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Isotope effect and cesium dependence of negative ion production in volume H^- and D^- ion sources

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Isotope effect of H^- and D^- productions with and without cesium vapor injection is studied theoretically as a function of plasma parameters. Model calculation in a tandem volume source is performed by solving a set of particle balance equations for steady-state hydrogen and deuterium discharge plasmas. In a pure volume case, as a whole, H^- production is higher than D^- production for various plasma conditions. This isotope effect is caused by mainly atomic collision processes, i.e., collisional cooling of vibrational molecules and collisional destruction of negative ions. Therefore, density of atoms plays an important role for deciding negative ion density. On the other hand, in a cesium case, there is no remarkable isotope effect on H^-/D^- production. Considering H^-/D^- surface production caused by both atoms and positive ions, H^-/D^- production is enhanced by a large factor and then isotope effect observed in pure volume case seems to be almost masked. © *1998 American Institute of Physics.* [S0034-6748(98)59002-8]

I. INTRODUCTION

Sources of H^- and D^- ions are required to generate efficient neutral beams with energies in excess of 150 keV. So far, the high-efficiency of negative ion production has been studied in the volume ion source with the magnetic filter. Most of the H^- ions are produced by a two-step process[1] which involves dissociative attachment of slow plasma electrons e (with electron temperature $\kappa T_e \sim 1$ eV) to highly vibrationally excited molecules $H_2(v'')$. Recent experimental studies have revealed that the H^- current is highly enhanced,[2,3] and the optimum pressure giving the highest H^- current for a certain arc current is reduced by adding cesium (Cs) to hydrogen discharge.[4,5] Furthermore, the value of this optimum pressure is almost independent of arc current.[4] Although these effects have been observed by many researchers, the mechanism of Cs catalysis in H^- production remains to be clarified.

To date, we have studied source modeling[6,7] and Cs effects on enhancement of H^- production.[8,9] Based on some experimental results (e.g., correlation between the H^- current and the work function of the plasma grid,[10] and dependence of H^- current on barium washer voltage),[11] we assume that dominant process of Cs effects is surface production,[9] where the surface has a low work function because of Cs coverage. Taking into account H^- surface production, the model calculation[9] well reproduces the characteristic features on enhancement of H^- production observed experimentally.

By the way, there is much interest in the isotope scaling[12] because the D^- ion source is required in the future. So, we have expanded the model of the tandem H^- ion source to the model which can deal with D^- production.[13] In this article, with the use of the modified model, we present the numerial results on H^-/D^- production, and discuss the isotope effects of H^-/D^- production as a fuction of plasma parameters.

II. SIMULATION MODEL

Details of the model are reported elsewhere.[7,9] Two chambers of volume $L \times L \times L_1$ (the first) and $L \times L \times L_2$ (the second) are in contact with each other in the region of magnetic filter (MF), shown in Fig. 1, where $L_1 + L_2 = L = 30$ cm. Fast electrons e_f are present only in the first chamber (source region with filaments) because the MF impedes e_f from coming into the second chamber (extraction region). Particles except e and e_f are assumed to move freely between two chambers without being influenced by the MF. The number of particles passing through the MF are treated in the form of flux nv, where n and v are the particle density and velocity, respectively.

The present model includes two kinds of reaction processes at the wall surface. One is negative ion surface production caused by Cs injection. For example, the following four processes are considered in H^- production: $Hn^+ + \text{wall} \rightarrow nH^-$ $(n = 1,2,3)$, $H + \text{wall} \rightarrow H^-$. The other is the effect of $H_2(v'')$ surface production due to wall recombination of H and neutralization of positive ions.

In modeling, surface production rates of negative ions are evaluated as follows: The term representing wall loss of

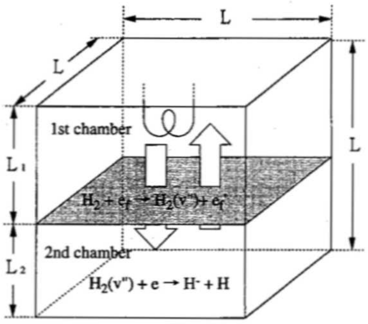

FIG. 1. Simulation model for the tandem two-chamber system.

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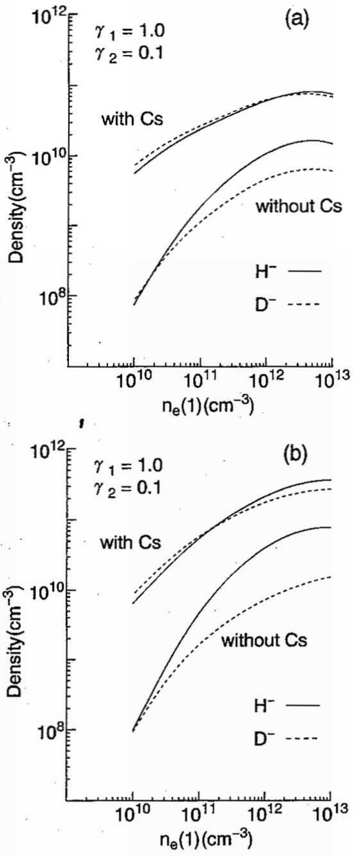

FIG. 2. H^- and D^- densities with and without Cs, $\mathrm{H}^-(2)$ and $\mathrm{D}^-(2)$, in the second chamber vs electron density in the first chamber $n_e(1)$, (a) gas pressure $p=1$ mTorr and (b) 5 mTorr.

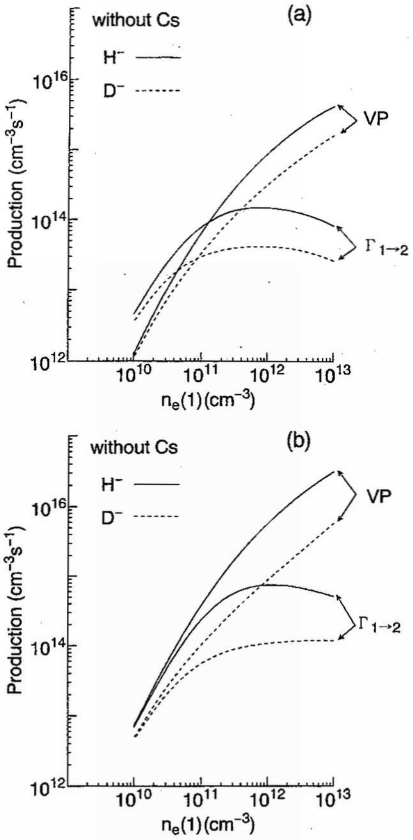

FIG. 3. Production rates without Cs vs $n_e(1)$, corresponding to the results in Fig. 2, (a) $p=1$ mTorr and (b) 5 mTorr.

H atoms is expressed as $-(\gamma_1+P_{\mathrm{CsH}})N_{\mathrm{H}}/\tau_{\mathrm{H}}$, where γ_1 is a wall recombination coefficient, P_{CsH} indicates the probability of H^- formation at the wall, N_{H} is H density, and τ_{H} is a confinement time of H. Then, the H^- production rate at the wall is expressed as $P_{\mathrm{CsH}}N_{\mathrm{H}}/\tau_{\mathrm{H}}$. At the same time, recombination of H to H_2 at the wall is written as $\gamma_1 N_{\mathrm{H}}/(2\tau_{\mathrm{H}})$. Therefore, production of $\mathrm{H}_2(v'')$ is expressed as $P_0\gamma_1 N_{\mathrm{H}}/(2\tau_{\mathrm{H}})$, where P_0 is the probability of finding $\mathrm{H}_2(v'')$ in H_2 formed at the wall. In the same way, the rates of production of H^- and $\mathrm{H}_2(v'')$ from positive ions at the wall are also estimated. In modeling D^- production, these wall effects are included in the same manner.

Model calculation is done by solving a set of particle balance equations including the charge neutrality and the particle number conservation for steady-state hydrogen and deuterium discharge plasmas, as a function of plasma parameters.

III. NUMERICAL RESULTS AND DISCUSSION

To determine the electron density dependence of H^- production, calculation is performed for various electron densities, $n_e(1)$, in the first chamber on the assumption that other plasma parameters are kept constant: i.e., e.g., the gas pressure $p=5$ mTorr, the electron density ratio between two chambers $n_e(1)/n_e(2)=0.2$, density of e_f in the first chamber $n_{fe}(1)/n_e(1)=0.05$, electron temperature in the first and second chambers, respectively, $\kappa T_e(1)=5$ eV, $\kappa T_e(2)=1$ eV, and MF position $L_1:L_2=28:2$ cm. The above mentioned plasma conditions were chosen to optimize H^- pure-volume production in the second chamber. Those are also used in the present study.

Figure 2 shows the H^- and D^- densities, $\mathrm{H}^-(2)$ and $\mathrm{D}^-(2)$, in the second chamber as a function of $n_e(1)$. Wall conditions are as follows: $\gamma_1=1.0$ and the wall de-excitation factor of $\mathrm{H}_2(v'')$, $\gamma_2=0.1$. Probability of H^- surface production from positive ions, $P_{\mathrm{Cs1}}(\mathrm{H}^+)=P_{\mathrm{Cs2}}(\mathrm{H}_2^+)=P_{\mathrm{Cs3}}(\mathrm{H}_3^+)=P_{\mathrm{Cs}}(+)$ and $P_{\mathrm{Cs}}(+)=20P_{\mathrm{CsH}}$, where $P_{\mathrm{CsH}}=5\times10^{-3}$. For surface production of $\mathrm{H}_2(v'')$, probability of finding $\mathrm{H}_2(v'')$ in H_2 formed at the wall, $P_0(\mathrm{H})=P_1(\mathrm{H}^+)=0.01$ and $P_2(\mathrm{H}_2^+)=P_3(\mathrm{H}_3^+)=0.3$.

When $P_{\mathrm{CsH}}=0$, i.e., curves without Cs, H^- and D^- ions are produced by the so-called two-step volume production process. With increasing P_{CsH}, H^- and D^- increases markedly.[9,13] In a high density region at $n_e(1)=5\times10^{12}\ \mathrm{cm}^{-3}$ in Fig. 2(b), H^- and D^- densities are enhanced by about a factor 5 and 20, respectively. To discuss Cs effects quantitatively, we must estimate precisely the relationship between P_{Cs} in our simulation and the theoretical value[14] of the probability β^- for the corresponding experiment. As discussed elsewhere,[9] values of P_{CsH} (from 10^{-3} to 5×10^{-3}) are quite reasonable.

As shown in Fig. 2, isotope effects on $\mathrm{H}^-/\mathrm{D}^-$ production are clearly observed. In the pure-volume case, density difference between H^- and D^- ions becomes large with $n_e(1)$. In

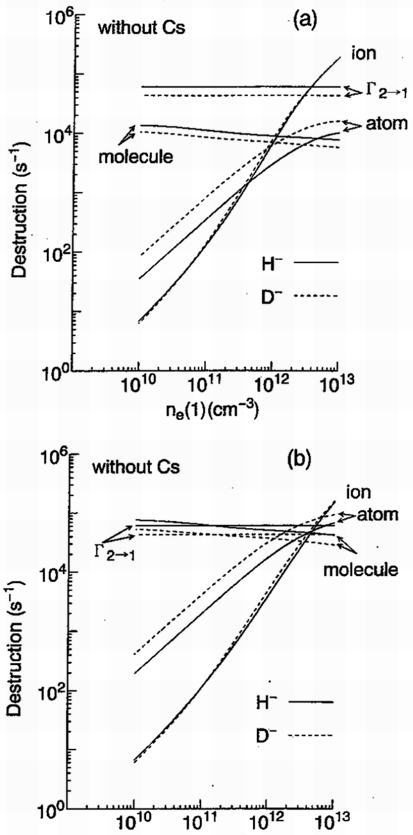

FIG. 4. Destruction probabilities without Cs vs $n_e(1)$, corresponding to the results in Fig. 2, (a) $p = 1$ mTorr and (b) 5 mTorr.

the high density region, at $n_e(1) = 5 \times 10^{12}$ cm^{-3}, H^- density is higher than D^- density about by a factor 2.6 in Fig. 2(a) and 5.8 in Fig. 2(b), respectively. On the other hand, in the presence of Cs, the enhancement of negative ion production due to surface processes (particularly D^- production) is so marked that density difference between H^- and D^- ions decreases in its magnitude. Namely, isotope effects seem to be masked. Besides these, even the density inversion between H^- and D^- ions is observed at a certain $n_e(1)$.

Next, we discuss the isotope effect of H^- and D^- production observed in pure-volume case. On Cs effects, details will be reported elsewhere. Figures 3 and 4 show the predominant production rates and destruction probabilities for H^- and D^- ions corresponding to the results (without Cs) in Fig. 2, respectively. In Fig. 3, VP and $\Gamma_{1\to2}$ represent the volume production (dissociative attachment) and the flow-in of negative ions from first to second chamber, respectively. In Fig. 4, "atom," "molecule," and "ion" severally represent the destruction process (collisional electron detachment) caused by atoms, molecules, and atomic ions.

On production of negative ions, both VP and $\Gamma_{1\to2}$ for H^- is higher than those for D^- in full range of $n_e(1)$. Furthermore, difference between VP and $\Gamma_{1\to2}$ for H^- and those for D^- has a tendency to become large with $n_e(1)$. On the other hand, according to the results in Fig. 4, destruction for D^- ions is lower than that for H^- in full range of $n_e(1)$ except the high density region in Fig. 4(b). In the high-pressure case (5 mTorr), both electron detachment caused by atom and ion predominate with increasing $n_e(1)$. Then, destruction processes for D^- ions become slightly higher than that for H^- ions, above $n_e(1) = 3 \times 10^{12}$ cm^{-3}.

Consequently, isotope effect of negative ion production observed in Fig. 2 is derived from the difference in production processes, mainly VP. There are two significant isotope effects suggested by this modeling effort. One is a stronger cooling of the vibrational distribution in deuterium due to collisions between molecules and atoms. The other is a smaller reaction rate[15] for collisional excitation of vibrational molecules caused by primary fast electrons in deuterium. These processes reduce VP in high-density region below that in equivalent hydrogen plasmas.

IV. CONCLUSIONS

We have theoretically studied modeling H^- and D^- production with cesium injection and its isotope effects. In the pure-volume case, H^- production is much stronger than D^- production clearly in the high density region. The most significant isotope effects are vibrational excitation and a cooling of the vibrational distribution. Including surface production caused by both atoms and positive ions, the H^- and D^- productions are enhanced markedly. Therefore, isotope effects are much reduced and in the low density region D^- ions are slightly higher than H^- ions. Other plasma parameter dependence and details of Cs effects will be reported in the forthcoming article.

ACKNOWLEDGMENTS

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