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The Negative Ion Mean Free Path And Its Possible Implications

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Abstract. The knowledge of the mean free path (mfp) of the negative ions is important for many purposes, *e.g.* evaluating the distance from which the ions can be extracted, or understanding the significance of experimental results. We will present the mfp for similar conditions in volume and caesium seeded sources. It appears that the mfp is longer in the caesium seeded source than in the volume source under identical conditions.

Keywords: negative ion, hydrogen, mean free path
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INTRODUCTION

Several types of collisions occurring in negative ion sources destroy the negative ions. These are collisions with positive ions (mutual neutralisation), collisions with electrons (electron detachment) and collisions with hydrogen atoms (associative and non-associative detachment.

The knowledge of the mean free path (mfp) is useful in order to evaluate the distance from which negative ions can be extracted and to understand the relative importance of various collisions. In the case of collisions of negative ions with another heavy particle (a positive ion or an atom) the mfp, λ, is defined as

$$\lambda = \frac{1}{n\sigma} \tag{1}$$

where n is the density of the positive ions or atoms, colliding with the H^- ion, and σ is the cross section of the corresponding collision process. In the case of negative ion destruction in collisions with electrons leading to electron detachment (ED), the mfp, $\lambda_{ED,}$ is :

$$\lambda_{ED} = \frac{v^-}{n_e < \sigma v_e >}. \tag{2}$$

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Here v^- is the negative ion velocity, n_e is the electron density and $<\sigma v_e>$ is the reaction rate coefficient. The latter can be found expressed by the electron temperature *e.g.* in [1].

Since the mfp is inversely proportional to the density of the particles colliding with the H^- ion, and to the cross section of the corresponding collision process (or in the case of electron collisions to its reaction rate coefficient), the shortest mfp corresponds to the dominating destruction process. One is most interested in the value of the mfp near the extraction opening, in order to evaluate the distance from which the negative ions can be extracted. We will estimate the mfp for the background plasma. No estimate will be made for the mfp in the sheath, since its size is small compared to the mfp.

THE MEAN FREE PATH IN VOLUME AND CAESIUM SEEDED SOURCES

The mfp for the same collision process and the same density of the collision partner may be very different in the volume source compared to the caesium seeded source, due to the different characteristics of the sheath in these two cases. In the volume source the plasma grid is usually biased at a potential close to the plasma potential, in order to optimize the extracted H^- current and reduce the extracted electron current. In this case the sheath is accelerating the plasma electrons and negative ions towards the plasma grid, but does not affect the energy of the volume produced negative ions in the presheath and background plasma. In the caesium seeded source, the plasma grid is biased negative with respect to the plasma potential and a sheath is formed accelerating the incident positive ions towards the plasma grid, and also accelerating the negative ions formed on the surface of the plasma grid (by atoms and positive ions) towards the plasma.

In the case of hydrogen, the cross sections of most processes can be found in Data Bases such as, *e.g.* EIRENE [2]. Some cross sections are presented versus the collision energy in eV / atomic mass unit (e.g. the resonant charge exchange cross section of H^- ion with a hydrogen atom). However most of the cross sections are presented versus the relative energy in the frame of the center of mass (E_{CM}). The calculation of E_{CM} in simple cases is exposed in textbooks of Classical Mechanics, *e.g.* [3]. In a first approach we will discuss the mfp in the background plasma, where positive ions and atoms have an isotropic distribution of the velocity v_1. We are interested in the following two cases :

Case 1. In the volume source negative ions have an isotropic distribution of the velocity v_2 in the complete space. The square of average relative velocity between two particles $< v^2 >$ is then given by

$$< v^2 > = < v_1^2 > + < v_2^2 >$$

or in terms of energy :

$$\frac{E_{CM}}{\mu} = \frac{E_1}{m_1} + \frac{E_2}{m_2} \qquad (3)$$

where $\mu = \dfrac{m_1 m_2}{m_1 + m_2}$ is the reduced mass. If the two particles have equal masses then this becomes :

$$E_{CM} = \frac{E_1}{2} + \frac{E_2}{2} \qquad (4)$$

Case 2. In the caesium seeded source the negative ions are emitted from the caesiated plasma grid surface with velocities having a cosine angular distribution (as suggested by Seidl et al [4]) and also acquire in the sheath the energy $e\Delta V$ (ΔV is the sheath voltage). Since the distribution of the atoms and ions in the plasma is isotropic, Eq. 4 is also relevant.

In order to estimate the emission energy of the negative ions it will be assumed, following Seidl *et al* [4] that the atoms are reflected with slightly reduced energy E':

$$E' = R_E E \qquad (5)$$

where E is the incident atom kinetic energy However, according to [4] only atoms with energy greater than the threshold energy E_{thr},

$$E_{thr} = \phi - E_A \qquad (6)$$

can form negative ions, where ϕ is the caesiated surface work function assumed to be 1.5 eV, and E_A = 0.75 eV is the electron affinity of the hydrogen atom. Based on an initial estimate a value of 1.2 eV has been chosen for the emission energy of the negative ions for an atom temperature of 0.8 eV, but this could be an upper value.

An important feature of the cross section for mutual neutralisation of H^- ions with positive ions and associative detachment of H^- with H atoms is that their highest values correspond to the lowest H^- ion energy. However, a second, non-associative detachment process exists along with the associative detachment in the collisions with H atoms, which becomes dominating at $E_{CM} > 4$ eV.

In the background plasma of volume H^- ion sources, assuming an isotropic distribution of both atoms and negative ions, E_{CM} for (associative and non-associative) detachment by H atoms (denoted H_{det}) is calculated using Eq. 4. If the temperatures of the H^- ions and hydrogen neutral atoms are known, their energy can be calculated as $E = (3/2)\, kT$. A similar calculation can be carried out for the H^- destruction by mutual neutralisation with positive ions.

We will consider the caesium seeded rf source studied by Wünderlich *et al* [5] using a PIC code for the plasma and sheath. The plasma parameters used as input for the PIC code are the electron temperature T_e = 2 eV, H^+ density $n(H^+) = 4\text{x}10^{17}$ m^{-3}, H^+ temperature $T(H^+)$ = 0.8 eV, H density $n(H) = 10^{19}$ m^{-3}, H temperature $T(H)$ = 0.8 eV,

$n(Cs^+) = 10^{16}$ m^{-3}. The electron density is found as a result of the simulation to be 2.74 x10^{17} m^{-3}. The negative ion temperature is not mentioned. We will calculate the mfp for a volume source and a caesium seeded source having these parameters.

Associative and non-associative detachment

Case 1: the volume source. We consider the negative ion temperature T(H^-) = 0.1 eV. This value was found in [6] from laser photodetachment experiments performed in the ion source extraction region.

With T(H) = 0.8 eV, we find from Eq. 4 E_{CM} = 0.67 eV and the corresponding σ_{Hdet} is 1.42 x10^{-19} m^2. With n(H) = 1 x 10^{-19} m^{-3} the mfp is λ_{Hdet} = 0.70 m.

Case 2: the caesium seeded source. The energy of the atomic population is E_1 = 1.2 eV while the negative ions emitted with an average energy 1.2 eV by the plasma grid, acquire an energy of ΔV = 4.2 eV in the sheath [5] and leave the sheath edge with an energy E_2 = 5.4 eV. Thus using Eq. 4 leads to E_{CM} = 3.31 eV. The cross section for detachment by atoms is in this case 1.46 x 10^{-19} m^2. With the same value n(H) = 1 x 10^{-19} m^{-3} as in the case of the volume source, λ_{Hdet} = 0.69 m.

Mutual Neutralisation

Case 1: the volume source. With E_{CM} = 0.67 eV relevant to the volume operation of the source, and σ_{MN} = 4.1x10^{-18} m^2, λ_{MN} = 0.61 m.

Case 2: the caesium seeded source. With the E_{CM} = 3.31 eV and σ_{MN} = 1.35 x10^{-18} m^2, the mfp is λ_{MN} = 1.85 m, three times longer than in volume operation. This is due to the higher negative ion energy and E_{CM} leading to a lower cross section for mutual neutralisation.

Detachment by Electrons

The reaction rate coefficients for electron detachment, calculated for a Maxwellian electron energy distribution, are from [1], where they are expressed versus the electron temperature. In this case for T_e = 2 eV $\langle \sigma v_e \rangle$ = 8x10^{-8} cm^3/s.

Case 1: the volume source. With $T(H^-)$ = 0.1 eV, the negative ion velocity in Eq. 2 is calculated from the H^- ion energy E_2 = 0.15 eV. Thus one finds, using Eq. 2, with n_e = 2.74 x10^{17} m^{-3}, λ_{ED} = 0.23 m.

Case 2: the caesium seeded source. In this case, the negative ion velocity in Eq. 2 is calculated from the energy at the sheath edge E_2 = 4.2 + 1.2 = 5.4 eV. One finds λ_{ED} = 1.47 m, seven times longer than in volume operation. This is due to the higher negative ion velocity in caesium seeded operation.

These calculations are summarised in Table 1. Note that these estimates were done for a hydrogen plasma and it was assumed that all the positive ions were atomic ones, H^+. Note that in the volume source the dominant destruction process is electron detachment, while in the caesium seeded source the H_{det} is dominant.

The mfp of the three destruction processes considered above are taken into account in the combined mfp $\lambda_C = (1/\lambda_{Hdet} + 1/\lambda_{MN} + 1/\lambda_{ED})^{-1}$. In the case of the caesium seeded source, the combined mfp $\lambda_C = 0.375$ m is almost two times shorter than that of the dominating destruction process due to atoms. In the volume source $\lambda_C = 0.135$ m is also almost two times shorter than that for electron detachment, which is the dominating destruction process in this case.

In the caesium seeded source the presence of caesium ions enhances the destruction by mutual neutralization. The cross section for this process is reported in [7]. With a caesium ion density $n(Cs^+) = 3x10^{15}$ m^{-3}, reported by Fantz *et al* [8], the mfp for mutual neutralisation with caesium ions is 166 m. The change of the combined mfp indicated in Table I due to mutual neutralisation with Cs^+ ions was neglected.

Resonant Charge Exchange and Elastic collisions

The MFP for momentum transfer to H_2 molecules [9] has been estimated for a hydrogen pressure of 0.45 Pa to be much longer than that for resonant charge exchange of H^- with hydrogen atoms.

The resonant charge exchange can, under certain conditions, interfere with the detachment process, since this collision, very efficient at low energy, can replace a fast H^- ion by a slow one, having the energy of the atom with which the ion exchanged its charge. Thus the detachment processes having large cross sections at low energy will become dominant and shorten the calculated mfp.

The cross section of resonant charge exchange is reported in [2, 10] versus the collision energy eV/amu.

The resonant charge exchange cross section relevant to the starting negative ion energy in the cesium seeded source (5.4 eV) is 1.08 $x10^{-18}$ m^2 and the mfp $\lambda_{CX} = 0.092$ m. In this case λ_{CX} is four times shorter than the combined mfp for detachment processes (0.375 m). Thus the effect of detachment processes will be enhanced in caesium seeded sources due to resonant charge exchange which will reduce the negative ion energy and thus increase the cross sections of H_{det} and mutual neutralisation, relevant to this case, and also reduce λ_{ED} (by reducing v^- in the equation for λ_{ED}). The situation is different in the volume source, since we consider a negative ion temperature much lower than the atomic temperature ($T(H^-) = 0.1$ eV, $T(H) = 0.8$ eV). Here the effect of resonant charge exchange will be opposite to its effect in caesium seeded sources, namely the heating of the negative ions and the increase of their mfp.

In the preceeding discussion, the collisions of negative ions with excited atoms H(n>2) have not been considered. These cross sections are not known. However it is suggested in [2] that in these collisions the detachment (associative and non-associative) will dominate, and thus suppress the charge exchange channel.

In conclusion in caesium seeded sources resonant charge exchange in the collisions with atoms, in ground or excited states, is shortening the negative ion mfp. In volume sources if the atomic temperature is higher than that of negative ions, the resonant charge exchange may have the opposite effect, *i.e*. enhance the negative ion mfp.

TABLE I. Mean Free Path and combined mfp (λ_c) for three destruction processes in a volume and a caesium seeded negative ion source. In the case of the caesium seeded source the sheath voltage is 4.2 V. The mfp for resonant charge exchange of H^- and H, and the mfp due to mutual neutralisation of H^- with Cs+ are also shown.

Type of source	**Mean free paths (m)**					
	λ_{Hdet}	λ_{MN}	λ_{ED}	λ_C	λ_{CX}	$\lambda_{MN(\mathrm{Cs}^+ + \mathrm{H}^-)}$
Volume	0.70	0.61	0.23	**0.135**	0.077	
Caesium seeded	0.69	1.85	1.47	**0.375**	0.092	166

ESTIMATE OF THE MFP IN A CAESIUM SEEDED DEUTERIUM ION SOURCE

The purpose of this section is to estimate the mfp in the caesium seeded source experiment using deuterium as discussed by Christ-Koch *et al* [11]. In this experiment the negative ion density and extracted beam current are reported versus the plasma grid bias which varies in the range 14 V to 24 V. The sheath voltage ΔV is reported to be 2.2 V at 14 V and 0 at 21 V (the plasma potential). The strong decrease of the negative ion density (measured at 0.022 m from the plasma grid) with increasing plasma grid bias is attributed by the authors to the decrease of the mfp of the H^- ions. Therefore the evaluation of the mfp at plasma grid bias values of 14 and 21 V is important.

Since no other information is provided in [11] on the plasma parameters in this experiment we used the data obtained for the same ion source by Langmuir probe measurements by McNeely *et al*. [12] The measurements of McNeely *et al* were done in hydrogen. However, it was reported by Fantz *et al* [13] that the electron temperatures and densities in the plane parallel to the plasma grid were the same in hydrogen and deuterium. We assumed that the gas temperature in this plasma was 1200 K as indicated by Fantz *et al* [9]. We used the indication that the deuterium discharges show a factor 1.5 higher atomic density in the extraction region than in hydrogen [9].

The experiment [11] was carried out at a deuterium pressure of 0.45 Pa and a power of 53 kW. We estimated the atomic density in deuterium to be 7.6 $\times 10^{18}$ m^{-3} (30% of the neutral particle density). The electron and positive ion density and electron temperature from [12] are as follows: electron temperature 0.75 eV, electron density 2×10^{17} m^{-3}, positive ion density 3.2×10^{17} m^{-3} . The decrease of the positive ion density with plasma grid bias was taken from Fig. 20 of [12]: 10^{17} m^{-3} at plasma grid potential 14 V, and 3×10^{16} m^{-3} at 20 V. The electron density was also decreased, accordingly.

Electron impact detachment and mutual neutralisation cross sections for deuterium can be scaled from hydrogen cross sections by scaling the collision energy (at equal relative velocity) [14]. The associative and non-associative detachment cross sections in H + H^-, and D + D^- collisions contain a genuine isotope effect [14], and the corresponding cross sections for deuterium are not available. However the cross section of these reactions can be derived from those in hydrogen, just by scaling the energy, as in the case of mutual neutralisation [14]. This may not be a quite accurate approach at very low energies, but it should be still appropriate even in the 5-20 eV energy range [14]. We will assume the same scaling for the associative and non associative detachment (denoted D_{det}), as for mutual neutralization. Note that the energy scaling factor is 2 when going from H to D, if the H data are given versus center of mass energy. For detachment by electrons the energy scaling factor is 1.

In the case of the resonant charge exchange of D^- with D atoms the cross sections can be easily scaled from those for hydrogen, since in [2, 10] the energy is reported in eV/amu.

The energy in the frame of the center-of-mass was calculated using Eq. 4. This energy has the same value for D_{det} and mutual neutralisation because the atom and positive ion temperatures are the same. E_{CM} are reported in Table 2 along with the mfp of D^- ions for the three detachment processes considered and for two values of the plasma grid bias: 14 V and 21 V. This corresponds to the sheath voltage values 2.2 V and 0 respectively. In both cases the combined mfp is more than ten times longer than the distance from the plasma grid to the probe (0.022 m). The mfp for resonant charge exchange of D^- with D atoms, also shown in Table 2, is in both cases at least two times shorter than the combined mean free path for detachment processes, but still much longer than the distance from the plasma grid to the probe.

TABLE 2. The mean free path for three detachment processes and the combined mfp (λ_c) in the experiment in deuterium reported in [11]. The mfp was calculated for two values of the plasma grid bias (PG bias). The corresponding sheath voltage ΔV and center of mass energy E_{CM} used for calculating the mutual neutralization and associative detachment (D_{det}) mfp are also indicated. The electron temperature used for calculating the mfp for electron detachment is 0.75 eV.

PG bias (V)	ΔV (V)	E_{CM} (eV)	Mean free paths (m)				
			λ_{Ddet}	λ_{MN}	λ_{ED}	λ_C	λ_{CX}
14	2.2	2.3	1.05	3.91	0.36	**0.25**	0.11
21	0	1.2	0.94	6.59	1.08	**0.47**	0.1

Thus the lower starting energy of the negative ions in the case of plasma grid bias 21 V does not explain the reduced negative ion density indicated by the photodetachment measurement at 0.022 m from the plasma grid, as suggested by the authors of [11].

ISOTOPE EFFECT IN EXTRACTED CURRENT

The comparison of the mfp of negative ions of hydrogen and that of its isotope deuterium is important since it can help understanding the difference in extracted currents. Table 3 presents the values of the mfp in hydrogen and deuterium for the same plasma conditions in a volume source: n(H) = 10^{19} m^{-3}, $n(H^+) = 4\text{x}10^{17}$ m^{-3}, n_e = 2.74x10^{17} m^{-3}, T_e = 2 eV. It can be noted that the combined mfp is shorter in deuterium than in hydrogen:

$$\frac{\lambda\left(D^-\right)}{\lambda\left(H^-\right)} = 0.73$$

This can explain in part the higher extracted hydrogen negative ion beam current.

TABLE 3. Comparison of the Mean Free paths in Hydrogen and Deuterium volume sources

Gas	Mean free paths (m)			
	λ_{det}	λ_{MN}	λ_{ED}	λ_C
Hydrogen	0.70	0.61	0.23	0.14
Deuterium	0.64	0.35	0.17	0.10

CONCLUSION

Several results have been obtained in this work.

1. The combined mfp in typical operation conditions of the rf caesium seeded source is several tens of cm. This is much longer than usually quoted.
2. The mfp in hydrogen is longer than in deuterium. This can explain in part the higher extracted hydrogen beam current under the same plasma conditions.
3. The mfp relevant to the combined extraction-photodetachment experiment at IPP Garching [11] is obtained. It is shown that the reduction of the negative ion density with increasing plasma grid bias is not due to the reduction of the mfp to values comparable to the distance between the plasma grid and the probe (0.022 m), as proposed by the authors.

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