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Some electron detachment data for H^- ions in collisions with electrons, ions, atoms and molecules -- an alternative approach to high energy neutral beam production for plasma heating--

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Abstract

In order to provide information on the effectiveness of the conversion of negative hydrogen ions in collision with multiply charged ions into neutrals for plasma heating, the present situation is reviewed on the cross sections involving negative hydrogen ions in collisions with electrons, ions, atoms and molecules. It is pointed out that, though electron detachment from negative hydrogen ions is estimated to be effectively achievable under collisions with multiply charged ions, reliable data for such processes are still scanty in particular at the MeV/amu energy range and measurements of the cross sections are deserved to be performed urgently.

key words [negative hydrogen ion, electron detachment,
cross section, ion target, neutral beam heating]

1. Introduction

Plasma heating by energetic neutral hydrogen beams has been realized to be one of the most promising techniques to get stable high temperature fusion plasmas in tokamaks and other fusion machines. Presently 50 - 100 keV neutral beams, converted from protons, are most often used for such machines to heat plasmas. On the other hand, if machines become bigger such as those proposed for ITER program, higher energy (≅ 1 MeV) beams become requisite to achieve better and effective heating of plasmas. It is known that with increasing proton energy the conversion from protons into neutrals becomes increasingly ineffective.[1)] For example, the conversion efficiency for 50 keV protons is about 40-50 %, meanwhile that for 1 MeV is estimated to be only about 1 %, resulting in significant loss of the primary beam input power.

Because the electron affinity (binding energy) to hydrogen atom is small (0.754 eV) the electron detachment (stripping) cross sections from negative hydrogen ions in collisions are known to be large and, thus, the conversion efficiencies of negative hydrogen ion beams into neutrals are expected to reach 60 - 70 % even at MeV energy region (It should be noted that roughly speaking the conversion efficiencies of negative hydrogen ions is determined by ratios of the cross sections for single electron detachment between negative hydrogen ions and neutral hydrogen atoms[1)]). Therefore, a number of laboratories are developing powerful ion sources which can deliver negative hydrogen ion beam of the order of 10 - 100 amperes, based upon so-called volume production mechanisms.

Though such data involving negative hydrogen ion beams in collisions with neutral rare gases and some molecular gases are well known and compiled, yet only a limited information is available on the conversion efficiencies of negative hydrogen ions into neutrals, more precisely the cross sections of electron detachment of negative hydrogen ions, in collisions with (multiply charged) ions.

The usefulness of plasma target as an efficient neutralizer of high energy negative hydrogen ions has already been pointed out by Berkner et al.[2] and some relevant problems have been discussed.

In this report, the present situation is summarized on the collision data involving negative hydrogen ions under impact of electrons, ions, atoms and molecules. It is found that the conversion of H^- ions into neutrals is much more effective in collisions with multiply charged ions than with neutral atoms or molecules but the cross sections for electron detachment of H^- ions in collisions with target ions resulting into neutrals are still scarce. Because the conversion of H^- ions into neutrals in the energy range from keV/amu to MeV/amu (this energy unit is convenient to know the energy of either projectile or target) is believed to be mainly due to the electron stripping or ionization, the cross sections for electron detachment can be estimated based upon empirical formulas of ionization mechanisms. It is also pointed out that confirmation of the extrapolated collision data for electron detachment from high energy H^- ions in collisions with multiply charged ions are urgently needed.

2. Collisions with neutral gases

$$H^- + A \rightarrow H^0 \quad (1)$$

Here A stands for neutral gas target. Collision data involving neutral rare gas atoms or molecules have been well summarized over a wide range of the collision energy. Some of them in collisions with He, Ne, Ar, Kr, Xe, H_2, N_2 and O_2, taken from a paper by Tawara and Russek and Tawara et al.[1], are shown in Fig.1 over the energy range of H^- ions of interest to plasma heating. These curves are smoothed through the experimental data points. It is found that the cross sections for atomic hydrogen (not shown in Fig.1) are slightly less than a half those for H_2 molecules. Generally speaking, the cross sections for electron detachment from negative hydrogen ions decrease relatively slowly with increasing the collision energy and increase as the target atoms become heavier. As become clear later, the electron detachment from negative hydrogen ions is caused dominantly by direct ionization (stripping) of a loosely-bound electron to hydrogen atom due to the Coulomb field of target, except for that at low keV energies where the electron transfer process might play a role in some cases.

3. Collisions of H^- ions with positive ions

3.1 Collisions with protons

It is technically difficult[3] to measure the cross sections for collisions between negative and positive hydrogen ions, because the effective target thickness of the fast-moving ions is very

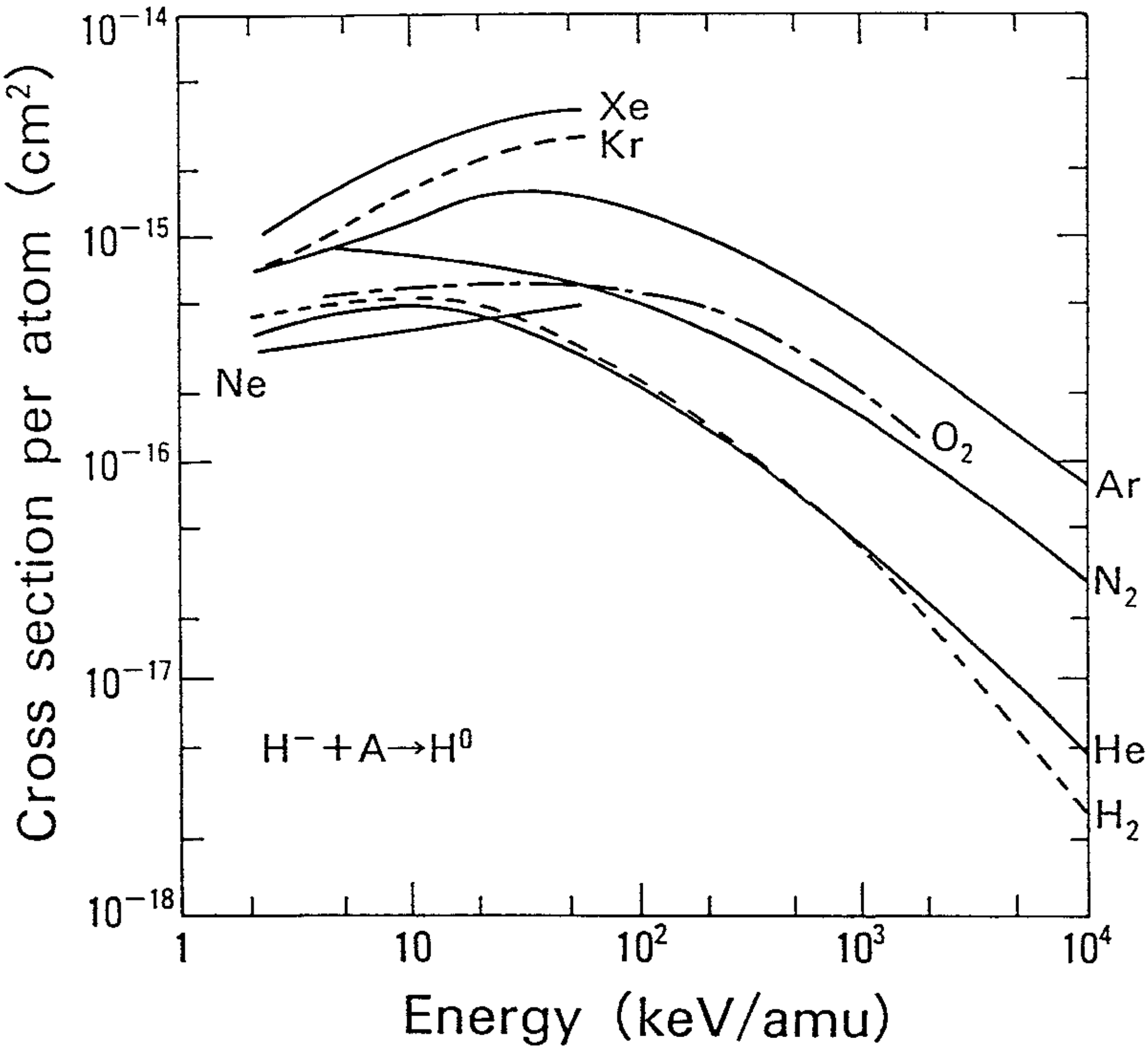

Fig.1 Cross sections for electron detachment from negative hydrogen ions in collisions with various neutral gas targets as a function of the collision energy. Note that the cross sections are given per atom.

dilute (usually equivalent to the pressure less than 10^{-10} Torr in nominal conditions of ion-ion collision experiments in the present-day laboratories), compared with background gases.
Up to now the following collision processes involving protons as target have been investigated experimentally :

$$H^- + \underline{H}^+ \rightarrow H + \underline{H} \qquad \text{(single electron transfer)} \tag{2}$$

$$\rightarrow H^+ + \underline{H}^- \qquad \text{(double electron transfer)} \tag{3}$$

$$\rightarrow H^+ + e + \underline{H} \qquad \text{(transfer ionization)} \tag{4}$$

$$\rightarrow H + e + \underline{H}^+ \qquad \text{(single electron detachment)} \tag{5}$$

$$\rightarrow H^+ + 2e + \underline{H}^+ \qquad \text{(double electron detachment).} \tag{6}$$

These experimental data, after smoothing, are shown in Fig. 2 over the energy range of 1 - 1000 keV/amu of H^- ions. For comparison, the following related experimental data by electron impact are also shown which are plotted at the equivalent negative hydrogen ion energy :

$$H^- + e \rightarrow H + e + e \qquad \text{(single electron detachment)} \tag{7}$$

$$\rightarrow H^+ + 2e + e \qquad \text{(double electron detachment)} \tag{8}$$

The single electron transfer (mutual neutralization) process (2) between negative and positive hydrogen ions has been investigated experimentally by Schön et al.[4] and Peart et al.[5] and theoretically by Shingal and Bransden[6] and is found to be dominant only at low keV energy region and decreases sharply above 10 keV. The cross sections for double electron transfer process (3) have been measured only below 1 keV by Peart and

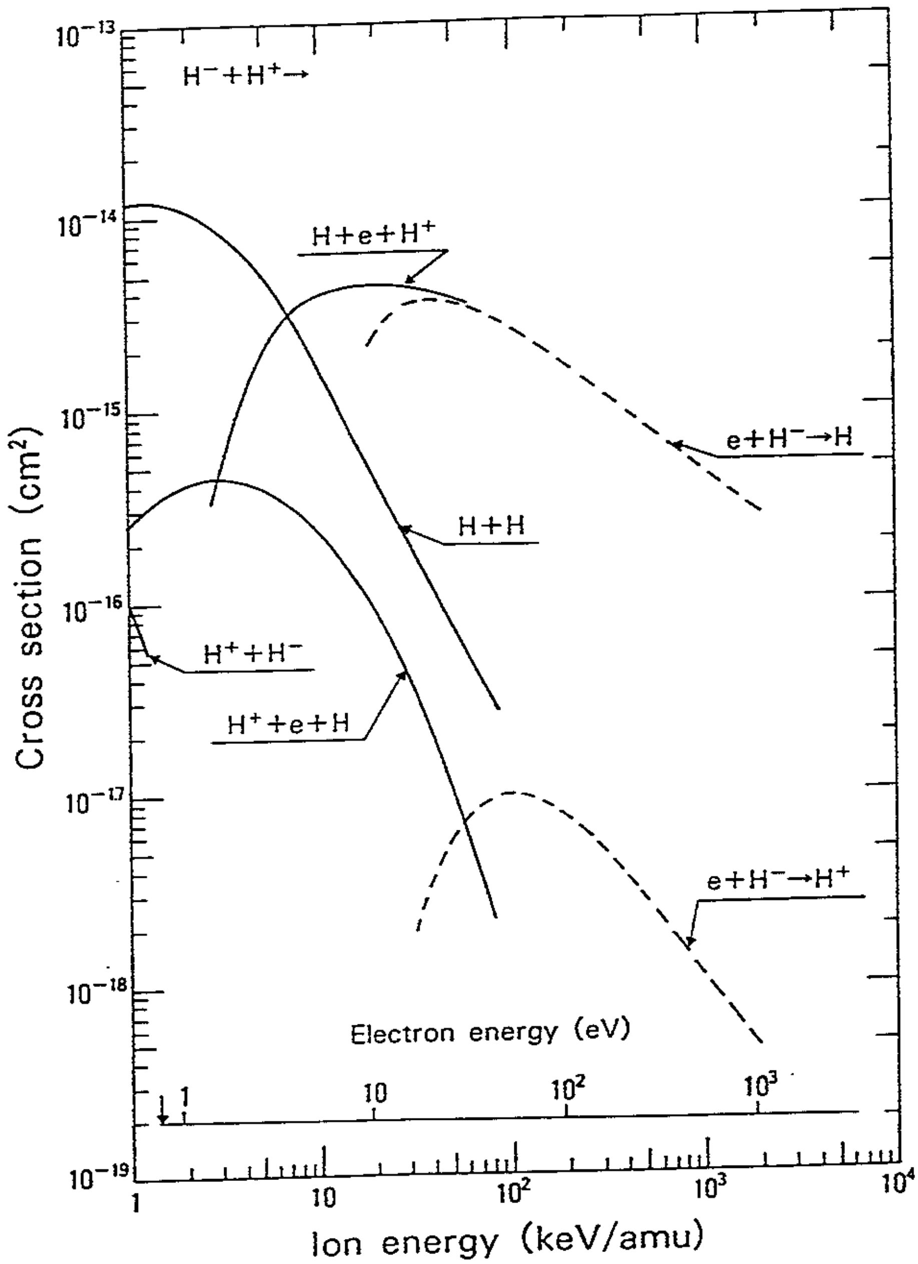

Fig.2 Experimental cross sections for H^- ions in collisions with protons and electrons as a function of the collision energy. The cross sections of single and double electron detachment by electron impact are also shown with dotted lines. The corresponding electron energy is also shown. An arrow on the energy scale of electron represents the electron affinity to atomic hydrogen.

Forrest.[7] Also the cross sections for electron transfer ionization processes (4) decrease sharply at higher energies.[8] These three electron transfer processes seem to be less important in the production of neutral hydrogen atoms from negative hydrogen ions at high energies.

On the other hand, the cross sections for single electron detachment process (5), measured by Peart et al.[9], are found to be relatively large and show a maximum of $4.5*10^{-15}$ cm^2 at around 20 - 30 keV and decrease slowly with increasing the collision energy. It should be noted that at higher energies ($\geq$ keV/amu) the single electron detachment cross sections from H^- ions in collisions with H^+ ions (5) become nearly equal to those[10,11] in impact of electrons with the corresponding velocities (7), indicating that both protons and electrons behave similarly in ionization process at asymptotically high energies, as expected theoretically in collisions with structureless projectiles. Thus at least at relatively high energies the cross sections for double electron detachment from negative hydrogen ions by protons (6), which have not been determined experimentally yet, can be inferred from those[13] by electron impact (8) shown in Fig.2. On the other hand, no reliable experimental and theoretical results at the electron impact energy lower than a few eV are available at present.[12]

3.2 Collisions with multiply charged ions

3.2.1 Low energies

It is interesting to compare the cross sections for electron detachment from H^- ions among target ions with different charge.

For example, the following electron detachment collision processes from H^- ions in collisions with doubly and triply charged ions have been investigated by Terao et al.[14], Peart et al.[15] and Peart and Wilkins[16] :

$$H^- + He^{2+} \rightarrow H \qquad (9)$$

$$H^- + B^{2+} \rightarrow H \qquad (10)$$

$$H^- + C^{3+} \rightarrow H \qquad (11)$$

over the energy range of 0.05 - 3 keV/amu. At lower energies, there are some differences of the cross sections of electron detachment among different projectiles with the same ionic charge. However, as the collision energy increases, the cross sections tend to converge and become independent of projectiles. The cross sections for electron detachment are found to increase roughly as $q^{1.3}$ when the ionic charge q increases. It should be noted that at this low energy region the conversion of H^- ions to neutrals seems to be mainly due to the electron transfer into projectiles. In fact, the $q^{1.3}$-dependence mentioned above seems to be very similar to the $q^{1.2}$-dependence of the electron transfer cross sections for keV/amu multiply charged ions which has been observed in collisions with neutral gas atoms.[17] Very recently experimental cross sections for collisions between 51 keV/amu negative hydrogen ion and multiply charged positive ion have been reported by Debus et al.[18] as a function of the target ion charge q :

$$H^- + Ar^{q+} \rightarrow H^0 \qquad \text{(single electron detachment)} \qquad (12)$$

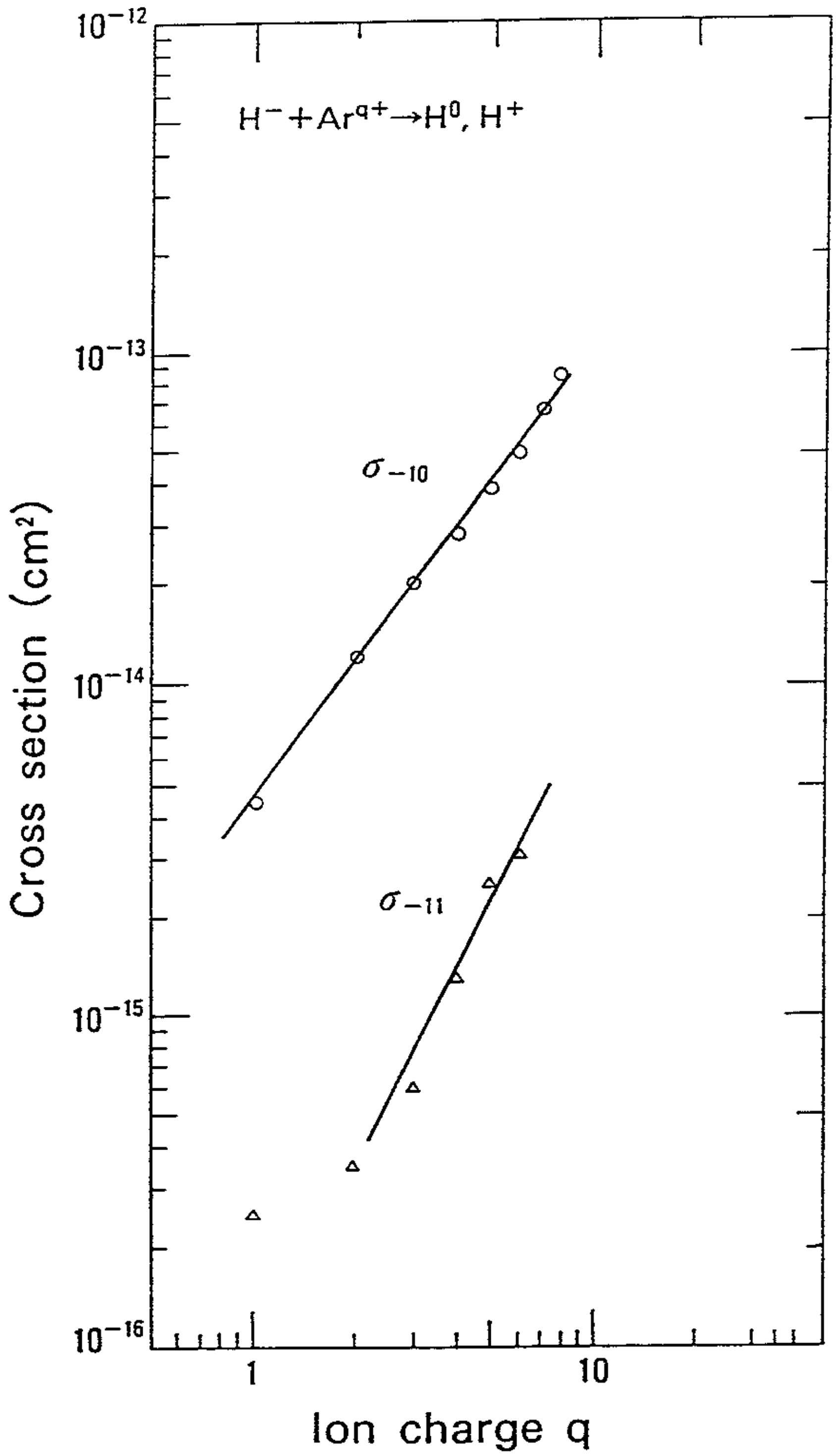

Fig.3 Cross sections for single and double electron detachment from 51 keV/amu H^- ions in collisions with multiply charged Ar^{q+} ions as a function of the ion charge q.

$\rightarrow H^+$ (double electron detachment) (13)

At this energy, the ionization of a loosely-bound electron from negative hydrogen ions is the main process in electron detachment. These results, as shown in Fig.3, suggest that, as the target ion charge increases, the electron detachment cross sections from negative hydrogen ions increases relatively sharply as $q^{1.4}$ which seems to be slightly weaker dependence than theoretical expectation (q^2). Similarly, the cross sections for double electron detachment also shown in Fig.3 have the q-dependence much stronger than those for single electron detachment.

3.2.2 High energies

Up to now no experimental investigation has been reported on the electron ionization or transfer processes between H^- ion and multiply charged ion at MeV/amu energy region. However, as the electron detachment from H^- ions is believed to be caused by direct ionization by Coulomb interaction, as mentioned above, we can estimate some important electron detachment cross sections from H^- ions through extrapolation based upon experimental and theoretical dependence of the cross sections of ionization of neutral gas targets by multiply charged projectiles.

For example, the ionization cross sections of rare gas atom targets at 1 MeV/amu fully stripped projectiles ranging from H^+ to Ne^{10+} have been determined experimentally by Be et al.[19] to be $q^{1.7}$, though slightly different dependence has been observed for partially ionized projectiles. The classical trajectory Monte

Carlo calculations by Olson[20] also suggest the dependence slightly weaker than q^2 at 1 MeV/amu energy region. Gillespie[21] has also developed empirical formulas for ionization by multiply charged ions which also deviate from the simple q^2-dependence in the Bethe cross sections and could be used in order to get information of electron detachment from negative hydrogen ions as a function of the collision energy.

4. Comparison of cross sections for various processes

In Table 1 are shown some cross sections for (single) electron detachment of 50 keV/amu and 1 MeV/amu H^- ions in collisions with various targets. Most of these data are taken from Tawara and Russek[1], Tawara et al.[1] and also from the previous figures shown above.

As seen in this Table, generally speaking, the cross sections for electron detachment from H^- ions by neutral gas atoms increase as the target gas becomes heavier and approach those by electrons and protons, both being bare projectiles. This fact suggests that bare nuclei or particles seem to be most effective in detachment of electrons in H^- ions. Clearly at higher energies, the screening effect by the surrounding electrons of neutral target becomes less important. For example, ratios of the cross sections of electron detachment from H^- ions by H^+ ions and those by Ar neutral atoms are found to be 2.3 and 1.1 at 50 keV/amu and 1 MeV/amu, respectively. Similar effects of the screening electrons have been observed in partially ionized ion targets (see 3.2).

If we assume that the ionization cross sections for H^- ions by multiply charged ions can be estimated through extrapolation, the

Table 1 Cross sections for electron detachment from 50 keV/amu and 1 MeV/amu H^- ions in collisions with various targets. The notation 3(-17) means $3*10^{-17}$.

50 keV/amu target	cross section (cm^2)	1 MeV/amu target	cross section (cm^2)
H	4.5 (-16)	H	3 (-17)
H_2	6 (-16)	H_2	8 (-17)
He	3 (-16)	He	4 (-17)
N_2	1.2 (-15)	N_2	3 (-16)
O_2	1 (-15)	O_2	4 (-16)
Ne	4 (-16)		
Ar	1.5 (-15)	Ar	4 (-16)
Kr	3 (-15)		
Xe	3 (-15)		
e	3.5 (-15)	e	4.5 (-16)
H^+	3.5 (-15)		

atoms or molecules. Thus, the electron detachment from H^- ions by electrons in plasma become less effective. Only multiply charged ions play their important role there.

To achieve the most effective conversion of H^- ions into neutrals, the target ions should be fully ionized with sufficient densities. Although some powerful ion sources for providing multiply charged ions, such as electron cyclotron resonance ion sources (ECRIS) or electron beam ion sources (EBIS) have been developed, the intensities or densities of multiply charged ions produced in such ion sources seem to be not sufficient.

Furthermore, high degree of ionization of targets is important to minimize the unionized neutral gas atoms in the target region which reduce the conversion efficiencies of H^- ions into neutrals. Therefore, the next important step is to know the charge distributions or the average charge of ions in plasma, getting the degree of ionization as high as possible.

Thus the development of high power ion sources capable of providing multiply charged ions of sufficient densities becomes urgent and requisite in achieving effective conversion of high energy negative hydrogen ions into neutrals for plasma heating.

6. Urgent issues

It is clear from the discussion above that high energy neutral hydrogen beams could be obtained most effectively through electron detachment from negative hydrogen ions in collisions with multiply charged ions yet reliable cross section data, in particular at high energy (MeV/amu) region, are scanty or nearly absent, though some extrapolation could be made to provide information on the effectiveness of neutralization of high energy negative ions for plasma heating.

Because radiation losses due to impurity ions with the charge of z in high temperature plasma increase as z^2, the influx of impurities originating from multiply charged neutralizing target ions should be kept minimum. In this sense, the trapping of such neutralizer atoms seems to be much easier that those of hydrogens. Also the optimum thicknesses or densities of target ions for neutralization of negative hydrogen ions are expected to be orders of magnitude less than H_2 gas targets which are most widely used presently, as the cross sections for electron detachment from negative hydrogen ions in collisions with multiply charged ions are extrapolated to be quite large even at 1 MeV/amu energy region.

However, such an extrapolation still includes a number of uncertainties which might result in significant errors of estimation of the important parameters in designing neutralizer target ions, for example the target thickness necessary for the most effective conversion.

The following problems should be investigated soon :

1) measurement of the cross sections for electron detachment from high energy negative hydrogen ions in collisions with multiply charged ions
2) development of powerful ion sources or plasma sources capable of providing intense multiply charged ions
3) minimization of influx of impurity ions originated from the neutralizing ion targets.

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