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Roles of Atomic and Molecular Processes in Fusion Plasma Researches

- from the cradle (plasma production) to the grave (after-burning) -

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Roles of Atomic and Molecular Processes in Fusion Plasma Researches

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Abstract

This short lecture given at RIKEN Winter School on Atomic and Molecular Processes in Tsunan, Niigata, has described some crucial roles of atomic and molecular (AM) physics in magnetic fusion plasma research. Particular importance has been stressed of collision processes involving species in the excited states in fusion plasmas, especially in divertor and edge plasmas.

[keywords : atomic physics, fusion plasmas, excited species, divertor plasmas, edge plasmas]

Contents

1. Introduction

Before describing the roles of collision processes in (fusion) plasmas[1)], it would be necessary to introduce some important issues relevant to magnetic plasma fusion research.

1.1 Nuclear fusion reactions usable in plasma fusion :

a) The following two nuclear fusion reactions (often called D-T and D-D reactions) seem to be good candidates for the present-day plasma fusion apparatus as they have large reaction cross sections at relatively low energies as shown in Fig.1 :

D + T -> ^{4}He + n + 17.59 MeV (σ_{max} = 6 b at 110 keV)

(3.52 MeV) (14.07 MeV)

D + D -> ^{3}He + n + 3.27 MeV (σ_{max} = 0.1 b at 2-3 MeV ; σ = 0.02 b at 110 keV)

(0.82 MeV) (2.45 MeV)

-> ^{3}T + p + 4.03 MeV

(1.01 MeV) (3.02 MeV).

As seen in Fig.1, D-T reaction is the most promising to achieve nuclear fusion through plasmas with reasonable temperatures and, therefore, tremendous effort is being directed to investigations of plasmas involving D-T reaction. On the other hand, D-D reactions need high temperatures and two channels in D-D reactions have roughly the same cross sections.

Plasma fusion schemes based on these nuclear fusion reactions have various features :

(1) a large fraction of fusion energy carried by neutrons

(2) radioactive ^{3}T needed for D-T reactions

(3) intense activation and irradiation damage to materials

In particular, the radiation damage due to intense neutrons produced in nuclear reactions is the most serious problems and thus systematic developments of radiation-resistant materials are under way.

b) Nuclear reaction for future fusion :

D + ^{3}He -> ^{4}He + p + 18.35 MeV (σ_{max} = 0.8 b at 400 keV)

(3.67 MeV) (14.68 MeV) .

On the contrary to D-T or D-D nuclear reactions, though this nuclear fusion reaction needs much high temperature plasmas (see Fig.1), this has the following features :

(1) Much clean ! High energy fusion products, 15 MeV protons, can be confined magnetically and thus practically no activation and damage of materials can occur.

(2) There are still big problems of how to get sufficient ^3He (It is known that the soils on the lunar surface contains significant quantities of ^3He of about 1 million tons, which is sufficient to provide the energy over 500 years).

1.2 Maxwellian distributions of plasma temperatures

Ions confined in the fusion plasmas usually have the Maxwellian-velocity distributions at the temperature T :

$$f(v) = (\sqrt{\pi}*v_m^2)^{-3}*\exp[-(v/v_m)^2],$$

with $(1/2)\, Mv_m^2 = kT$

v_m: most probable velocity

T : ion temperature

M : ion mass.

In D-T (as well as D-^{3}He) plasmas, both D and T ions have their velocity distributions. Therefore, D-T nuclear reaction rate coefficients can be obtained after double-Maxwellian-averaging :

$$<\sigma v> = \int f(v_D) f(v_T) /v_D - v_T/ \sigma(/v_D - v_T/) dv_D dv_T \quad (cm^3/s)$$

where v_D and v_T are the velocities of D and T ions in the plasma, respectively.

1.3 Comparison with nuclear fission

Nuclear fission reactions are widely used in the present-day fission power reactors. The following nuclear reactions of ^{235}U by thermal neutrons are typical fission reactions which generate huge energy :

$$^{235}U + n_{th} \rightarrow {}^{90}Sr + {}^{137}Cs + n*n_f + 200\ MeV \qquad (\sigma_{th} = 600\ b).$$

The fission reactions have features different from those in fusion reactions :

(1) most fission energy carried by heavy fission products and lost inside fission materials

(2) efficient neutron thermalization with minimum losses for chain reactions.

1.4 Fusion plasmas versus other plasmas

It is interesting to know various plasmas with different (temperature and density) parameters around us : fluorescent lamp (typical low temperature and low density), discharge plasmas (low density and low temperature), solid state plasmas (low temperature and high density), plasmas in the sun (typical high temperature and high density).

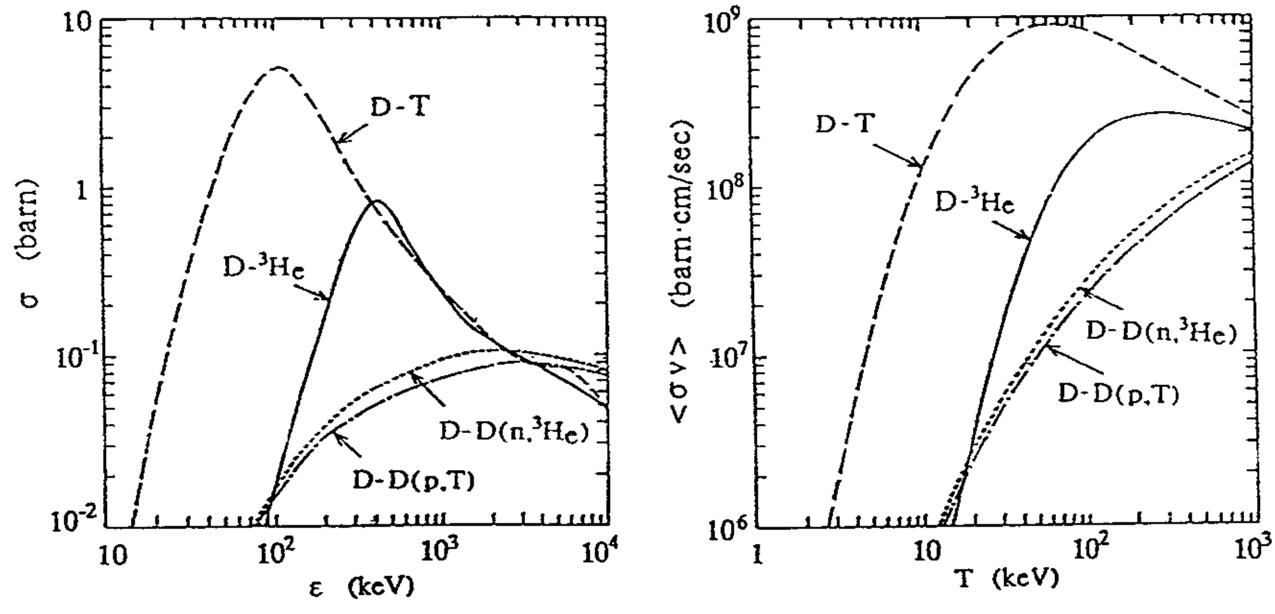


Fig.1 Cross sections as a function of impact energy and Maxwellian-averaged rate coefficients as a function of plasma temperature for various nuclear fusion reactions (note that 1 eV = $1.1605*10^4$ K : 10 keV = $1.16*10^8$ K = 1.16 億度) (courtesy by Dr. Y.Tomita, NIFS)

In plasma nuclear fusion reactors, similar to those occurring in the sun, we at many laboratories around the world are trying to produce our future energy resource. But there is a big difference between two plasmas : plasmas in the sun are confined by its gravity and there is no wall around the plasmas. On the other hand, laboratory fusion plasmas have to be confined through electromagnetic force in order to avoid the contact with the walls of vacuum vessels.

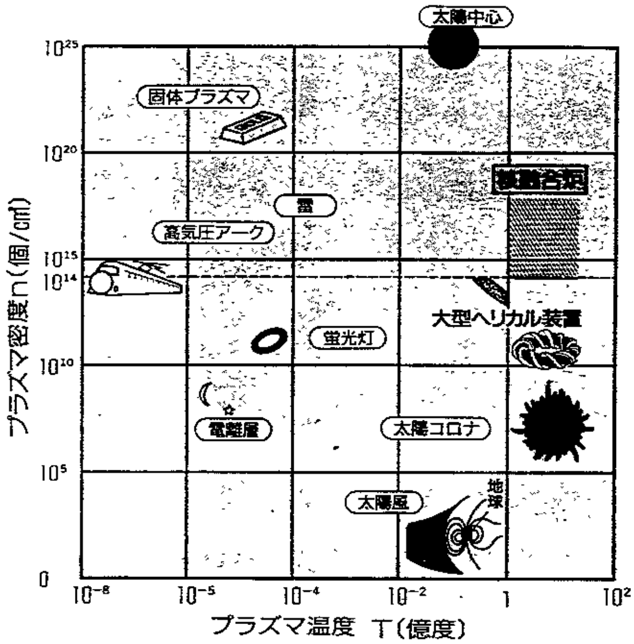


Fig.2 Comparison of plasma parameters (temperature in 10^8 K and density in /cm^3) in various plasmas

1.5 Lawson criterion in aiming plasma fusion

In order to produce the energy through fusion reactions in plasmas with sufficiently high temperatures by compensating the energy losses due to plasma radiations (mainly electron bremsstrahlung) and particle losses via drift/conduction through the produced fusion power, the following criterion (so-called Lawson) has to be fulfilled :

$$n*\tau*T > \text{constant}$$

where n is the plasma density, τ the plasma confinement time and T the plasma temperature, respectively.

For ignition (meaning that the plasmas can produce the energy sufficient to sustain nuclear fusion reactions without any additional external power), the D-T plasmas have to fill the following minimum condition :

$$n*\tau > 10^{14}\ \text{s/cm}^3 \text{ at } T > 10\ \text{keV}.$$

Of course, the optimum conditions change with the plasma conditions, as the nuclear fusion reaction cross sections decrease and the radiation losses increase at higher temperatures.

1.6 Tokamak

Though a number of different types of fusion plasma apparatus and devices have been proposed so far, one of the most promising devices for achieving high temperature fusion plasmas seems to be so-called "tokamak" type. Its principle, as shown in Fig.3, is transformer-like secondary-induced-current plasmas in a torus with toroidal magnetic fields for plasma confinement. There are many

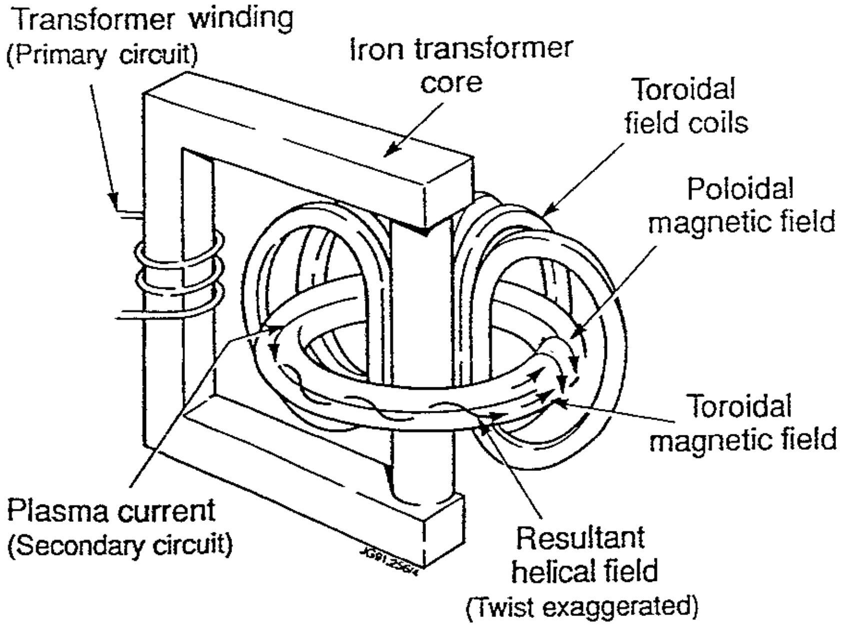


Fig.3 Principal structures of tokamaks.

different configurations of magnetic fields in order to get better confinement and control of plasmas.

The largest present-day tokamaks are represented by those such as JET (EU), JT-60-U (JAERI), TFTR (USA). The largest tokamak is the planned International Tokamak Experimental Reactor (ITER), now under design stage in the international collaboration program among US, EU, Russia and Japan. In Table 1 are shown the most relevant plasma parameters in these tokamaks. Other parameters of ITER are also shown in Table 2.

Table 2 clearly demonstrates that the fission and plasma fusion reactors have the output power densities very much different by three orders of magnitude. As will be discussed later, the most important and urgent issues in ITER design are how to dissipate such huge power densities at divertors near the exhausting pump stations[2)].

Table 1 Comparison of features in large tokamaks

	plasma current (MA)	torus diameter (m)	plasma diameter (m)	magnetic field (T)
JET (EU)	7.0	2.96	1.2	3.45
JT-60 (Japan)	3.2	3.00	0.9	4.80
TFTR (USA)	2.5	2.50	0.85	5.20
T-15 (Russia)	2.0	2.40	0.70	4.00
ITER	25.0	7.75	3.00	6.00

Table 2 Important output parameters in ITER (International Tokamak Experimental Reactor)

Fusion power	> 1.5 GW (≈ 1 MW/m^3)*
Thermal output	500 MW
Exhausting alpha power	3 - 600 MW
Power on tilted divertor	24-100 MW/m^2**

Note :

* largest nuclear power station ≈1.3 GW in reactor volume 1 m^3

** maximum power to material should be < 5MW/m^2.

1.7 Various plasmas in tokamaks

In order to get controlled high temperature plasmas and achieve nuclear fusion reactions, different types of plasmas are necessary, as shown in Fig.4, and indeed do play their own significant roles in various fusion plasma apparatus :

a) Main high temperature plasmas where nuclear fusion reactions occur :

temperature : >10 keV, density : 10^{14} /cm^3

b) Edge or scrape-off layer (SOL) plasmas which is the isolating interface between high and low temperature plasmas and walls :

temperature : < 100-500 eV, density : 10^{13} - 10^{14} /cm^3

c) Divertor plasmas, working as energy/gas damper, from which cold, unusable gases (also impurities) are exhausted and pumped out temperature : < 10-100 eV, 10^{15}- 10^{16} /cm^3.

1.8 Atomic/molecular/ionic species present in plasmas

Many different particle (atom and ion) species are present in plasmas, depending on the time and locations as well as plasma conditions :

1) H (H_2 : isotope, D, T : fuel)

2) He (mostly fusion reaction product): Their densities in the main plasmas can not be larger than the fatal fraction of 20 %, otherwise the controllable high temperature plasmas can not be obtained.

2) Li, Be, B, C, O :

These materials with low-Z are often used as surfaces or surface coatings in order to minimize radiation losses from high temperature plasmas. C and O are the main impurities released from the surfaces in the form of CO and H_2O molecules. The fatal fractions of these species in the main plasmas are estimated to be < a few %.

3) Si, Ti, Cr, Fe, Ni, Mo, W

These are the most widely used as vacuum inner-walls and as protector armor/divertors because of their high melting points. The fatal fraction of these materials should be small : < 0.1 - 0.01 %. Still a lot of discussion is going on which materials are the best for such purposes and indeed the best possible candidate materials often change with time.

1.9 Main collision processes which play a key role in plasmas

There are number of the collision processes involved in plasma production and diagnostics. The following collisions involving ion/atom/molecule under collisions with electrons, plasma protons, hydrogens, the injected high energy neutral particles (H, He, etc.), heavy (impurity) ions and fusion reaction product (He) are important :

elastic scattering : $e + A^{q+} \text{-->} e' + A^{q+}$

ionization : $e + A^{q+} \text{-->} e' + e'' + A^{(q+1)+}$

excitation : $e + A^{q+}(nl) \text{-->} e' + A^{q+*}(n'l')$

dissociation : $e + H_2 \rightarrow e' + H + H$

dissociative ionization : $e + H_2 \rightarrow e' + H^+ + H$

recombination : $e + A^{q+} \rightarrow A^{(q-1)+*}$

electron capture : $A^{q+} + H \rightarrow A^{(q-1)+*} + H^+$

particle transfer : $A + BC \rightarrow B + AC$.

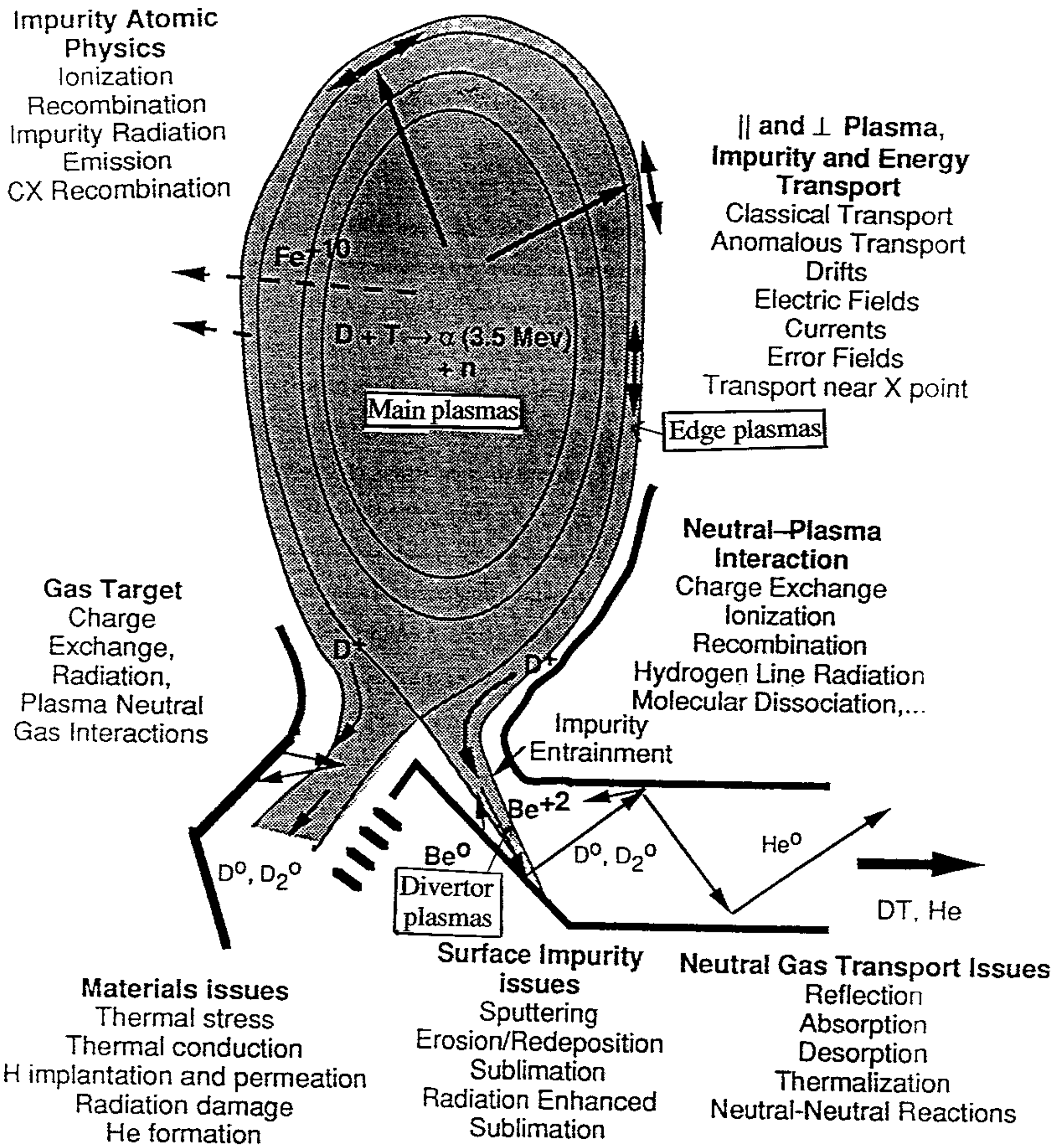


Fig.4 Cross sectional view and important features in different plasmas in a tokamak viewed from atomic physics point.

In order to understand the overall plasma features, we need a huge amount of systematic data for all the charge states of these species mentioned in sec. 1.8 over a wide range of the collision energy and under various plasma densities as a function of A, q, $n_0 l_0$, E, n_e etc. where A is the ion/particle species, q the ionic charge state, $n_0 l_0$ the initial quantum state, E the collision energy (plasma temperature), and n_e the plasma electron density, respectively.

Some institutes or international organizations (for example International Atomic Energy Agency-IAEA, Vienna[3,4]) coordinate such big tasks of data compilation and evaluation and finally recommendation/dissemination of the best data available for use of atomic and molecular data in fusion community and others.

2. Atomic processes in main plasmas

2.1 AM processes in the initial plasma generation

The most efficient, stable and high density plasma generation through gas discharges is still an important issue in fusion plasma experiments. The most critical to get such plasmas is better control and confinement of the initially-generated electrons along electro-magnetic fields. In fact, the very origin of these electrons forming the initial discharge is believed to be due to the ionization of gases by cosmic rays.

Typical pressures in discharge vessels in tokamaks are of the order of 10^{-4} Torr H_2/D_2 and the voltage induced along the single turn is about 20 V. It is sometimes said that 15-20 % of the pulsed discharges fail to form the stable plasmas in tokamaks.

2.2 AM processes for plasma heating

Plasmas have to be heated and confined (see Lawson criterion) through various techniques to get sufficiently high temperatures for achieving nuclear fusion reactions.

2.2.1 Plasma heating techniques

The followings are the techniques most often used for plasma heating :

a) Ohmic heating

b) Electron cyclotron resonance heating

c) Ion cyclotron resonance heating

d) Ion wave heating

e) Neutral beam injection (NBI) heating.

The first fours (a-d) are based upon the interaction and acceleration by electro-magnetic fields to the charged particles. On the other hand, NBI heating technique (e) is to heat plasmas by directly injecting high power, energetic particles and depositing their energy onto plasmas and seems to be the most promising and, at the same time, is the most interesting from atomic physics view as its principle is largely based upon various collision processes and their cross section data. In the following are given some detailed discussions on collision processes related to NBI.

2.2.2 Plasma heating by high energy neutral beam injection (NBI) into the main plasmas

The efficient NBI heating needs the following two processes, namely formation/injection of high power neutral beams and their trapping into the torus of tokamaks :

a) Formation of neutral beams :

The neutral H^0 beams with proper energy are formed through electron capture into protons (H^+) or electron stripping from negative hydrogen ions (H^-). The generation of powerful neutral hydrogen beams (H_{inj}^0) strongly depends on the electron capture/stripping cross sections of hydrogen particles (see sec.2.2.3 and Fig.5).

b) Injection of neutral beams into plasmas and trapping of "converted" high energy H^+ ions into tokamak orbits :

The injected neutral beams H_{inj}^0 are trapped in tokamaks via ionization/stripping or electron capture through the following collisions with plasma electrons and protons :

$$H_{inj}^0 + e \text{ (plasma)} \rightarrow H^+ + e' + e''$$

ionization by electrons

$H_{inj}^{0} + H^{+}(plasma) \rightarrow H^{+} + H^{0}$

electron capture by plasma protons (dominant at low energies)

$H_{inj}^{0} + H^{+}(plasma) \rightarrow H^{+} + e'' + H^{+}$:

ionization by protons (dominant at high energies)

If there are some impurities in the main plasmas, the effective conversion efficiencies are enhanced, depending on the amount of impurities, through similar collisions :

$H_{inj}^{0} + A^{q+} \rightarrow H^{+} + e + A^{q+}$: ionization

$\rightarrow H^{+} + A^{(q-1)+}$: electron capture

$\rightarrow H^{+} + 2e + A^{(q+1)+}$: ionization of both particles, which increases the effective charge of impurity ions, Z_{eff}, resulting in the enhancement of electron bremsstrahlung from the plasmas.

In principle, the NBI scheme is simple and reliable (a) direct energy conversion of NBI particles to plasma energy as well as (b) fuel (particle) injection into the main plasmas.

Thus, NBI can be used

1) as a source of plasma current drive
2) as a stable plasma initiator through the "converted ion"-neutral-particle interaction, which plays a role for starting better plasma with low plasma densities at the beginning of plasma discharges.
3) as a controller of plasma current density distributions over the main plasmas, thus producing stable plasmas.

2.2.3 Production of powerful (> 10 - 100 MW) H^{0} beams for NBI

In order to achieve high plasma temperatures for fusion through NBI, powerful neutral hydrogen beams, of the order of 10 - 100 MW at sufficiently high energies, are necessary. Thus the efficiencies of production of H^{0} beams are very important.

a) $H^{+} \rightarrow H^{0}$

High power, relatively low energy (< 100 keV) neutral hydrogen particles for NBI are often obtained through neutralization of protons in collisions with neutral gases such as H_2 molecules. In this case, the cross sections of the following electron capture process is important to get neutral H^0 beams :

$H^+ + H_2 \text{-->} H_0 \quad (\sigma_{10})$.

On the way to the main plasmas, on the other hand, some fractions of neutrals produced may be lost back into protons through electron stripping collisions :

$H^0 + H_2 \text{-->} H^+ \quad (\sigma_{01})$.

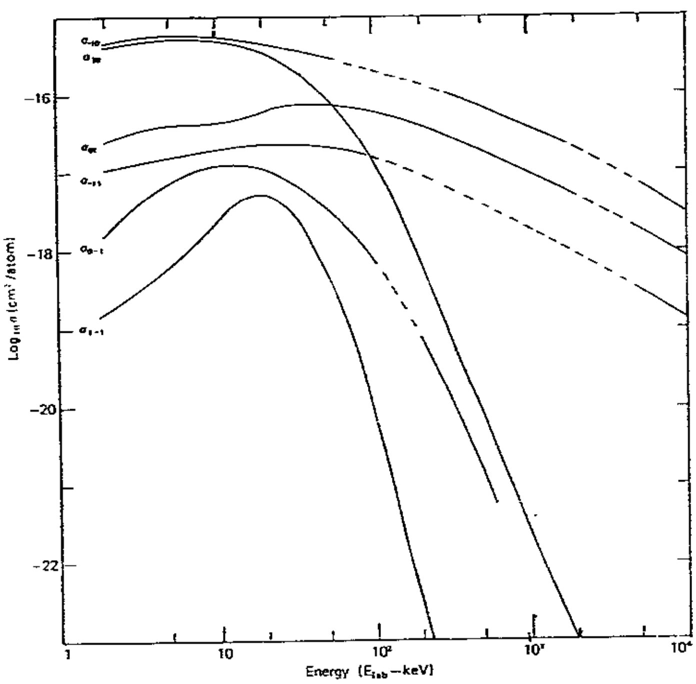


Fig.5 Cross sections (per atom) for hydrogen beams in H_2 gases[5)] relevant to NBI

Therefore, at < 100 keV NBI energy range, two processes (electron capture and electron stripping) play a dominant role, meanwhile there is very minor role of H^- :

Then, their rate equations for protons and neutral hydrogens can be given as follows :

$$dF^+/d\pi = -\sigma_{10}F^+ + \sigma_{01}F^0$$

$$dF^0/d\pi = \sigma_{10}F^+ - \sigma_{01}F^0$$

$$F^+ + F^0 = 1$$

where σ is the charge changing cross section, F^{q+} the fraction of particles in charge q (q = 0, 1 in this case), $\pi = nl$ (n : gas density and l : interaction length), respectively. From these rate equations, the H^+ --> H^0 conversion efficiencies, depending on the cross sections of various charge changing processes, are given :

$$\eta = \sigma_{10}/(\sigma_{10} + \sigma_{01})*[1 - \exp\{-(\sigma_{10} + \sigma_{01})*nl\}].$$

Note that there is no optimum pressure.

At > 100 keV NBI which is required for large plasma apparatus, the cross sections, σ_{10}, decrease very sharply, meanwhile σ_{01} decrease relatively slowly and thus $\sigma_{10}/\sigma_{01} << 1$. Using the cross sections shown in Fig.5, the conversion efficiency (H^+ --> H^0) can be estimated to be :

η = 20 % at 100 keV H^+

= 2-3 % at 200 keV H^+

= < 1 % at 500 keV H^+.

As the NBI energy becomes higher, the H^+ --> H^0 conversion efficiencies become intolerably small and the power losses become serious. Therefore, it is necessary to develop new techniques with better conversion efficiencies.

b) H^- --> H^0 :

It is obvious from Fig.5 that much better conversion efficiencies from negative hydrogen ions (H^-) into H^0 could be obtained. Of course, it is necessary to get negative hydrogen ions with sufficient intensities first.

b.1) Negative hydrogen ion (H^-) production

There are two methods in getting sufficient negative H^- ions :

(1) direct extraction from plasma ion sources

(2) double electron attachment to protons (H^+ --> H^-)

Similar to $H^+ \rightarrow H^0$ conversion, double electron capture (2) is less likely to occur at high energies. It is well known that, in both (1) and (2) cases, the addition of Cs vapors enhances the production of negative hydrogen ions through $H^+ + Cs \rightarrow H^-$ process which has large cross sections at low energies. Yet it is difficult or practically impossible to get such intense (1-10 A) H^--ions. Some new methods have to be developed or devised.

b.2) New processes for intense H^--ion production

Recently has been developed a new technique capable of producing intense H^- ions, based upon dissociative electron attachment process onto vibrationally excited (v) hydrogen molecules[6) :

$$e + H_2(v) \rightarrow H_2^- \rightarrow H^- + H(1s)$$

which has very large cross sections just above the threshold energies with the enhancement of a factor of 10^6 at $v = 5\text{-}7$ over those for the ground vibrational state ($v = 0$).

Thus, the following two-step processes are involved in so-called "volume production" of powerful H^- ions, namely in the first place, production of hydrogen molecules in the vibrationally excited states through collisions with relatively high energy electrons and, in the second, very low energy electron attachment to these vibrationally excited molecules resulting in dissociation into H^- ion production (see Fig.6) :

(1) $e + H_2(v{=}0) \rightarrow H_2(v)$:

The cross sections are large at relatively high electron energies ($E_e \approx$ 20-50 eV).

(2) $e + H_2(v) \rightarrow H_2^- \rightarrow H^- + H(1s)$:

Their cross sections are very large at low electron energies ($E_e \approx$ 1-2 eV).

In actual negative hydrogen ion sources, a large number of other collision processes including those with surfaces are found to contribute to the final H^- ion production. In very large scale apparatus at NIFS, JAERI and other institutes, 10 - 100 A H^- ion beams have already been obtained.

b.3) $H^- \to H^0$ conversion processes

H^- ion conversion into H^0 is controlled somewhat differently from $H^+ \to H^0$ conversion. In fact, the most important roles are played by single- and double-electron stripping processes, σ_{-10} and σ_{01}, with a minor role of σ_{-11} and σ_{10}, at > 200 - 1000 keV region.

The rate equations for governing the main three-components (H^+, H^0, H^-) in $H^- \to H^0$ conversion processes are as follows :

$$dF^+/d\pi = -(\sigma_{10} + \sigma_{1-1})F^+ + \sigma_{01}F^0 + \sigma_{-11}F^-$$

$$dF^0/d\pi = \sigma_{10}F^+ - (\sigma_{01} + \sigma_{0-1})F^0 + \sigma_{-10}F^-$$

$$dF^+/d\pi = \sigma_{1-1}F^+ + \sigma_{0-1}F^0 - (\sigma_{10} + \sigma_{-11})F^-.$$

From these rate equations, the best target densities for maximum H^0 yields are given :

$$\pi_{opt} = 1/(\sigma_{-10} + \sigma_{-11} - \sigma_{01})*\ln[(\sigma_{-10} + \sigma_{-11})/\sigma_{01}].$$

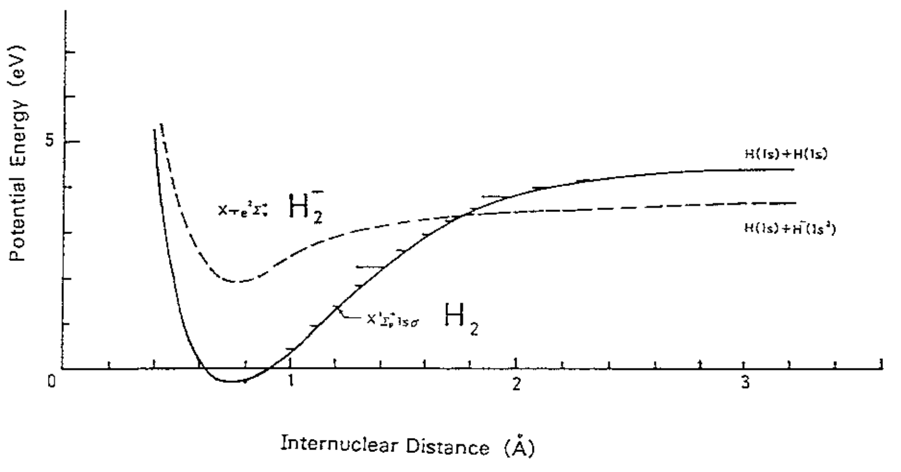


Fig.6 Production mechanisms of intense H^- ions through electron attachment to vibrationally excited hydrogen molecules

Then, the optimum fraction of H^0 beams is given :

$$F_{opt}^0 = (\sigma_{-10}/a)*[\exp\{-(\sigma_{01}/a)*\ln(\sigma_{-10} + \sigma_{-11})/\sigma_{01}\} - \exp\{-((\sigma_{-10}+\sigma_{-11})/a)*\ln(\sigma_{-10} + \sigma_{-11})/\sigma_{01}\}]$$

$$a = \sigma_{-10} + \sigma_{-11} - \sigma_{01}.$$

It is clear that large σ_{-10} results in (a) better conversion efficiencies and (b) small target densities of π_{opt} (indicating low pressures and less vacuum loads to pumping systems).

(2) best conversion efficiencies in neutral gases

As seen above, there exist optimum convertor gas densities for H^0 production, meanwhile too high gas target densities for conversion result in significant loss of the converted H^0 and increase of H^+ fractions, thus deteriorating the H^- -> H^0 overall conversion efficiencies.

The well-established data[5)] show the conversion efficiencies of at best < 56 -60 % when hydrogen molecules are used as a conversion gas. This indicates still too much loss of NBI power (> 50 MW at ITER !). Again more efficient convertors have to be developed.

Table 3 Cross sections (cm^2) in hydrogen molecules and hydrogen plasmas for 1 MeV/amu H^-

	H_2	H^+
σ_{-10}	$6.0*10^{-17}$	$5.0*10^{-16}$
σ_{-11}	$4.0*10^{-18}$	$1.0*10^{-18}$
σ_{01}	$1.6*10^{-17}$	$1.3*10^{-17}$

c) Plasma charge convertors

We need to find more efficient methods of H^- ion conversion into H^0 neutrals, namely to find some collision processes with large single-electron stripping cross sections from H^- ions. It is also important to know ratios of the cross sections (σ_{-10}/σ_{01}) in order to maximize the neutral fractions over protons produced. As can be seen in Table 3, some plasmas can be used as better charge convertors because of the following reasons :

(1) No electron capture in fully ionized plasmas : $\sigma_{10} \approx 0$,

(2) large σ_{-10} resulting in high electron stripping efficiencies from H^-.

However, presently are available only a limited data relevant to plasma charge convertors[7] and it is necessary to measure more systematic data involving H^--positive ion (A^{q+}) collisions. Some of these data obtained at relatively low energies (50 keV/amu)[8] suggest that the electron stripping cross sections from H^- ions increase relatively slowly as the ion charge q increases (as roughly q but not q^2, as expected from a simple scaling).

Thus, the development of highly ionized plasma sources becomes a critical issue in finding good convertors. It is well known that it is not easy to get highly (fully) ionized plasma targets with sufficient densities.

These cross sections relevant to plasma charge convertors indicate :

(1) $\geq$ 85-90 % conversion efficiencies can be achieved and therefore compact H^- ion sources can be constructed.

(2) Lower conversion medium densities by an order of magnitude can be sufficient, compared with those of neutral gases, and thus conversion gas effusion into the main plasmas can be kept minimum.

(3) Through technical feasibilities, we can get tentative conclusions :

(a) 100 % ionized hydrogen plasmas are better for plasma charge convertors.

(b) Highly ionized plasmas seem to be much efficient but their production needs new technological developments !

d) Laser-(detachment) ionization of H^- ions into H^0 with photons of 1.6 nm has 100 % conversion efficiencies. However, the overall efficiencies including the laser power are too small.

2.2.4 Losses of ions and neutral beams

a) Loss of H^- ions

These H^- ions may be lost in ion sources immediately after production and later during acceleration stage through various collision processes and can be estimated using the collision cross sections available.

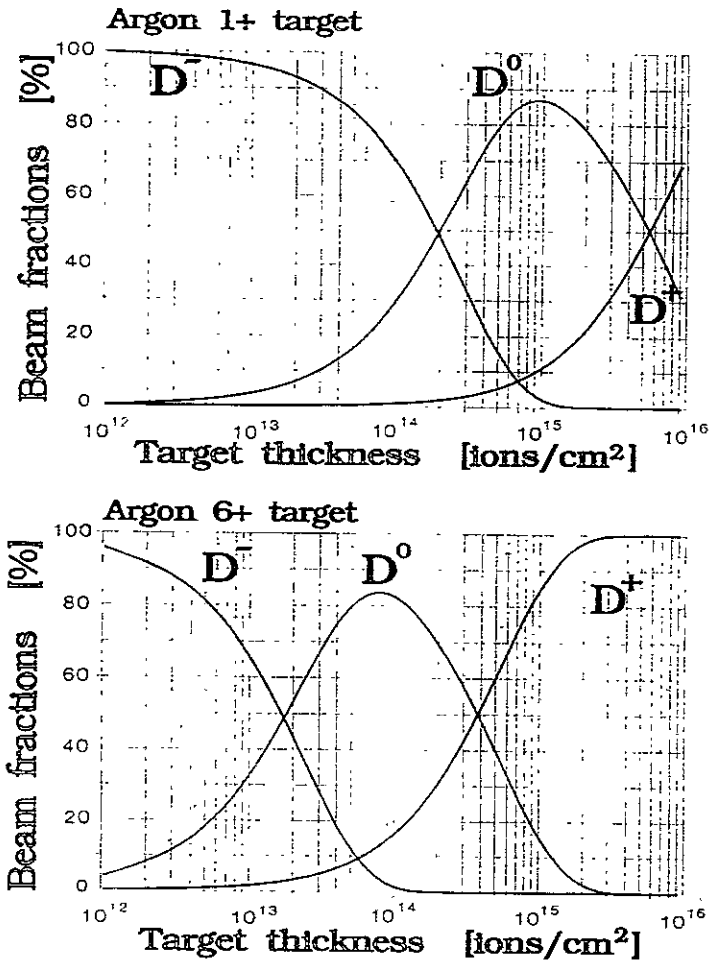


Fig. 7 Growth of 400 keV deuterium (D^0) beams from D^- ions in a plasma neutralizer as a function of plasma density (courtesy by Prof. E.Salzborn, Univ. Giessen)[8]. Note significant reduction of the optimum target densities for highly ionized (Ar^{6+}) plasmas (bottom), compared with those for Ar^+ plasmas (top).

(1) Loss in ion sources :

$H^- + H^+ \dashrightarrow H^0 + H^0$:

The mutual neutralization in collisions with protons in the source whose cross sections are huge at very low energies, being 10^{-12} - 10^{-13} cm^2 at 0.01 - 1 eV[9].

$H^- + e \dashrightarrow H^0 + e'' + e'$:

The electron detachment or ionization by electron impact which seems to be not so significant at the electron energy in the ion source (10^{-16} cm^2 at $E_e \approx 20$ eV).

(2) Acceleration stage :

The H^- ion loss also occurs through single and double electron stripping in collisions with residual gases before and after reaching the final energy :

$H^- + H_2$ --> H^0, H^+ $(\sigma_{-10}, \sigma_{-11})$.

Total losses of negative ions are given as $\exp\{-(\sigma_{-10} + \sigma_{-11})*nl\}$.

b) Loss of neutral particles

Neutrals formed may be lost through electron stripping in collisions with convertor gases or plasmas and, on the way to the main plasmas, with residual gases :

Loss = $\exp\{-\Sigma\sigma_{01}nl\}$

σ_{01} : electron stripping cross section in diffused hydrogens

+ impurity gases

nl : gas density after neutral particle formation.

Thus, the H^0 neutral beam loss on way to the main plasmas has to be kept minimum.

2.3 AM processes for plasma diagnostics

Two broad classes of plasma diagnostics techniques are widely used : passive and active. However, the active methods are more useful and powerful to get more accurate information on plasmas. Techniques themselves depend on which plasmas have to be diagnosed.

2.3.1 Main high temperature ($\geq$ 10 keV) plasmas

a) passive diagnostics :

A part of plasma constituents (protons or alpha particles) collide with other particles present in the plasmas, for example impurities, and are charge-changed into neutrals, which in turn escape from the main plasmas :

$A^{(z-1)+} + H_f^+ \rightarrow A^{z+} + H_f(n)$.

By analyzing the energy of the neutralized H escaped, the plasma temperatures can be determined. Through this collision, the effective charge of impurity ions increase and thus bremsstrahlung losses are enhanced (It should be noted that small K-shell-to-K-shell electron transfer cross sections of the order of 10^{-19} cm^2 at 400 keV/amu $H^+ + C^{5+}$ collisions will make this method not easy to apply to plasma diagnosis).

Similar but reverse collisions can also occur in plasmas, in particular near the edge plasma regions :

$A^{z+} + H_f(n) \rightarrow A^{(z-1)+*}(nl) + H_f^+$.

As an electron is captured into the excited states of ions, photons are emitted during decay into the ground state of the ions. As these ions move fast, the photons emitted from the ions are Doppler-broadened/shifted. The degree of broadening includes information on the velocity or temperature of particles in plasmas. This collision is very interesting in analyzing atomic hydrogens in the excited (n) state which are often present near the edge plasmas (see Fig.9 and later section).

a.1) Neutral particles escaped from the main plasmas

The neutrals escaped from the main plasmas are reionized through collisions with gas/foil stripper and then their energy is analyzed. For this, the electron detachment cross sections from H^0 neutrals[5)] are necessary to know the intensities of the ions in plasmas.

a.2) Doppler broadening of spectral lines

The Doppler-broadened spectra include information of the ion velocities or temperatures of plasma constituent particles. Assuming the Maxwellian distributions of the plasma temperatures, the ion temperatures are given using the observed broadening of photons (often called Charge Exchange Spectroscopy--CXS) :

$$T_i = 1.7*10^8*M*[\Delta h\nu(FWHM)/h\nu_0]^2 \quad (eV)$$

M : ion mass

$h\nu_0$: wavelength in Å at the center

$\Delta h\nu$: observed broadening in Å

b) Active diagnosis :

This active method, by injecting particles from the outside of the main plasmas, is more powerful and accurate than the passive method.

b.1) Injection of neutral H^0 or He^0 or pellets

Highly ionized ions in the main plasmas capture an electron into the excited states through the following process and emit their photons, as described above :

$A^{z+} + H \rightarrow A^{(z-1)+*}(nl) + H^+$.

b.2) Easy observation of visible photons

An electron is captured into some preferentially excited n-states[10], whose cross sections can be calculated quite accurately. Thus the photons emitted would be in UV region or sometimes in soft X-ray region which is not easy, particularly in absolute intensity measurements. Visible photon observations are much convenient in plasma diagnostics and then the transitions between high n-states become useful. Unfortunately any theories become unreliable in calculating the cross sections for such less dominant channels (10^{-3} - 10^{-4} of the main channel)[11]. To get reasonably accurate cross sections for weak channels, a huge number of channels have to be included in the calculations, thus requiring more computing time. In Fig.8 are compared typical calculated cross sections for n-state distributions for C^{6+}, N^{7+} and O^{8+} + H(1s) --> $C^{5+}(n)$, $N^{6+}(n)$ and $O^{7+}(n)$ + H^+ electron capture collisions. It is noted that there are significant discrepancies of the n-distributions among theories. More accurate calculations are needed for applications to fusion plasma diagnostics.

One of the most interesting photon spectra in an active plasma diagnostics is shown in Fig.9 which is taken during He^0 injection and there are clearly observed four Doppler-broadened components with different velocities which are produced in $He^{2+} + He_{inj} \rightarrow He^+\ II(nl) + He_{inj}^+$ electron capture collisions[12] :

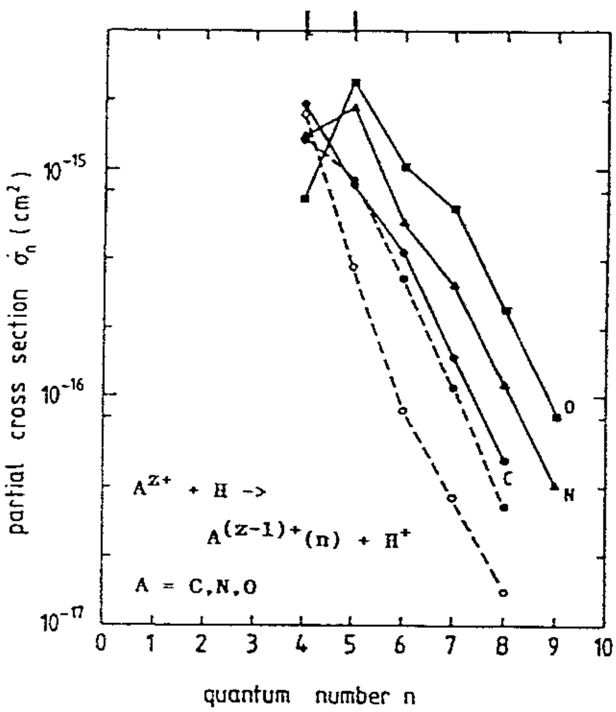


Fig. 8 n-distributions of C^{5+}, N^{6+} and $O^{7+}(n)$ ions produced in C^{6+}, N^{7+} and O^{8+} + H(1s) collisions.

(1) a sharp peak due to collision of slow (80 eV) alphas at the edges -- (I)

(2) the second broad peak due to "lukewarm" (~ 0.3 keV) alphas at the main plasma boundary -- (II)

(3) the third peak, more broadened, due to "hot" (~ 2.4 keV) alphas in central plasmas -- (III)

(4) the fourth peak due to high energy "trapped" injected alphas -- (IV).

2.3.2 Ion density, temperature and plasma rotation measurements

The Doppler-broadened/shifted CXS method based on "active" beam injection can be used to determine temporal and spatial distributions of a) ion density and b) ion temperature in plasmas. This can also be applied to measurement of other plasma parameters such as plasma rotation.

2.3.3 Electro-magnetic fields in plasmas

The electro-magnetic fields induced inside plasmas have significant influences on plasma motions and features. In order to measure such fields, heavy ion beam probe (HIBP) techniques are under development at various laboratories.

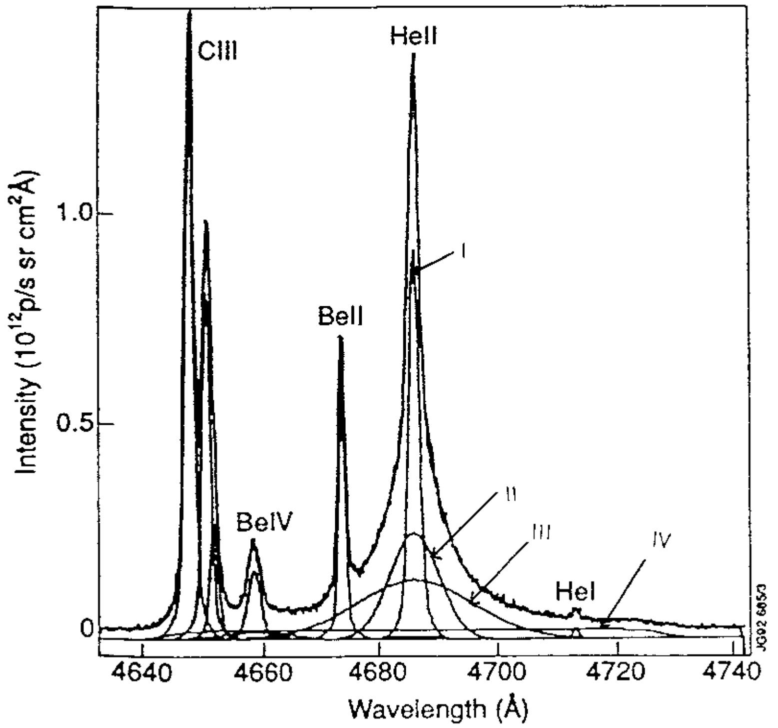


Fig. 9 He II (n=4->3) 468.52 nm line shape observed during 150 keV neutral He beam into JET plasmas

a) Electro-static plasma potential ϕ_p:

The injected heavy ions, of the mass of about 200 and possibly singly-charged, encounter with plasma constituent particles. If they are ionized/charged-changed at a point of the electro-static potential, ϕ_p, in plasmas, slight change of their kinetic energy, $(q-q')*\phi_p$, of the order of 500 eV occur and can be measured after coming out of the plasmas. For example, Au or Tl can be good candidates for such heavy ions.

In HIBP at NIFS, negative Au^- ions, accelerated through a tandem accelerator up to 3 MeV, are converted into Au^+ ions and again accelerated down to the final energy at 6 MeV. Then these Au^+ ions are injected into the main plasmas and ionized to Au^{2+} in collisions with plasmas. Finally after coming out of the plasmas, their energy gain can be energy-analyzed to know the energy change.

For HIBP, high stabilities ($< 1*10^{-4}$) of the incident ions and small energy spread (< 100 eV) are required, in addition to the necessary collision cross sections for production of useful Au ions. Yet very little is known on the energy losses during charge-changing and ionization processes.

n_q : ion density with charge q

$\sigma_{q-1,q}{}^{i}$: cross section of ionization from charge q to q+1

$\sigma_{q,q-1}{}^{r}$: cross section of recombination from charge q to q-1

n_e : electron density

v_d : drift velocity.

Here the first term represents the gain of ions with charge q from other charge states, the second term, the loss of ions with charge q into other charge states and the third term, the loss of ions due to drift out from plasmas. A typical example of the variation of X-ray spectra from Fe ions are shown in Fig. 10 at different plasma temperatures. It is seen clearly that as the plasma temperatures rise the observed X-ray spectra shift toward higher ion charge states[13].

Multiple collision effects becomes important at high plasma densities ($>10^{15}$ /cm^3) due to the successive collisions within the finite life-times of the excited states. These multiple collisions enhance the effective cross sections[14].

2.4.2 Necessary accuracies of AM data

The accuracies required slightly depend on how the data are used, either in modeling or diagnostics.

a) Modeling

Systematic collision data are needed for all the charge states of ions (the accuracies of a factor of two could be sufficient) for a large number of collision processes.

b) Optical measurements

(1) Transition energies for identification of line peaks should be accurate ($< 10^{-4}$) in order to correctly identify the spectrum lines.

(2) Transition rates for determination of ion densities should be known with less accuracies (a factor of 2-5)

2.5 Collision processes after D-T burning

If the nuclear fusion reactions are achieved through high temperature plasmas, the product alpha particles (He^{2+}) with 3.45 MeV energy can play some roles in the plasmas. At the very beginning they have large kinetic energy which is sufficient to heat plasmas and then gradually lose their energy through collisions. Finally they have to be extracted from the main plasmas in order to keep the plasma temperatures high enough. Thus it is important to know their kinetic energy distributions and spatial/temporal distributions. To understand plasma behaviors including alpha particles, a number of atomic processes involving He^{2+}, He^{+} and He^{0} should be known.

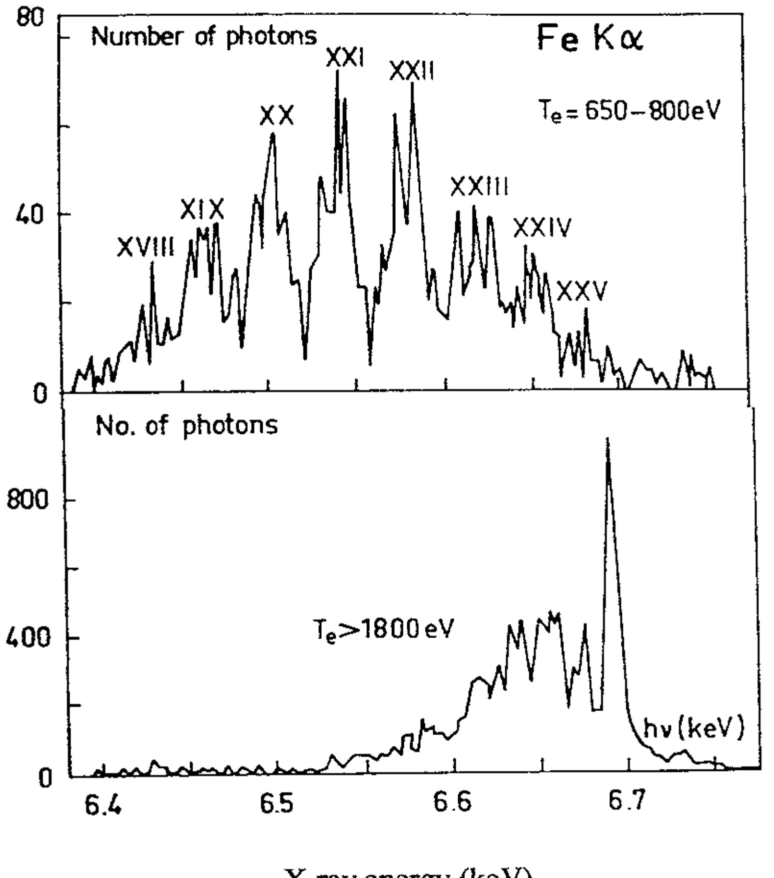


Fig. 10 Variation of Fe-α spectra in various ionization stages from PLT tokamak at different plasma temperatures[13)]

a) Plasma heating (momentum transfer) by 3.45 MeV He^{2+} (alpha) particles :

3.45 MeV He^{2+} + (plasma) H^+ --> (heated) H_f^+

The maximum transferred energy to protons in plasmas

$$T_{max} = [4*M_1M_2/(M_1+M_2)^2]*E_0 = 2.3 \text{ MeV}$$

is indeed sufficient to heat plasmas.

b) Collisions of He ions and atoms with electrons, protons/hydrogens and impurity ions/atoms :

Among collisions involving He^{2+}, He^+, He($1s^2$, 1s2s ^1S, ^3S), He^-(1s2s2p ^4P), single and double electron capture as well as ionization processes are important in order to diagnose behavior of alpha particles in the plasmas.

2.5.1 Diagnostics of alpha particles inside plasmas

Information on energy and spatial distributions of alpha particles during slowing-down processes inside plasmas can be obtained through collisions of high energy (MeV) He^0 beam injection :

a) 3.45 MeV He^{2+} + He_{inj} --> $He^+(nl)$ + $He^+(1s)_{inj}$:

These cross sections are well known to have maximum values at 100-200 keV with the dominant electron capture into n=1 state. From a technical convenience for diagnostics, the n=4 -> 3 (4685 Å) transition are often used, though the cross sections are expected to be small. It is necessary to have accurate information on n-distributions in the electron capture processes above.

b) 3.45 MeV He^{2+} + He_{inj} --> He^0 + $He^{2+}{}_{inj}$:

This process is resonant and therefore the cross sections are large at small relative velocities. The neutral helium produced in this double electron capture can escape from the main plasmas and be detected/energy-analyzed to know the energy of alpha particles.

2.5.2 Production of intense He^0- beams at 3.5 MeV

There is a big problem of how to get high energy helium particles with sufficient intensities which should be formed through electron capture :

a) He^+ --> He^0 : electron capture

As seen in H^+ --> H^0 conversion, He^+ --> He^0 conversion has very low efficiencies at high (3.5

MeV) energies. It is necessary to find better conversion processes.

b) $He^-(1s2s2p\ ^4P)$ --> $He^0(1s2s)$: electron stripping :

Indeed, He^- --> He^0 processes should have better efficiencies as the electron detachment cross sections are much larger than the electron capture into helium ions. It is also note to be hard to get intense negative He^- ions as the formation cross sections for He^- ions are known to be small.

Another serious drawback is the fact that He^- ions have sufficiently long life-times only in the metastable states, $1s2s2p\ ^4P$. The 2s electron in the neutralized $He^0(1s2s)$, also in the metastable state, is easily ionized before reaching the center of the main plasmas.

c) $He^-(1s2s2p\ ^4P)$ --> $He^0(1s^2)$: auto-detachment

In order to get the ground state helium atoms, $He(1s^2)$, we can use the auto-detachment process of the metastable He^- ions with the lifetime of about 350 μs which needs the flight path of 50 m.

d) laser-photo-detachment -->

hv + $He^-(1s2s2p\ ^4P)$ --> $He^-(1s2p2p')$

--> $He(1s2p\ ^3P)$?

2.5.3 AM during the slowing-down processes

Collisions of He^{2+} and He^+ ions with protons/impurity ions come into play a role in diagnosis and modeling of alpha-slowing-down plasmas.

a) $He^{2+} + A^{q+}$ --> $He^{2+} + A^{(q+1)+}$:

ionization (dominant at high energies)

--> $He^+ + A^{(q+1)+}$:

electron transfer (dominant <100 keV/amu)

Both processes increase the effective charge of impurity ions, thus enhancing bremsstrahlung losses.

b) $He^+ + H^+/A^{q+}$ --> $He^{2+} + H^+/A^{q+}$:

ionization (dominant at high energies)

$He^+ + H^+/A^{q+} \rightarrow He^{2+} + H/A^{(q-1)+}$:

electron transfer (important at intermediate energies).

However, only a limited experimental data for these ion-ion collision processes are available because of technical difficulties.

2.5.4 Collisions of slow alphas in edge/divertor

. In divertor region, very slow alpha particles may be taken away through the following accidental double electron capture processes which have very recently been known to have large cross sections at low eV energies :

$He^{2+} + H_2 \rightarrow He^0(1s3l) + H_2^{2+} \rightarrow He^0(1s3l) + H^+ + H^+$.

This process could play a key role in cooling the plasmas containing alpha particles, as discussed later on. On the other hand, the cross sections for

$He^+ + H_2 \rightarrow He^0(1s^2) + H_2^+$

are known to be small at low energies, except for those for the vibrationally excited H_2 species (see later discussion in sec. 4.2.1).

3. AM processes in edge/SOL plasmas

3.1 Features of edge/SOL plasmas

a) These plasmas are necessary to form stable high temperatures at the center in order to avoid the direct contact of the main high temperature plasmas with walls/low temperature plasmas and to entrap impurities in the edge plasma region.

b) Edge/SOL plasmas generally have the following features :

(1) Low (<100 eV) temperatures

(2) Medium density of 10^{12} - 10^{14} /cm^3

(3) Short transversal length (thickness) : 1 - 2 cm

Thus the rapid variation of plasma features over such a short length occurs, though the longitudinal length is practically infinity.

(4) High concentration of neutral particles :

There are a number of different atomic and molecular species such as H, H_2, CH_4, backscattered/sputtered/released impurity atoms/molecules from walls. As the plasma temperature is relatively low, most of these species are neutral or in low-charge states.

3.2 Collisional features

Because of low plasma temperatures and short residence times through SOL plasmas, collisions involving neutral atoms and low charge atomic ions as well as molecules and molecular ions become important in the SOL region. It is also noted that a significant fraction of species may be in the excited states. In fact, the presence of a significant fraction of the excited hydrogen neutrals, H(n), are observed near the edge plasmas.

In addition to plasma phenomena, another anomalous particle diffusion can occur through thin SOL layers into the main plasmas due to electron transfer between fast proton in plasmas and cold, slow atomic hydrogen near the edge :

$$H_f^+ + H_s^0(n) \dashrightarrow H_f^0\,(n') + H_s^+.$$

In fact these neutralized hydrogen atoms, of relatively high temperatures (velocities), have a long penetration length into the main plasmas (10-20 cm), compared with 2-3 mm of impurity species. Also they may hit the walls or surfaces of vacuum vessels, resulting in their sputtering/erosion.

3.3 Main collision processes in SOL plasmas

As mentioned above, the following collisions involving atoms and molecules play a dominant role in the edge plasmas :

a) Excitation :

In particular, the formation of the excited H(n) species should be important in the edge region :

$$e + H(n) \dashrightarrow e + H(n').$$

The cross sections for these processes have been calculated but are not established experimentally. The presence of such excited hydrogen species has been confirmed through X-ray observation (see Fig.12) produced in collisions with highly charged ions.

Similarly, the metastable transition-metallic atom and ion species are also formed through electron impact excitation :

$$e + A^{q+}(nl) \rightarrow e + A^{q+*}(n'l').$$

For these processes, only a limited cross sections are available[15]. At these low temperature regions, radiation emission from collision-excited molecules/molecular ions plays a role in cooling the edge plasmas.

b) The ionization processes should be of minor contribution.

c) Molecular dissociation/dissociative ionization into neutral and ion species should be important in the formation of energetic neutrals and ions, which have longer penetration lengths into plasmas due to large kinetic energies provided via dissociation.

d) Dissociative recombination of molecular ions with electron is particularly important at very low temperature plasmas :

$$e + H_2^+ \rightarrow H_2^* \rightarrow H + H.$$

The cross sections for this process are known to strongly depend upon the internal energy of species. These dissociation products generally have large kinetic energies[9].

f) Electron capture from the excited state $H(n \geq 2)$

These processes play two significant roles :

(1) Formation of excited (impurity) ion species :

$$A^{q+} + H^*(n) \rightarrow A^{(q-1)+*}(n'l') + H^+.$$

As this process has large cross sections, compared with those in the ground state hydrogen atoms (see Fig.11), small fractions of the excited hydrogens results in the formation of highly excited states of impurities. Thus these ions emit photons[16]. In Fig. 12 are shown VUV spectra from JET tokamak observed at different location. This clearly indicates the presence of the excited neutral hydrogen H(n=2) near the inner-walls.

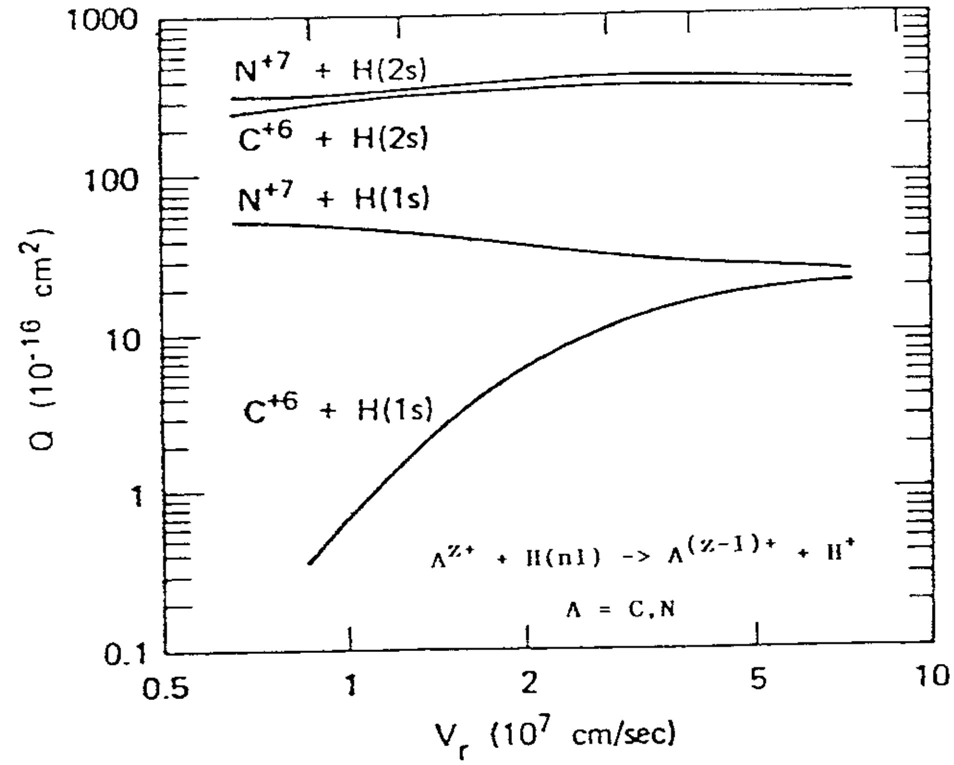


Fig.11 Calculated electron capture cross sections from the excited H(1s, 2s) by various ions.

(2) Spatial redistribution of H(n) particles :

$H_f^+ + H_s(n) \text{-->} H_f(n') + H_s^+$.

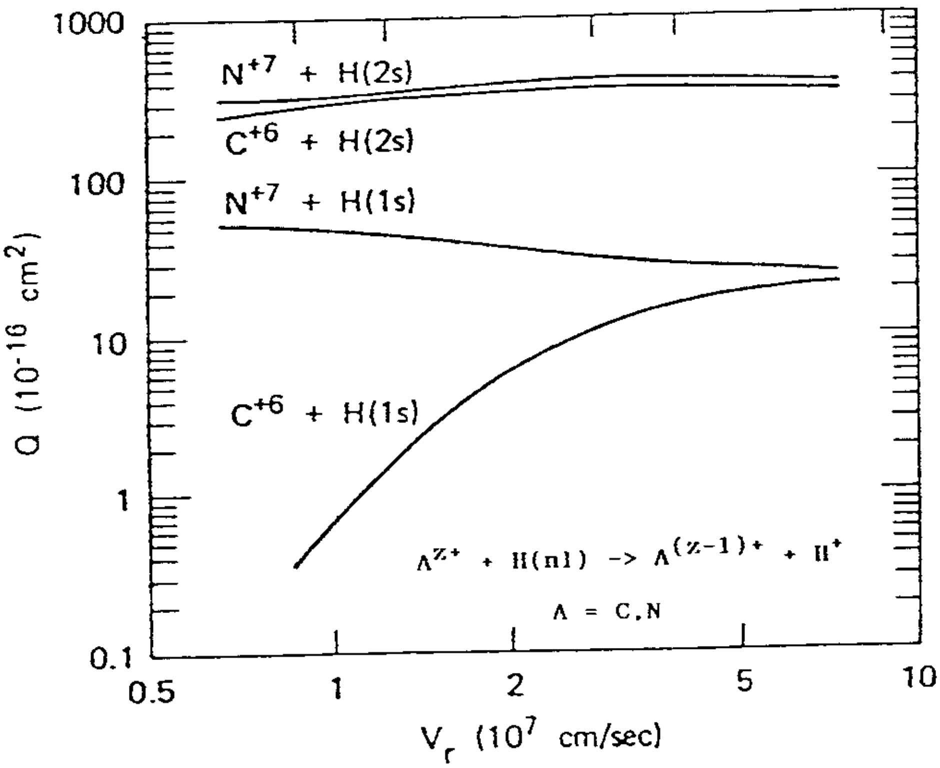
Collisions of fast protons in plasmas with cold hydrogen atoms near the edge should have large cross sections. Thus, the presence of slow excited hydrogens may result in the redistribution of the excited states of hydrogens as n' = n is expected to be dominant (symmetric) in the electron capture processes above.

g) Heavy particle collisions

Chemical reactions/particle interchange reactions become a key issue in low temperature plasmas, in particular in gas divertor regions (see later section in detailed discussion).

3.4 Plasma-solid interactions[18)]

The interaction of plasma constituent particles with solid surfaces is important in the edge plasma regions and usually results in the erosion of the surfaces, which in turn generates impurities into



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g) Heavy particle collisions

Chemical reactions/particle interchange reactions become a key issue in low temperature plasmas, in particular in gas divertor regions (see later section in detailed discussion).

3.4 Plasma-solid interactions[18)]

The interaction of plasma constituent particles with solid surfaces is important in the edge plasma regions and usually results in the erosion of the surfaces, which in turn generates impurities into the surfaces is somehow delayed after hydrogen impact.

b) On the other hand, at thermal energies, CH_3 molecules are dominantly produced near surfaces of graphites and their production could be prompt.

c) Simultaneous irradiation of thermal hydrogen atoms with other energetic particles strongly enhances chemical sputtering yields, indicating intense synergistic effect on graphite surfaces.

3.5 Collisions involving hydrocarbons and other impurity molecules such as CO, CO_2, H_2O

There are always common impurities such as CO[21)] in vacuum systems.

3.5.1 New collision channels of molecules

When molecules come to play a role, there are a number of new channels open in collisions :

a) molecular rotational/vibrational excitation,

b) dissociation (neutral species),

c) dissociative ionization (ions, neutrals),

d) dissociative recombination of molecular ions (neutral, ions).

In order to understand behavior of these impurities in plasmas, the kinetic energy/angular distributions of products in chemical reactions have to be known. It should be pointed out that the energy distributions of the ground state hydrogen atoms, H(1s), from $H_2(v)$ --> H(1s) + H(1s) dissociation processes have never been measured yet, though they can be estimated from the energy diagram of H_2 molecules. Complicated structures in energy distributions of dissociation product H(n = 3, 4) atoms have been observed through broadening of the Balmer lines and found to be due to the contribution of various dissociation channels, which changes with the impact energy.

3.5.2 Collision features

Molecular collisions have strong influences of their internal energy states :

a) It has been realized that atomic and molecular collisions are strongly dependent upon on the internal energy of the species[22)].

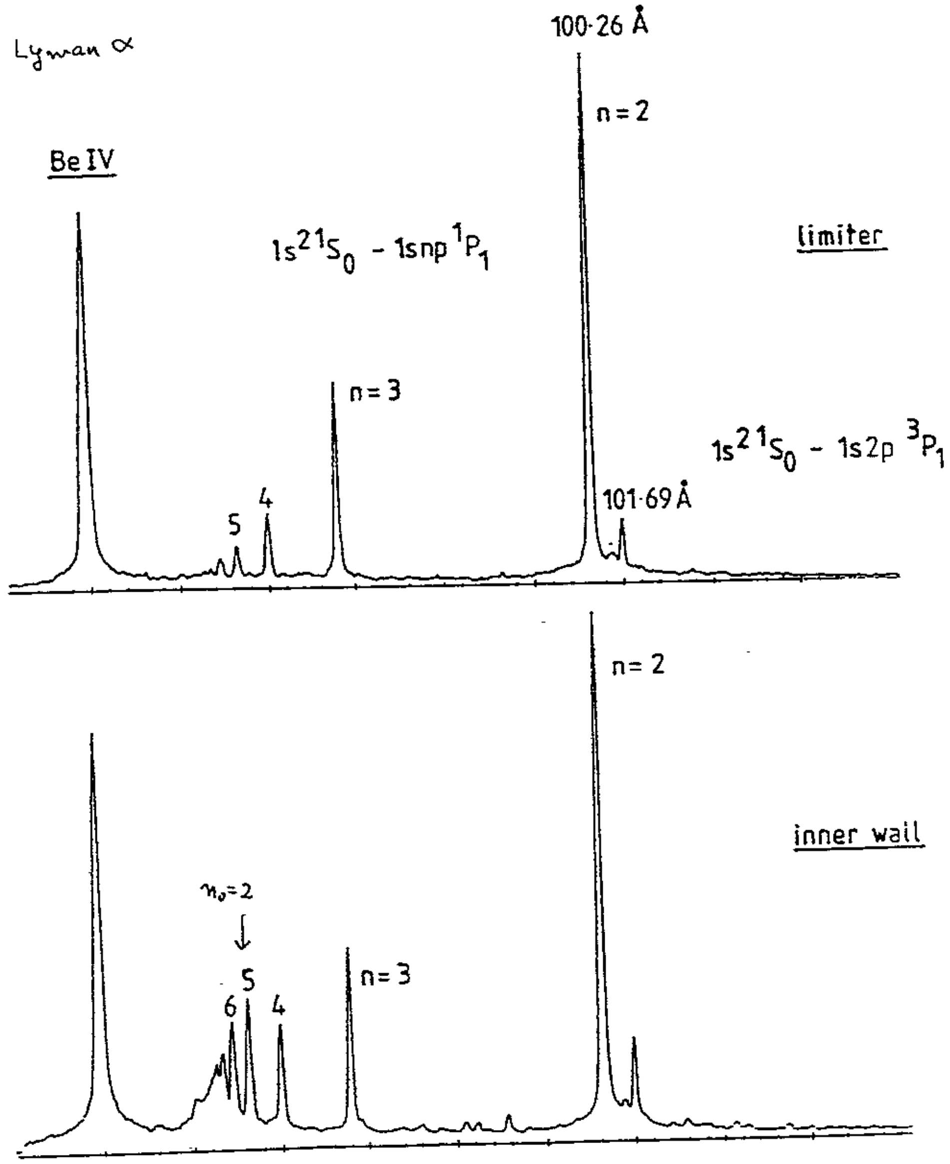

Fig.12 XUV spectra of Be III in $Be^{3+}(1s) + H(n) \rightarrow Be^{2+}(1snp\ ^1P_1 \rightarrow 1s^2\ ^1S_0)$ collisions when plasmas contact with different surface regions[16] (Note the contributions from the ground H(n=1) and excited H(n=2) states in spectra observed near inner walls).

b) Significant difference of collision properties is also observed in electron and heavy particle impact.

Generally heavy particles are more efficient to produce the vibrationally excited species.

c) Careful collections of the dissociation (ion and neutral) products are absolutely necessary as they have large kinetic energies, thus often resulting in incomplete collection[18].

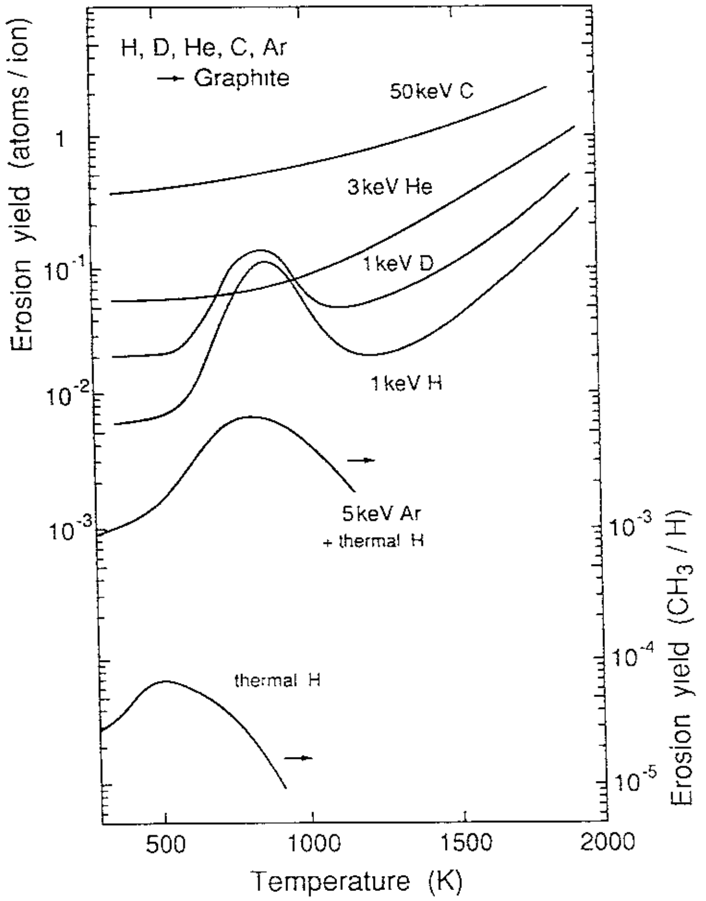

Fig. 13 Sputtering yields of graphite under hydrogen impact as a function of temperature.

Table 4 Factions of molecular ions produced under electron impact dissociation of CH_4 molecules with different internal energies

products	CH_4^+	CH_3^+	CH_2^+
neutral gas CH_4	100	85	15
neutralized CH_4	100	400	15

3.6 Collisions of metallic neutral/low-charged species

The neutral atom/low-charge state ion species are present near the divertors or other metal surfaces and they tend to penetrate into the main plasmas. Systematic data for ionization over a wide range of species ions are available[23)] but no reliable ionization/excitation cross sections for metallic atoms under electron impact have been measured up to now as the preparation of these atomic species is difficult. Some extensive calculations[24)] have been reported for ionization cross sections of some metals such as e + Cr, Mo --> Cr^+, Mo^+.

A proposal to use neutralized metallic species converted from negative metallic ions (any negative ions, except for rare gases, can be produced) in combining with the crossed-beam techniques, has been made by the present author quite sometime ago. These electron-detached neutralized particles are believed to be mostly in the ground state. This is in contrast with those neutralized through the electron capture from singly charged positive ions which are often in their excited states.

Table 5 Fractions of molecular ions from CH_4 molecules produced under 30 eV proton electron transfer, 30 eV electron and 1 MeV/amu Ar^{12+} ion impact (%)

product ion	CH_4^+	CH_3^+	CH_2^+	CH^+	C^+	comments
30 eV electron impact	1.00	0.30	0.05			electron capture
30 eV electron impact	1.00	0.81	0.12			ionization dominant
1MeV/amu Ar^{12+} impact	1.00	0.83	0.19	0.14	0.14	ionization dominant

4. AM processes near divertors, in particular gas radiative divertor/gas dumpers

The plasma temperatures near divertors should be low and thus not only physical collisions but also chemical collisions between heavy particles (H, H_2, He) play a role[2)].

4.1 Plasma features in divertor region

Their features are summarized as follows :

a) very low temperatures (< 10-50 eV)

b) relatively high densities (> 10^{15} - 10^{16} cm^3).

To divert high power (energy) densities (for example 50 MW/m^2 at ITER divertor) directly reaching divertor plates, collision processes involving atomic and molecular hydrogens, in particular the species in the excited states or metastable states, should play a decisive role. In such plasma conditions where the plasma density is high, the successive collisions, namely the second collisions before the excited state species generated in the first collisions decay into the ground state, play an important role in determining plasma features (see Fig.14 where an expanded region of ITER gas divertor is schematically shown[2]).

Most of ions, neutral atoms as well as molecules present in gas divertor region are expected to be in the excited states. However, work done so far is devoted mostly to those in the ground state species.

4.2 Important collision processes

The following new types of collisions between ion and neutral heavy particles, which have not been discussed in detail in the previous sections, become more important in the divertor plasmas than in other plasmas in tokamaks (see Fig.15 for electron impact on H_2 molecules) :

a) Elastic scattering (momentum transfer)

b) Rotational and vibrational excitation of molecules (electronic excitation could be weak at this energy region)

c) Charge transfer (pure and dissociative)

d) Dissociation

e) Chemical (particle transfer/exchange) reactions

Similar data compilation in H^++ H_2 collisions are given[25].

4.2 Collisions between heavy particles (< 10 eV)[26]

The kinetic collisions is significant only at higher energies (> 5 - 10 eV), meanwhile the chemical reactions can be important at lower energies (< 1 - 2 eV).

4.2.1 Collision features at low energies

a) Strong dependence on the energy defects ΔE (even ~ 10 meV) results in big differences in collision features at low energies (see Fig.16).

b) Collision cross sections strongly depend on the internal energy of species. Generally the cross sections for the ground state species are small :

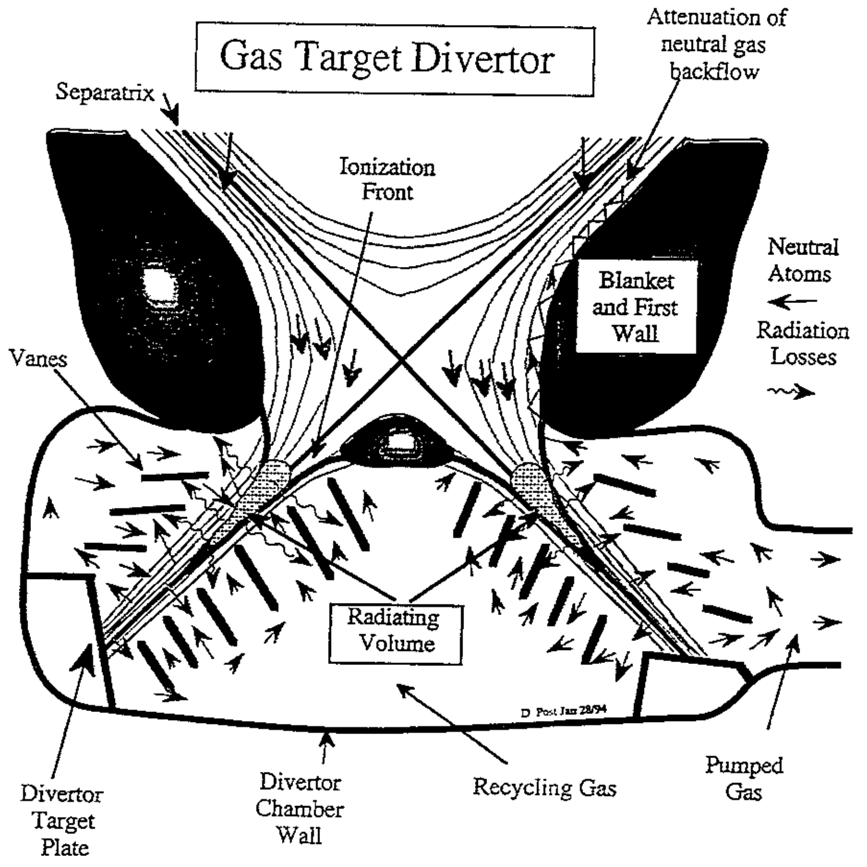

Fig.14 Sketch of ITER gas divertor.

(1) $H_2^+(v_i) + H \rightarrow H + H + H^+ + \Delta E$:

$\Delta E = 2.6$ eV (v=0) : small σ at low eV energies

(2) $He^+ + H_2(v_i) \rightarrow He + H + H^+$:

As $\Delta E = 6.6$ eV (v=0), the cross sections are small at low eV energies.On the other hand, the cross sections for the vibrationally excited hydrogen molecules are strongly enhanced :

$\sigma(v_i{=}1) \approx 100*\sigma(v_i{=}0)$ at $\approx$ eV.

c) Most molecular species in divertor region are in the vibrationally excited states. Thus, new channels become dominant :

(1) $H^+ + H_2(v_i = 4) \rightarrow H^0 + H_2^+$:

As $\Delta E \approx 0$ and is nearly resonant, the cross sections are expected to be large at low energies, indicating a significant role in power divergence in divertors.

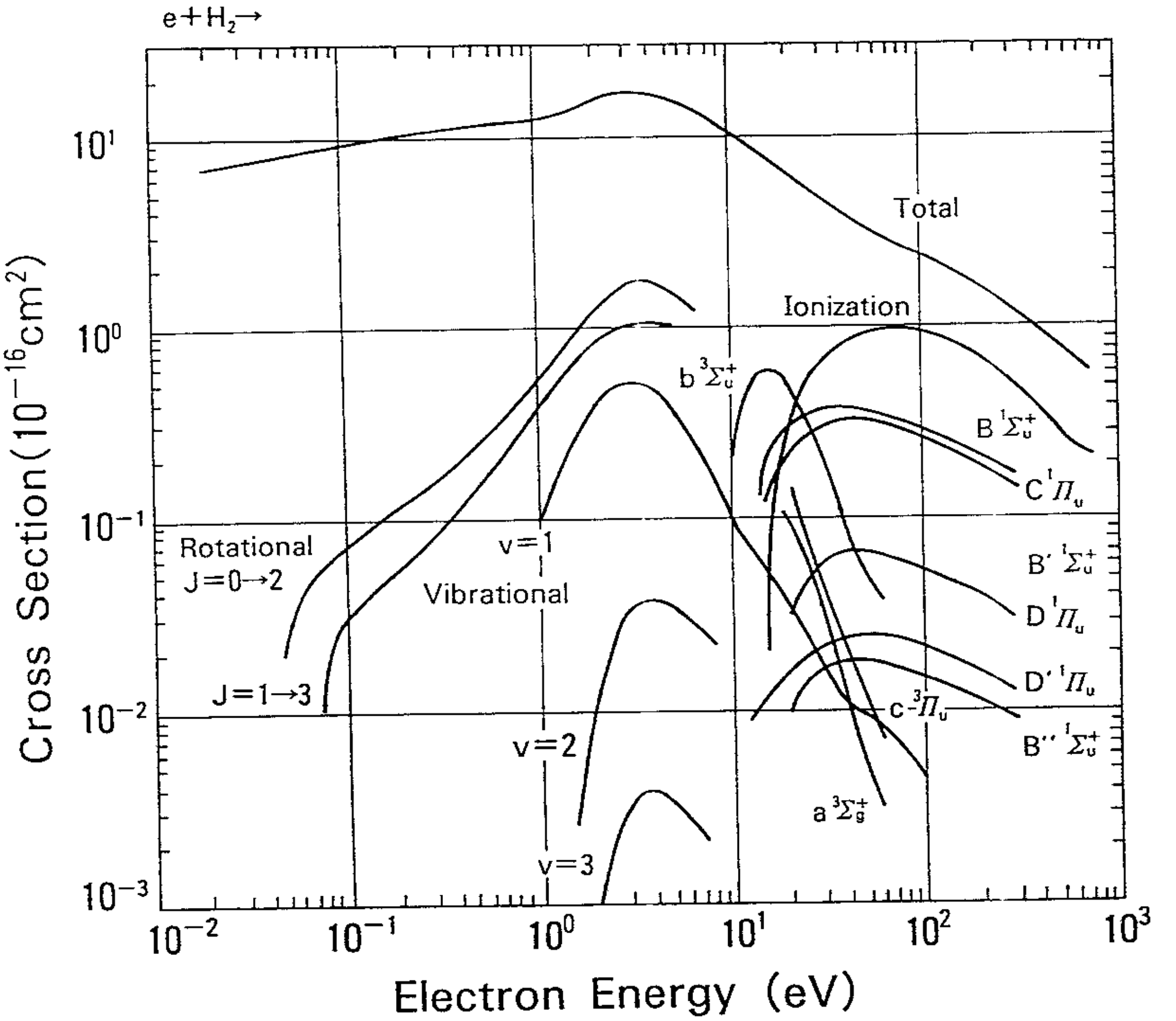

Fig.15 Systematic compilation of data for e + H_2(v=0) collisions.

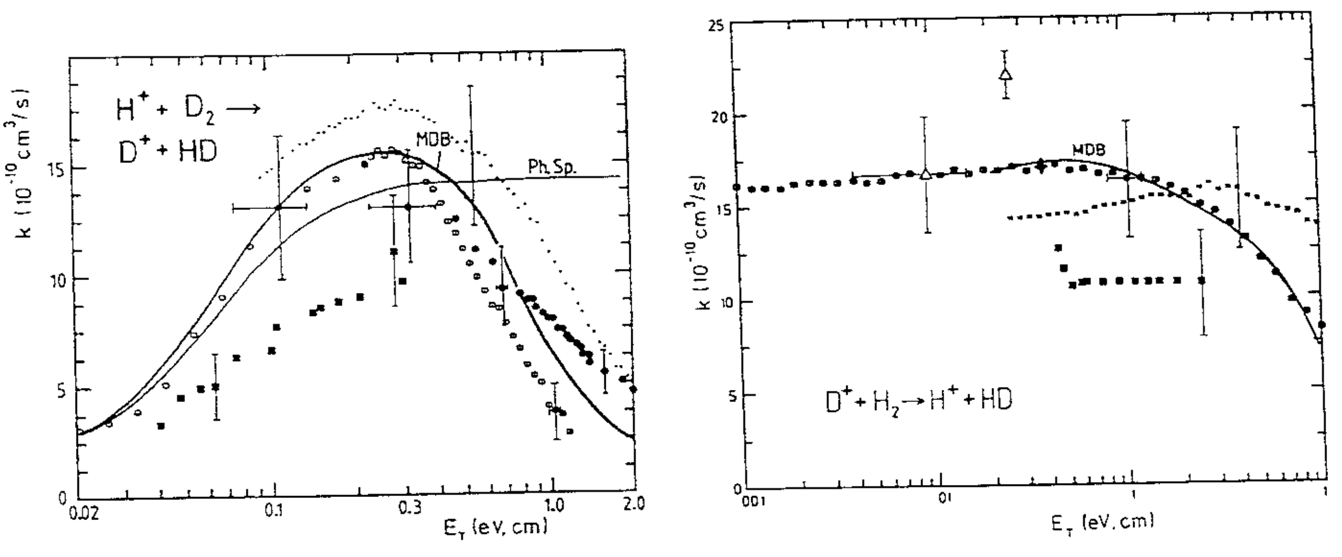

Fig.16 Rate coefficients for $H^+ + D_2$ --> D^+ + HD and $D^+ + H_2$ --> H^+ + HD (Note that a slight change of the energy defects results in significant change of collision features).

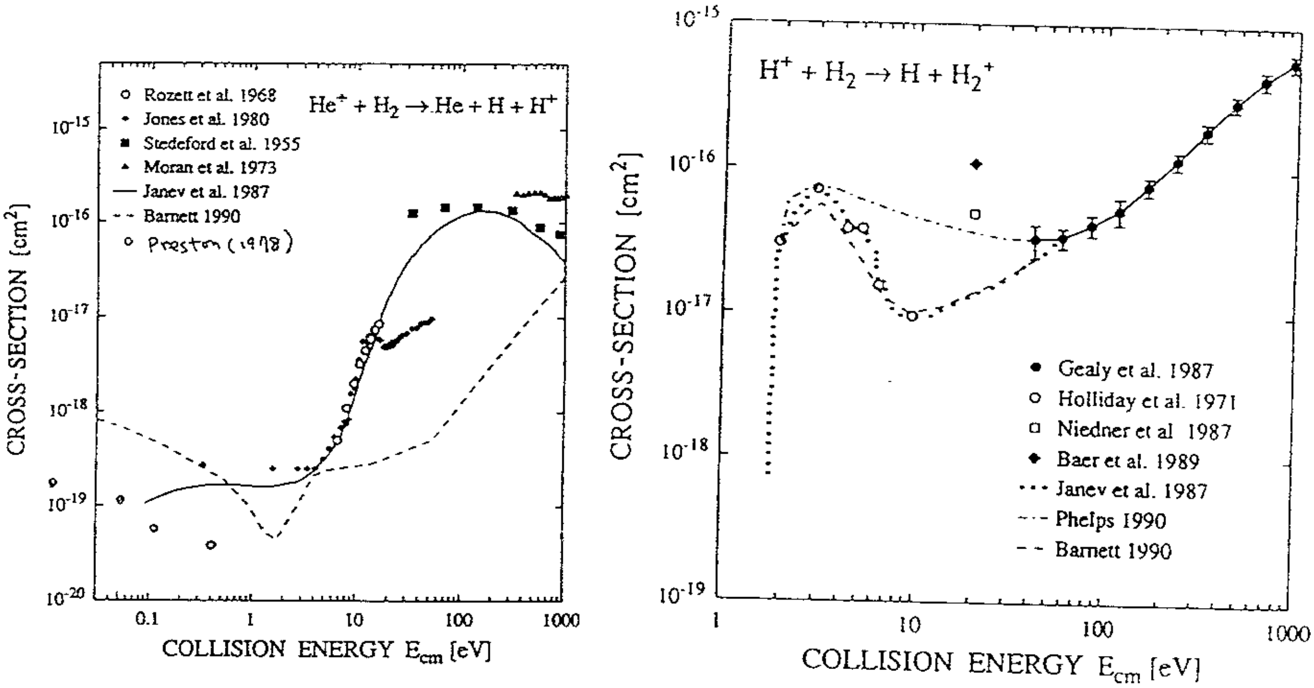

Fig.17 Total cross sections for $He^+ + H_2(v_i=0)$ --> $He + H + H^+$ and for $H^+ + H_2(v_i = 0)$ --> $H^0 + H_2^+$ as a function of collision energy.

(2) $H^+ + H_2(v_i = 0)$ --> $H^0 + H_2^+$: $\Delta E = 1.8$ eV

The cross sections for the ground state species are known to be small at low energies, with the contribution from particle transfer at 4-5 eV (see Fig.17).

Data with the collisions involving state-specified collision partners, which are very limited presently, are urgently needed in order to understand the plasma features, in particular those near divertors in detail[26) :

$$AB^+(v_i^1) + CD(v_i^2) \text{ --> } AB^*(v_f^1) + CD^{+*}(v_f^2) + \Delta E.$$

4.3 Collisions of low energy molecules and molecular ions with surfaces[27)

a) Scattering from surfaces

(1) dissociation/charge state/energy distributions or partitions among products

(2) dependence on molecular axis

(3) relaxation of vibrational states at surfaces

b) Sticking on and reflections from surfaces

(1) The reflection coefficients of particles from surface are known to increase as the impact energy decreases and nearly complete reflection of particles are observed at 2-5 eV and then sharply decrease due to chemical reactions on the surfaces involved.

(2) Sticking probabilities become roughly unity at < 1 eV.

(3) The enhanced sticking due to high rotational and vibrational excitation of molecules is reported below 1 - 2 eV.

8. Concluding remarks

As mentioned, strong interactions between plasma physics and atomic/molecular physics exist.

8.1 plasmas viewed from atomic physics :

(1) new targets for atomic physics

(2) excited state targets such as H(n)

(3) high, variable density targets (up to 10^{25} - 10^{26} /cm^3) : new fields of atomic physics

8.2 Atomic/molecular physics viewed from plasma physics :

(1) Information of AM physics is requisite and important in understanding plasma phenomena. Thus, future developments are strongly dependent upon AM physics.

(2) It would be still conservative to say that plasma fusion reactors can be realized only with full knowledge of AM physics.

A large amount of AM data are already available but many of them are still of lack in systematics or accuracies. In particular the cross sections with the state-specified collisions are very limited. They are important and interesting in basic collision aspects as well as in many applications.

Indeed AM physicists can provide precise, important and requisite AM data for studying basic plasmas and also for achieving thermo-nuclear fusion reactors through high temperature plasmas. In fact, AM physics plays a decisive role from the cradle to the grave in fusion plasma research :

"Roles of atomic and molecular physics are surely not the least but the great in any fusion plasma research programs !"

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