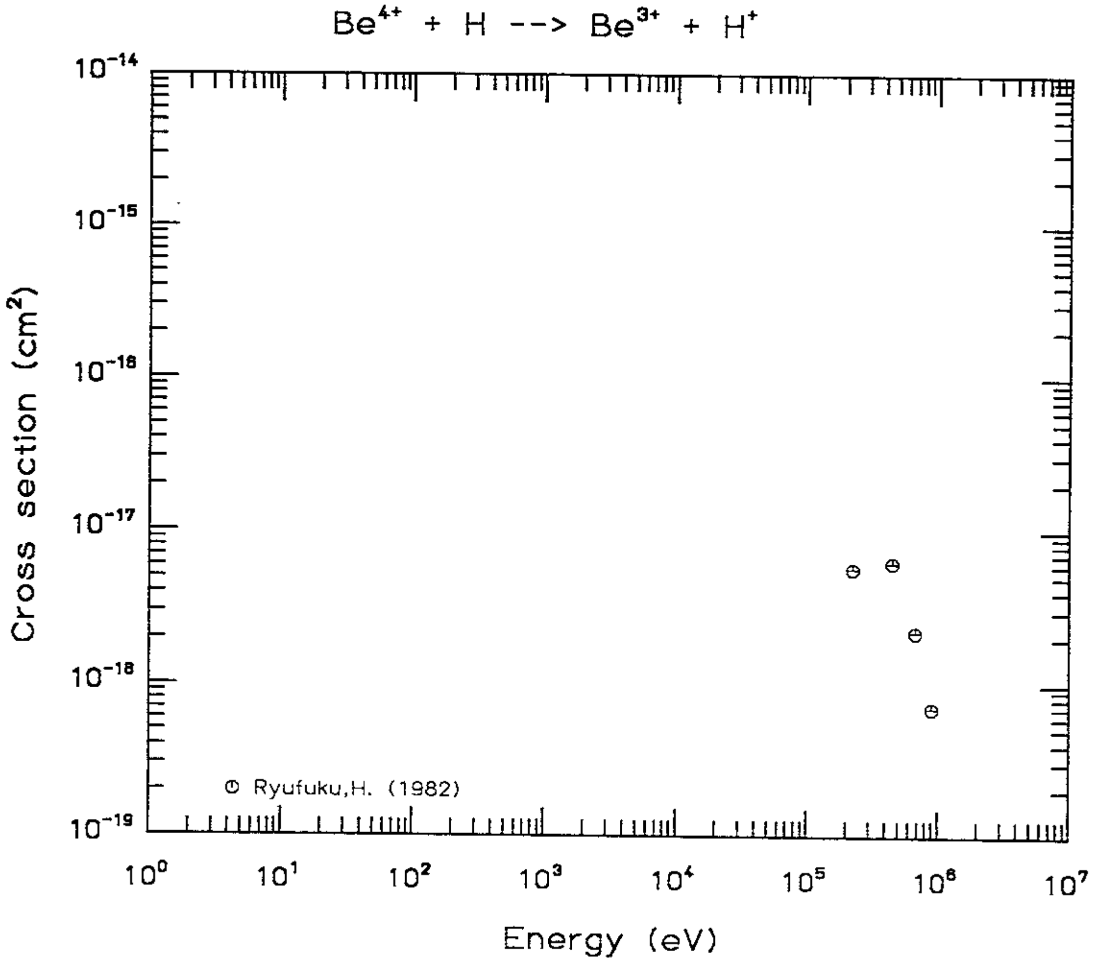

Fig.39 Partial cross sections into Be^{3+}(6h) in Be^{4+} + H collisions

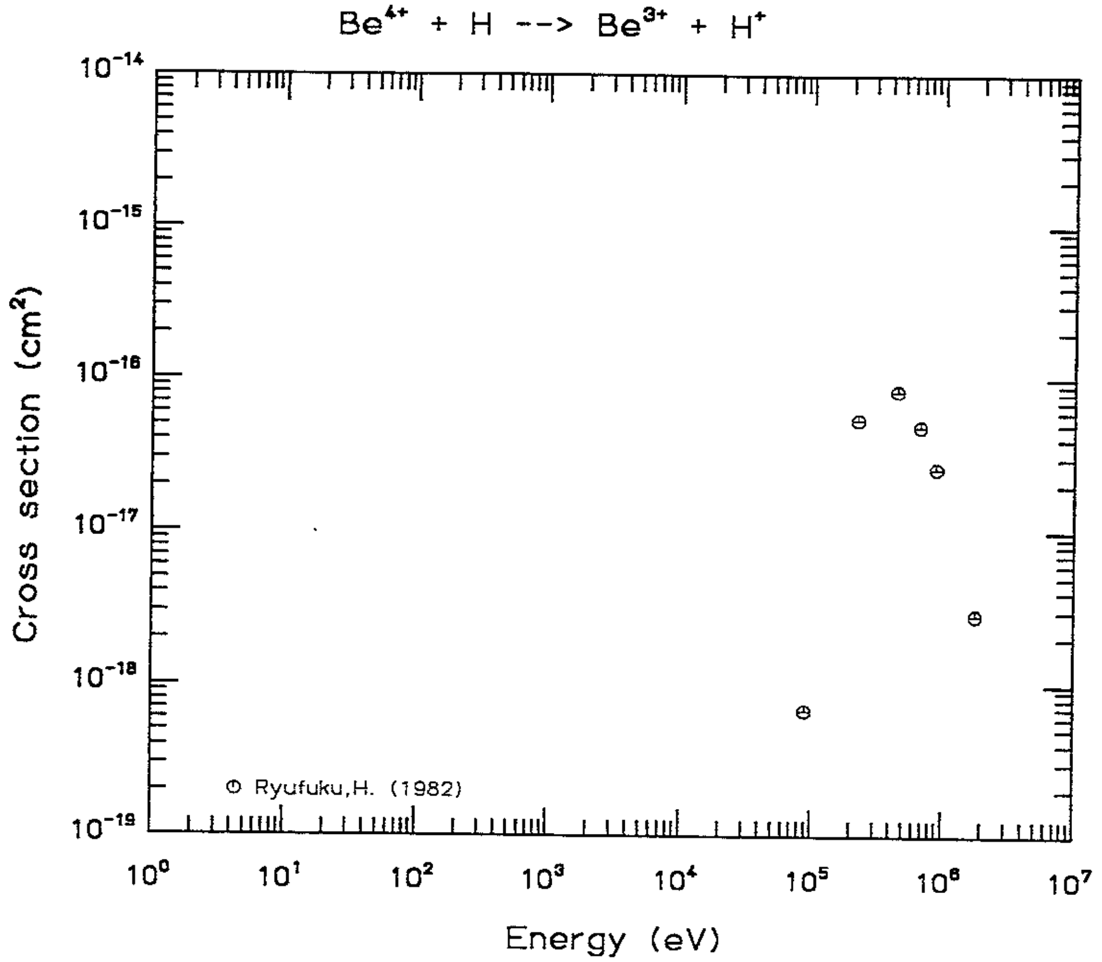

Fig.40 Partial cross sections into Be^{3+}(n=6) in Be^{4+} + H collisions

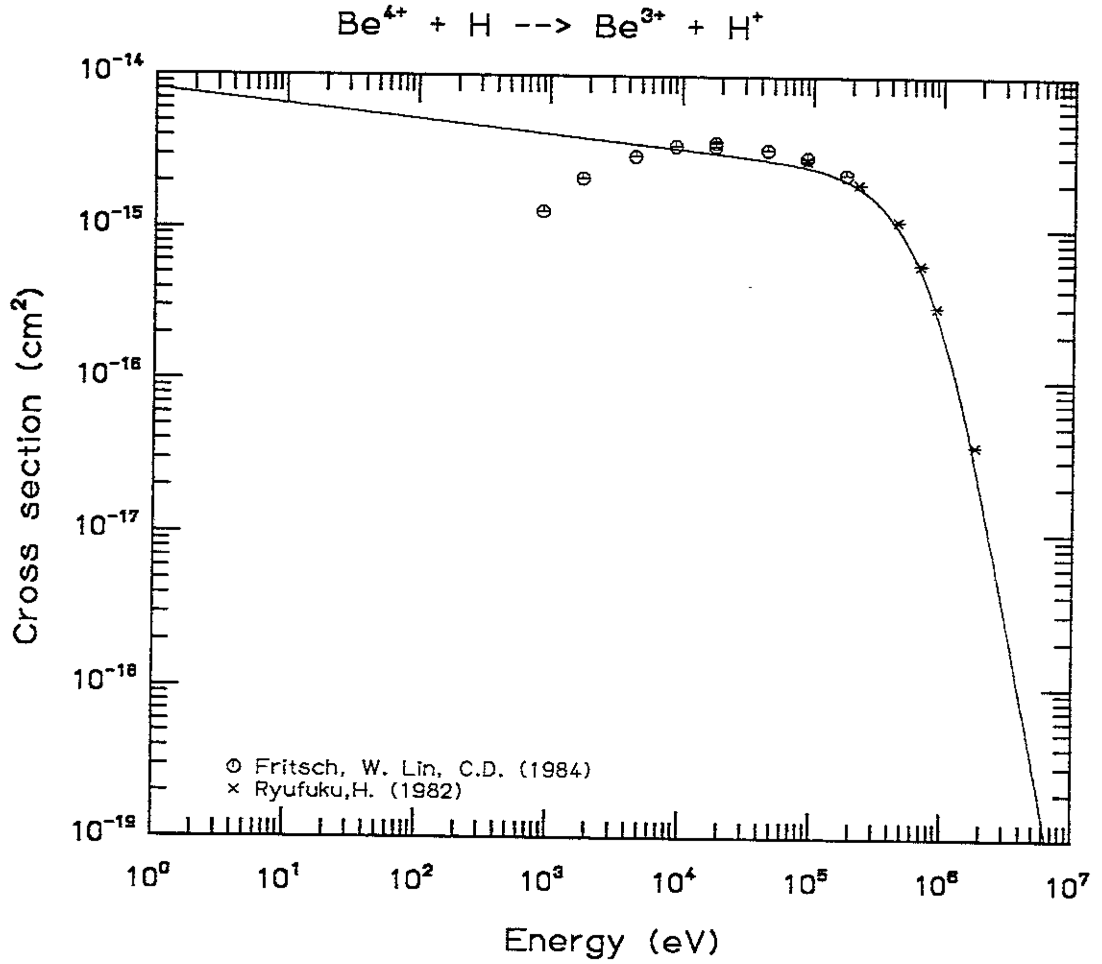

Fig.41 Total cross sections into Be^{3+} in Be^{4+} + H collisions

Be^{q+} + H_2 (Figs.42-44)

Only very few experimental data points for Be^+ ions have been reported by Sherwin at 1-3 keV/amu region. Also a few experimental total cross sections for Be^{q+} (q= 2,3,4) have been reported over the limited energy range by Takagi et al. No theoretical calculation has been performed up to now.

C.W.Sherwin, Phys. Rev. **57** (1940) 814

S.Takagi, S.Ohtani, K.Kadota and J.Fujita, J. Phys. Soc. Japan **52** (1983) 3759

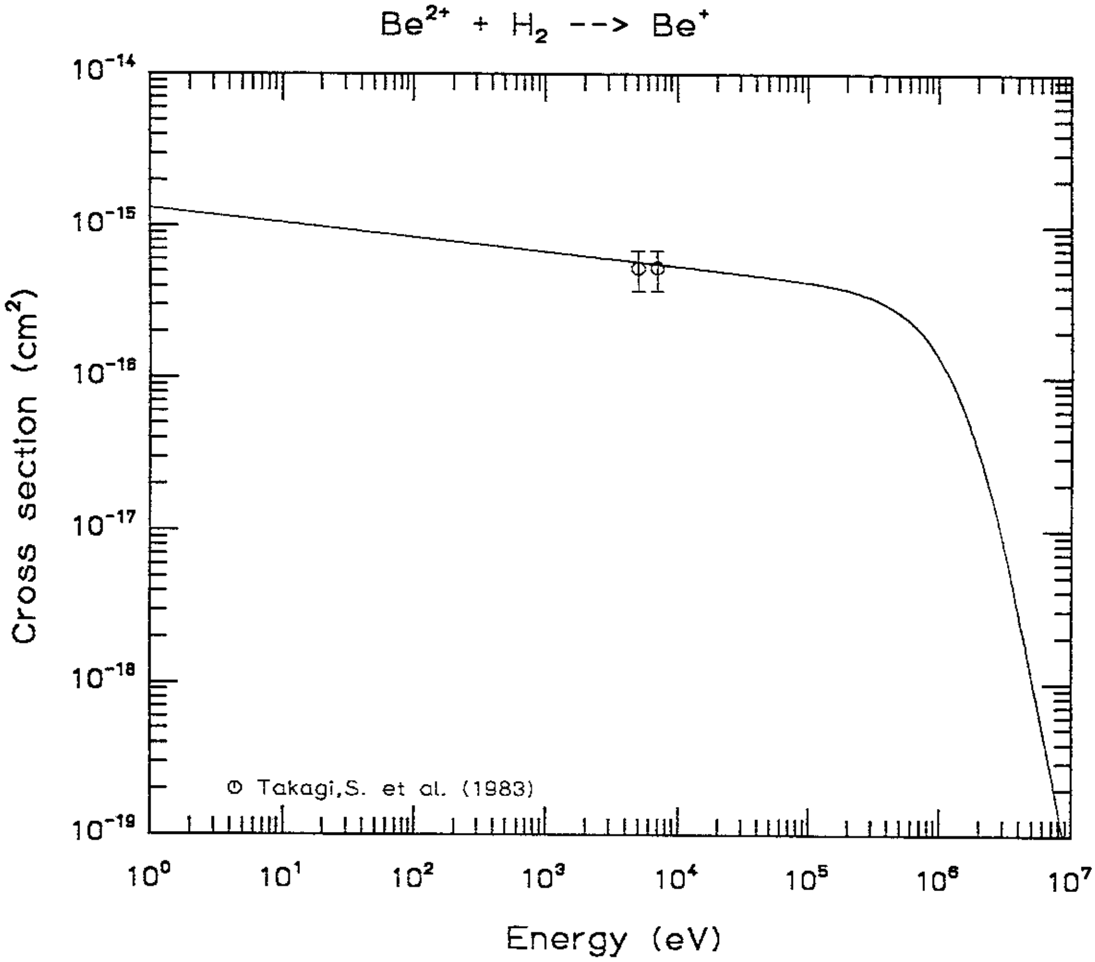

Fig.42 Total cross sections into Be^+ in Be^{2+} + H_2 collisions

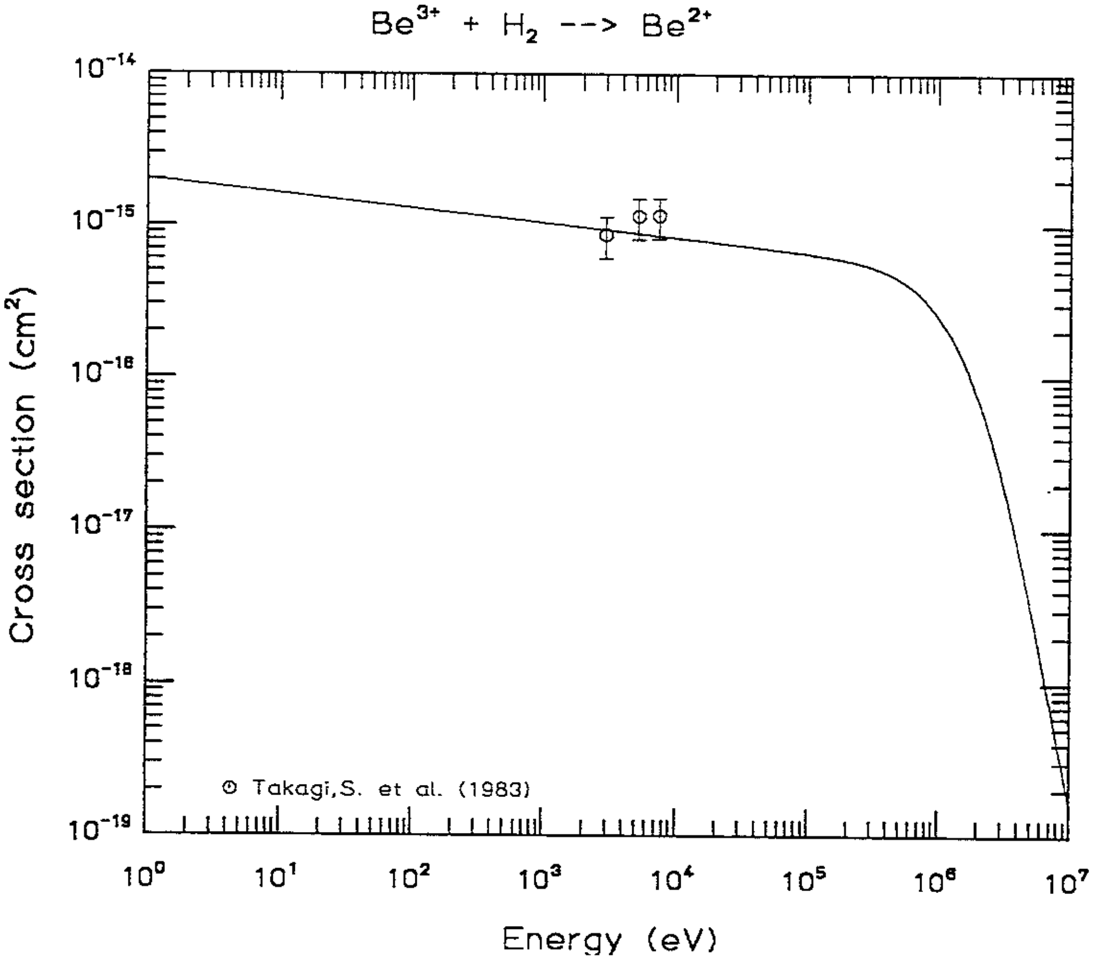

Fig.43 Total cross sections into Be^{2+} in Be^{3+} + H_2 collisions

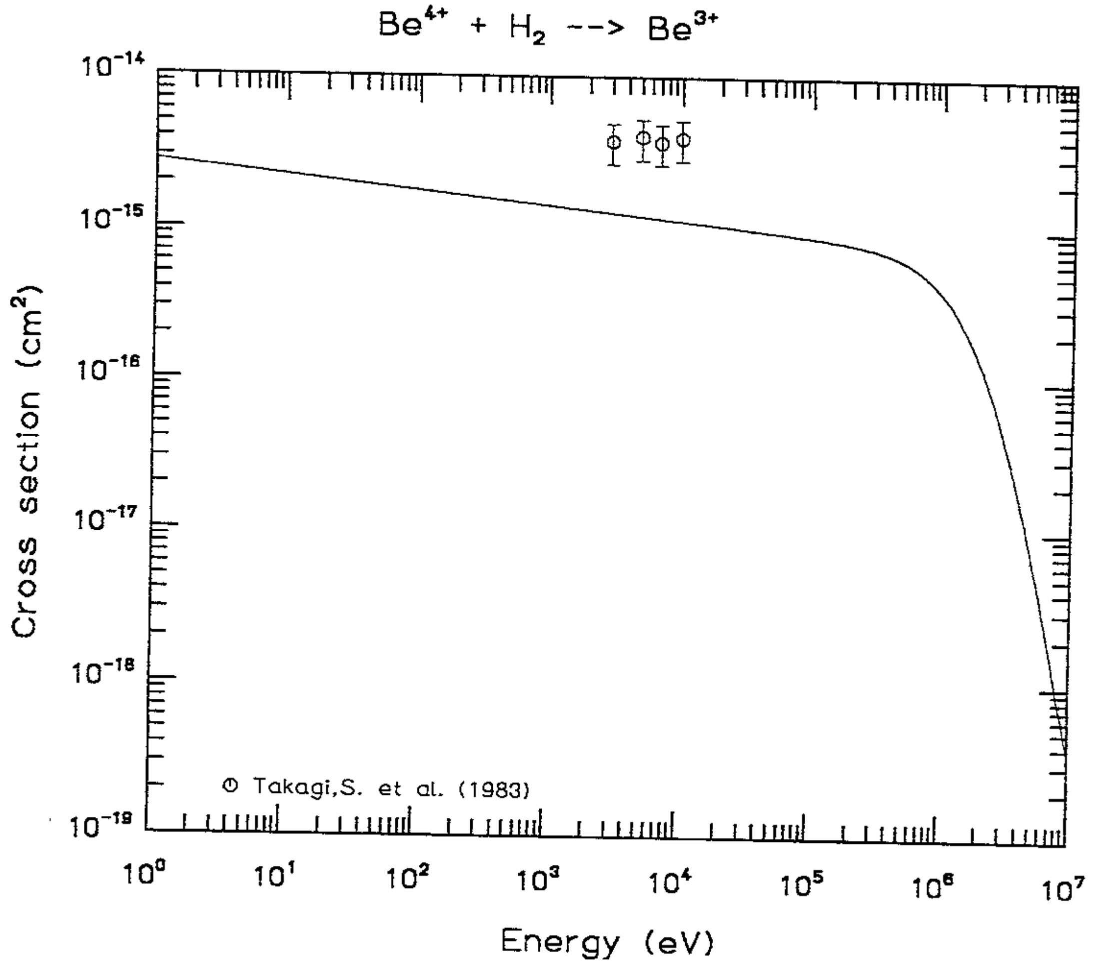

Fig.44 Total cross sections into Be^{3+} in Be^{4+} + H_2 collisions

Be^{q+} + He

No measurement has been reported for B^{q+} ions in collisions with He targets up to now. Some theoretical calculations have been performed only for Be^{4+} ions.

Be^{4+} + He (Fig.45)

Only a few theoretical results for total cross sections have been reported by Olson based upon classical Monte Carlo technique and Suzuki et al.(0.1-1000 keV/amu) using EDWA (exponential distorted wave approximation). On the other hand, Martin et al., using Feshbach method, have calculated the cross sections for single electron capture into Be^{3+}(2s+2p) as well as double electron capture into $Be^{2+}(2s^2+2s2p+2p^2)$ over 0.25 - 25 keV/amu region. A comparison of calculations by Suzuki et al. and Martin et al. indicates that the contribution to total cross sections by the (2s+2p) states is dominant at intermediate energy range but becomes small below 1 keV/amu.

R.E.Olson, Phys. Rev. A **18** (1978) 2464

H.Suzuki, Y.Kajikawa, N.Toshima, H. Ryufuku and T.Watanabe, Phys. Rev. A **29** (1984) 525

F.Martin, A.Riera and M.Yanez, Phys. Rev. A **34** (1986) 4675

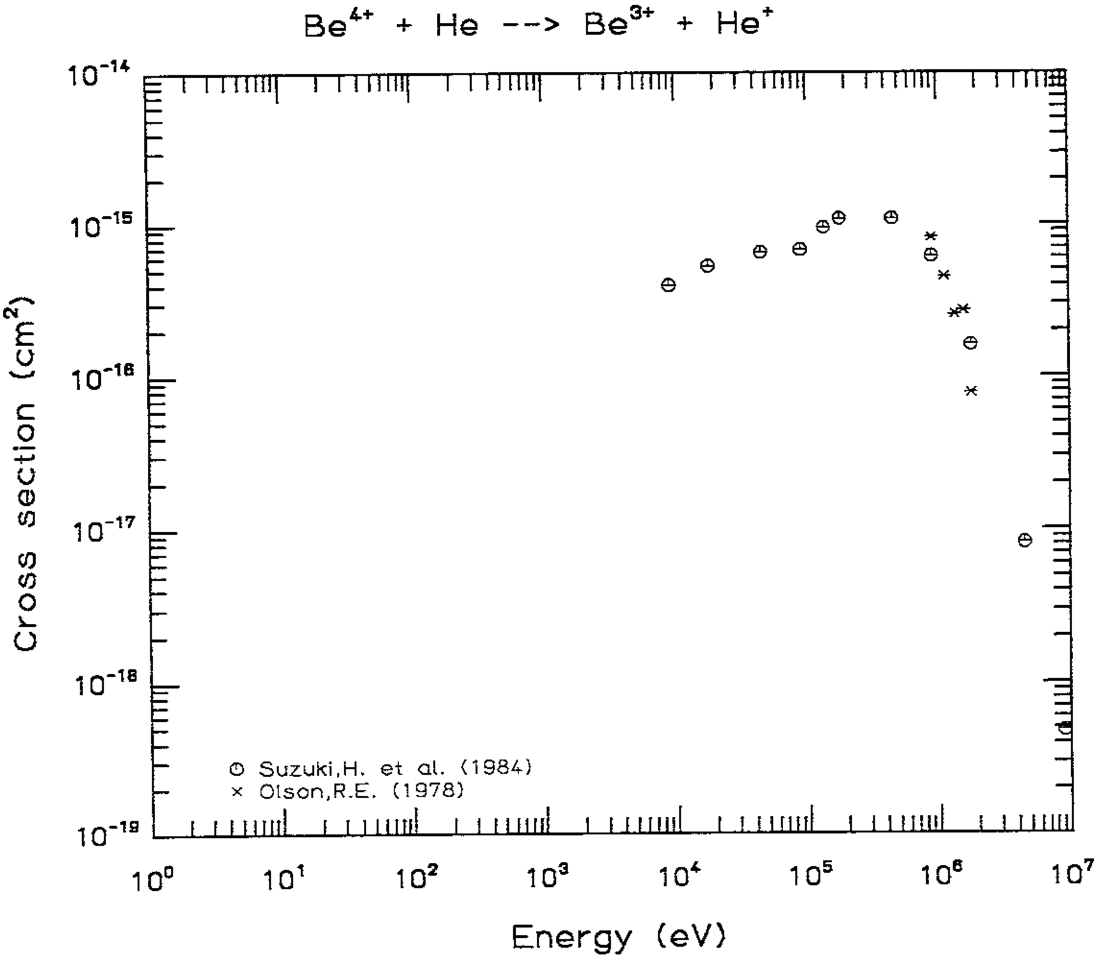

Fig.45 Total cross sections into Be^{3+} in Be^{4+} + He collisions

B^{q+} + H

B^{+} + H (Fig.46)

Only a single set of data for total cross sections have been reported by Goffe et al. at relatively high energies.

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

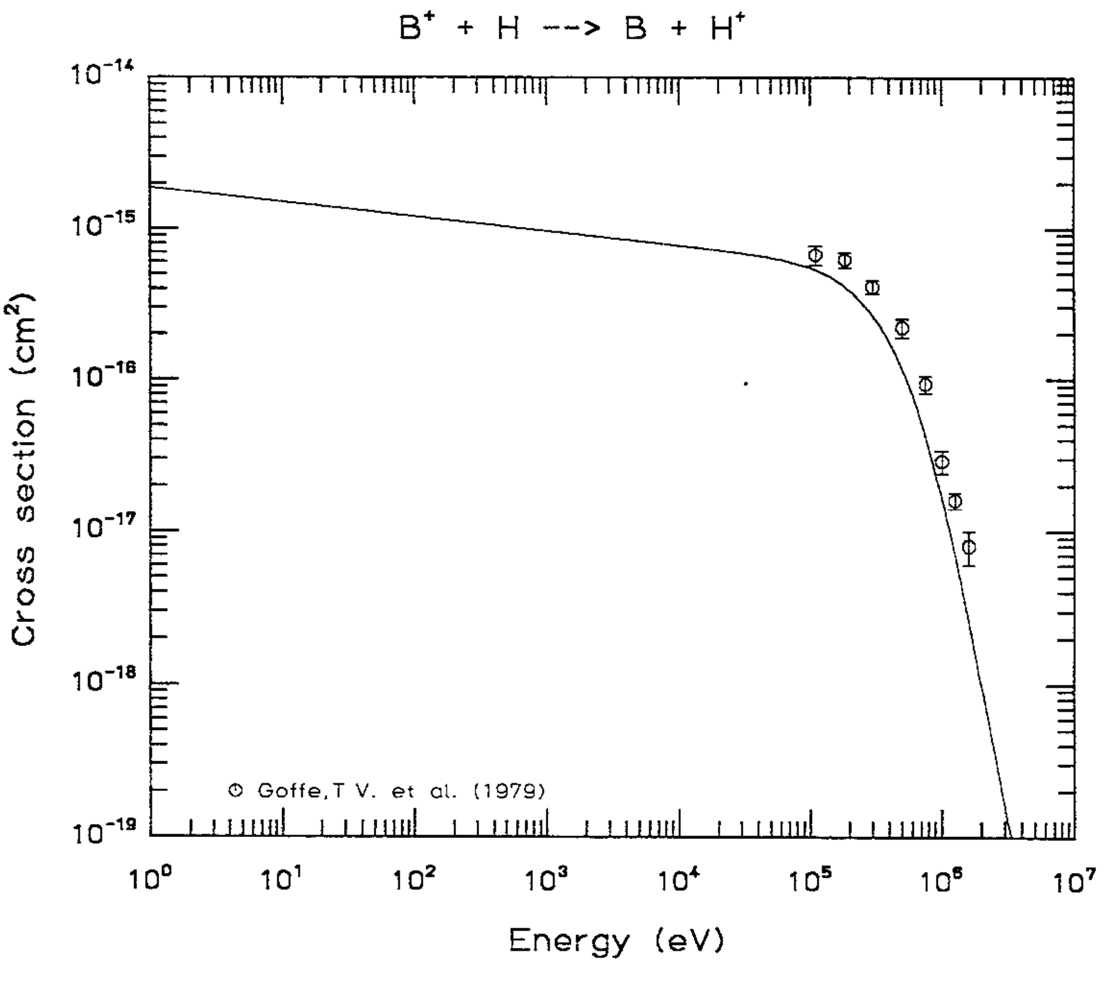

Fig.46 Total cross sections into B in B^{+} + H collisions

B^{2+} + H (Fig.47)

Relatively reliable sets of data are available for total cross sections measured by Goffe et al., Crandall, McCullough et al. and Gardner et al. over a wide range of the collision energy. All are in good agreement with each other. Clearly the cross sections below 1 keV/amu begin to decrease drastically with decreasing the energy, as expected. No partial cross sections, experimental as well as theoretical, have been reported yet.

A.Dalgarno, Proc. Phys. Soc. A **67** (1954) 1010

D.H.Crandall, Phys. Rev. A **16** (1977) 958

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

D.S.F.Crothers and N.R.Todd, J. Phys. B **13** (1980) 547

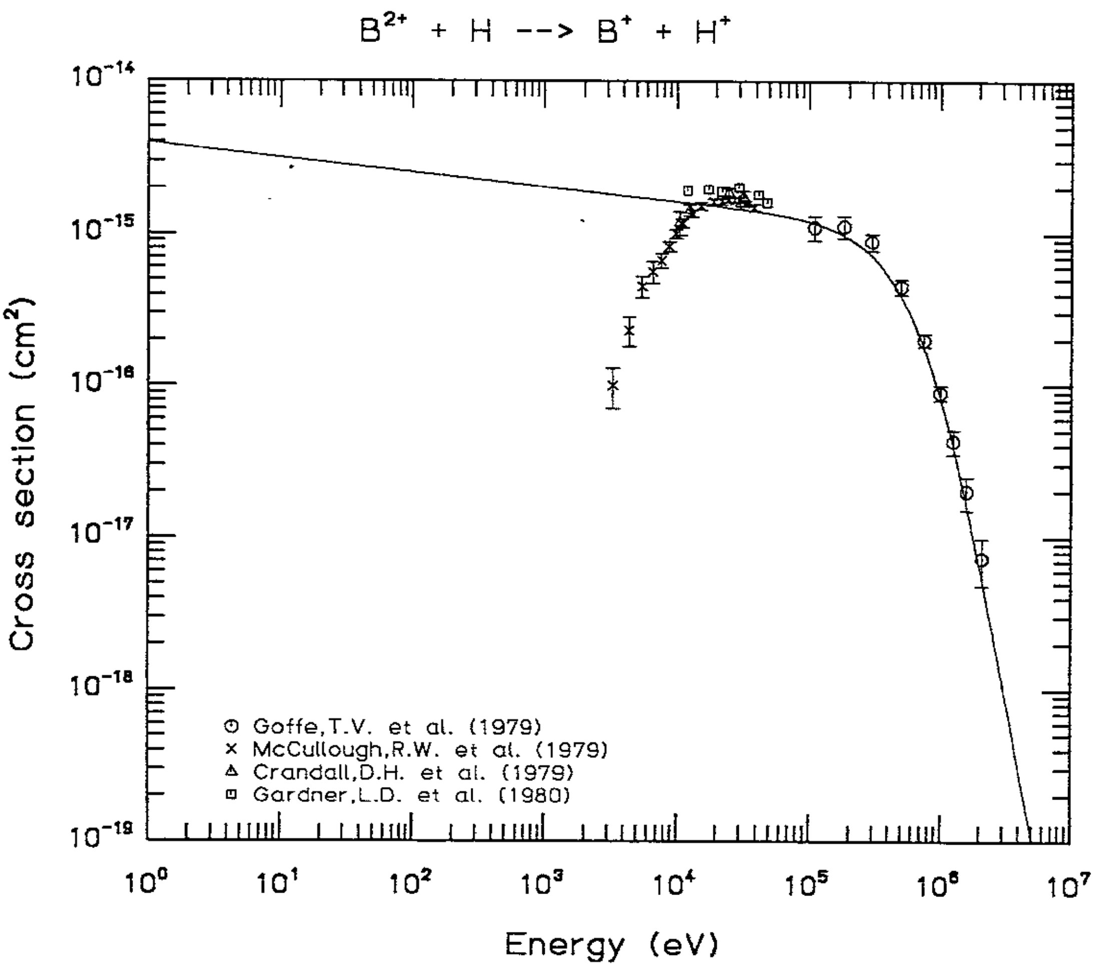

Fig.47 Total cross sections into B^{+} in B^{2+} + H collisions

B^{3+} + H (Fig.48)

Three sets of measurements of total cross sections seem to be in agreement with each other and show sharp reduction at low energies. Theoretical calculations by Wetmore et al. and by Olson et al. for total cross sections show reasonable agreement with these measurements, though those by Olson et al. show some oscillatory behavior at lower energies.

Calculation of total cross sections at higher energies has been reported by Olson and Salop.

D.H.Crandall, Phys. Rev. A **16** (1977) 958

R.E.Olson and A.Salop, Phys. Rev. A **16** (1977) 531

A.Dalgarno and S.E.Butler, Comments At. Mol. Phys. **7** (1978) 129

R.E.Olson, E.J.Shipsey and J.C.Browne, J. Phys. B **11** (1978) 699

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

H.Ryufuku, K.Sasaki and T.Watanabe, Phys. Rev. A **21** (1980) 745

A.E.Wetmore, H.R.Cole and R.E.Olson, J. Phys. B **19** (1986) 1515

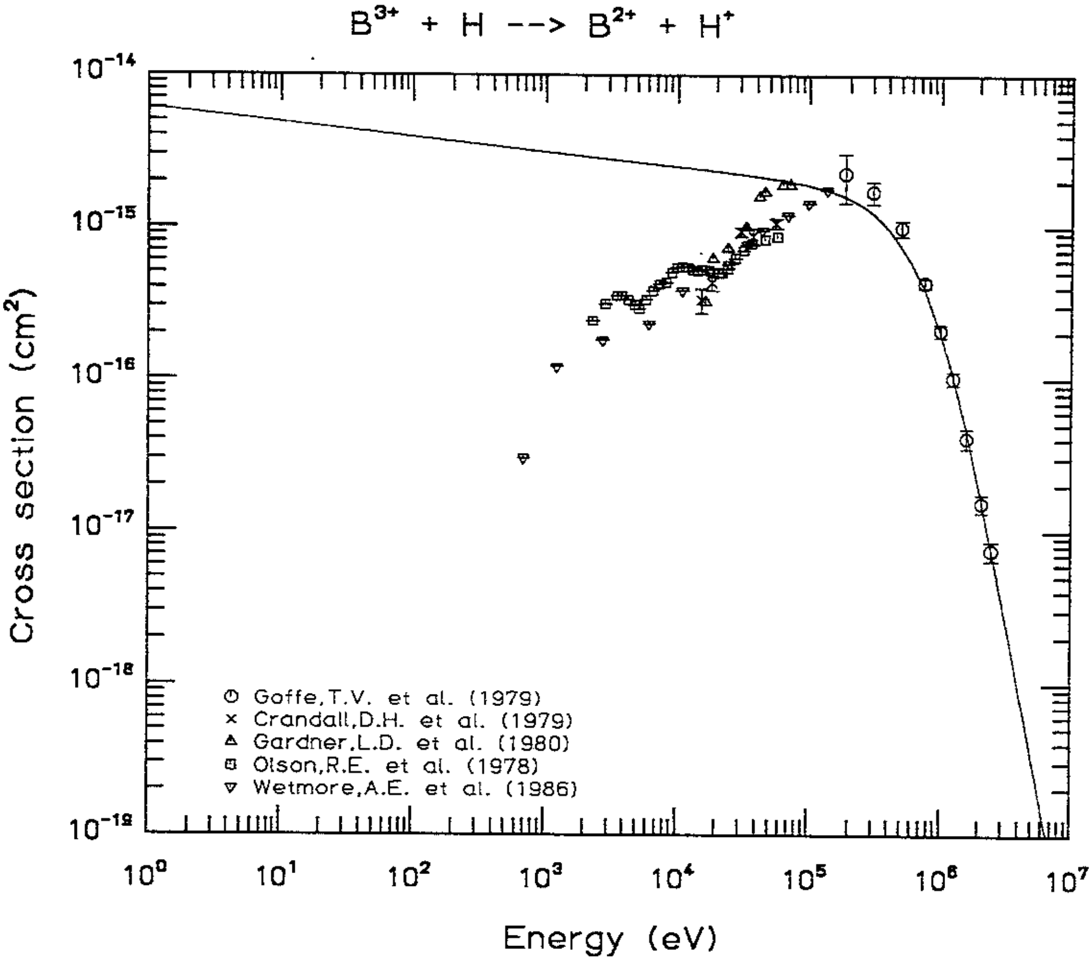

Fig.48 Total cross sections into B^{2+} in B^{3+} + H collisions

B^{4+} + H (Fig.49)

Three measurements of total cross sections seem to be reasonably reliable. It should be noted that the cross sections do not decrease but show somewhat flat behavior at lower energies. Calculation by Olson and Salop at 10 - 150 keV/amu is in agreement with experimental results.

R.E.Olson and A.Salop, Phys. Rev. A **16** (1977) 531
D.H.Crandall, Phys. Rev. A **16** (1977) 958
L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766
T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763
H.Ryufuku, K.Sasaki and T.Watanabe, Phys. Rev. A **21** (1980) 745
Dz.Belkic, S.Saini and H.S.Taylor, Phys. Rev. A **36** (1987) 1601

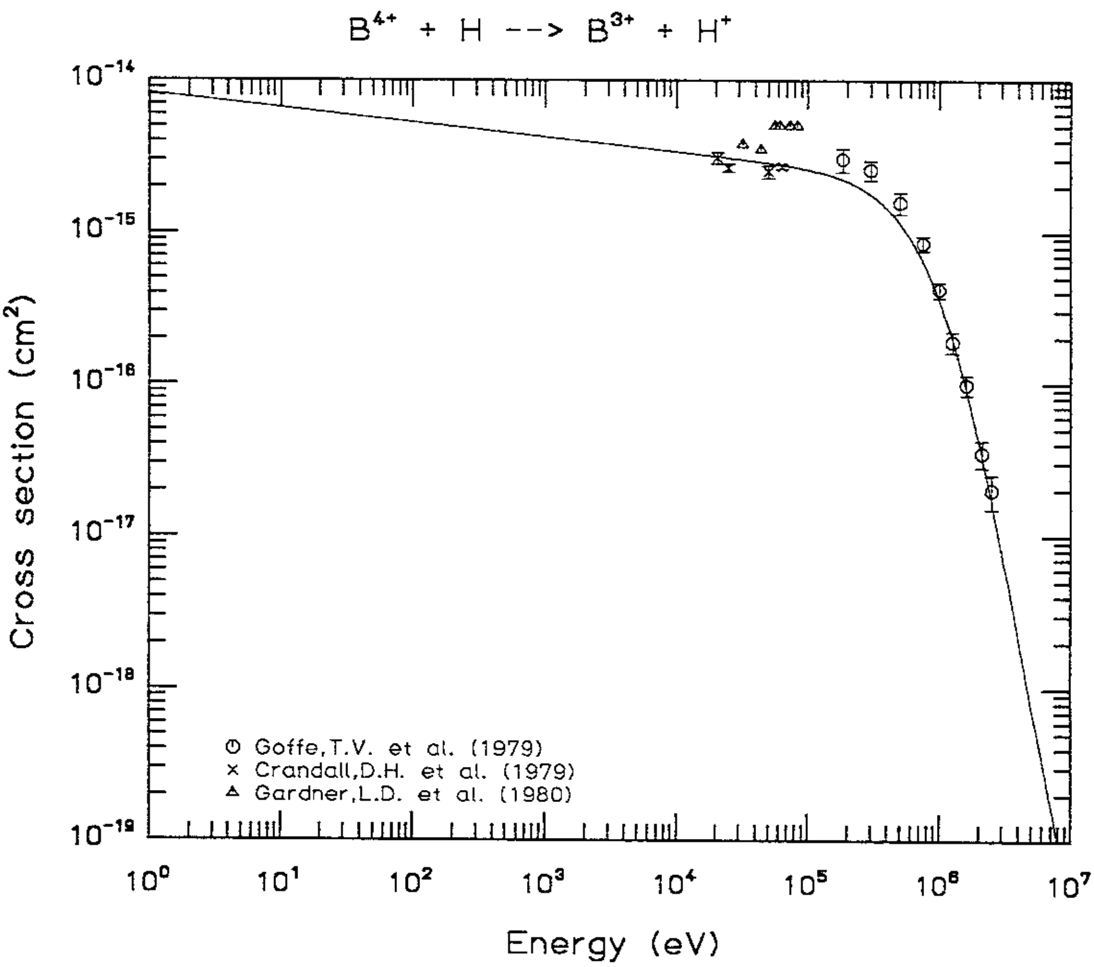

Fig.49 Total cross sections into B^{3+} in B^{4+} + H collisions

B^{5+} + H (Figs.50-83)

Only total cross sections have been measured by Goffe et al. and Crandall at intermediate energies. Calculation by Olson and Salop at high energy region seems to be in reasonable agreement with those observed. Also theoretical results for total cross sections have been given by Bransden et al., Kimura and Thorson, and Bendahman et al. Partial cross sections have been systematically by Ryufuku and Fritsch and Lin.

R.E.Olson and A.Salop, Phys. Rev. A **16** (1977) 531

D.H.Crandall, Phys. Rev. A **16** (1977) 958

C.Bottcher, J. Phys. B **10** (1977) L213

C.Harel and A.Salin, J. Phys. B **10** (1977) 351

E.L.Duman and B.M.Smirnov, Sov. J. Plasma Phys. **4** (1978) 650

A.Salop, J. Phys. B **12** (1979) 919

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

B.H.Bransden, C.W.Newby and C.J.Noble, J. Phys. B **13** (1980) 4245

H.Ryufuku, K.Sasaki and T.Watanabe, Phys. Rev. A **21** (1980) 745

D.S.F.Crothers, J. Phys. B **14** (1981) 1035

J.K.M.Eichler, Phys. Rev. A **23** (1981) 498

R.E.Olson, Phys. Rev. A **24** (1981) 1726

H.J.Ludde and R.M.Dreizler, J. Phys. B **15** (1982) 2713

H.Ryufuku, Phys. Rev. A **25**(1982) 720

H.Ryufuku, JAERI Memo-82-031 (1982) (His previous results in Phys. Rev. A **19** (1979) 1538 have been revised here)

C.Bottcher and T.G.Heil, Chem. Phys. Letters **86** (1982) 506

M.Kimura and W.R.Thorson, J. Phys. B **16** (1983) 1471

H.Suzuki, N.Toshima, T.Watanabe and H.Ryufuku, Phys. Rev. A **29** (1984) 529

W.Fritsch and C.D.Lin, Phys. Rev. A **29** (1984) 3039

C.R.Mandal, S.Datta and S.C.Mukherjee, Phys. Rev. A **30** (1984) 1104

M.Bendahman, S.Bliman, S.Dousson, D.Hitz, R.Gayet, J.Hanssen, C.Harel and A.Salin, J. de Phys. **46** (1985) 561

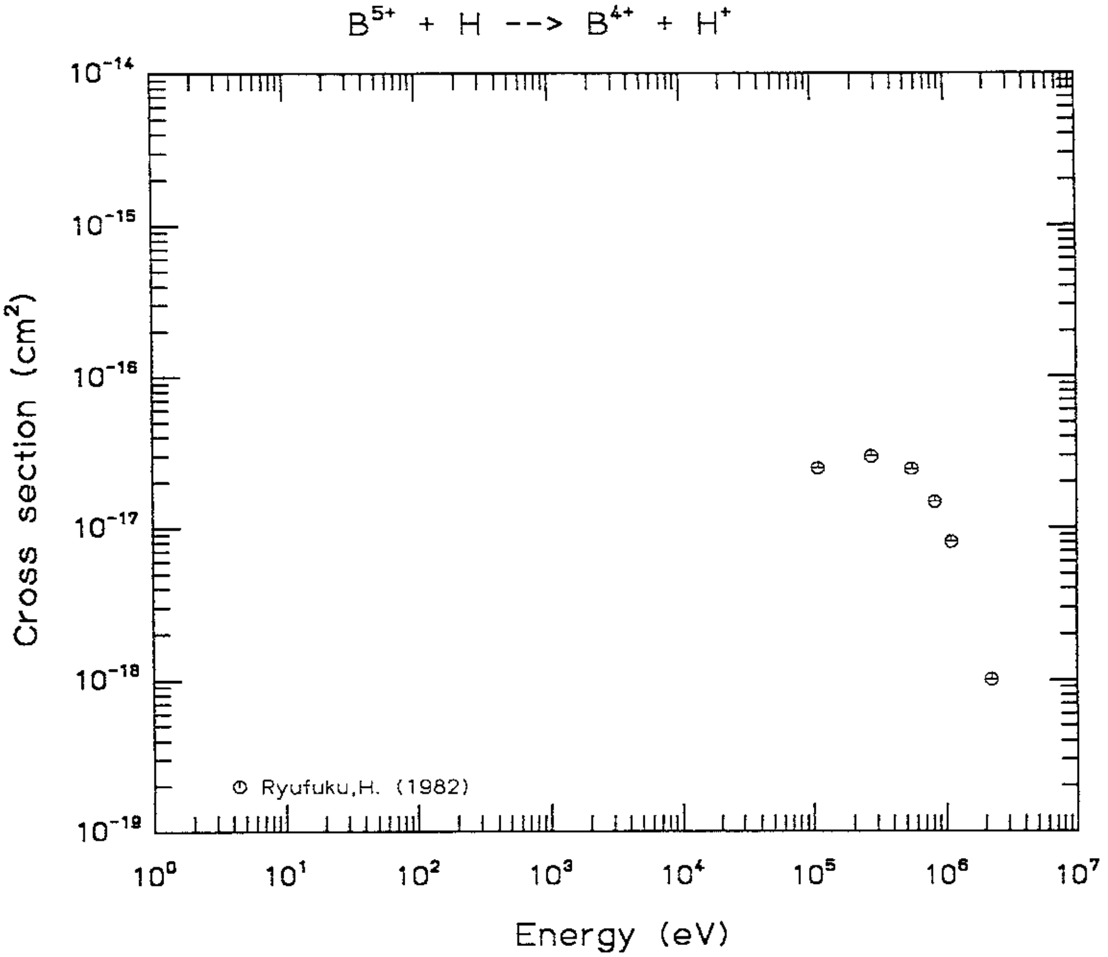

Fig.50 Partial cross sections into $B^{4+}(2s)$ in B^{5+} + H collisions

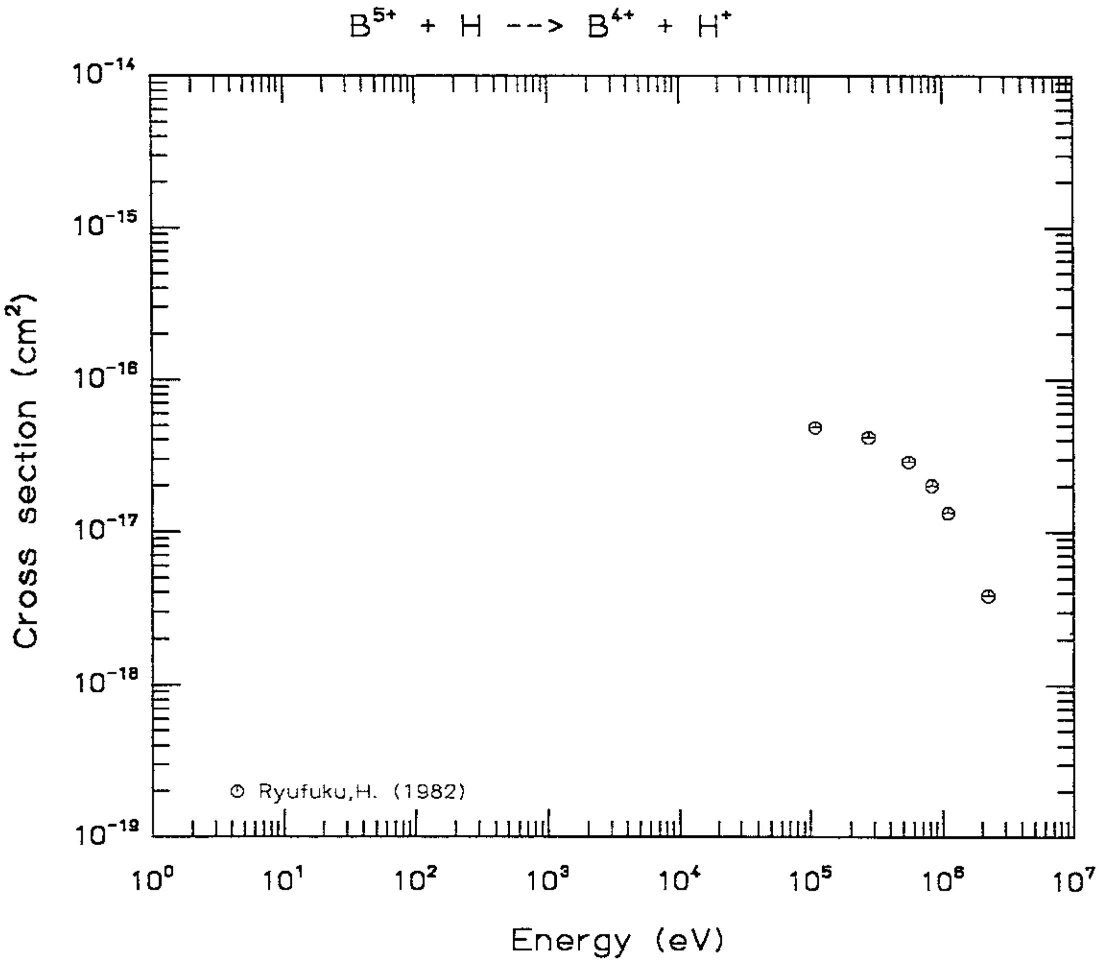

Fig.51 Partial cross sections into $B^{4+}(2p)$ in B^{5+} + H collisions

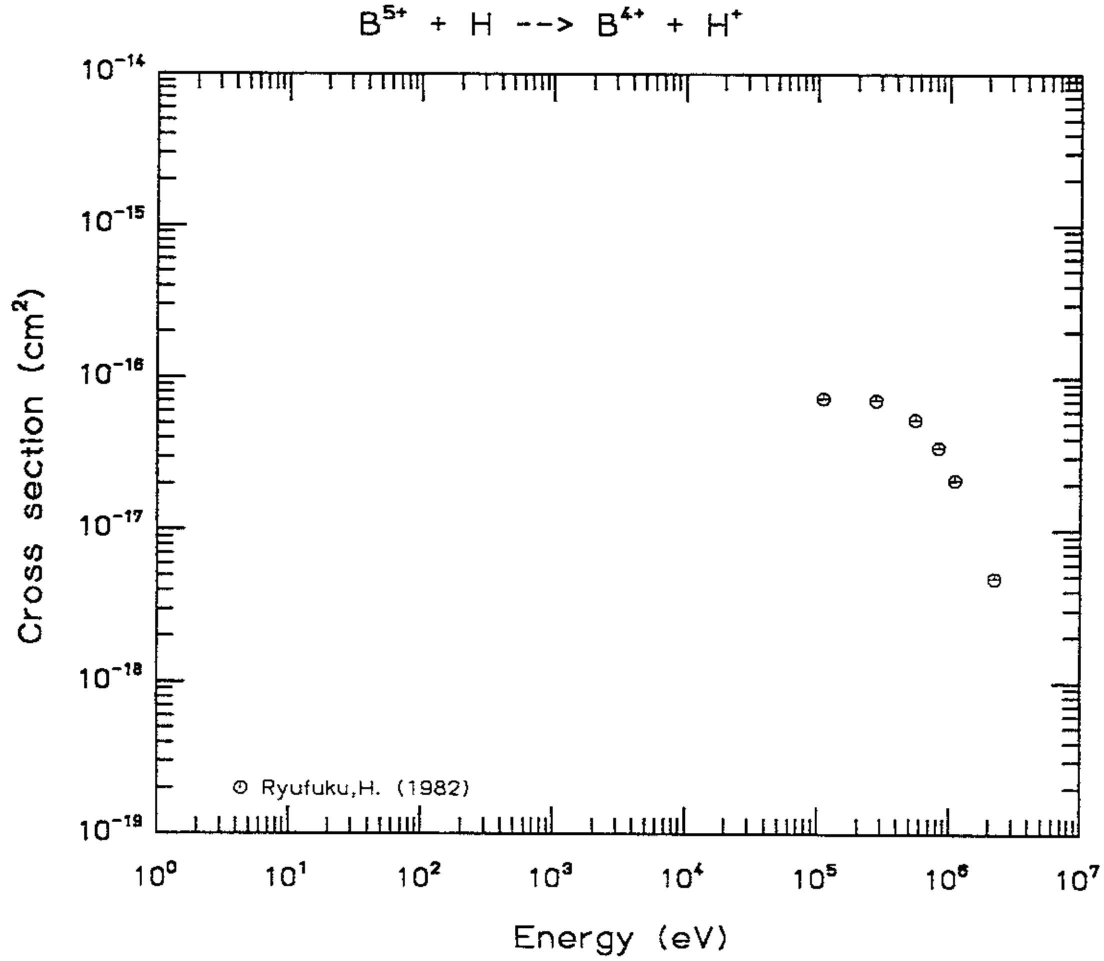

Fig.52 Partial cross sections into $B^{4+}(n=2)$ in B^{5+} + H collisions

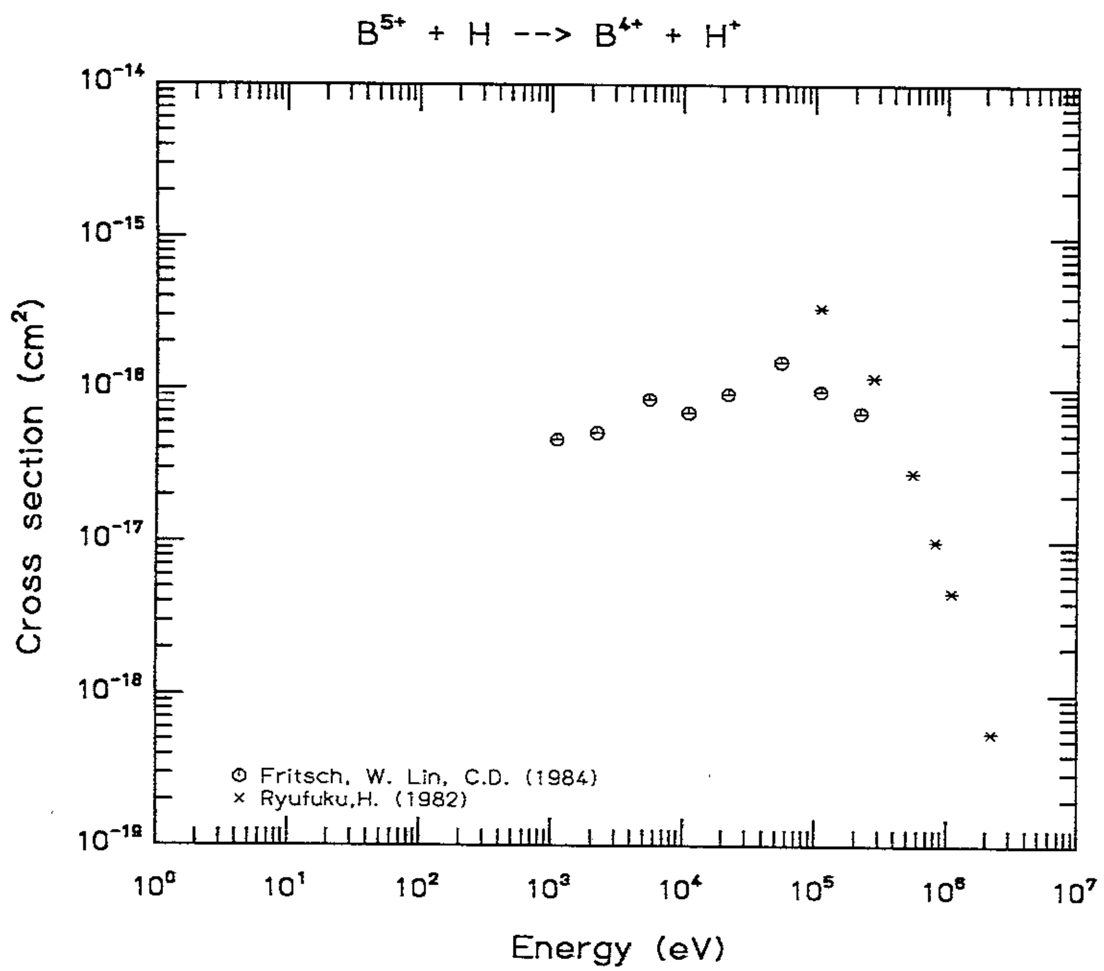

Fig.53 Partial cross sections into $B^{4+}(3s)$ in B^{5+} + H collisions

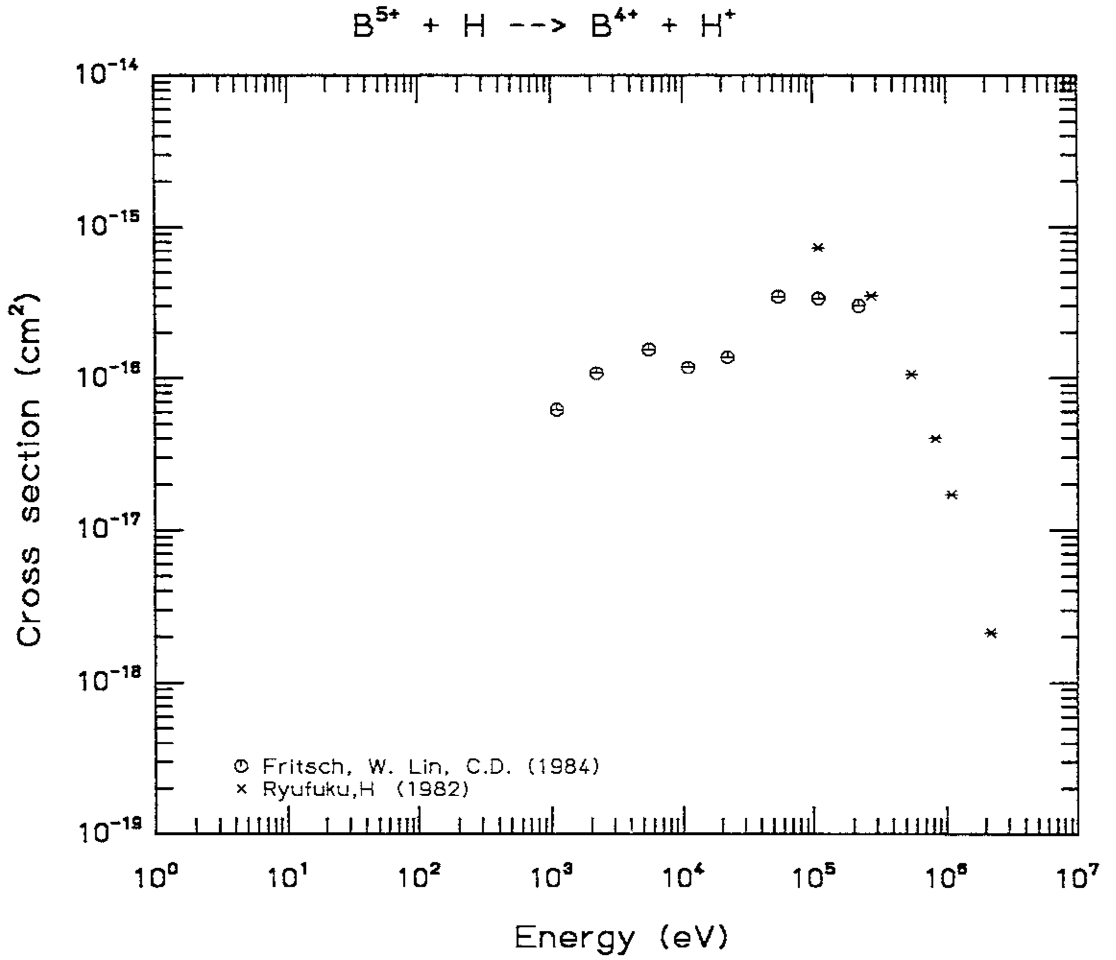

Fig.54 Partial cross sections into B^{4+}(3p) in B^{5+} + H collisions

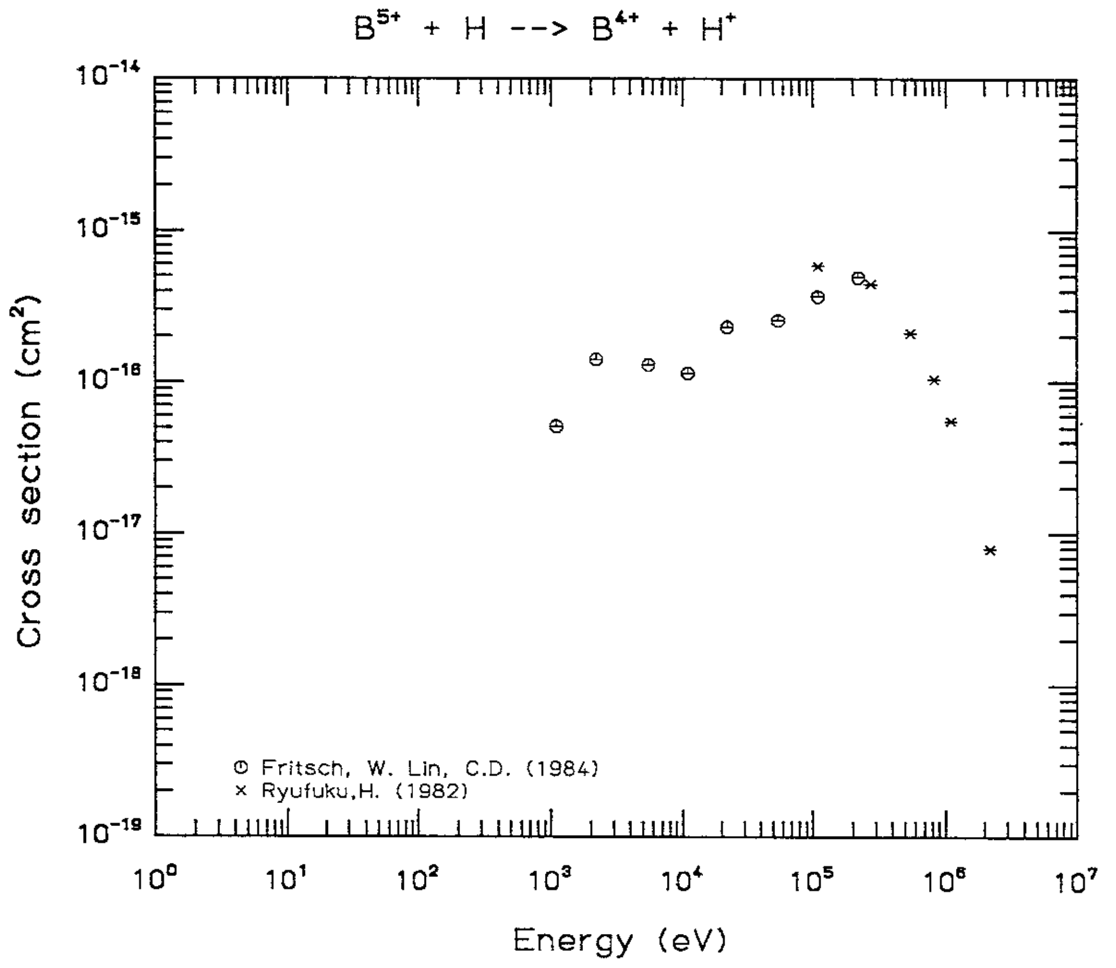

Fig.55 Partial cross sections into B^{4+}(3d) in B^{5+} + H collisions

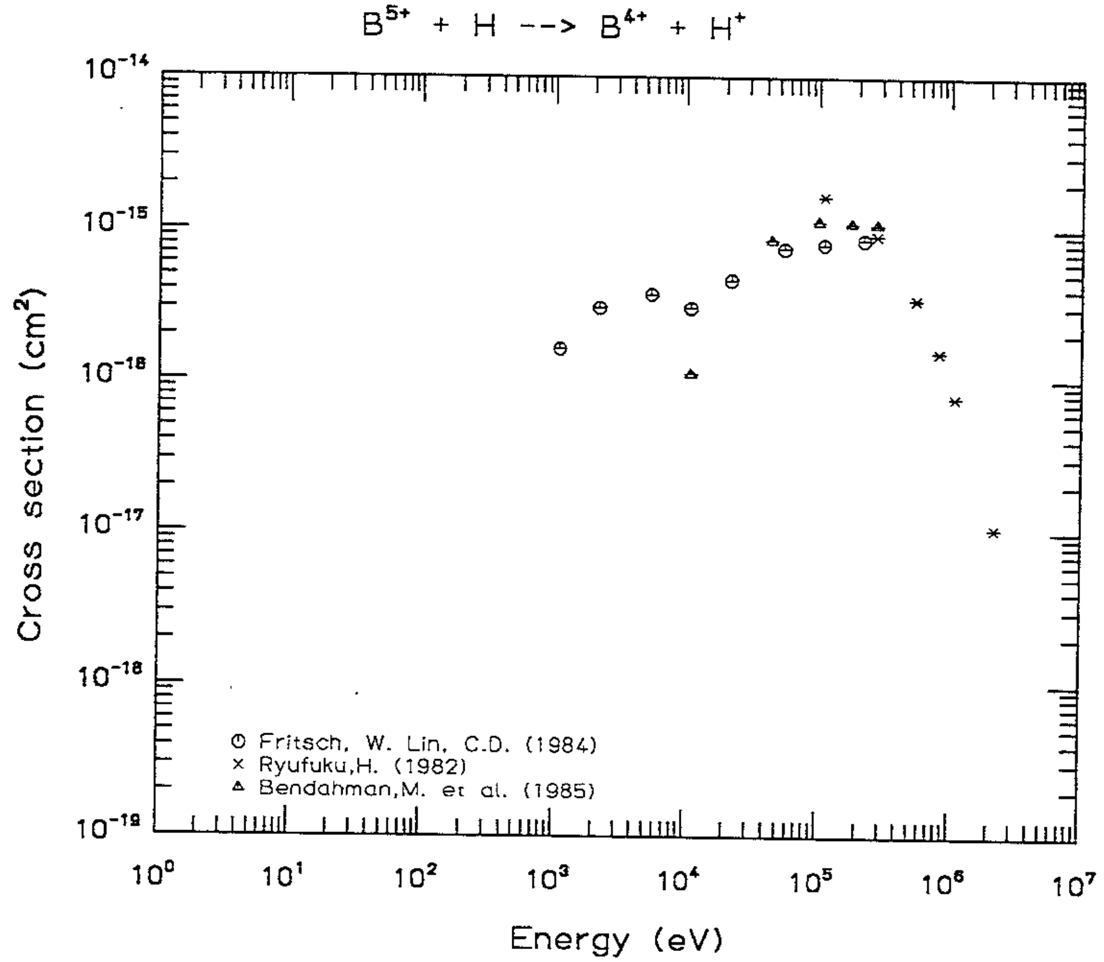

Fig.56 Partial cross sections into $B^{4+}(n=3)$ in B^{5+} + H collisions

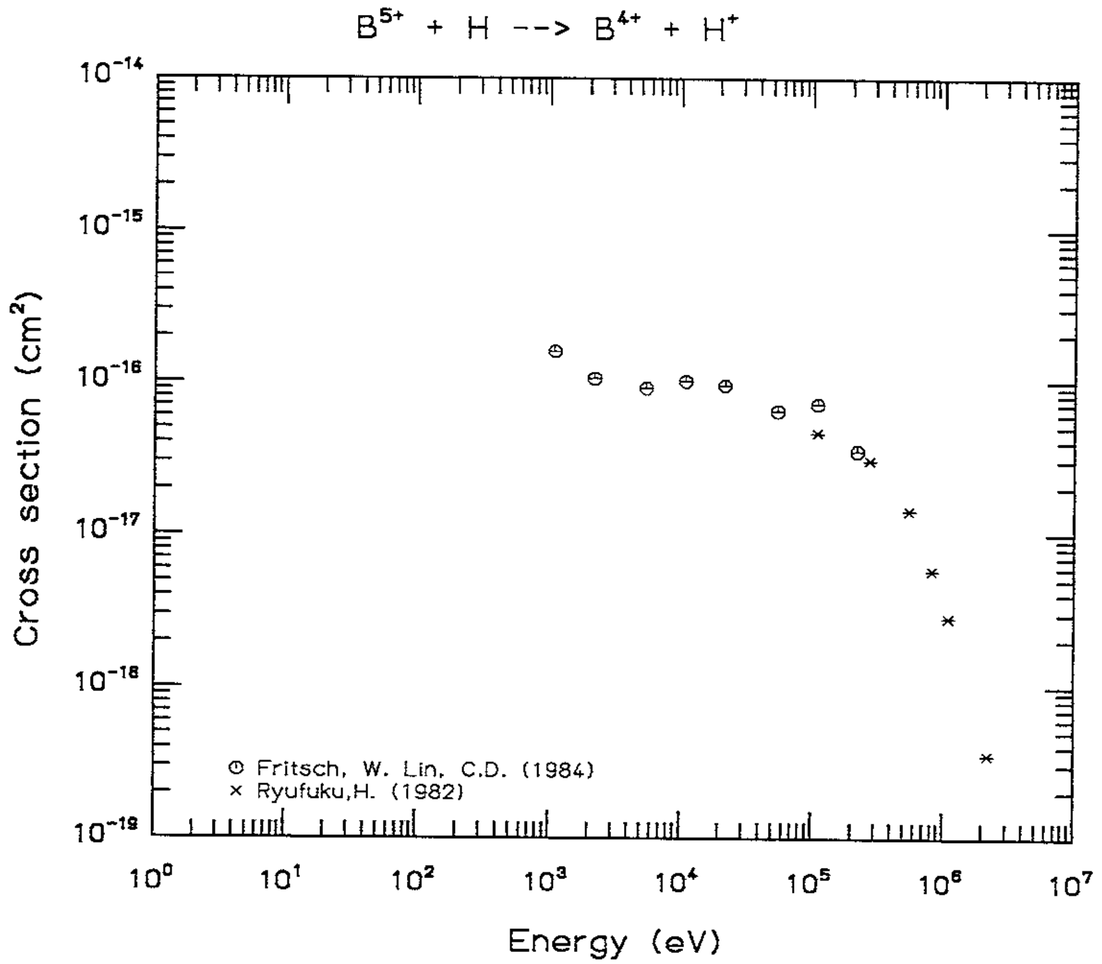

Fig.57 Partial cross sections into $B^{4+}(4s)$ in B^{5+} + H collisions

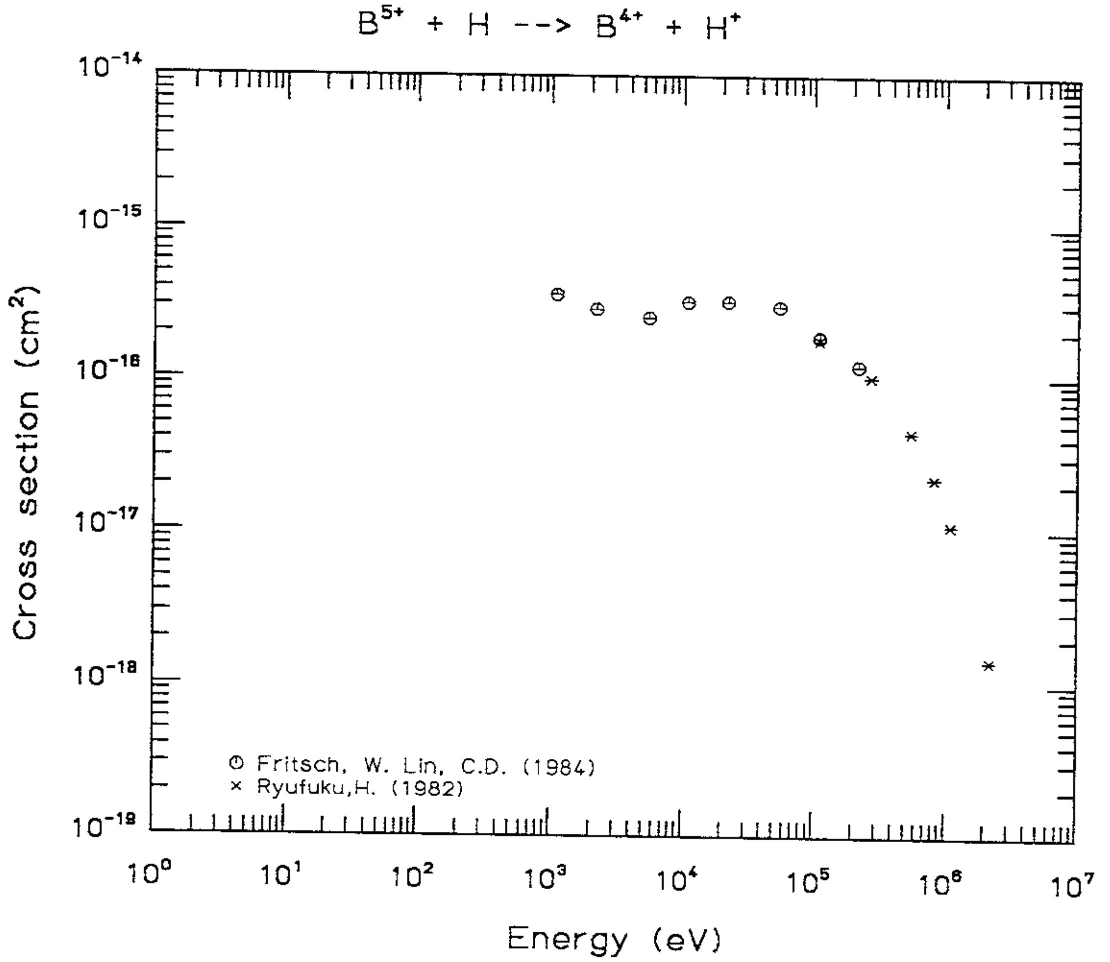

Fig.58 Partial cross sections into B^{4+}(4p) in B^{5+} + H collisions

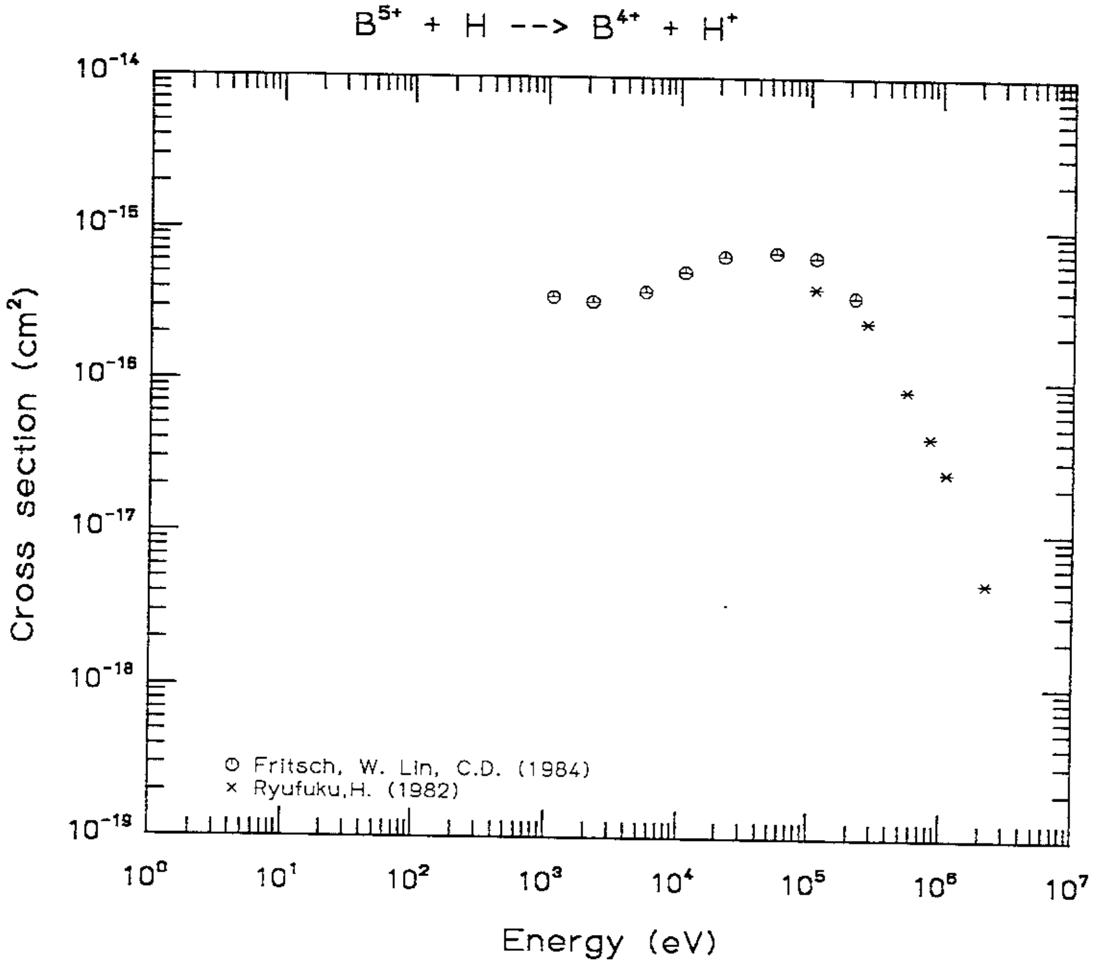

Fig.59 Partial cross sections into B^{4+}(4d) in B^{5+} + H collisions

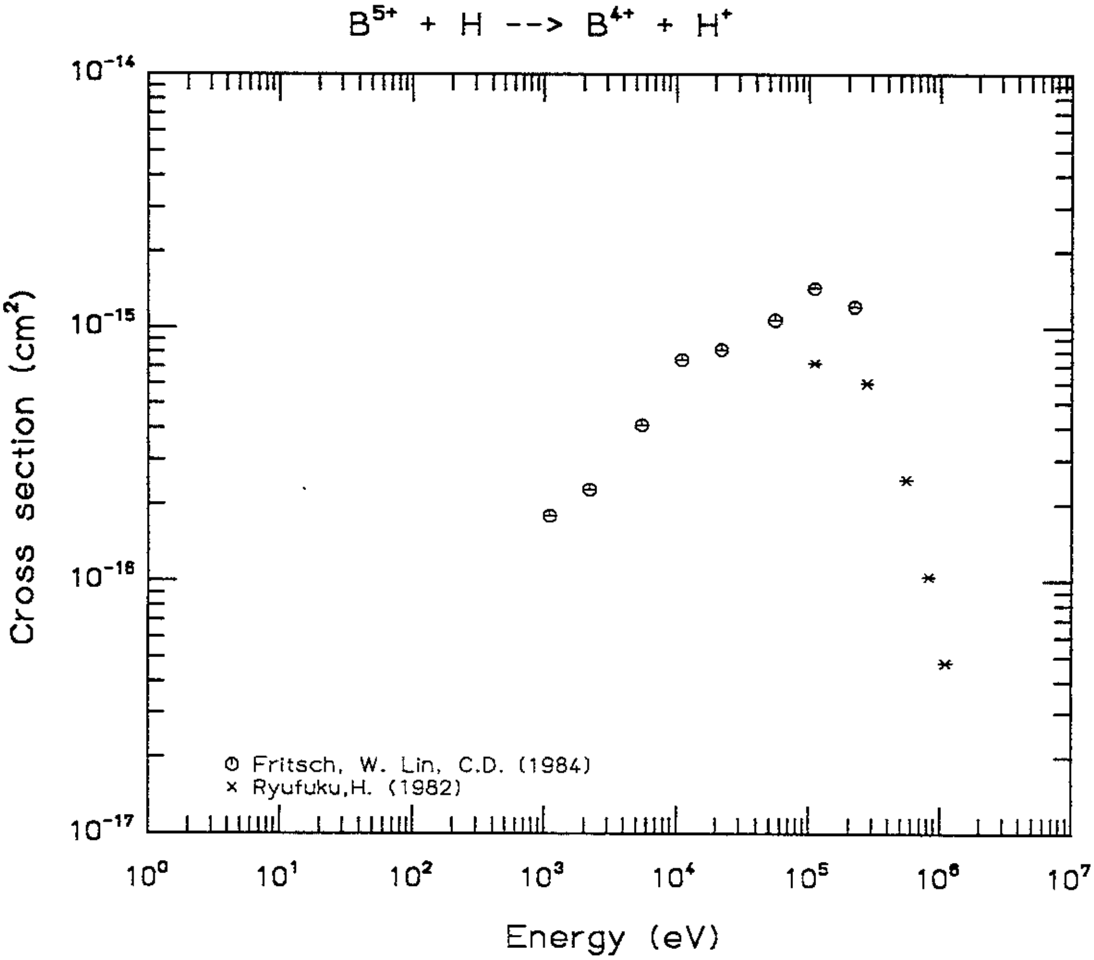

Fig.60 Partial cross sections into B^{4+}(4f) in B^{5+} + H collisions

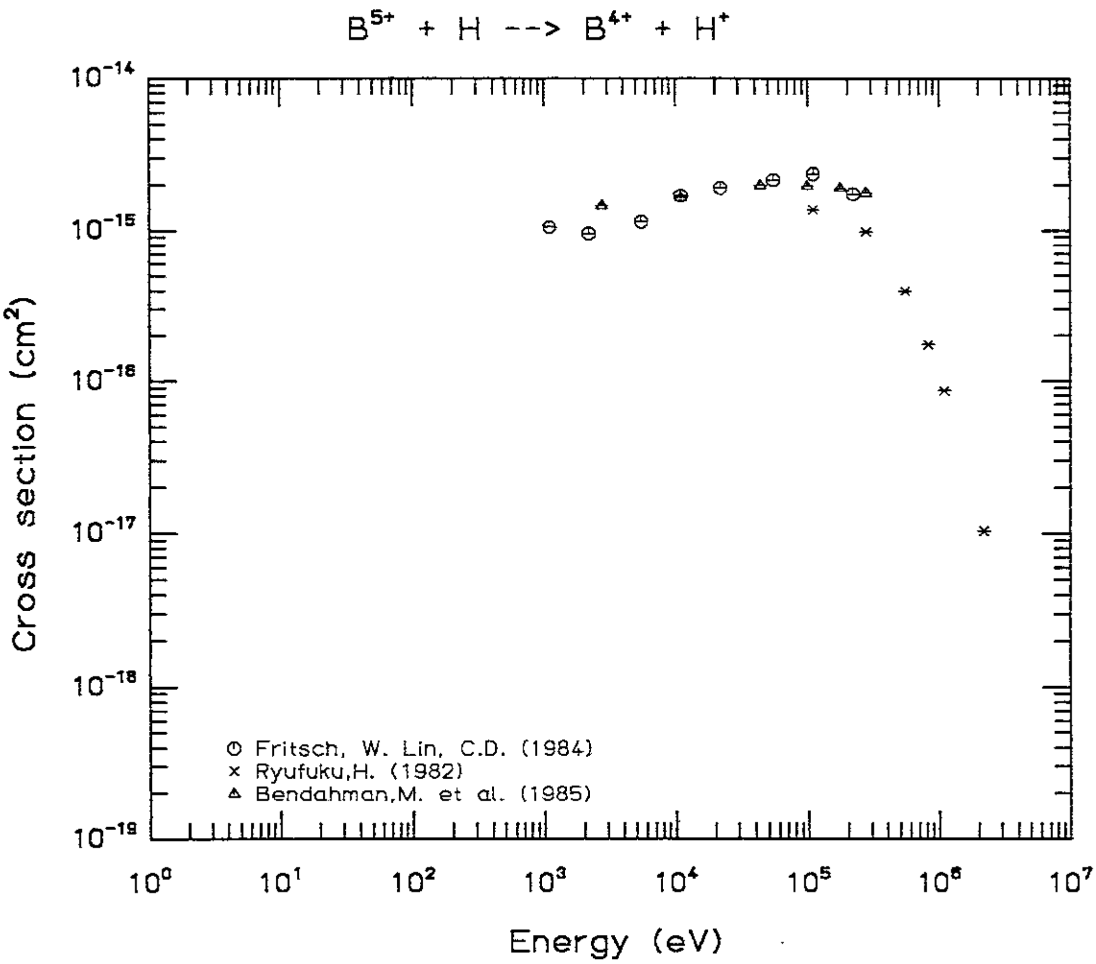

Fig.61 Partial cross sections into B^{4+}(n=4) in B^{5+} + H collisions

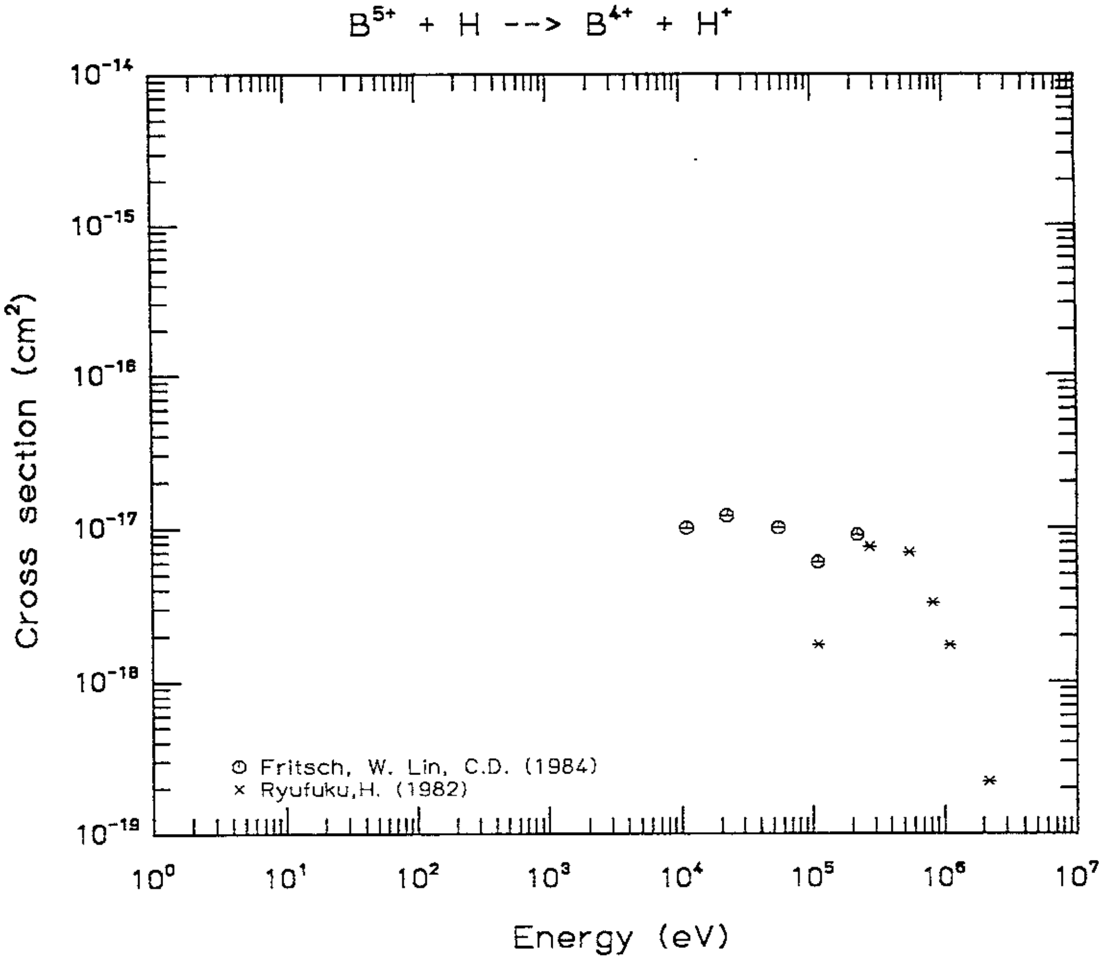

Fig.62 Partial cross sections into $B^{4+}(5s)$ in B^{5+} + H collisions

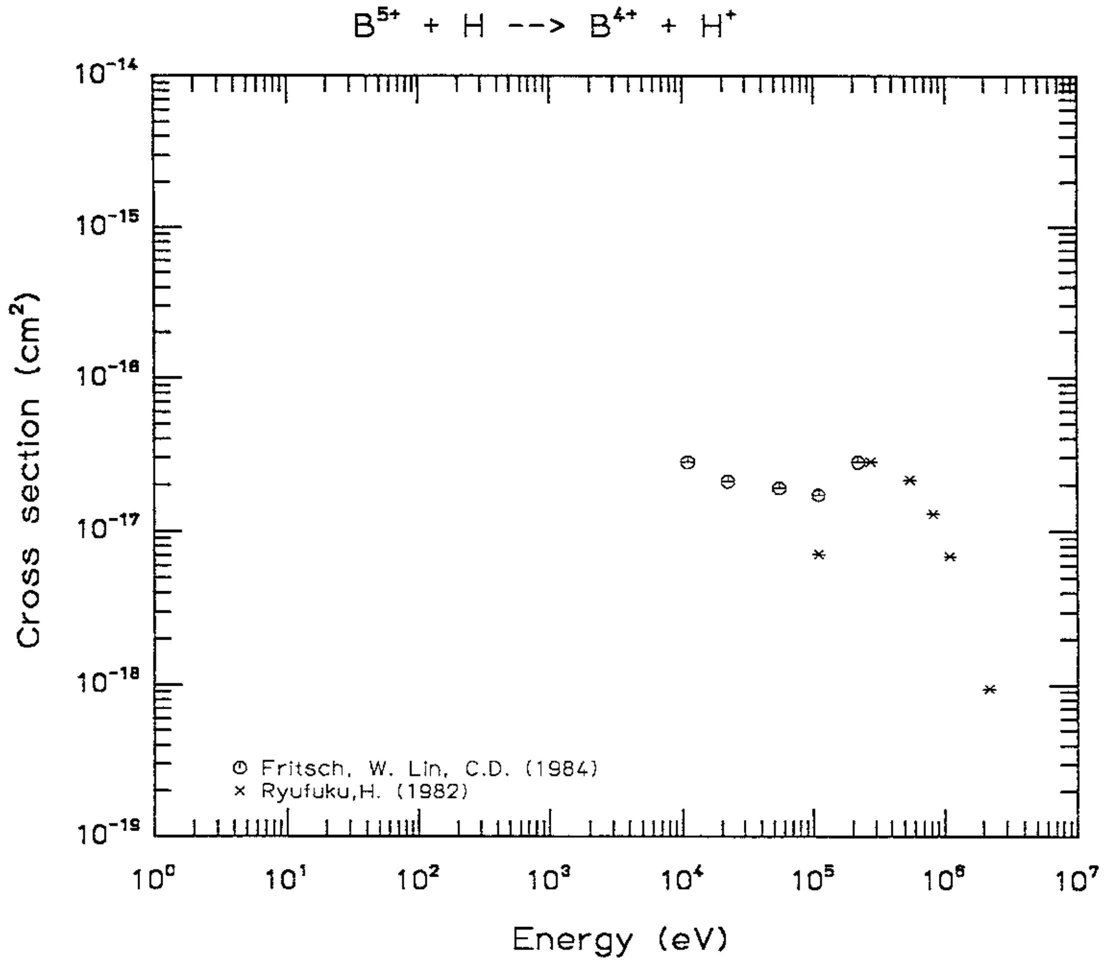

Fig.63 Partial cross sections into $B^{4+}(5p)$ in B^{5+} + H collisions

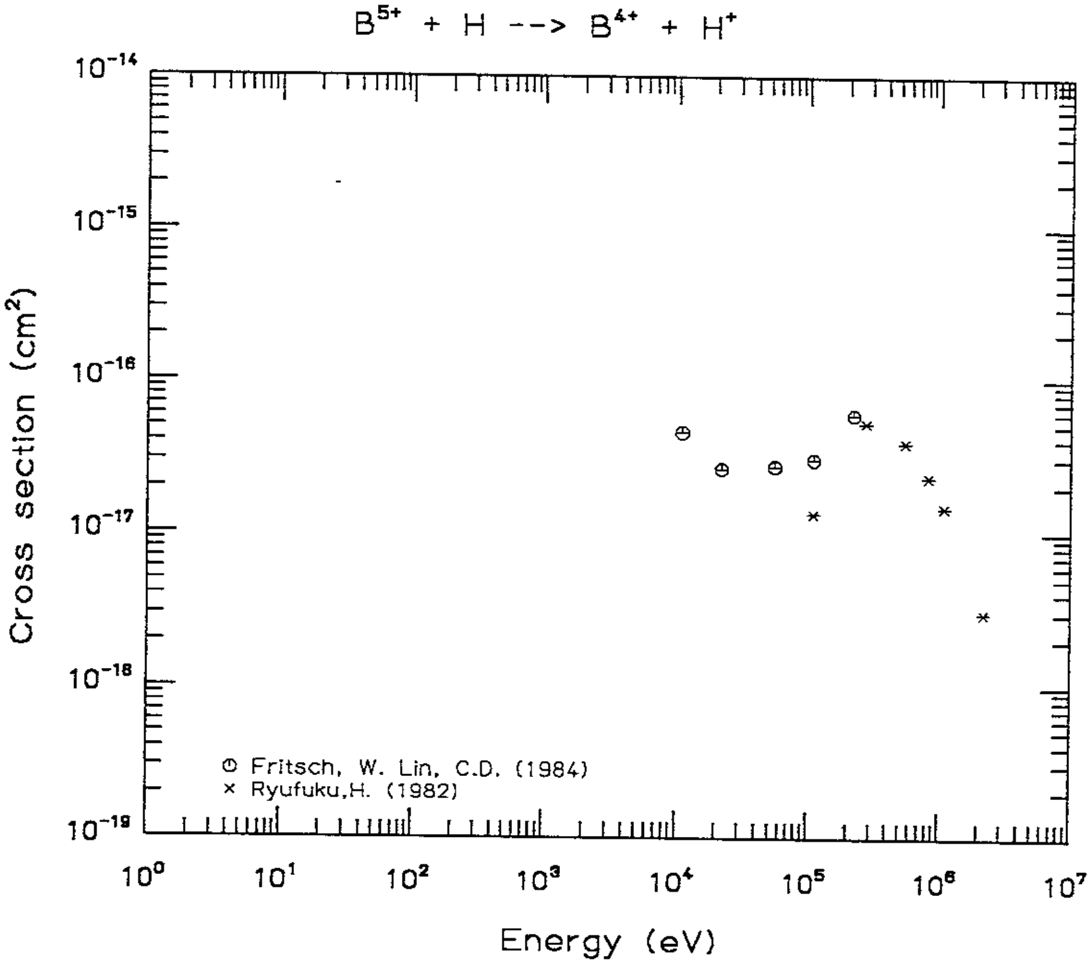

Fig.64 Partial cross sections into $B^{4+}(5d)$ in B^{5+} + H collisions

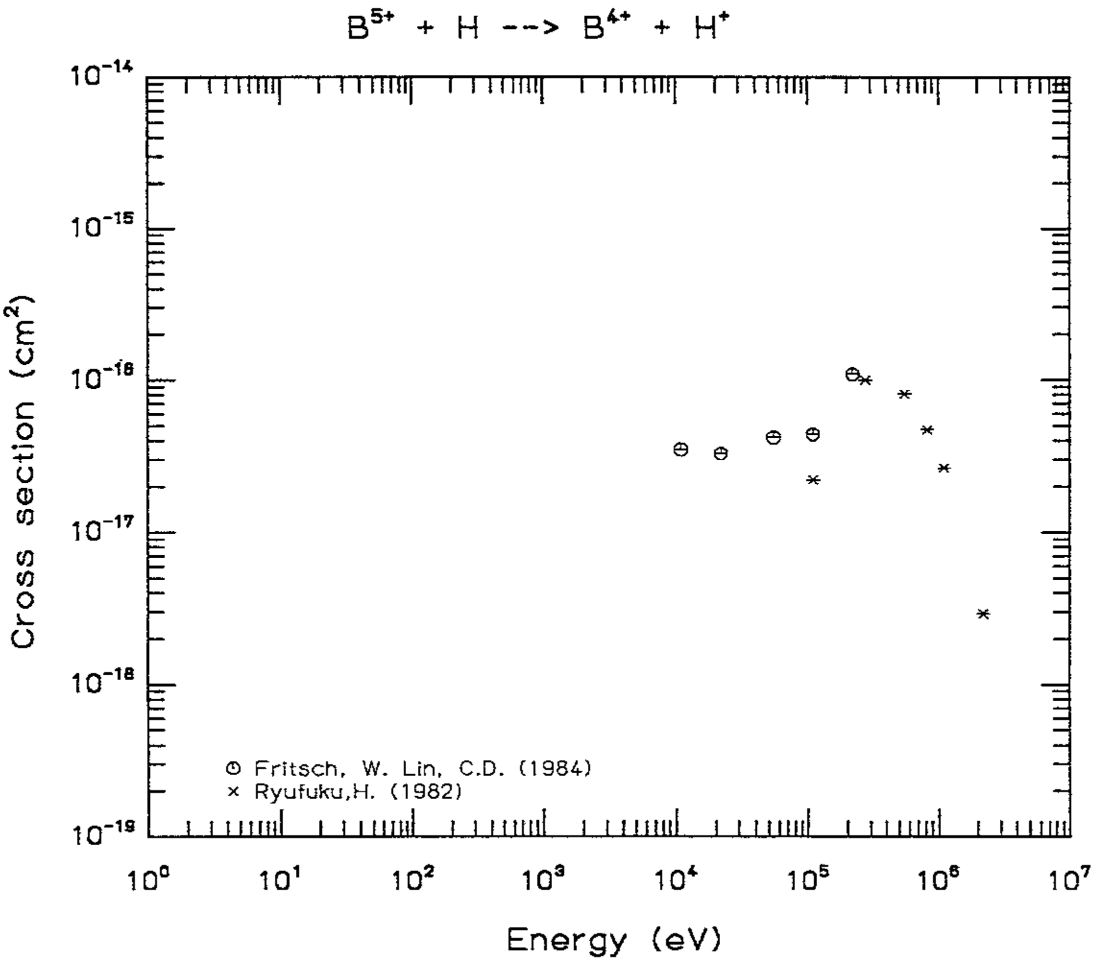

Fig.65 Partial cross sections into $B^{4+}(5f)$ in B^{5+} + H collisions

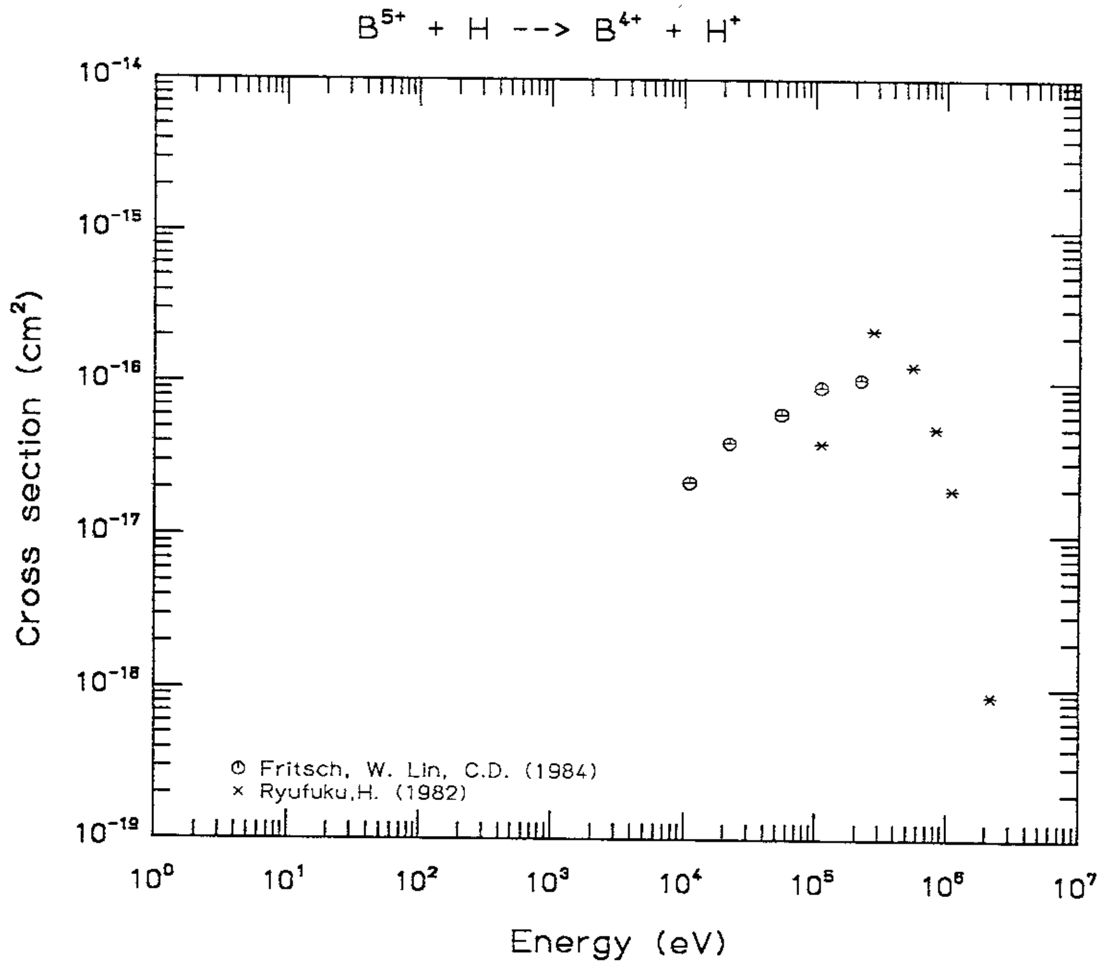

Fig.66 Partial cross sections into $B^{4+}(5g)$ in B^{5+} + H collisions

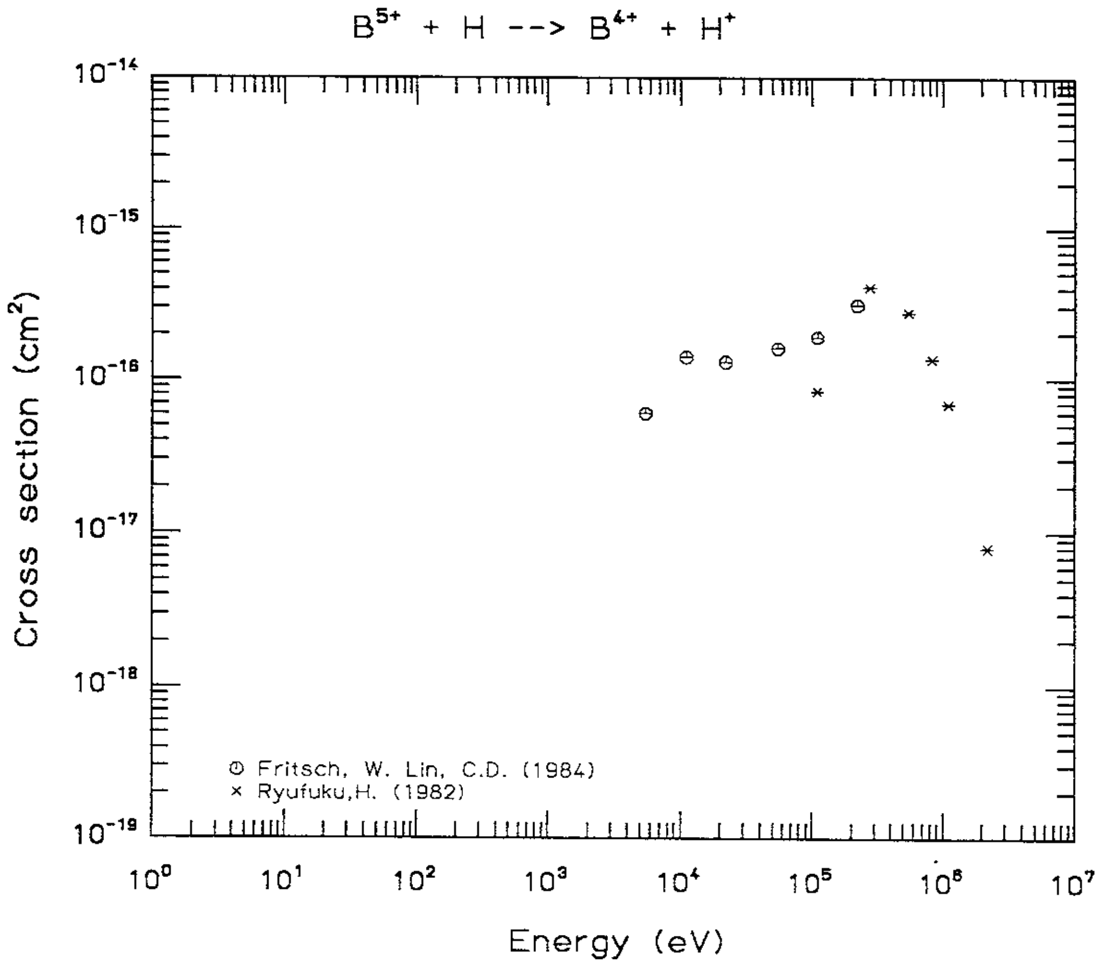

Fig.67 Partial cross sections into $B^{4+}(n=5)$ in B^{5+} + H collisions

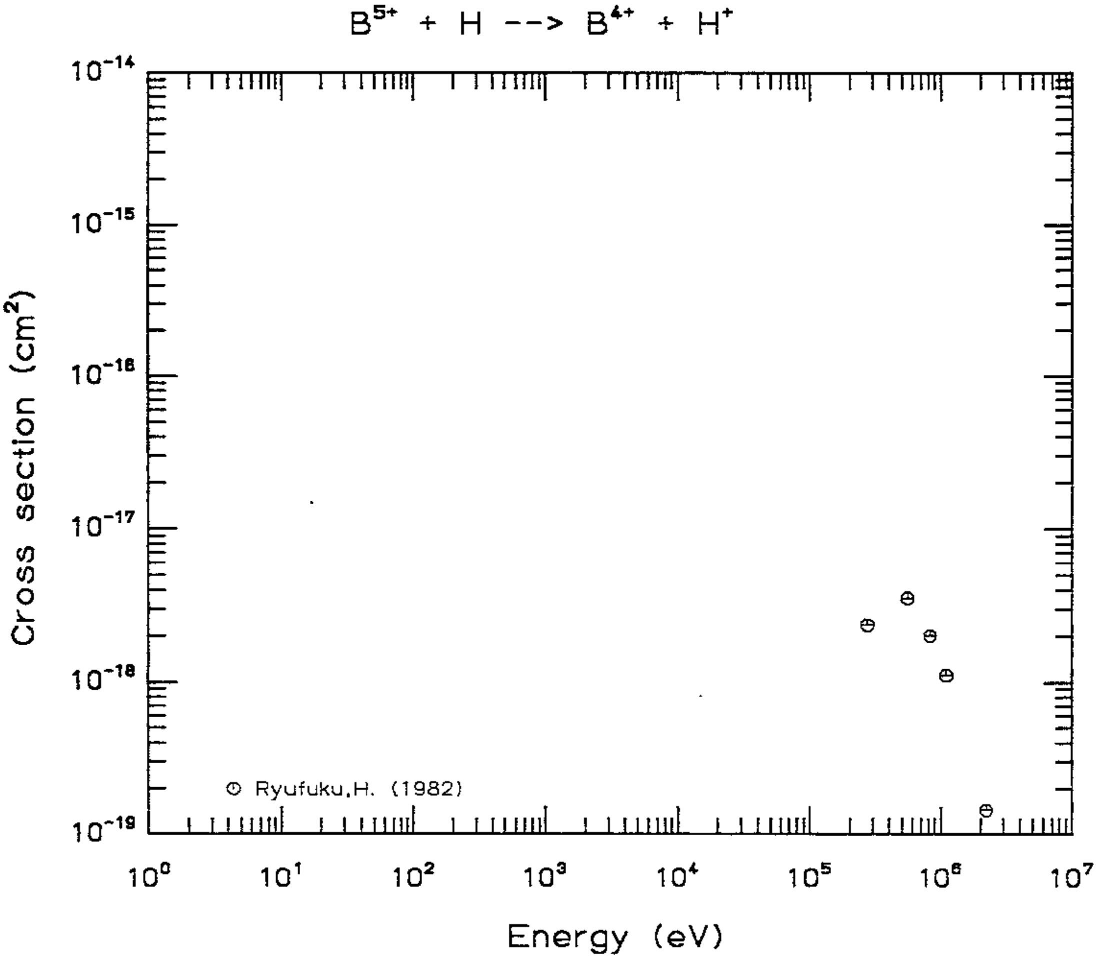

Fig.68 Partial cross sections into B^{4+}(6s) in B^{5+} + H collisions

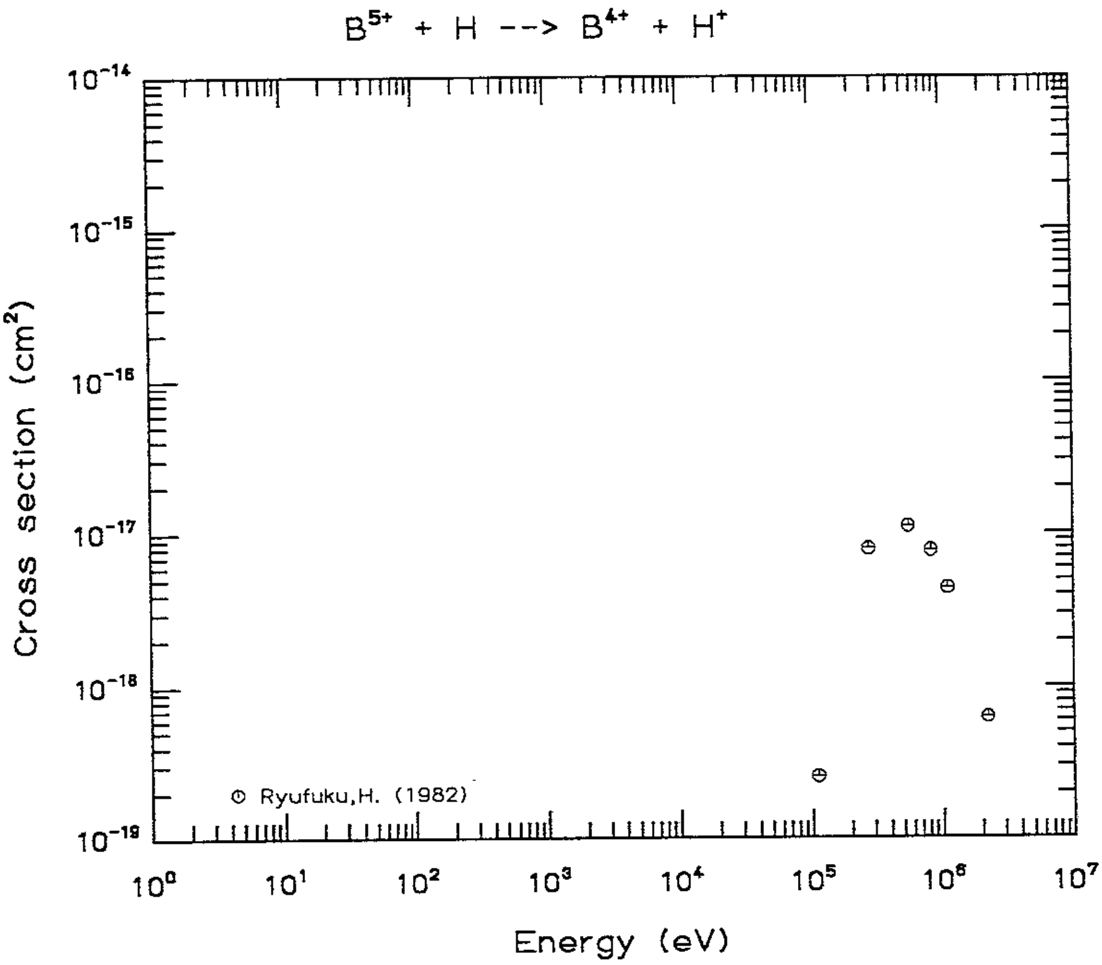

Fig.69 Partial cross sections into B^{4+}(6p) in B^{5+} + H collisions

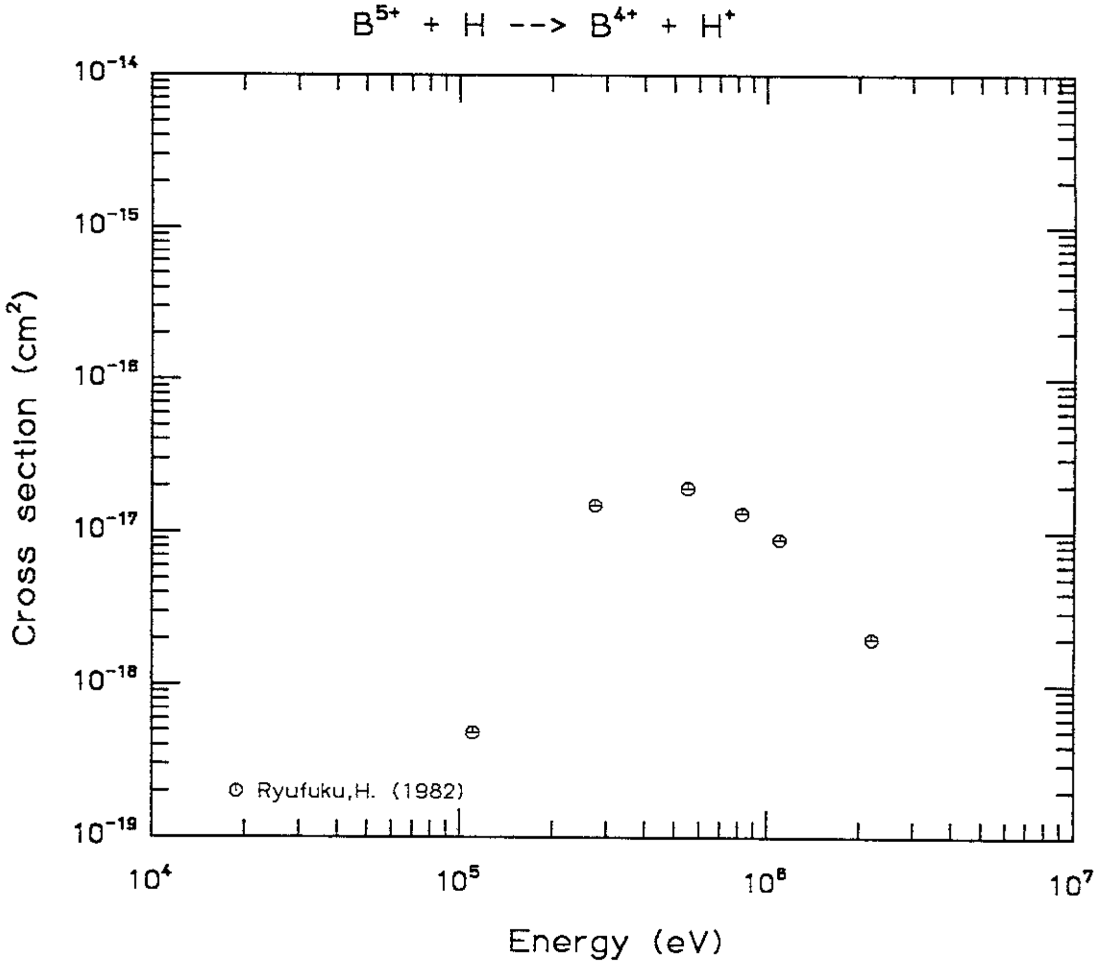

Fig.70 Partial cross sections into B^{4+}(6d) in B^{5+} + H collisions

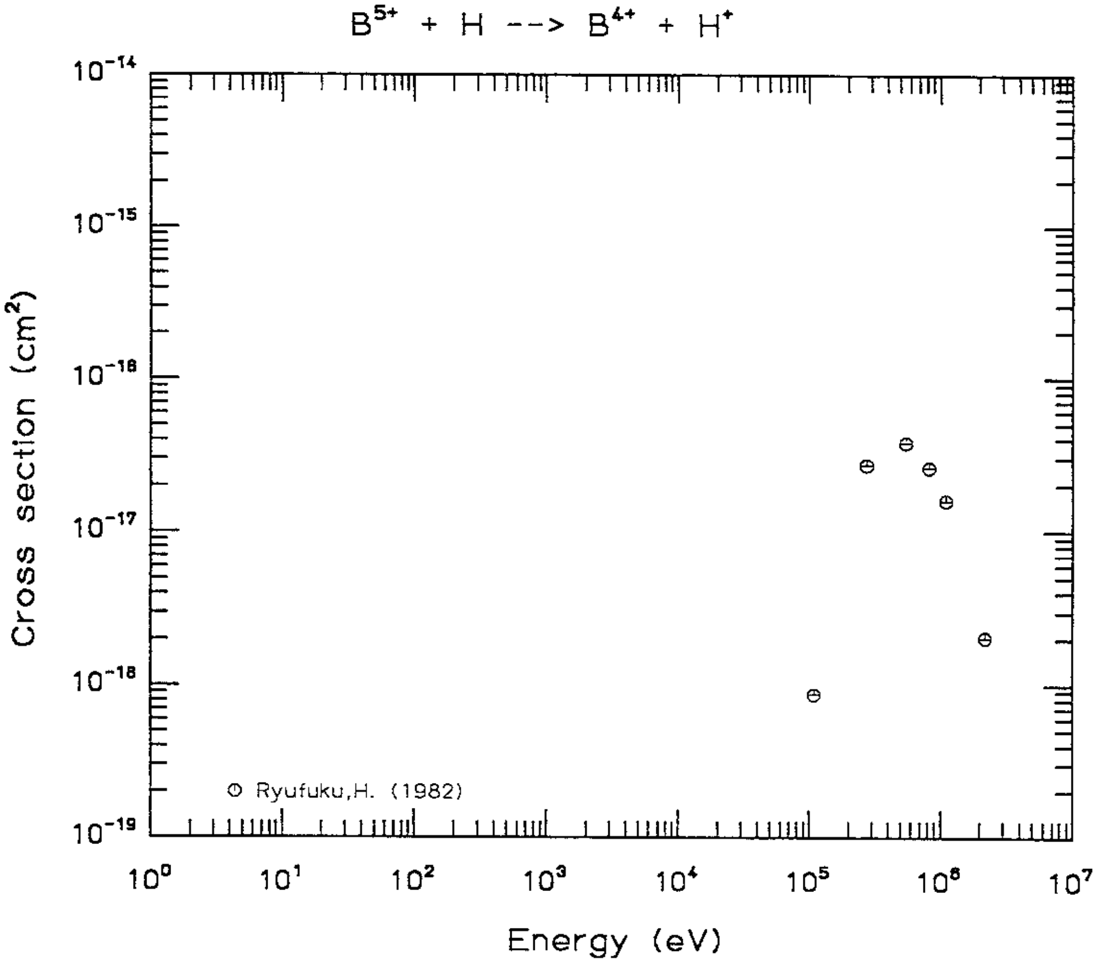

Fig.71 Partial cross sections into B^{4+}(6f) in B^{5+} + H collisions

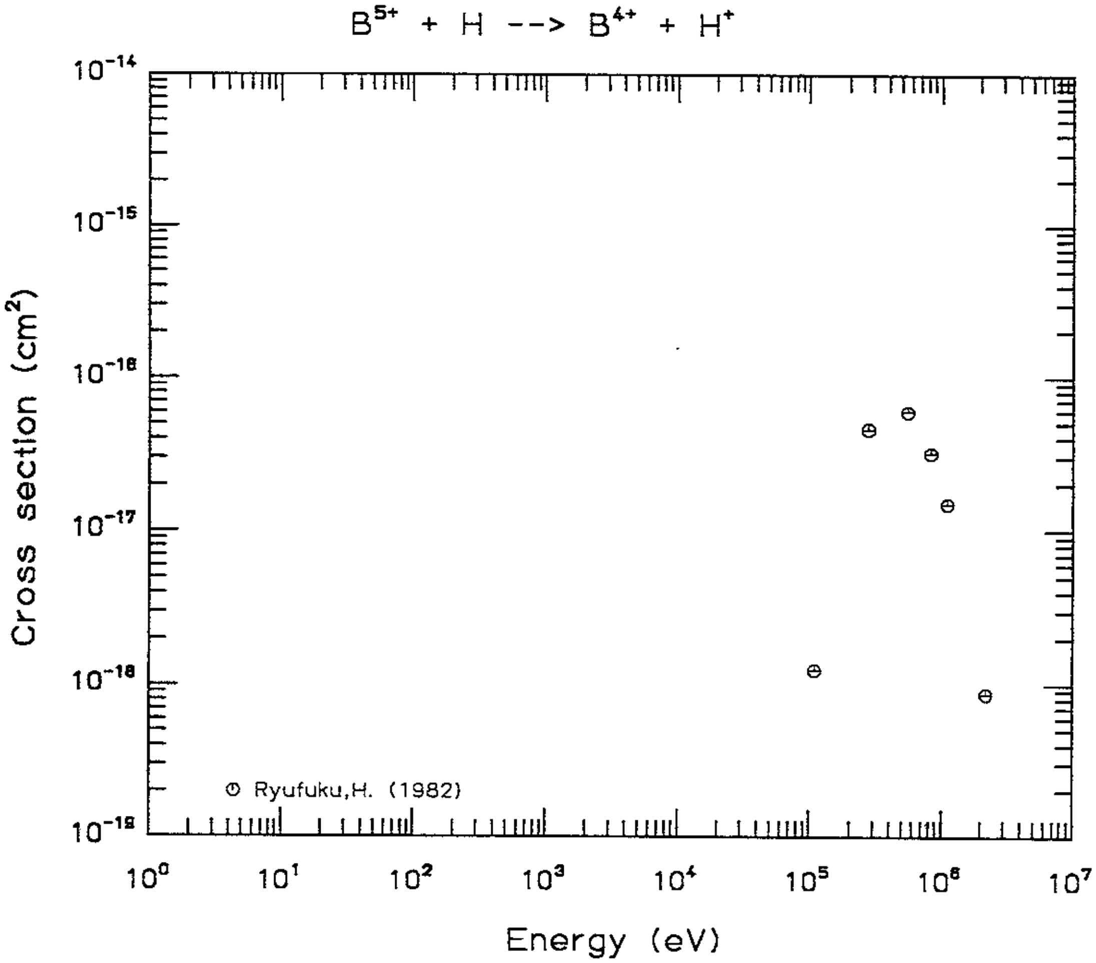

Fig.72 Partial cross sections into B^{4+}(6g) in B^{5+} + H collisions

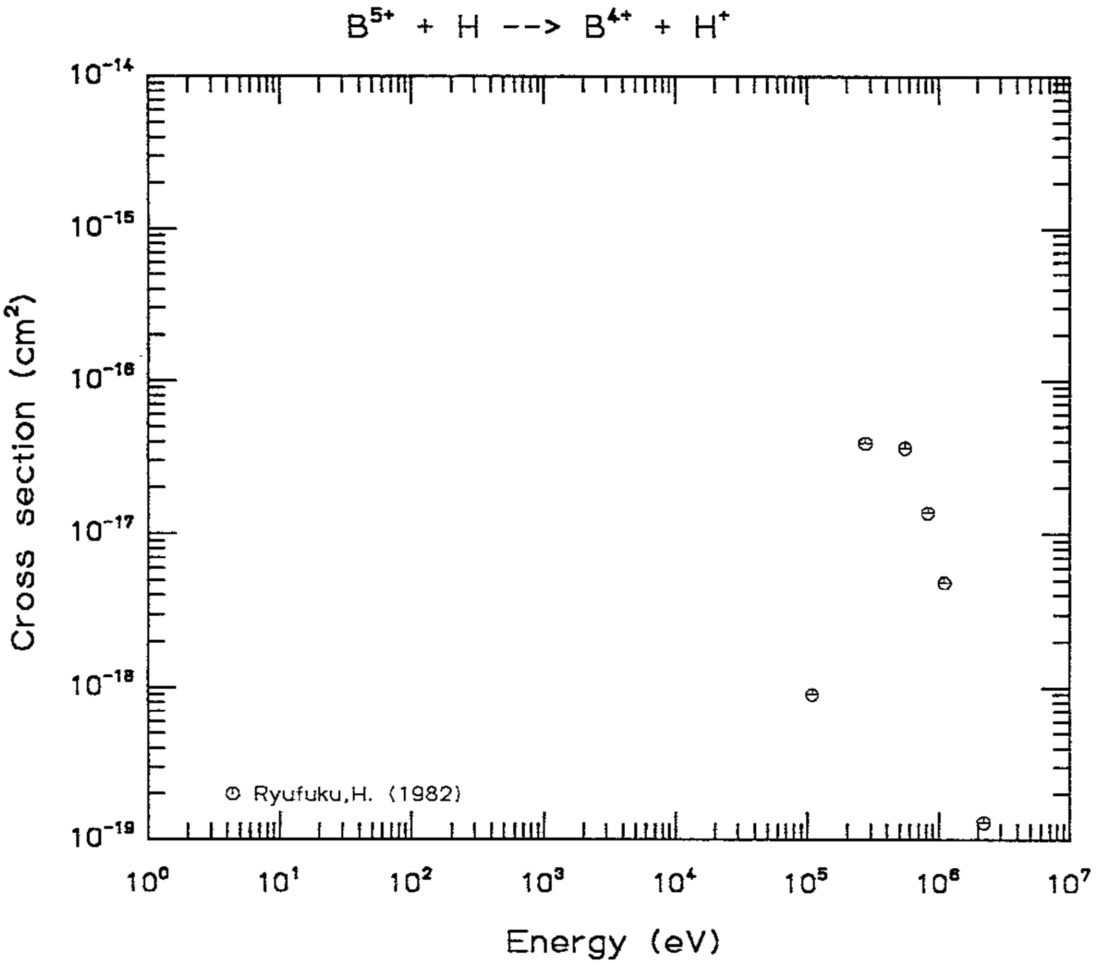

Fig.73 Partial cross sections into B^{4+}(6h) in B^{5+} + H collisions

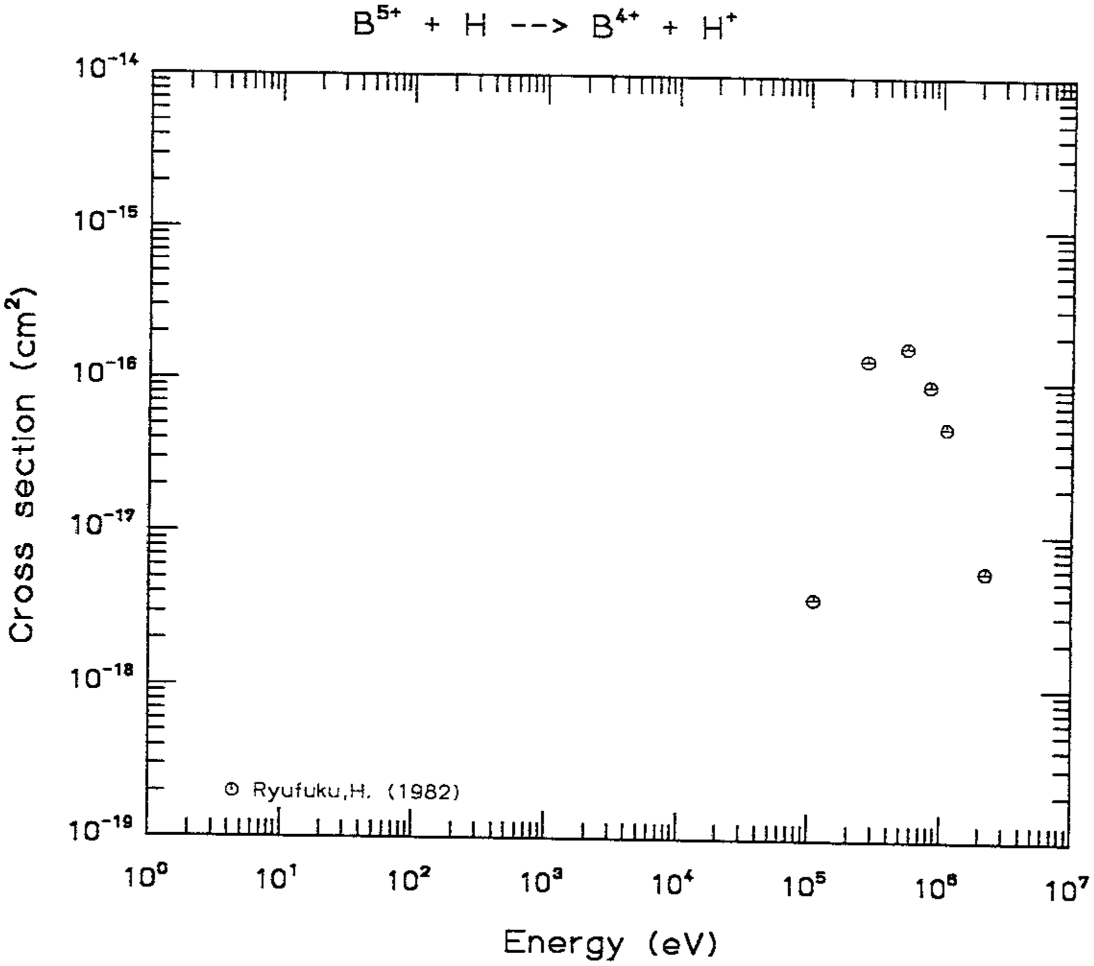

Fig.74 Partial cross sections into $B^{4+}(n=6)$ in B^{5+} + H collisions

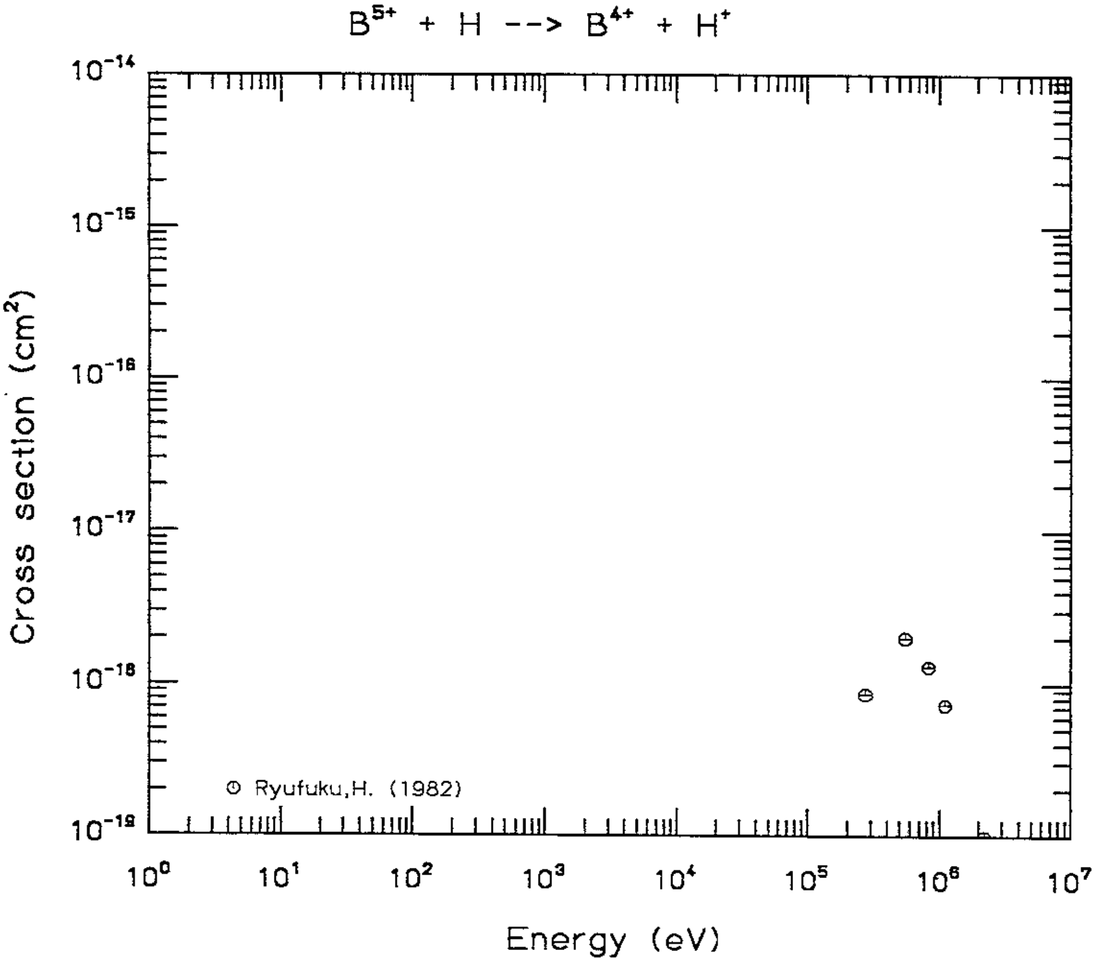

Fig.75 Partial cross sections into $B^{4+}(7s)$ in B^{5+} + H collisions

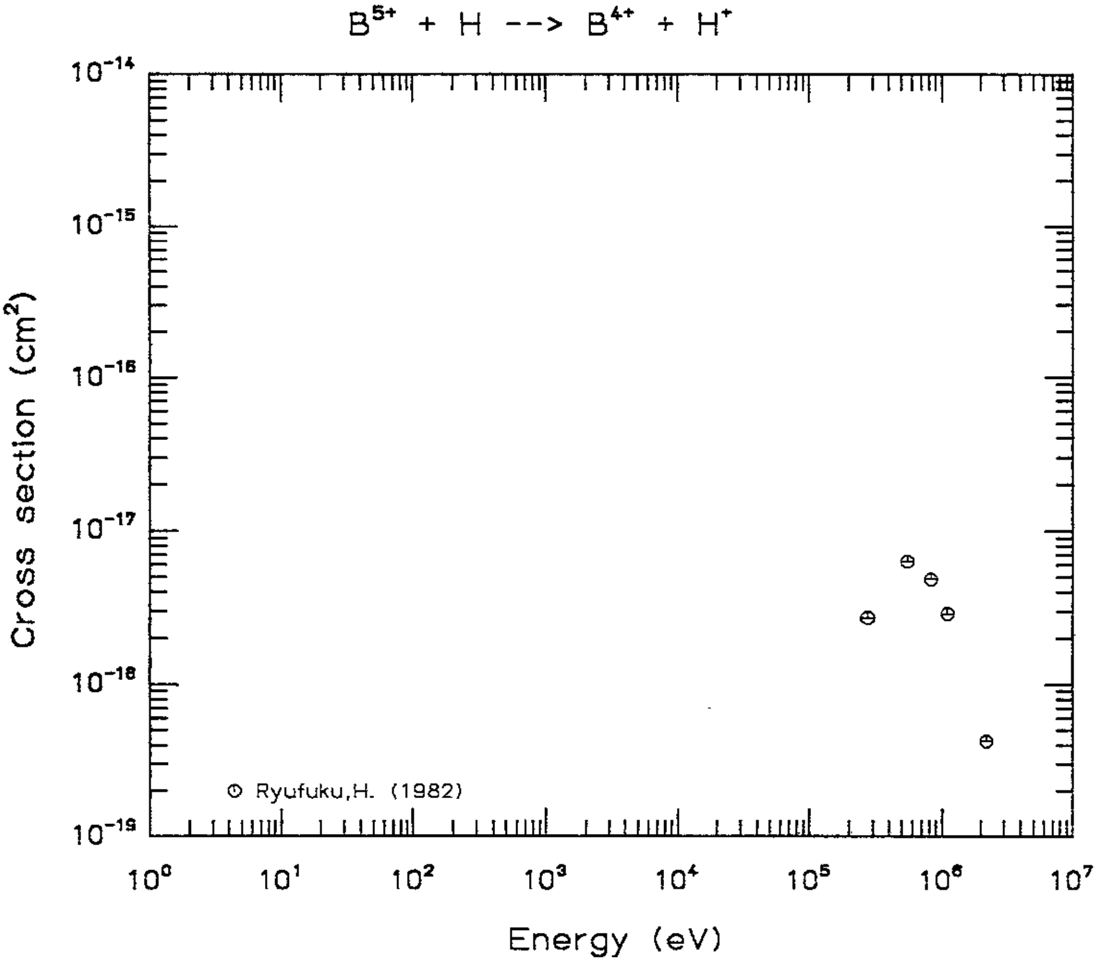

Fig.76 Partial cross sections into $B^{4+}(7p)$ in B^{5+} + H collisions

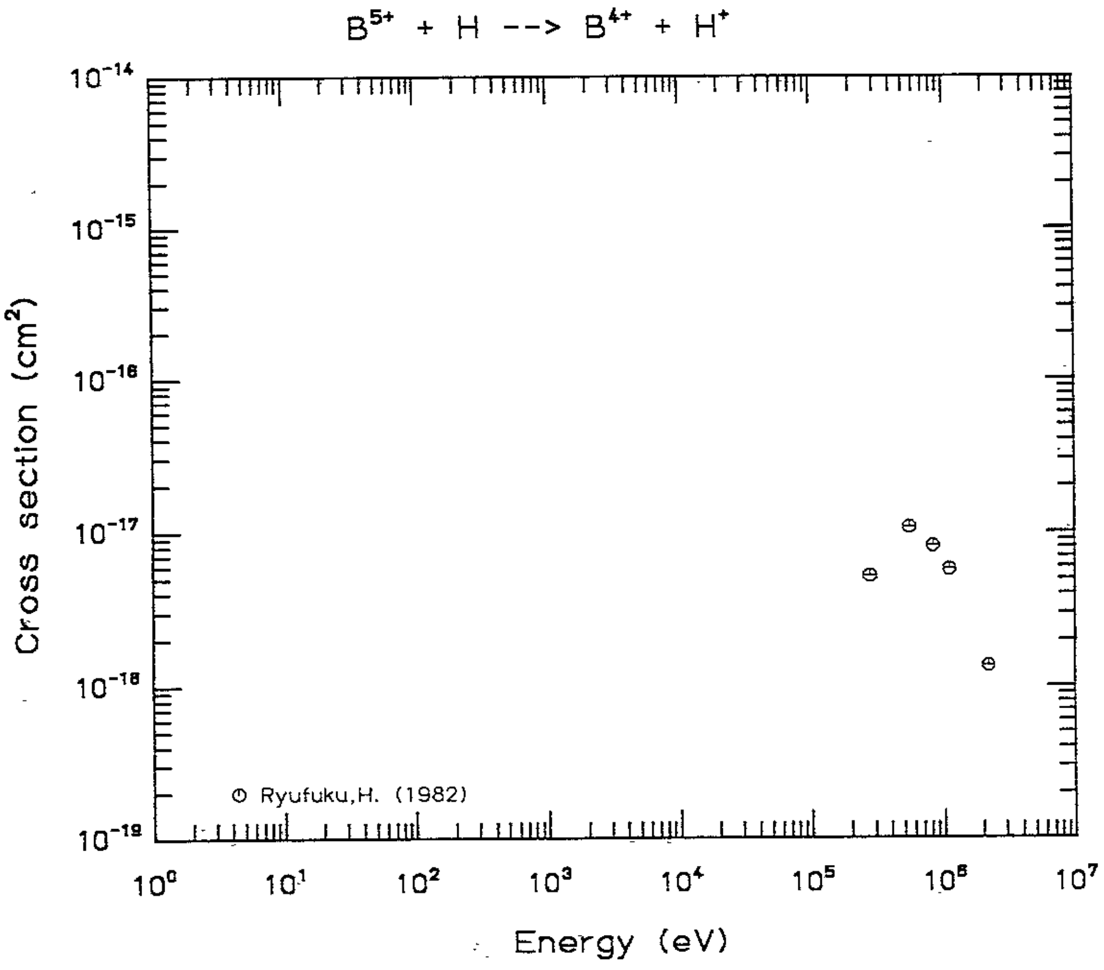

Fig.77 Partial cross sections into $B^{4+}(7d)$ in B^{5+} + H collisions

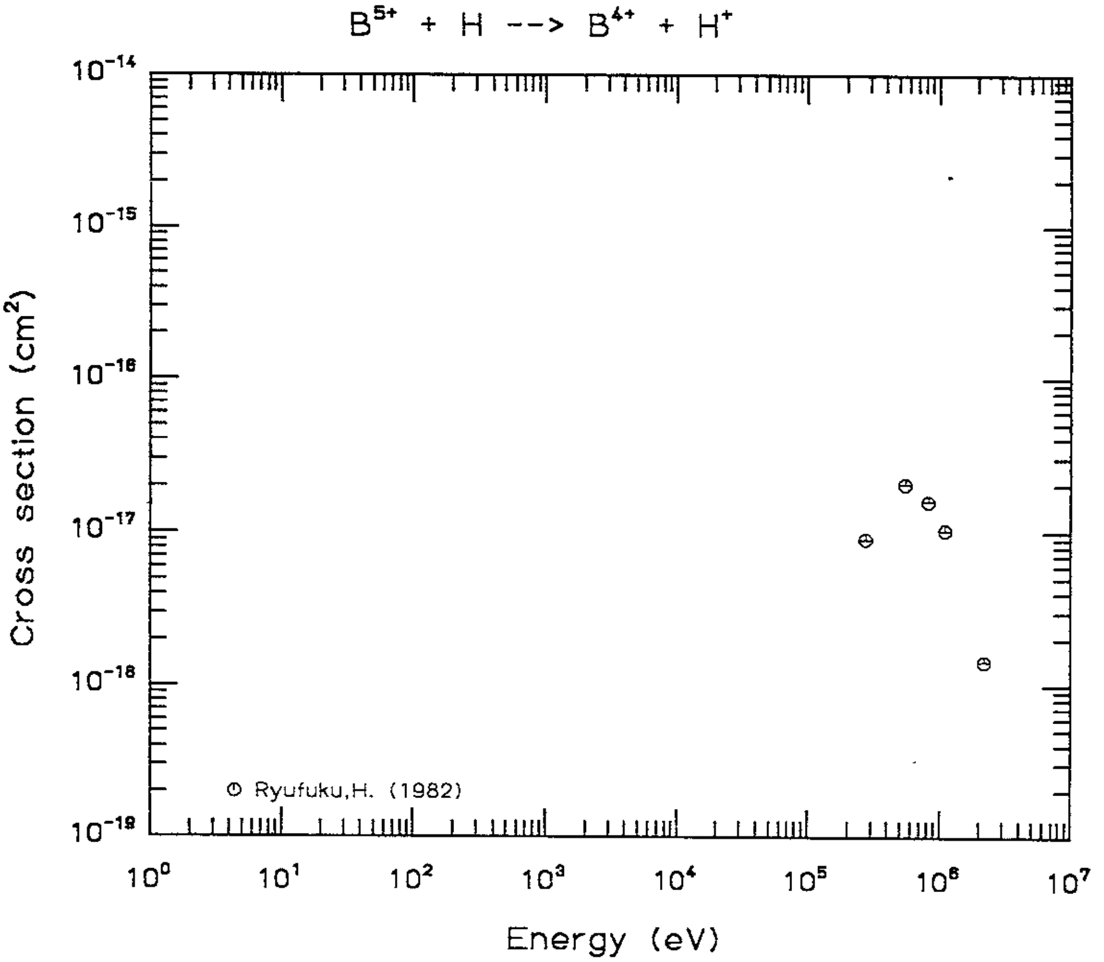

Fig.78 Partial cross sections into B^{4+}(7f) in B^{5+} + H collisions

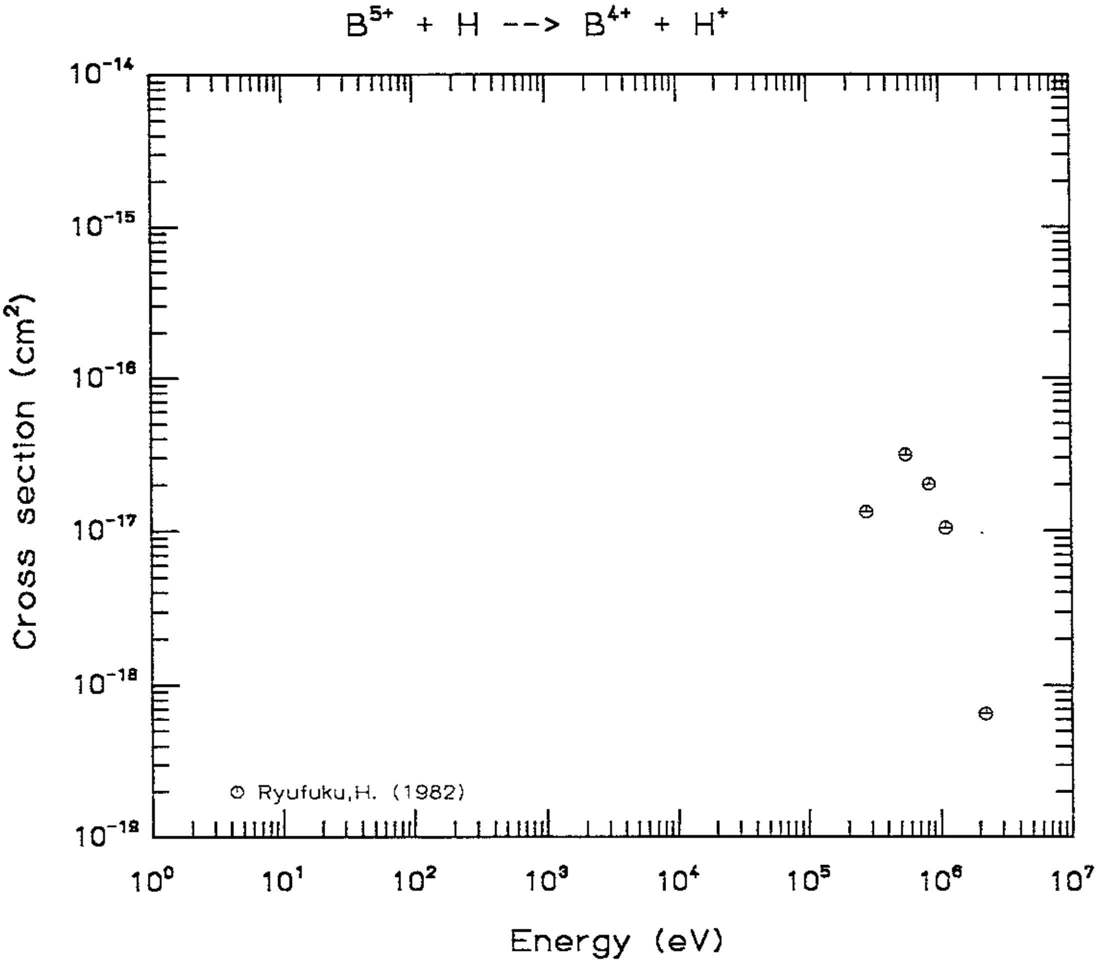

Fig.79 Partial cross sections into B^{4+}(7g) in B^{5+} + H collisions

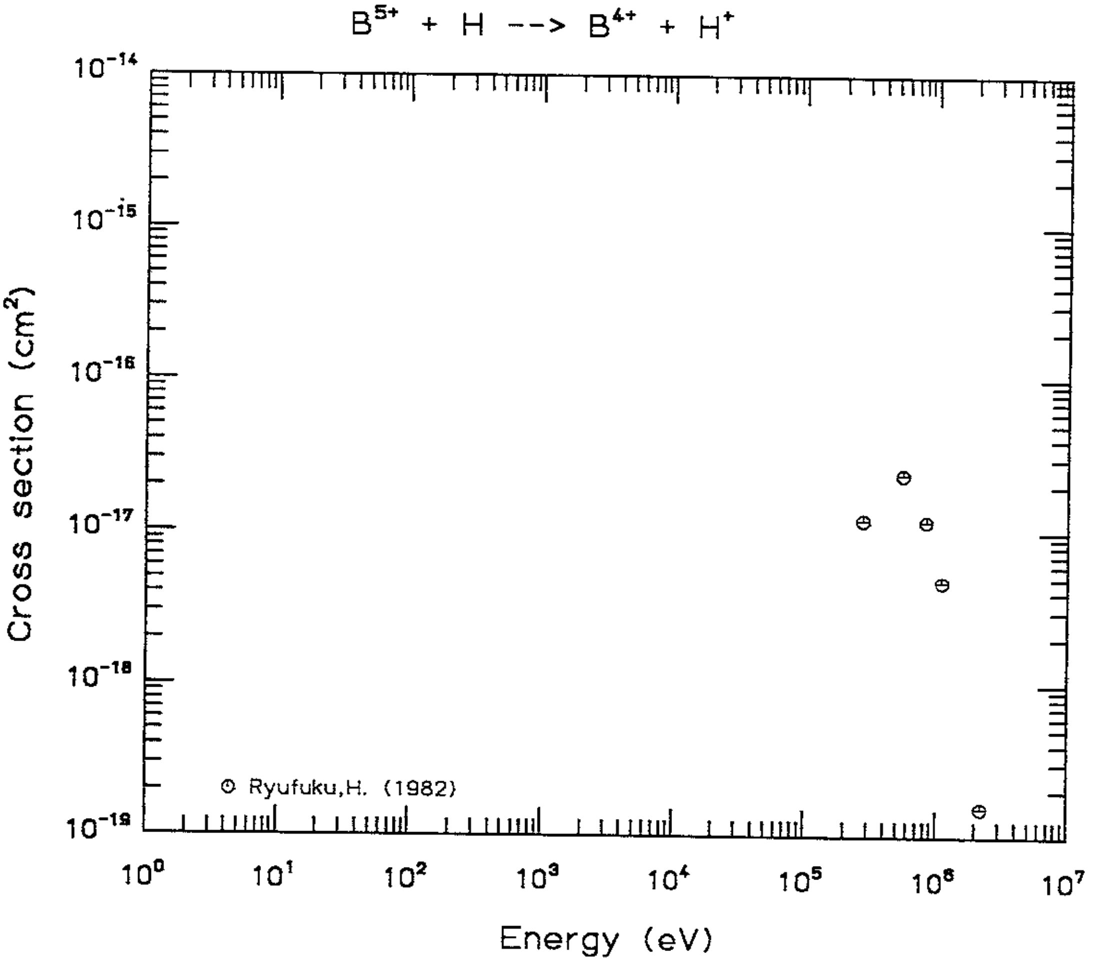

Fig.80 Partial cross sections into B^{4+}(7h) in B^{5+} + H collisions

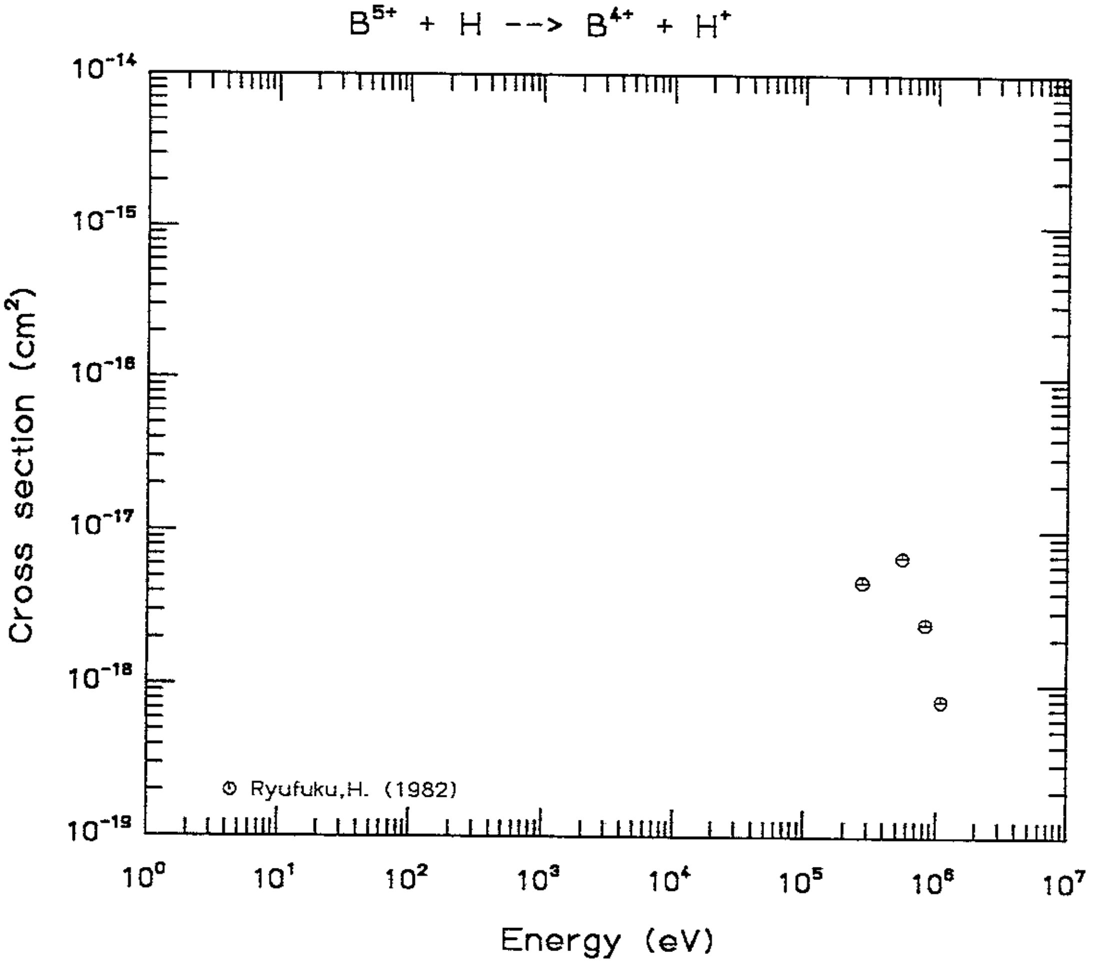

Fig.81 Partial cross sections into B^{4+}(7i) in B^{5+} + H collisions

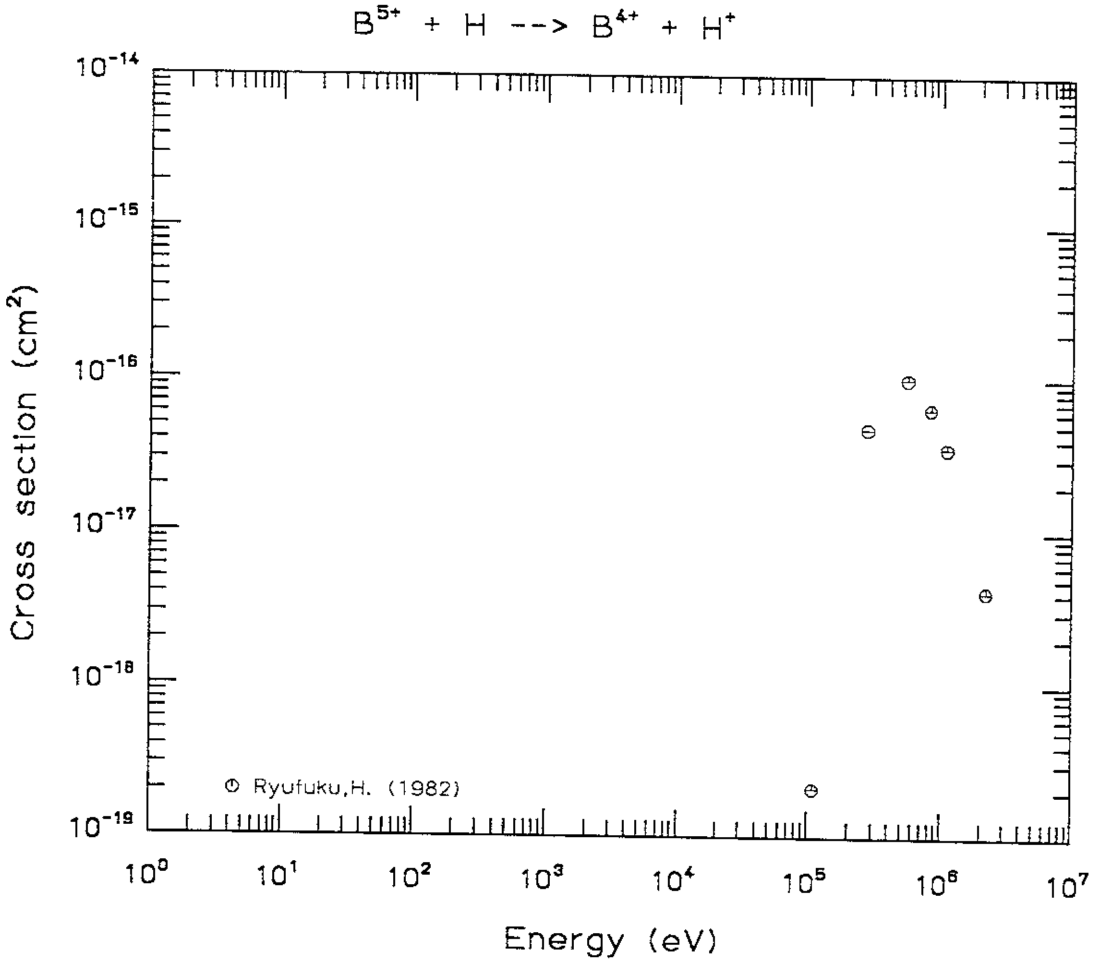

Fig.82 Partial cross sections into B^{4+}(n=7) in B^{5+} + H collisions

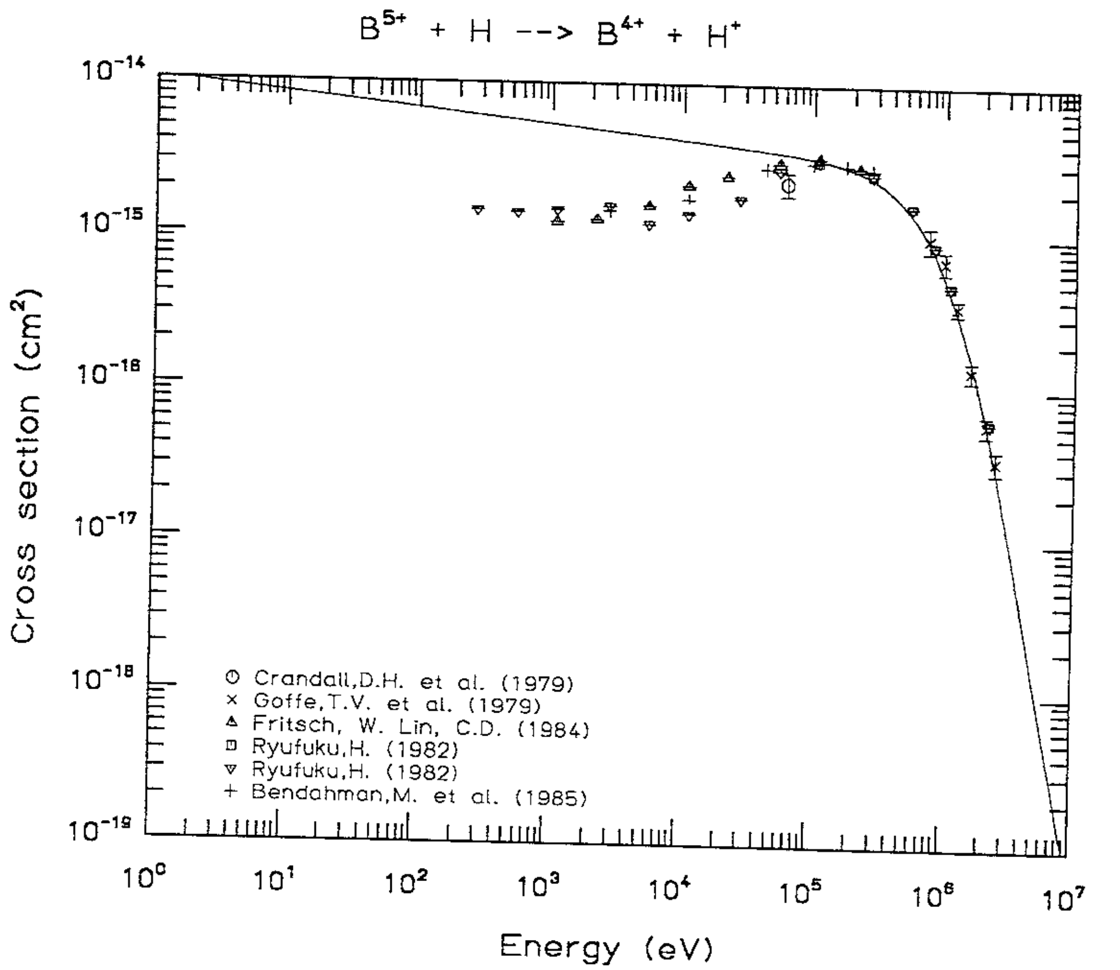

Fig.83 Total cross sections into B^{4+} in B^{5+} + H collisions

$B^{q+} + H_2$

$B^+ + H_2$ (Fig.84-85)

Only a single set of measurements have been reported by Gofee et al. over a limited energy range.

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

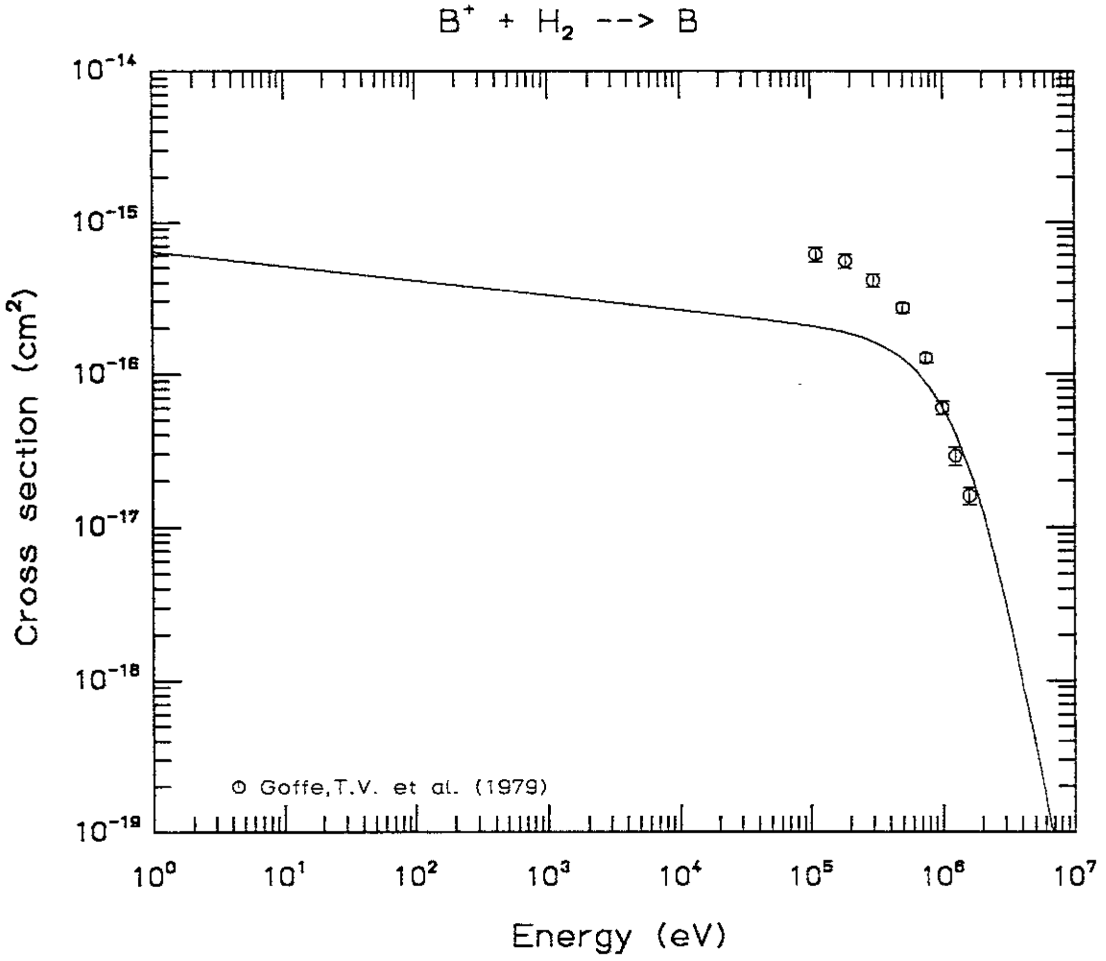

Fig.84 Total cross sections into B in $B^+ + H_2$ collisions

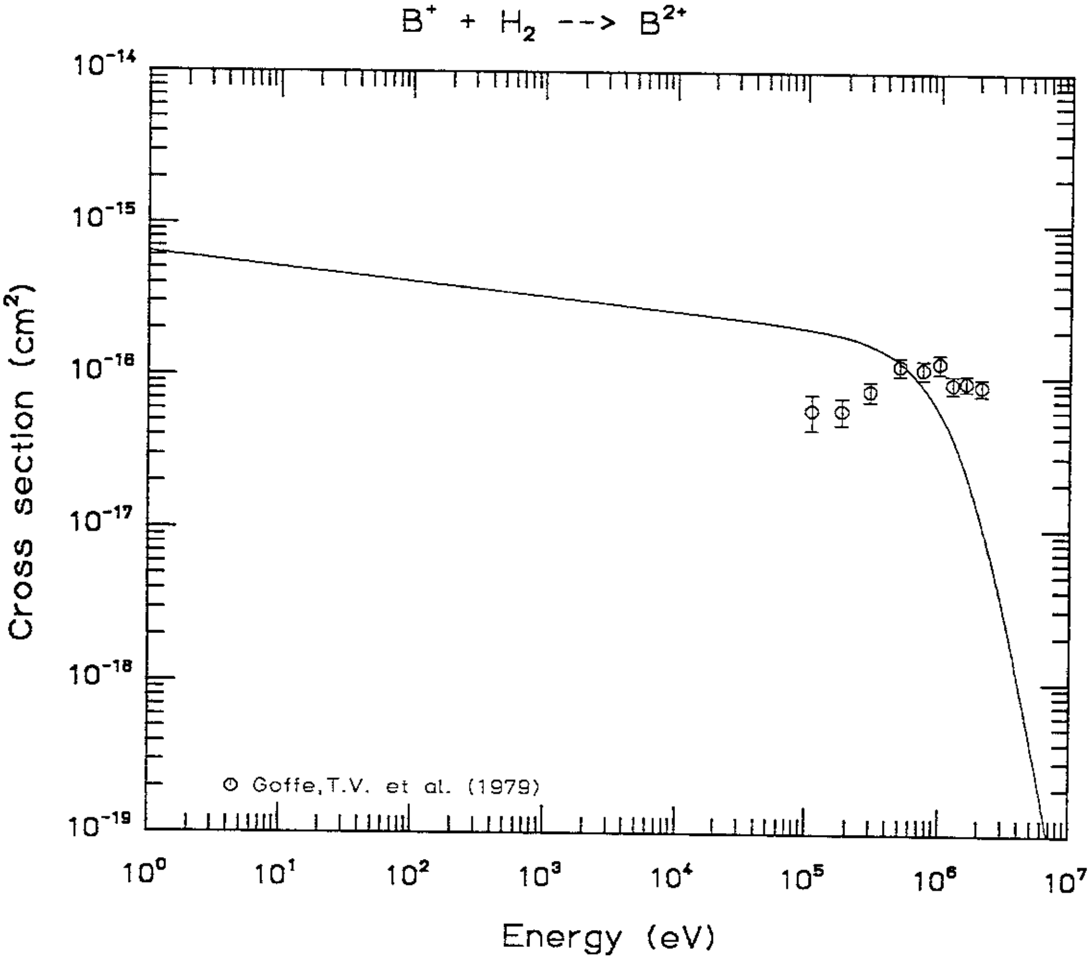

Fig.85 Total cross sections into B^{2+} in B^{+} + H_2 collisions

B^{2+} + H_2 (Figs.86-87)

Only total cross sections have been measured by four groups over relatively wide range of the energy. However, data by Gardner et al. seem to be too small by 50%, compared with other two sets of data by Crandall and McCullough et al., which can be extrapolated reasonably well to those by Goffe et al. at higher energies. a few data points for double electron capture have been measured by Gardner et al.

D.H.Crandall, Phys. Rev. A **16** (1977) 958

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

R.W.McCullough, W.L.Nutt and H.B.Gilbody, J. Phys. B **12** (1979) 4159

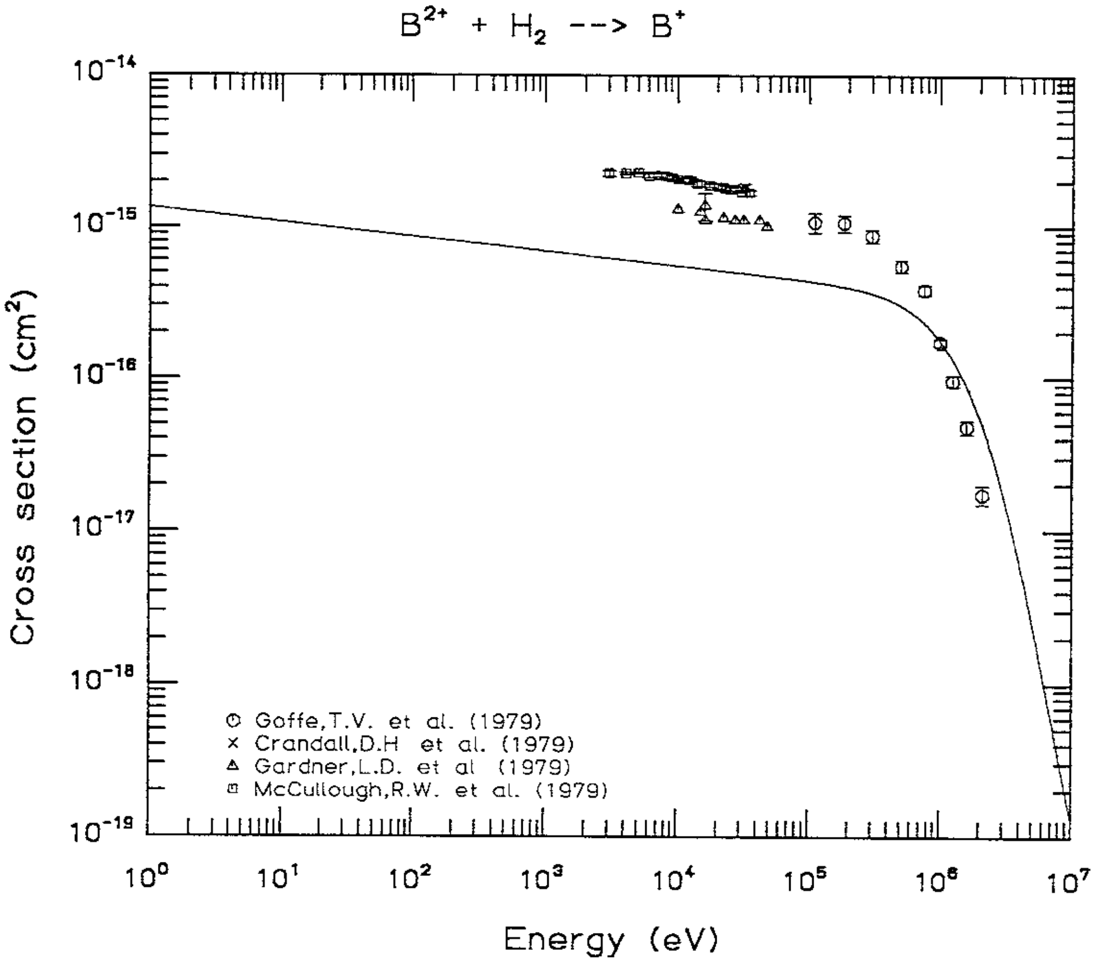

Fig.86 Total cross sections into B^+ in B^{2+} + H_2 collisions

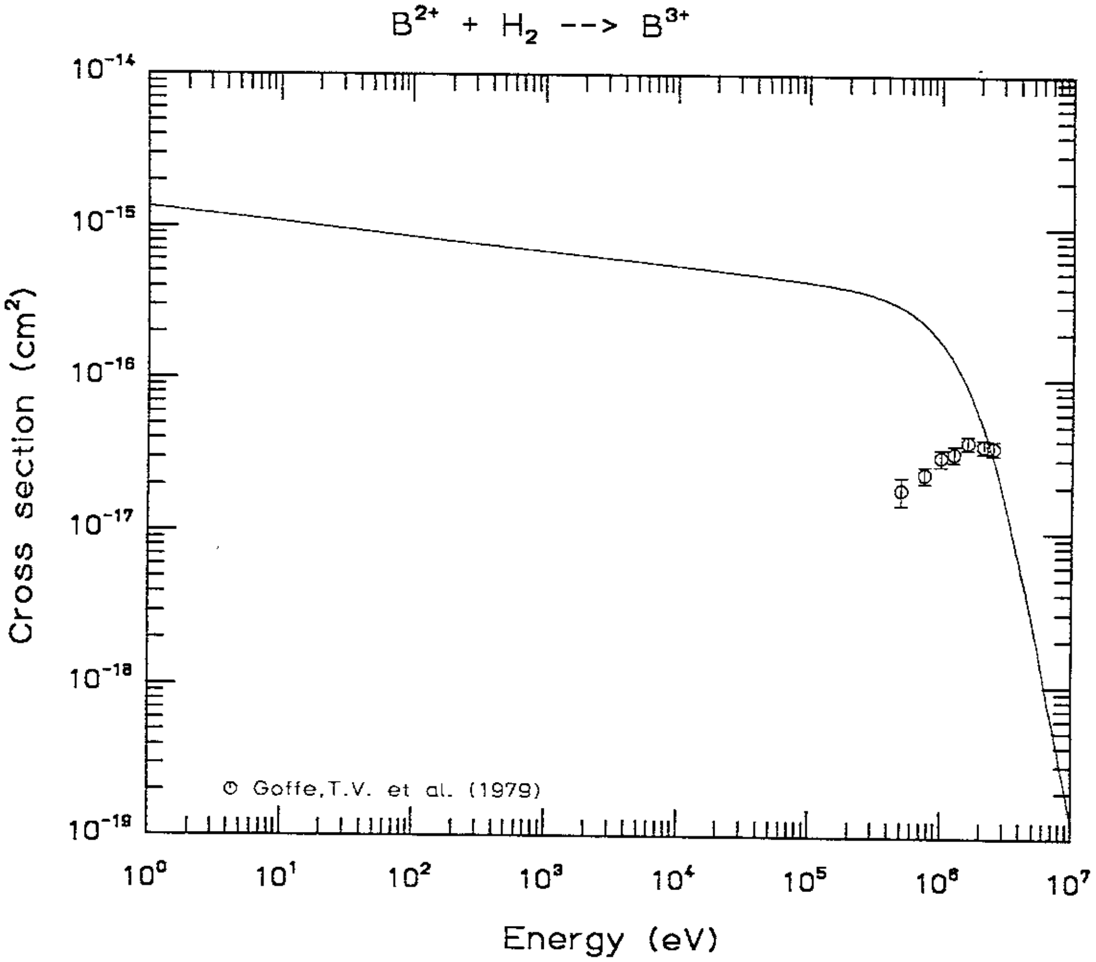

Fig.87 Total cross sections into B^{3+} in B^{2+} + H_2 collisions

B^{3+} + H_2 (Figs.88-89)

Again data by Gardner et al. seem to be too small, compared with other sets of data by Crandall and those extrapolated from high energies by Goffe et al.

D.H.Crandall, Phys. Rev. A **16** (1977) 958

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

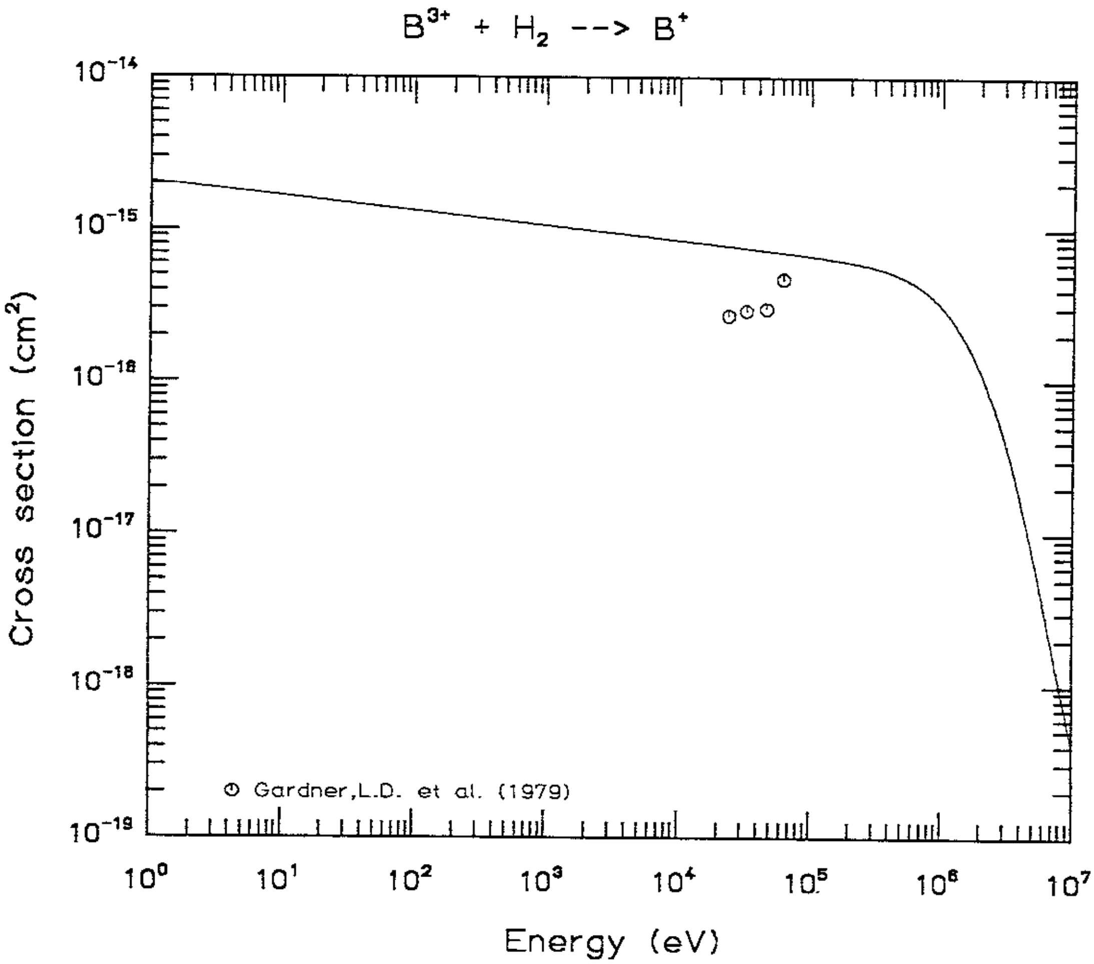

Fig.88 Total cross sections into B^+ in B^{3+} + H_2 collisions

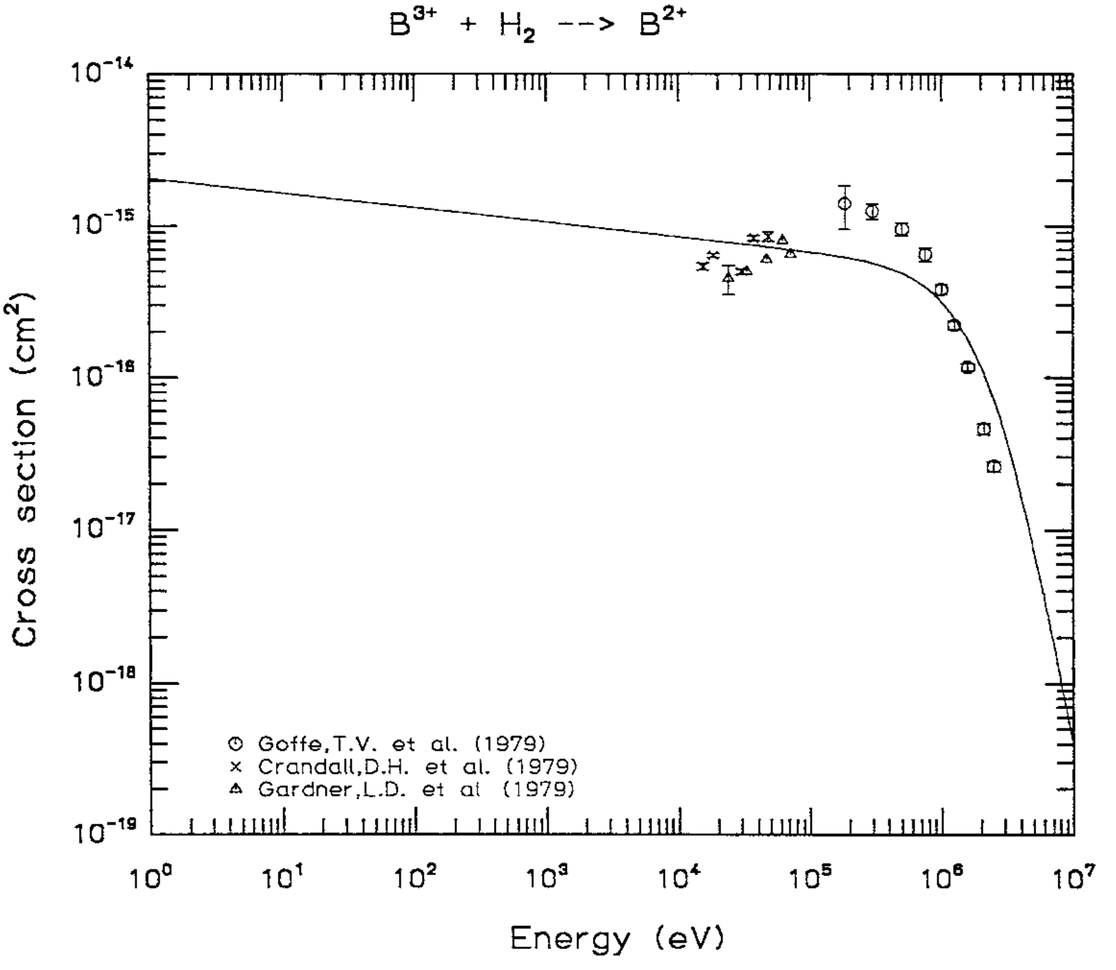

Fig.89 Total cross sections into B^{2+} in B^{3+} + H_2 collisions

$B^{4+} + H_2$ (Fig.90-91)

Only total cross sections have been measured over 10 keV/amu energy and tend to be relatively constant at lower energies. Also total cross sections for double electron capture have been obtained over a limited energy region by Gardner et al.

D.H.Crandall, Phys. Rev. A **16** (1977) 958

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

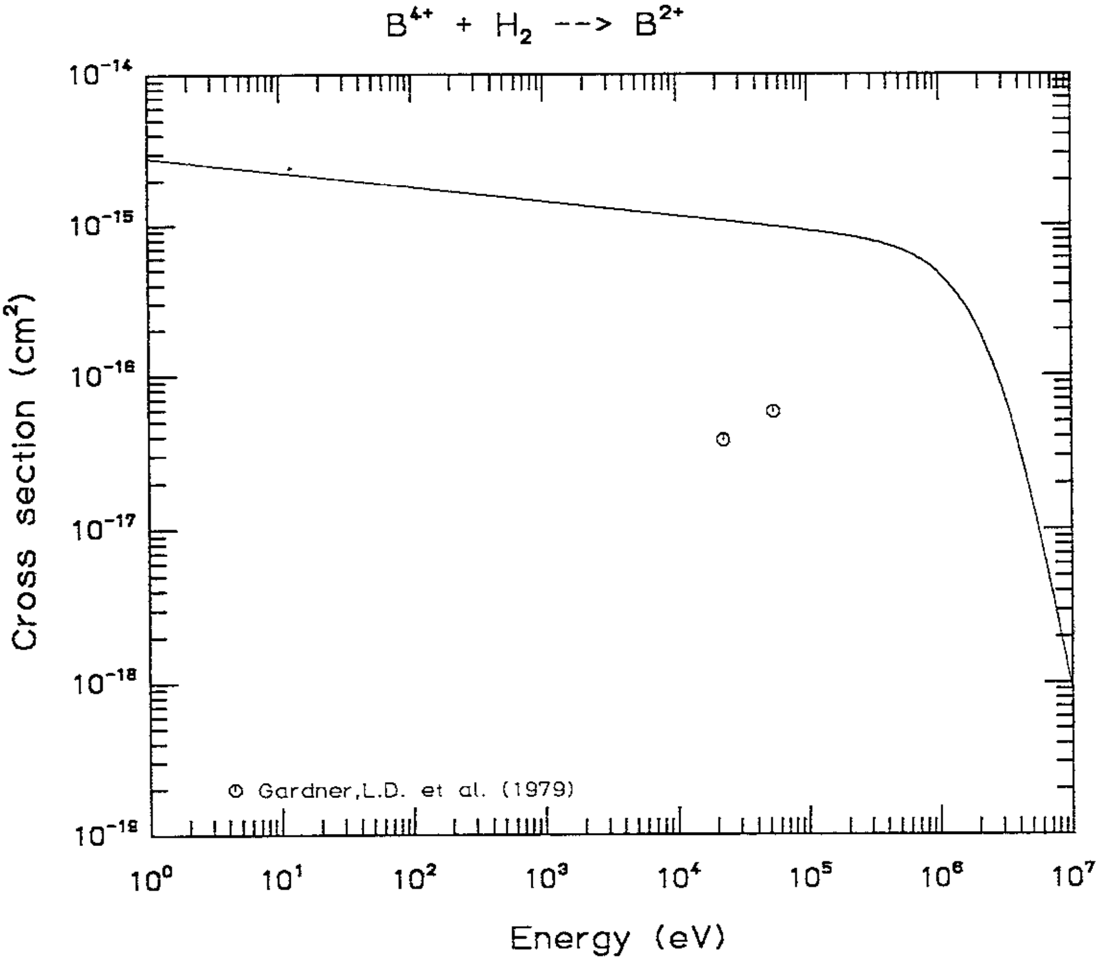

Fig.90 Total cross sections into B^{2+} in $B^{4+} + H_2$ collisions

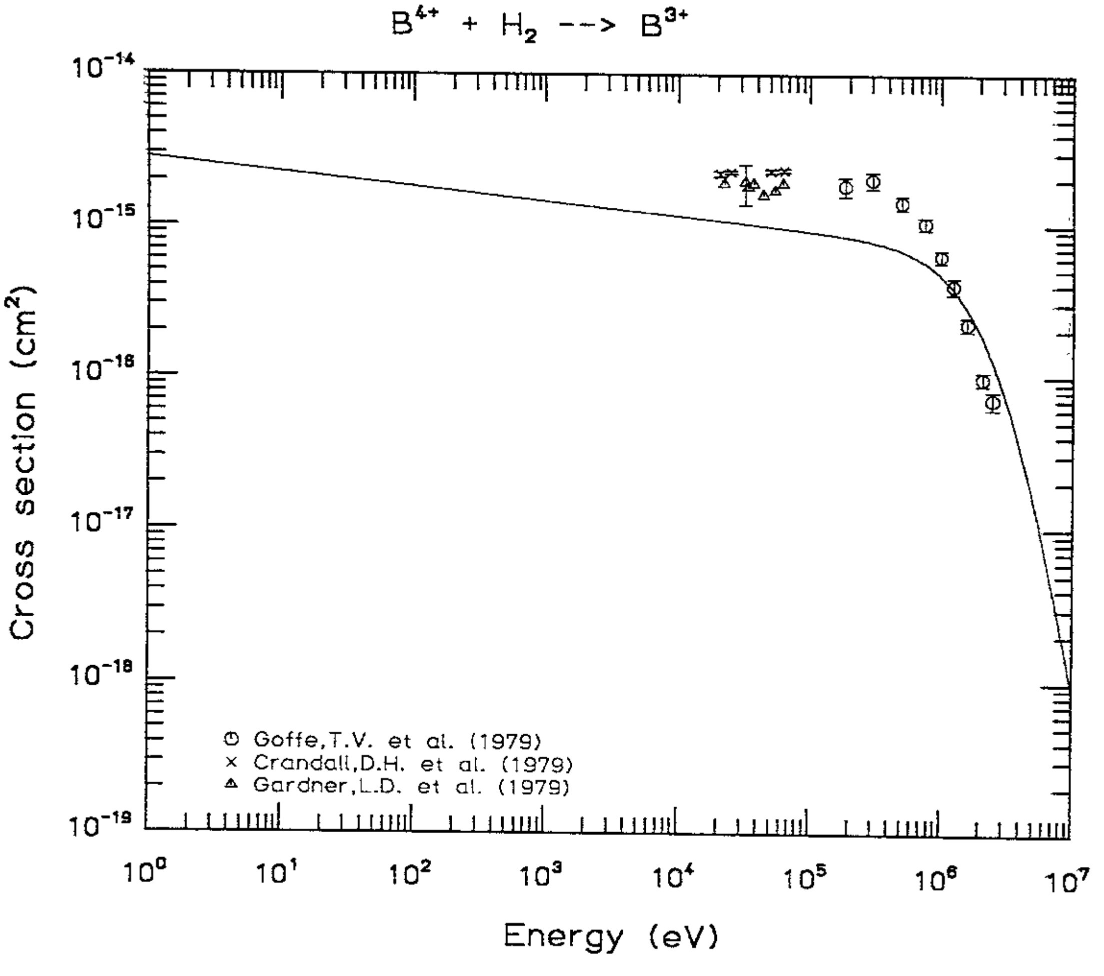

Fig.91 Total cross sections into B^{3+} in B^{4+} + H_2 collisions

B^{5+} + H_2 (Fig.92)

Total cross sections measured by Goffe et al. at relatively high energies seem to be in agreement with the extrapolated values of those by Crandall at low energies.

D.H.Crandall, Phys. Rev. A **16** (1977) 958

T.V.Goffe, M.B.Shah and H.B.Gilbody, J. Phys. B **12** (1979) 3763

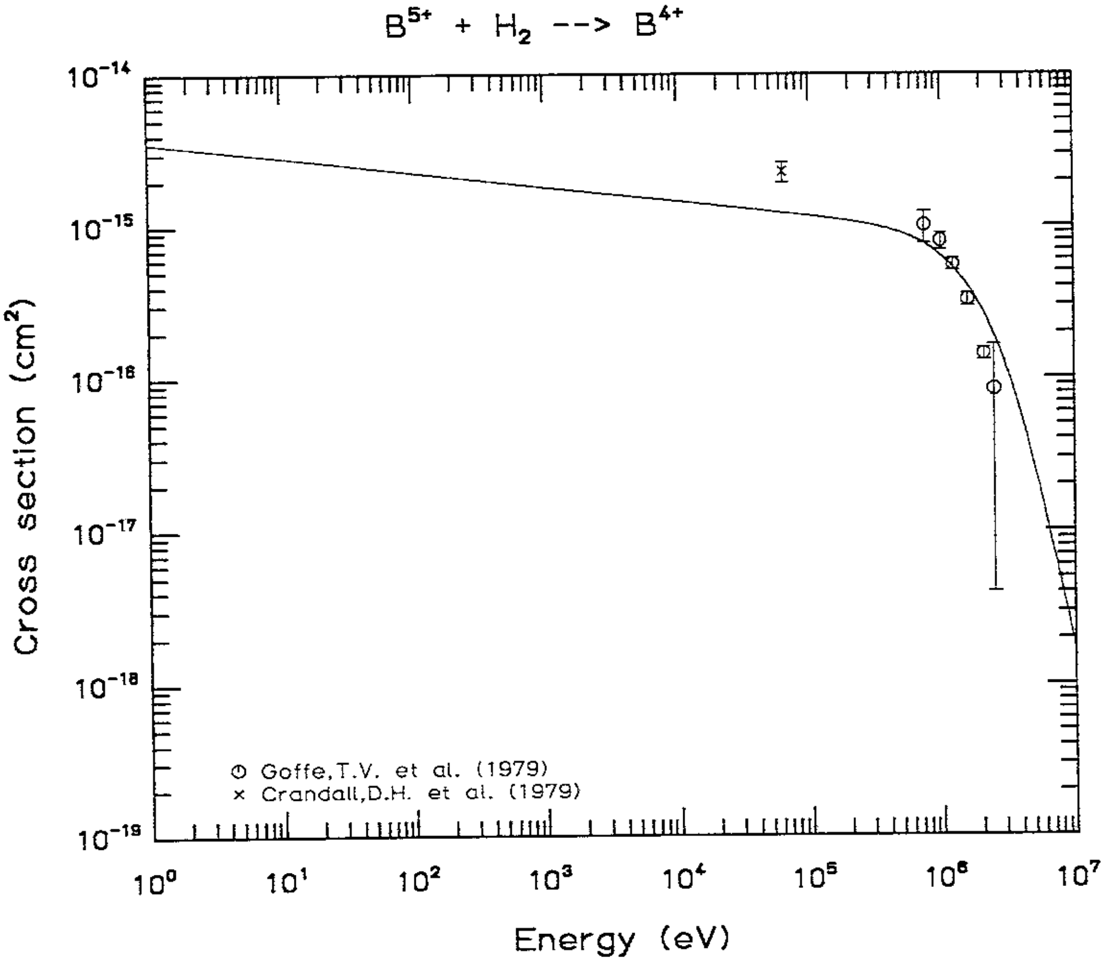

Fig.92 Total cross sections into B^{4+} in B^{5+} + H_2 collisions

B^{q+} + He collisions

B^+ + He (Fig.93)

Only total cross sections have been measured by Nikolaev et al. at high energy range.

V.S.Nikolaev, I.S.Dmitriev, L.N.Fateeva and Ya.A.Teplova, Sov. Phys.-JETP **13** (1961) 695

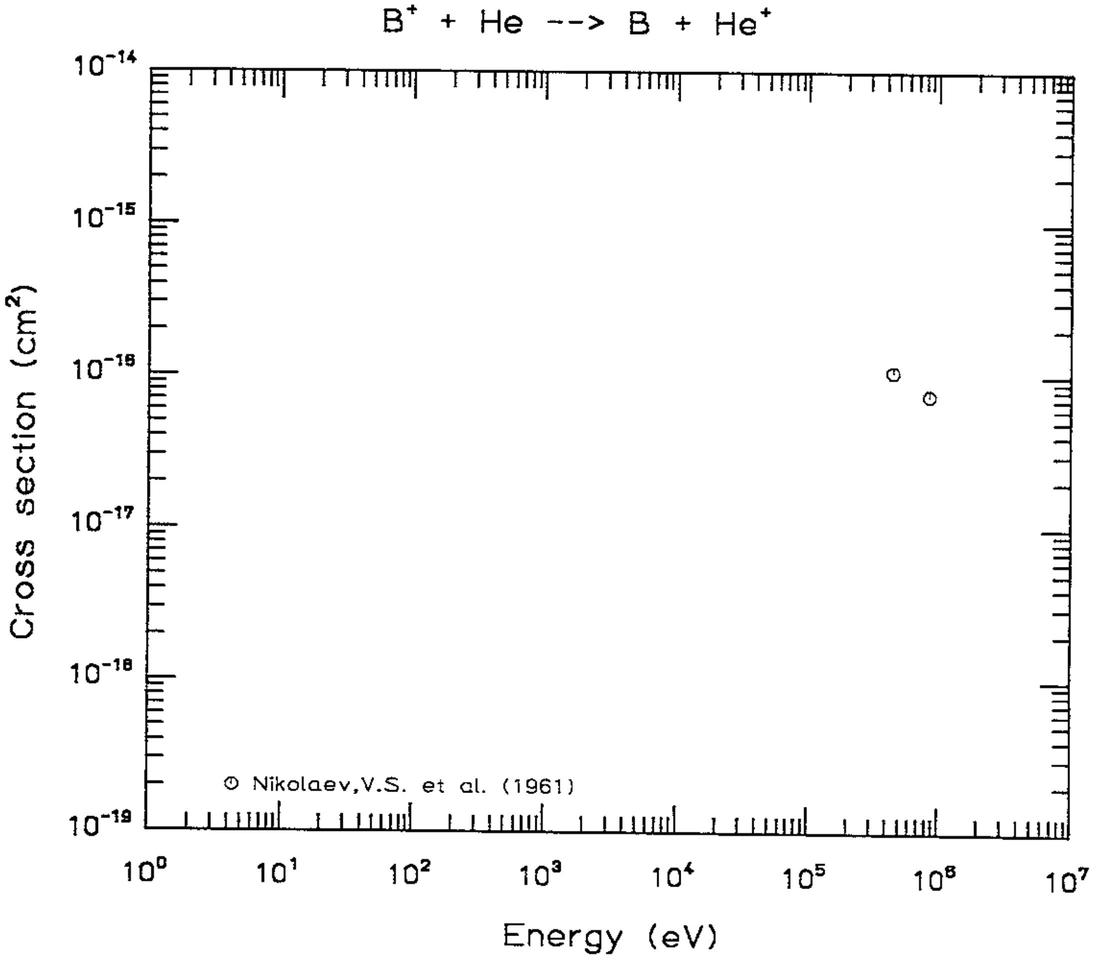

Fig.93 Total cross sections into B in B^+ + He collisions

B^{2+} + He (Fig.94)

Only total cross sections have been measured. However, the agreement among different experimental data seems to be not good at low energies, probably because of the limited of acceptance of product ions in the apparatus.

C.W.Sherwin, Phys. Rev. **57** (1940) 814

V.S.Nikolaev, I.S.Dmitriev, L.N.Fateeva and Ya.A.Teplova, Sov. Phys.-JETP **13** (1961) 695

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A 20 (1979) 766

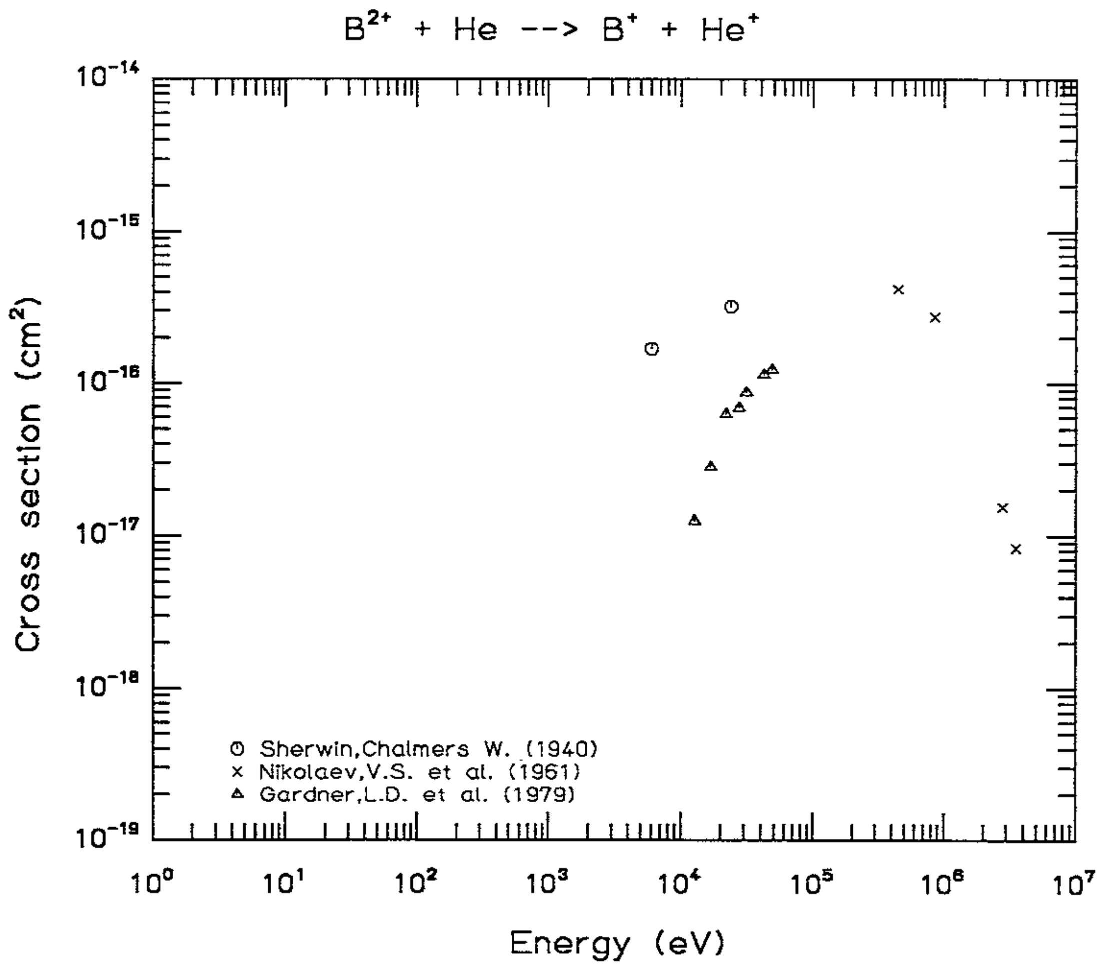

Fig.94 Total cross sections into B^{+} in B^{2+} + He collisions

B^{3+} + He (Figs.95-98)

Partial cross sections into $B^{2+}(1s^22s, 1s^22p)$ have been calculated only by Shipsey et al. using molecular basis set. Their results show that the dominant capture of an electron occurs into $B^{2+}(1s^22s)$ state down 0.1 keV/amu from higher energies, meanwhile below 0.1 keV/amu the capture into 2s-state becomes dominant, though the cross sections themselves decrease with decreasing the collision energy. On the other hand, relative partial cross sections for capture into 2s and 2p states have been measured experimentally by Matsumoto et al. using the translational energy spectroscopy, indicating the switch-over of the dominant state around 0.1 keV/amu as predicted.

Total cross sections have been measured by Nikolaev et al., Zwally and Cable, Crandall, Gardner et al. and Iwai et al. The agreement seems to be reasonable among the measured data.

V.S.Nikolaev, I.S.Dmitriev, L.N.Fateeva and Ya.A.Teplova, Sov. Phys.-JETP **13** (1961) 695

H.J.Zwally and P.G.Cable, Phys. Rev. A **4** (1971) 2301

D.H.Crandall, Phys. Rev. A **16** (1977) 958

E.J.Shipsey, J.C.Browne and R.E.Olson, Phys. Rev. A **15** (1977) 2166

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

T.Iwai, Y.Kaneko, M.Kimura, N.Kobayashi, S.Ohtani, K.Okuno, S.Takagi, H.Tawara and S.Tsurubuchi, Phys. Rev. A **26** (1982) 105

A.Matsumoto. T.Iwai, Y.Kaneko, M.Kimura, N.Kobayashi, S.Ohtani, K.Okuno, S.Takagi, H.Tawara and S.Tsurubuchi, J. Phys. Soc. Japan **52** (1983) 3291

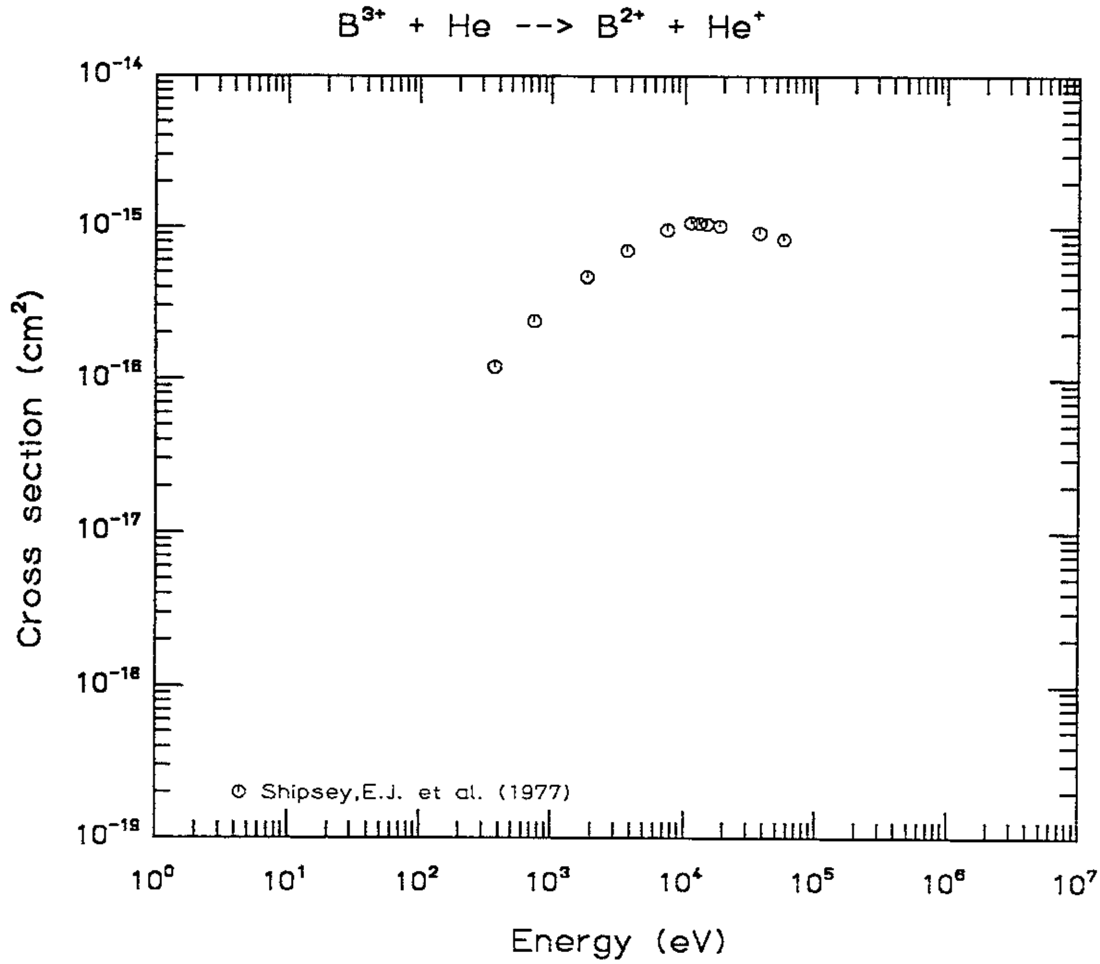

Fig.95 Partial cross sections into $B^{2+}(2s)$ in B^{3+} + He collisions

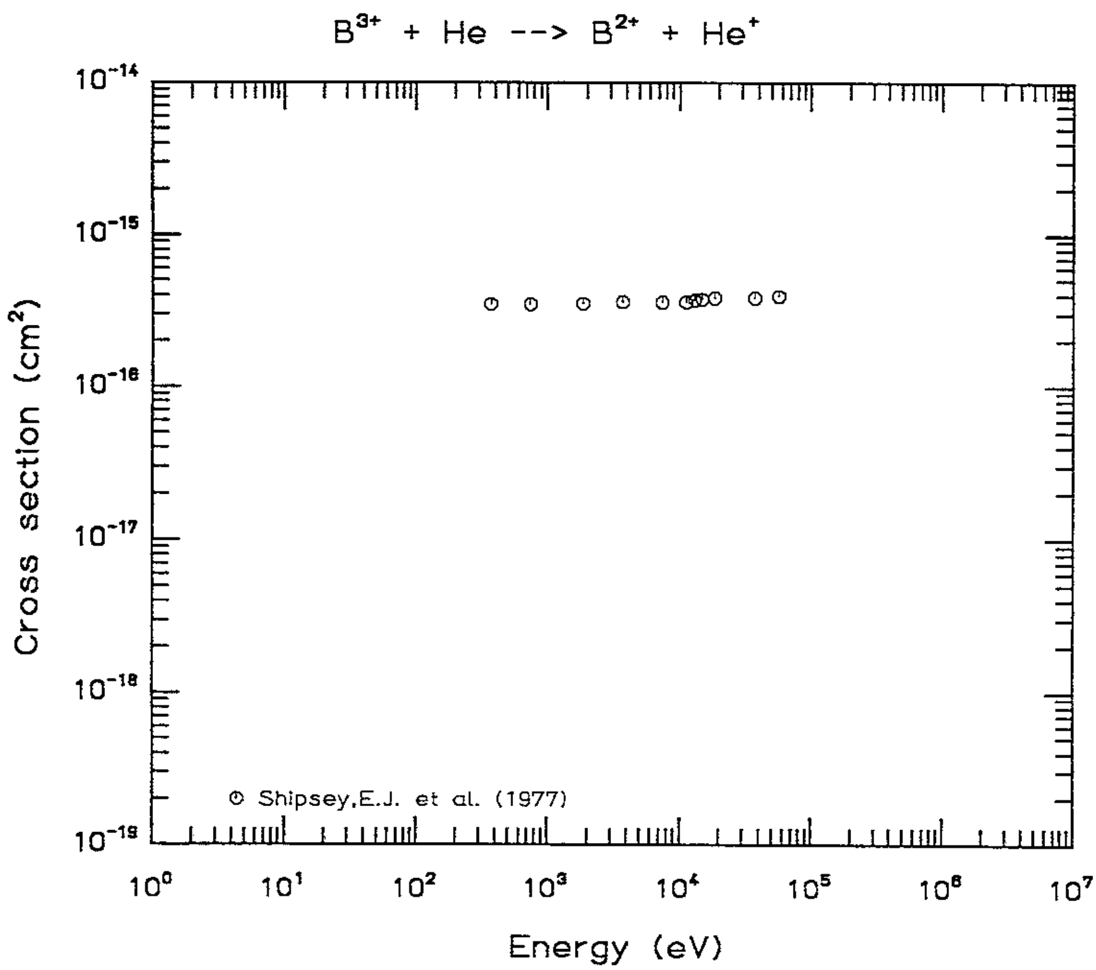

Fig.96 Partial cross sections into $B^{2+}(2p)$ in B^{3+} + He collisions

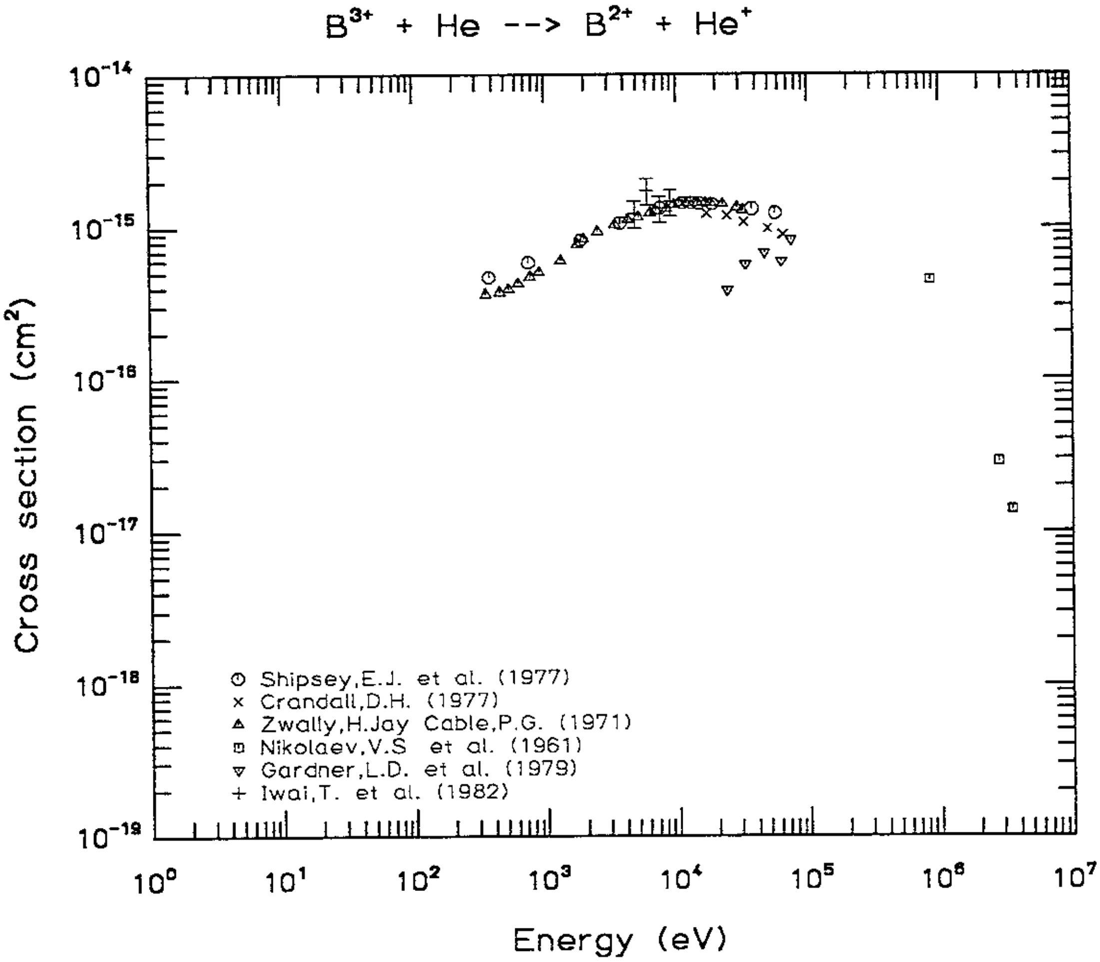

Fig.97 Partial cross sections into B^{2+} in B^{3+} + He collisions

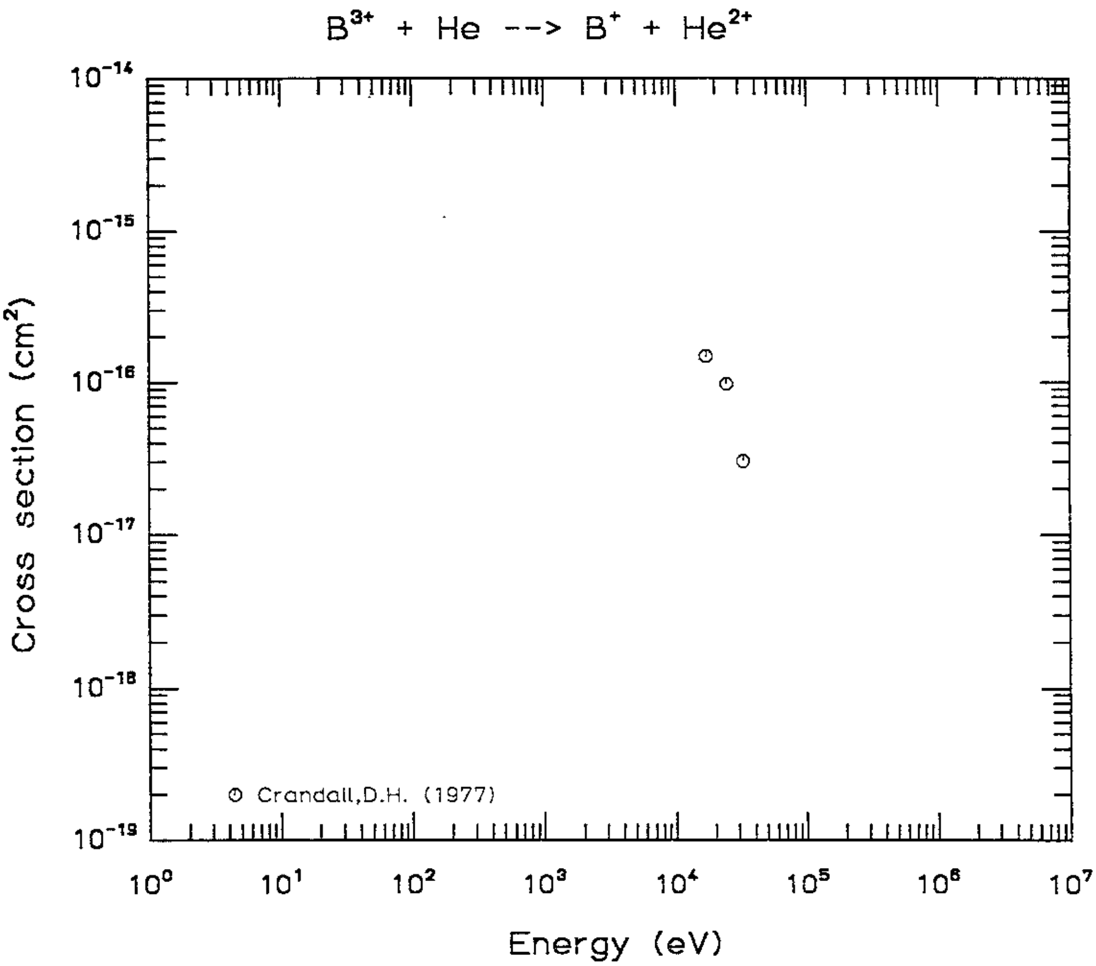

Fig.98 Total cross sections into B^{+} in B^{3+} + He collisions

B^{4+} + He (Fig.99)

Only total cross sections have been reported over the scattered energy region by Nikolaev et al., Gardner et al. and Iwai et al. The extrapolation between two measurements at different low energy regions seems to be in agreement with each other. The cross sections decrease with decreasing the collision energy.

V.S.Nikolaev, I.S.Dmitriev, L.N.Fateeva and Ya.A.Teplova, Sov. Phys.-JETP **13** (1961) 695

L.D.Gardner, J.E.Bayfield, P.M.Koch, I.A.Sellin, D.J.Pegg, R.S.Peterson, M.L.Mallory and D.H.Crandall, Phys. Rev. A **20** (1979) 766

T.Iwai, Y.Kaneko, M.Kimura, N.Kobayashi, S.Ohtani, K.Okuno, S.Takagi, H.Tawara and S.Tsurubuchi, Phys. Rev. A **26** (1982) 105

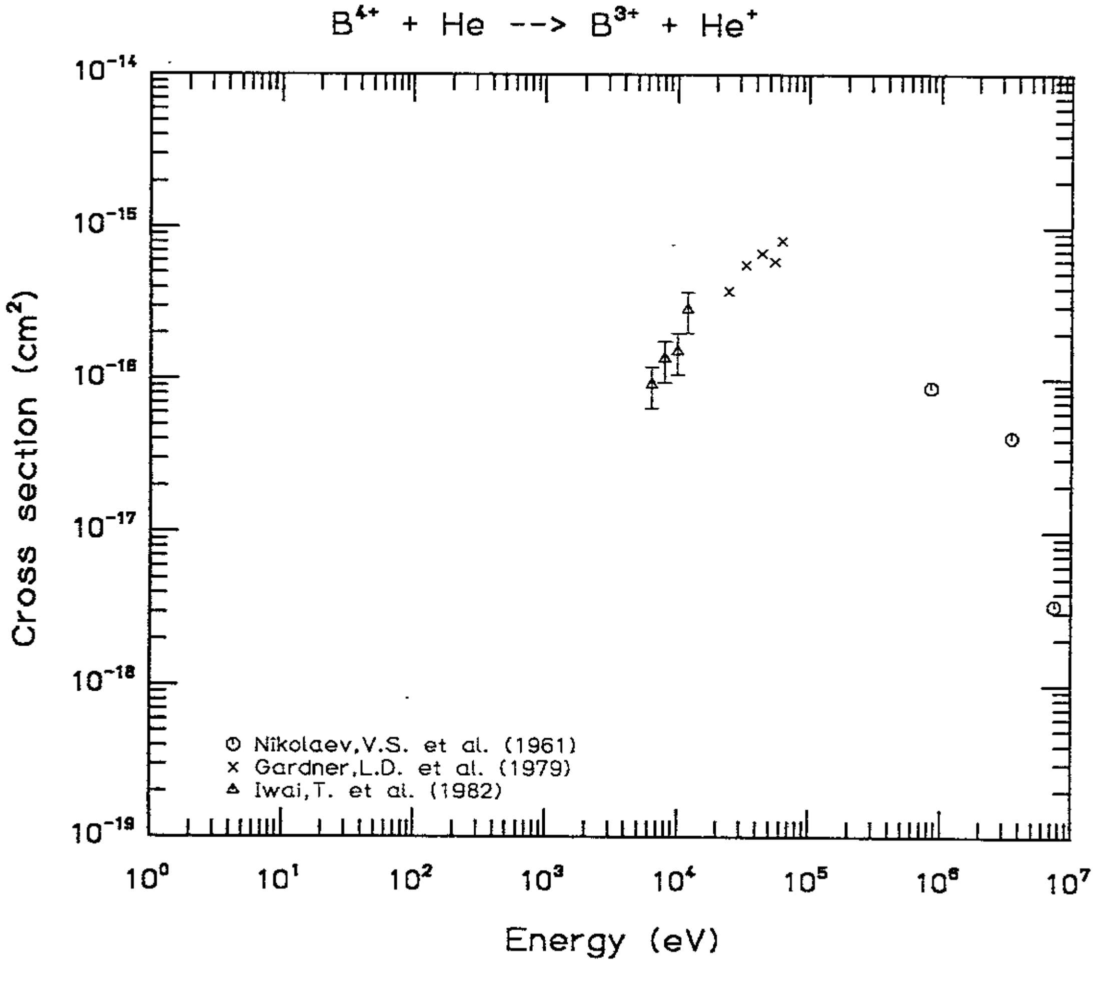

Fig.99 Total cross sections into B^{3+} in B^{4+} + He collisions

B^{5+} + He (Fig.**100**)

Only total cross sections have been measured by Nikolaev et al. and Guffey et al. at high energies which are in good agreement with each other and also Iwai et al. at low energies. The distinctive difference of the energy dependence, compared with those for q= 3-1, is the fact that the cross sections do not decrease even at low energies and are roughly constant.

A single theoretical result has been reported by Olson at high energy region.

V.S.Nikolaev, I.S.Dmitriev, L.N.Fateeva and Ya.A.Teplova, Sov. Phys.-JETP **13** (1961) 695

J.A.Guffey, L.D.Ellsworth and J.R.Macdonald, Phys. Rev. A **15** (1977) 1863

R.E.Olson, Phys. Rev. A **18** (1978) 2464

T.Iwai, Y.Kaneko, M.Kimura, N.Kobayashi, S.Ohtani, K.Okuno, S.Takagi, H.Tawara and S.Tsurubuchi, Phys. Rev. A **26** (1982) 105

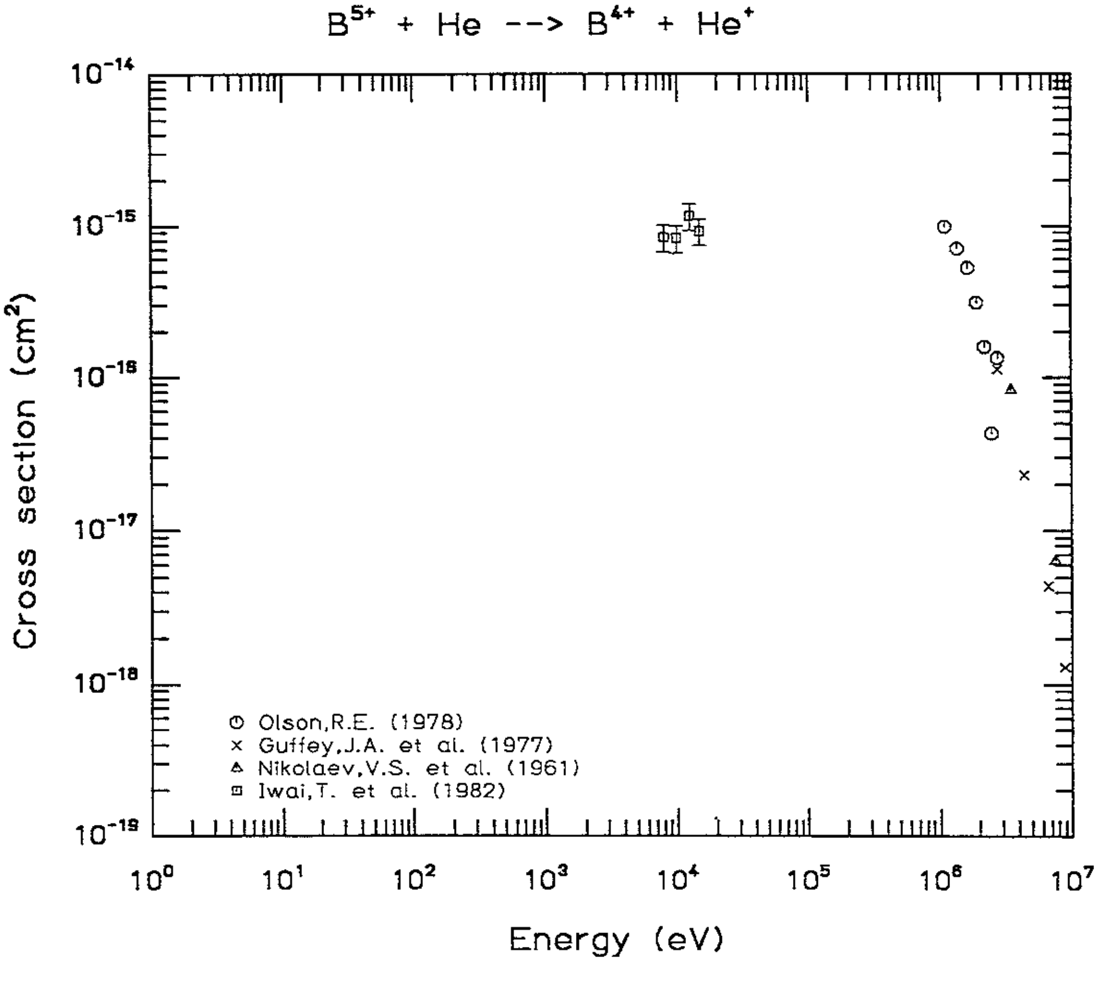

Fig.100 Total cross sections into B^{4+} in B^{5+} + He collisions

Be^{q+} & B^{q+} Electron Transfer Data References List

Theoretical

D.R.Bates and B.L.Moiseiwitsch, Proc. Phys. Soc. **67** (1954) 805
Inelastic heavy particle collisions involving the crossing of potential energy curves I : charge transfer from H atoms to Be^{2+}, Si^{2+} and Mg^{2+} ions
(Be^{2+} + H -> Be^{+} + H^{+} : total)

A.Dalgarno, Proc. Phys. Soc. A **67** (1954) 1010
Inelastic heavy-particle collisions involving the crossing of potential energy curves II : charge transfer from H-atoms to Al^{3+}, B^{2+}, Li^{2+} and Al^{2+}
(B^{2+} ?)

C.Bottcher, J. Phys. B **10** (1977) L213
Charge transfer to highly stripped ions from hydrogen atoms
(Be^{4+}, B^{5+} + H -> total)

Dz.Belkic and R.McCarroll, J. Phys. B **10** (1977) 1933
Projectile charge dependence of electron-capture cross sections
(Be^{4+} + H -> total)

C.Harel and A.Salin, J. Phys. B **10** (1977) 351
Charge exchange in collisions of highly ionised ions and atoms
(Be^{4+} + H -> Be^{3+}(n=3) ; B^{5+} + H -> B^{4+}(n=3,4))

E.J.Shipsey J.C.Browne and R.E.Olson, Phys. Rev. A **15** (1977) 2166
Theoretical charge-exchange total cross sections for B^{+3} + He and C^{+4} + He collisions
(B^{3+} + He -> B^{2+}(nl=2s,2p))

R.E.Olson and A.Salop, Phys. Rev. A **16** (1977) 531
Charge-transfer and impact-ionization cross sections for fully and partially stripped positive ions colliding with atomic hydrogen
(B^{q+}[q=3,4,5] + H -> : total)

R.E.Olson, Phys. Rev. A **18** (1978) 2464

Electron-capture and impact-ionization cross sections for multiply charged ions colliding with helium
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A.Dalgarno and S.E.Butler, Comments At. Mol. Phys. **7** (1978) 129
Charge transfer of multiply-ionized species
(Be^{3+}, B^{3+} + H -> rate coefficient)

R.E.Olson, E.J.Shipsey and J.C.Browne, J. Phys. B **11** (1978) 699
Charge-transfer cross sections for B^{3+}, C^{4+} + H collisions
(B^{3+} + H -> total)

J.E.Golden, J.H.McGuire and K.Omidvar, Phys. Rev. A **18** (1978) 2373
Electron capture from atomic hydrogen into excited n,l levels of projectiles with $Z_1 \geq 1$
(Be^{4+} + H -> Be^{3+}(nl) only at 100 keV/amu)

F.T.Chan and J.Eichler, J. Phys. B **12** (1979) L305
Charge exchange between H(2s) and energetic projectiles
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A.Salop, J. Phys. B **12** (1979) 919
The distribution of excitation resulting from electron capture in stripped-ion-hydrogen-atom collisions
(B^{5+} + H -> B^{4+}(n,l)

H.Ryufuku and T.Watanabe, Phys. Rev. A **19** (1979) 1538
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