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A HYPOTHESIS FOR THE MECHANISM OF NEGATIVE ION PRODUCTION IN
THE SURFACE-PLASMA NEGATIVE HYDROGEN ION SOURCE*

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A HYPOTHESIS FOR THE MECHANISM OF NEGATIVE ION PRODUCTION IN THE SURFACE-PLASMA NEGATIVE HYDROGEN ION SOURCE*

ABSTRACT

An analysis of the surface-plasma negative hydrogen ion source has shown that the tungsten cathode supports approximately a monolayer of cesium. The backscattering of protons from the cathode as energetic neutrals and the subsequent backscattering of these neutrals from the anode provides for a flux of energetic atoms incident upon the cathode which is comparable to the ion flux. A hypothesis is proposed for the generation of negative ions during the collision of these energetic atoms with the cathode. Several mechanisms for negative ion production by proton collision with the surface are discussed.

INTRODUCTION

Within the last few years, a magnetron-type negative hydrogen ion source has been developed by Belchenko, Dimov, and Dudnikov^{1,2} (BDD) that has the remarkable capability of producing negative hydrogen-ion current densities up to $3.7 \text{ A}\cdot\text{cm}^{-2}$. The novel feature of this source is a plasma discharge maintained in an atmosphere of hydrogen and cesium and employing a cold cathode of either tungsten or molybdenum. A similar source has been developed by Prelec and Sluyters,^{3,4} their source employing a cold molybdenum cathode and achieving a current density of $1.7 \text{ A}\cdot\text{cm}^{-2}$. The operation of these sources has been reviewed recently at the Berkeley Ion Source Symposium.^{5,6}

Bearing in mind the potential for scaling these sources to produce large negative-ion beams for CTR applications, interest has centered on the specific mechanism for negative ion production. Dimov⁵ has offered evidence that the negative ions are created in the region of the cathode. Dimov⁵ and Kishinevsky⁷ suggest that hydrogen atoms from the discharge are adsorbed as negative ions, being bound to the surface by image forces, and are dislodged from the cathode by fast particles falling through the cathode sheath. In the alternative hypothesis developed in this paper, the negative ions are formed in a surface catalysis involving a CsH molecular configuration interacting with the cathode material. To develop this hypothesis, we must first summarize those system parameters that are presently available from the data

and that form the basis for this discussion.

For optimum source operation, the hydrogen gas density is $n(\text{H}_2) \approx 10^{16}$ molecules cm^{-3} , the Cs density $n(\text{Cs}) \approx 10^{12}$ atoms cm^{-3} . The atomic hydrogen density in the anode gap can be inferred from the resonant charge-transfer cross section for the process⁸

together with the experimental observation⁵ that the charge-transfer reaction goes on to completion as the H_2 gas density is varied over the operating range. The cross section of reaction (1) for negative ions that have fallen through the 120-V cathode potential is approximately $6 \times 10^{-14} \text{ cm}^{-2}$; the path length, L , in the cathode-anode region is 0.2 cm; setting this length equal to at least two mean free paths, a lower limit to the neutral atom density is $n(\text{H}) \approx 2/L \approx 10^{15}$ atoms cm^{-3} .

The cathode temperature is also a significant parameter. Sluyters⁹ has observed an optimum source operation when the cathode is cooler than a cherry red (900 K) color. Information from Novosibirsk, communicated by R. V. Pyle,¹⁰ specifies a cathode operating temperature near the range 700-800 K.

Only an estimate of the electron density and electron temperature in the discharge region can be obtained from the currently available data. In Fig. 1 is plotted the current density in $\text{A}\cdot\text{cm}^{-2}$ versus the discharge electron density. From Fig. 2 of Ref. 1, a negative ion current density of $3.4 \text{ A}\cdot\text{cm}^{-2}$ is achieved for a cathode current density of $40 \text{ A}\cdot\text{cm}^{-2}$. Subtracting the electron and negative ion current densities, the maximum positive ion current density onto the cathode is $31 \text{ A}\cdot\text{cm}^{-2}$. The minimum H^- current density leaving the cathode is $3.4 \text{ A}\cdot\text{cm}^{-2}$; assuming at least one positive ion is required to generate a negative ion, the upper limit to the negative ion current density leaving the cathode is $17 \text{ A}\cdot\text{cm}^{-2}$.

The maximum current density which can be extracted at the cathode surface is given by the space-charge limit as being equal to

$$j = 5.5 \times 10^{-12} V^{3/2} d^{-2}, \text{ A}\cdot\text{cm}^{-2} \quad (2)$$

where V is in volts and d is in centimeters. The distance d is determined by the cathode sheath thickness; Thompson¹¹ shows that the sheath thickness

is equal to twice the Debye length. But upon examining the variation of sheath potential shown in Fig. 3.2 of Thompson's book, the potential gradient is steepest near the cathode. Since it is the variation of potential nearest the cathode that will determine the space-charge limit, the distance d is taken equal to the Debye length,

$$d \approx (kT_e / 4\pi e^2 n_e)^{1/2}. \quad (3)$$

The negative ion current density limits using Eqs. (2) and (3) are shown in the figure for different values of electron temperature. The 120-V cathode potential implies an upper limit to the electron temperature of about 80 eV.

The processes

and

are the two principal mechanisms that destroy negative ions as they pass through the discharge region in their flight from the cathode to the anode.

The fractional change in current density after traversing a distance ℓ through the discharge is determined from

$$\frac{\Delta j}{j} = \ell n_e \left[\sigma(4) + \frac{\sigma v}{v_-} \right], \quad (6)$$

where $\sigma(4)$ is the cross section for reaction (4), σv the rate for reaction (5), and v_- the negative ion velocity at 120 eV. The cross section¹² for reaction (4) is only weakly dependent on energy in the range 100-500 eV. The cross section for reaction (5) has a maximum near 15 eV.¹³ BDD report a discharge layer thickness, ℓ , equal to 0.05 cm. Figure 2 of the paper of BDD¹ shows that the extraction current rises with increasing cathode current, tending toward saturation at the largest cathode currents. BDD interpret this saturation as due to negative ion destruction in the discharge region. At a cathode current density of 40 A.cm^{-2} , the extraction current density is about one half that which would be indicated by a linear extrapolation from

the origin. Setting $\Delta j/j = 1/2$ and solving Eq. (6) for the n_e at different electron temperatures, one obtains the points shown in Fig. 1 indicated by the crosses and labeled according to electron temperature. The space-charge-limited current densities and the attenuation processes are consistent for electron temperatures of 8 to 9 eV and electron densities of about 10^{14} electrons cm^{-3} .

These numbers can be confirmed by comparing the rate of ionization at H_2 molecules with the cathode current. At an electron density of 10^{14} electrons cm^{-3} , the rate of generation of H_2^+ ions from H_2 equals the positive cathode current, $31 \text{ A} \cdot \text{cm}^{-2}$, multiplied by the cathode area, 6 cm^2 , for an electron temperature of 7 eV.

A somewhat larger electron density is required if we calculate a positive flux emerging from the discharge plasma. The positive ion energy in the discharge is unknown. The minimum gap separating the anode and cathode is 0.05 cm; in a 2000-G field, this gap will admit a 0.1-eV proton. In the anode groove region, the gap is 0.22 cm, admitting a 2-eV proton. The flux of particles entering the cathode sheath is

$$f = v_D n_e, \quad (7)$$

where v_D is the directed velocity. Taking a value for v_D appropriate to a 2-eV proton, a flux equivalent to $31 \text{ A} \cdot \text{cm}^{-2}$ is obtained for $n_e = 4 \times 10^{14}$ electrons cm^{-3} . This larger density may in fact be more representative of the density on the opposite side of the cathode from the extraction gap, where the H_2 gas is admitted.

The principal source of hydrogen atoms in the discharge region is from the dissociation of H_2 molecules,¹⁴

These atoms are created with an energy of about 2.4 eV; the rate of their subsequent thermalization by wall collisions is unknown. Another source of atoms is the backscattering of positive ions striking the cathode. The 120-eV protons will backscatter from the cathode as positive ions, negative ions and neutral atoms. Based upon a large body of data,¹⁵⁻¹⁸ one would expect perhaps 80% of the incident protons to backscatter as neutrals and to have a

mean energy equal to about one third the incident energy. These back-scattered neutrals are in turn backscattered off the anode with further energy degradation. Probably 65%, or $20 \text{ A}\cdot\text{cm}^{-2}$, of neutrals with energies up to 10 eV are returned to the cathode. Their density would be approximately $10^{14} \text{ atoms cm}^{-3}$, small compared to the thermal atom density. We have then an important conclusion: The energetic atom equivalent current and the positive ion current striking the cathode are comparable.

The mean free paths for H_2 and H_2^+ are short compared to system lengths, and the densities of these constituents in the discharge plasma region opposite the extractor gap are not expected to be significant.

The system parameters that form the basis for the discussion that follows are summarized in Table 1.

Table 1. Parameters of the surface plasma source.

Thermal	2-eV hydrogen atom density:	$10^{15} \text{ atoms cm}^{-3}$
Energetic (2 to 10 eV)	hydrogen atom density:	$10^{14} \text{ atoms cm}^{-3}$
Cesium	atom density:	$10^{12} \text{ atoms cm}^{-3}$
Discharge	electron density:	$1 \text{ to } 3 \times 10^{14} \text{ electrons cm}^{-3}$
Electron	temperature:	5 to 10 eV
Cathode	temperature:	600 to 800 K

The central problem is to identify which of the particles is the active particle in producing the negative ion, and by what process. Probably, both the protons and the hydrogen atoms contribute to the total negative ion production. In the next section, we shall develop an hypothesis for negative ion production resulting from the energetic atom bombardment of the cesium-loaded tungsten surface.

There exists at present no information on the three-component system of tungsten-cesium-hydrogen, although there are available considerable data pertaining to both the cesium-tungsten interaction and the cesium-hydrogen interaction. The data relevant to these binary systems will be reviewed in the next sections, and these data will be combined to form a hypothesis for the tertiary system.

PROPERTIES OF THE CESIUM-TUNGSTEN INTERACTION

The cathode temperature and flux of cesium atoms striking the tungsten cathode imply a surface coverage of cesium of about one monolayer. The extent of the cesium coverage is determined from an equilibrium between the rate of adsorption and the rate of evaporation. The equilibrium coverages have been studied by Taylor and Langmuir,¹⁹ and a summary is shown in Fig. 2. Here, the fractional surface coverage, θ , is plotted as a function of surface temperature, for several values of the cesium flux. A surface coverage of unity corresponds to 4.8×10^{14} cesium atoms cm^{-2} . For the values listed in Table 1, the surface coverage will be in the range 0.5 to 0.7.

The cesium is adsorbed to the tungsten surface through a combination of ionic and covalent electron bonds. The relative degree of ionic versus covalent bonding depends upon the position of the electronic level in the cesium atom relative to the Fermi level of the tungsten substrate. As the cesium atom moves up to the surface, the electronic level is broadened into a band approximately 1-eV wide.²⁰ This broadening is a consequence of the finite lifetime of the electron against leaking through the potential barrier into an electronic level of the substrate. Two situations apply here and are illustrated in Fig. 3. On the left-hand side of the figure, the atomic band spans the Fermi level. An electron near the top of the band will spend some fraction of its time in the unfilled level of the substrate, this shift of charge from the atom to the substrate contributing to an ionic bond. Near the lower part of the band, electrons from the substrate can be shared with the atom, thereby forming a covalent bond. On the right-hand side of the figure, the atomic band lies entirely below the Fermi level. Throughout the band, substrate electrons are shared with the cesium atom to form a purely covalent bond.

Depending upon the surface coverage, the work function, ϕ , decreases in value as the cesium atoms accumulate. The work function of tungsten is 4.62 eV, and that of cesium metal 1.81 eV.²¹ As the surface coverage of cesium increases from zero, the work function of the composite surface decreases, passing through a minimum which is less than that of cesium at θ values between 0.6 and 0.8, then increasing to the cesium value in the limit of large coverage.¹⁹ At the minimum, the work function is 1.69 eV.

At low surface coverages, the cesium is bound to the substrate with a combination of ionic and covalent bonds; but for larger coverages, $\phi > 0.5$, the bond is almost purely covalent;²¹ the cesium resides on the surface as an atom and not as an ion.

The variations of the work function can be understood qualitatively from the following discussion. For less than full surface coverages of cesium, the work function reflects local surface conditions. If there are but few cesium atoms on the tungsten surface, these atoms will lose their valence electron to the tungsten, and the apparent work function will be that of tungsten. The situation shown on the left-hand side of Fig. 3 applies. For an intermediate surface coverage, the loss of electrons from the cesium to the tungsten establishes a dipole layer that acts to prevent a full electron transfer. The situation is illustrated in Fig. 4. On the left is shown the energetic configuration of the separated metals. As these metals are brought into contact, electrons from near the top of the Fermi level of cesium pass over into the unfilled levels of tungsten, then fall to the tungsten Fermi level. This transfer of charge generates a dipole between the two metals, the potential for electrons being lower on the cesium side. The transfer continues until the configuration has reached an equilibrium where the uppermost occupied levels of the cesium are at the same level as the Fermi level of the substrate, as seen in the right-hand diagram. Since cesium has lost some of its electrons, the work function of the surface is now larger than that of cesium metal. As the surface coverage of cesium increases, a smaller and smaller fraction of cesium electrons must be donated to support the dipole layer, and the work function tends to that of metallic cesium. The potential V tends to the contact potential, $V = V_c = \phi(w) - \phi(Cs)$. The cesium-tungsten bond is now as shown on the right-hand side of Fig. 3.

There is no experimental data for the separation distance of the cesium atom from the substrate. A consensus of opinion however,^{21,22} is that this separation should be determined approximately by the covalent radius of the substrate (1.3 Å) and of the adsorbate (2.35 Å). The substrate atoms are spaced 2.73 Å apart. One imagines then that the cesium atom is placed at the apex of a pyramid, supported by four substrate tungsten atoms, and spaced a distance of 3.1 Å from the plane of the substrate surface.

THE CESIUM-HYDROGEN INTERACTION

We shall assume for our purposes that the relevant cesium-hydrogen interaction is the potential function for the cesium hydride molecule. In Fig. 5 is shown the potential function²³ for the $1\Sigma^+$ ground electronic state of the system together with that for the first excited $1\Sigma^+$ state. At large internuclear separation, the ground state divides into a cesium atom and hydrogen atom, each in its own ground state. At higher energies, there exists a state which asymptotically dissociates into a cesium ion and negative hydrogen ion. The dashed line is a continuation to small internuclear separations of the Coulomb energy of this ionic interaction.

All alkali hydride potentials show a similar behavior. The properties of LiH have been investigated theoretically in some detail,²⁴ and we can extrapolate these results to CsH to provide for an understanding of the variation of the molecular wave function for different values of the internuclear separation. Referring now to the ground state in Fig. 5, as the two atoms approach each other from infinity, the molecular wave function evolves from the atomic form to an ionic configuration, Cs^+H^- , near the minimum of the potential. The first excited state follows a similar pattern. At large separation, the function has an atomic form; at intermediate separations where the potential functions passes near the dashed curve, it assumes the ionic form, Cs^+H^- ; and at still smaller separations, where the ground state is ionic, the function again changes form. Where the dashed curve passes near a particular electronic $1\Sigma^+$ state, the function is predominantly ionic. What is important for our purposes is the fact that the ground state, in the region of the potential minimum, is ionic.

Also shown on Fig. 5 is a schematic of the CsH^- negative molecular ion. The curve has been drawn taking the H_2^- potential²⁵ as the prototype for the alkali-hydride negative ion sequence, but expanding both the abscissae and the ordinate appropriate to the scale of the CsH molecule. The negative molecular ion is presumed to be a less tightly bound configuration than the neutral molecule. In the case of CsH, each atom provides one valence electron to pair into a tightly bound singlet configuration; for CsH^- , the extra electron is left unpaired, forming a doublet state. The electronic level of the outermost electron in CsH^- would be expected to lie several eV higher than the outer electron of CsH near the minimum of the CsH potential.

FORMATION OF NEGATIVE IONS BY HYDROGEN ATOM SURFACE COLLISIONS

With the background of the two previous sections, one can now discuss the hypothesis of negative ion formation by atomic wall collisions. A typical sequence is shown schematically in Fig. 6. Fig. 6a, the electronic energy levels are shown for the tertiary W-Cs-H system. On the left is indicated the electronic work function and Fermi level of tungsten; the electron forming the covalent bond with cesium is labeled A. A hydrogen atom approaches from the far right.

Fig. 6b, the hydrogen atom has moved up to the cesium atom temporarily forming a CsH molecular bond, thereby lowering the energy level of electron A. Electron A is now resonating between the cesium and hydrogen atoms, with the electron preferentially associated with the hydrogen atom in a manner analogous to the electronic configuration at the minimum of the CsH molecular potential. Simultaneously with the lowering of the level of electron A, a new electronic state moves down to the approximate original position of electron A, and an electron B attracted by the positive Cs ion on the surface is donated by the tungsten to the molecular configuration.

In the third schematic, Fig. 6c, the negative ion has moved away from the cesium atom, and the energy level of electron A has been raised to that of the free negative ion, while the cesium atom bound to the substrate has returned to its original state. The energy required to raise the electron from its level in the cesium-tungsten bond to its asymptotic level in the negative ion has been derived from the relative motion of the H atom. The formation of the negative ion has involved two catalytic processes: the CsH molecular configuration has catalysed the transfer of an electron from the cesium atom to the hydrogen atom, and the tungsten-cesium interaction has catalysed the transfer of the second electron, thereby leaving the cesium in its initial state. The process is represented schematically by the reaction

Of critical importance for the operation of this mechanism is the requirement that the energy level of electron B shown in Fig. 6b lie lower than the top of the Fermi level of the tungsten-cesium system. The position

of electronic level B has its origins in part in the electronic affinity of the outer electron of CsH^- , and in part in the image potentials experienced by electron B. The following arguments are offered as a suggestion for the necessary lowering of this electronic state below the Fermi level.

Let $H_0 + A$ be the Hamiltonian or eigenvalue for the free CsH^- negative ion, where A is the electron affinity. The total energy level for the system in the presence of the surface is then presumed to be

$$H_0 + A + I, \quad (10)$$

where I is the contribution to the energy level of B due to the images of the underlying CsH core.

Consider first that there exists a sufficiently low coverage of Cs that the appropriate image plane is the surface of the tungsten substrate. The Cs^+ ion and the H^- ion induce negative and positive images in the substrate at a distance R_1 and R_2 , respectively, interior to the substrate surface. Moving electron B from infinity up into position at the Cs^+ ion induces in addition a positive image, and the potential energy of electron B in the presence of its own image is equal to $-e^2/4R_1$. The total potential energy of electron B_2 is then

$$I = -\frac{e^2}{4R_1} + \frac{e^2}{2R_1} - \frac{e^2}{R_1+R_2} = +\frac{e^2}{4R_1} - \frac{e^2}{R_1+R_2}. \quad (11)$$

For a $\text{Cs}^+ - \text{H}^-$ separation distance corresponding to the minimum of the CsH potential, $R_2 \approx 2R_1$, and

$$I \approx \frac{e^2}{4R_1} - \frac{e^2}{3R_1} \approx -\frac{1}{12} \frac{e^2}{R_1}. \quad (12)$$

The image potential in this case contributes to a lowering of energy level of electron B.

On the other hand, for a large surface coverage of cesium, the H^- ion will form its positive image in the cesium plane. The Cs^+ and electron images remain reflected in the substrate plane. Again taking $R_2 \approx 2R_1$, the image potential is now

$$I \approx +\frac{e^2}{4R_1} - \frac{e^2}{R_1} \approx -\frac{3e^2}{4R_1}. \quad (13)$$

The image potential in this example would contribute a lowering of several eV.

While these examples suggest that the energy level of electron B will lie below the Fermi level, detailed calculations will be required to determine quantitatively the position of this energy level.

FORMATION OF NEGATIVE IONS BY ION SURFACE COLLISIONS

The flux of ions impinging on the cathode may also be a source of negative ions. In the case of an ion flux, the processes can be divided into two broad categories, depending upon the energy of the particles as they reflect back through the surface. The positive ions are presumed to strike the cathode with the cathode potential equal to 120 eV. After penetration into the substrate lattice with the associated energy degradation, some fraction of these particles will backscatter through the surface with suprathermal (10-eV) energies. In general, these backscattered particles will emerge as positive ions, neutrals, and negative ions. As mentioned above, one would expect some large fraction, probably more than half, of the incident ions to be reflected as suprathermals. For most metals, the suprathermals will reflect mainly as neutrals; data that yield the fraction reflected as negative ions are scant.

Levine and Berry²⁶ (LB) observed the backscattering of negative ions for 1 keV H^+ , H_2^+ , He^+ , and Ar^+ ions incident upon tungsten. These backscattered ions showed a double peak, the low-energy peak (10 eV) declined and then disappeared as the tungsten temperature was raised to 480 and 1000 K, respectively, driving off the surface hydrogen. A point of some significance is the fact that the low-energy negative hydrogen ion peak exists regardless of the nature of the incident ion. Their interpretation of the low-energy peak is similar to that of Dimov⁵ and Kishinevsky.⁷ The magnitude of the low-energy peak was not reported (although it was claimed to be the prominent feature). The high-energy peak is representative of backscattering suprathermals and gave an integrated yield that was 10^{-4} of the incident beam.

In an earlier experiment, Mitropan and Gumenik²⁷ observed low-energy negative ions (10 eV) emitted from copper, aluminum, and stainless-steel

surfaces bombarded by 200- to 1000-keV hydrogen and deuterium ions. A high-energy flux of backscattered positive ions was observed with energies in excess of 400 eV. The negative ion fraction was observed to be a descending function of incident energy, the maximum at 200 keV being of order 10^{-3} . These authors show that the negative ion emission is associated with the presence of a surface layer of hydrogen adsorbed to the metal surface. No attempt was made to observe negative hydrogen ions by bombarding the surface with positive ions of a different species, but the source of negative ions in this experiment is probably the same as the source of the low-energy peak in (LB)'s experiment.

The negative ion fluxes observed in these experiments are not sufficient to explain the observed ion source currents. In the model of DK it is the cesium layer on the tungsten surface that causes the negative ion flux enhancement, presumably from the low-energy peak.

Incident positive ions that backscatter as suprathermal negative ions will reach the anode with an energy equal to the sum of the cathode potential energy drop and their kinetic energy at the point of re-emergence from the surface. In Fig. 7 is reproduced the energy distribution of negative ions at the anode as observed in the planotron source, Fig. 7 of Ref. 5, for different voltage drops on the discharge. The low-energy peak centered about zero is a consequence of reaction (1). About half the negative ions in the high-energy peak have energies above the discharge voltage. If the low-energy side of this peak is reflected through the maximum to provide a "natural width", the high-energy side of distribution is still some 20% rich in negative ions. Taking this data at face value would indicate that a substantial fraction of the negative ions may be produced by positive ions backscattering as suprathermal negative ions.

Those positive ions which backscatter from the tungsten substrate through the cesium layer as energetic neutrals may also result in the generation of negative ions through reaction (9).

Finally, while they are in the vicinity of the surface, positive ions may capture two electrons directly from the surface through the Auger process. The relative importance of this mechanism is outside the scope of this paper.

In summary, negative ions may be generated by positive ions bombarding the cathode in at least four ways: via the mechanism of the low-energy peak

observed by LB, suprathreshold backscattering, suprathreshold neutral backscattering combined with process (9), and via the Auger process.

CONCLUSIONS

In the operation of the surface-plasma negative ion source, the tungsten cathode supports a near monolayer of cesium. This cesiated cathode is bombarded by comparable fluxes of positive ions and energetic neutral atoms. A hypothesis has been offered for a mechanism of negative ion formation resulting from the atomic bombardment. A critical element in this hypothesis is the position of the energy level of the donor electron. An accurate determination of the system energetics will require a numerical calculation of the tertiary tungsten-cesium-hydrogen system. To within the scope of the qualitative arguments offered here, negative ion production should occur for any tungsten-alkali-hydrogen system. The relative contribution of ionic and atomic bombardment of the cathode to the total negative ion production is unknown.

FIGURE CAPTIONS

1. The negative ion current density at the cathode as a function of electron density. Diagonal lines are space charge current density limits for different temperatures, given by Eq. (2). The crosses indicate the expected current density versus electron density at different electron temperatures derived from Eq. 6.
2. The fractional monolayer coverage, θ , as a function of cathode temperature for cesium fluxes of 10^{15} and 10^{17} atoms cm^{-2} .
3. The relative positions of the bonding valence electron in the cesium-tungsten adsorption bond.
4. Schematic indicating the differences in surface work function for different cesium coverages.
5. Potential functions for the $C_s - H$ interaction and the $C_s - H^-$ interaction. The dashed curve is the ionic interaction.
6. Schematic illustrating the formation of negative ions in a surface collision.
7. The energy spectrum of H^- ions extracted for different voltage drops across the discharge: Curve 1 - 120 volts; Curve 2 - 160 volts.

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