PHYSICAL REVIEW B

CONDENSED MATTER

Production of negative hydrogen ions by sputtering adsorbed hydrogen from a cesiated molybdenum surface

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We have investigated the production of negative hydrogen ions by bombarding hydrogen adsorbed onto a cesiated molybdenum surface with positive cesium ions. The negative hydrogen yields are measured as a function of hydrogen gas pressure, cesium coverage, and energy of the incident cesium ions. The optimum yield obtained was 0.4 for 750-eV cesium ions bombarding hydrogen adsorbed onto the molybdenum surface covered with 0.65 monolayers of cesium. It is observed that the sticking coefficient of hydrogen decreases as the cesium coverage increases. We measure the energy distribution of the negative hydrogen ions as they leave the surface. The energy spread is about 0.5% of the incident cesium-ion energy. We compare our results for the production probability of negative hydrogen ions with the results obtained by Hiskes and Schneider.

I. INTRODUCTION

The production of negative hydrogen ions on solid surfaces has been recently studied by many authors. The major motivation of this work was the need for H^- or D^- sources in thermonuclear fusion research and for particle accelerators. Simultaneous new developments in atomic and surface physics helped to put these surface processes into a more general perspective.

Basically there are two surface processes leading to the formation of H^- ions: backscattering and sputtering. The yields of H^- production by backscattering of positive hydrogen ions in the energy range of 0.1 to 5 keV were measured by several authors.[1-4] Backscattering yields of thermal hydrogen atoms in the 1-eV energy range were also measured.[5,6] The experimental results were compared[3,6] with a theory derived by Hiskes et al.[7] Sputtering of H^- ions from metallic targets with dissolved hydrogen is most effective when the target is bombarded with Cs^+ ions in the keV range. This was originally observed by Krohn[8] for all negative ion sputtering and is now interpreted as owing to the work-function reduction by cesium coverage.[9,10] A partial understanding of the sputtering process can be obtained by combining

the theory of neutral atom sputtering with theories developed for electron exchange processes for backscattering[7,11-13] as discussed by Wittmaack.[14] Absolute yields of H^- ions sputtered from metal hydride targets have been measured by Seidl et al.[15]

The most promising sources of H^- ions are surface conversion sources[16] studied by many laboratories. In these sources the target (converter, cathode) is placed into a hydrogen-cesium discharge and negatively biased with respect to the plasma potential. H^- ions are produced at the surface of the target. There has been a long-standing controversy on which of the possible surface processes is responsible for H^- production (backscattering of H^+ ions or fast hydrogen atoms, sputtering of adsorbed hydrogen by cesium or hydrogen ions bombarding the target). It is difficult to answer these questions by studying the surface conversion sources directly because the elemenatry processes cannot be easily separated.

In this paper we report on an experiment in which only one of the above four processes, namely sputtering of adsorbed hydrogen by cesium bombardment, could occur. A molybdenum target is exposed to a flux of cesium atoms and cesium ions. By changing the ratio of these two fluxes, the cesium coverage of the target and hence its work func-

tion can be controlled. Hydrogen gas is adsorbed onto the cesiated molybdenum surface. Hydrogen coverage can be controlled by the gas pressure. The sputtering yield is defined by the equation

$$\gamma_{H^-} = \phi(H^-)/\phi(Cs^+)$$

where $\phi(H^-)$ is the flux of H^- ions desorbed from the surface and $\phi(Cs^+)$ is the flux of Cs^+ ions incident on the surface. We measure the sputtering yield as a function of cesium and hydrogen coverage and the energy of the Cs^+ ions. We also measure the energy distribution of the sputtered H^- ions.

By analyzing the experimental results, we establish direct contact with the theory[7] by finding the production probability as a function of the initial velocity of the H^- ions at the surface of the target.

II. EXPERIMENTAL APPARATUS

The experimental apparatus is an approximately planar diode shown in Fig. 1. The anode of the diode consists of two 2×40 mm^2 molybdenum ribbons separated by a 3-mm-wide extraction slot. When heated to above 1000 °C, the ribbons are the source of Cs^+ ions produced by surface ionization of Cs atoms piped into the diode region from a cesium oven.

The cathode is a molybdenum base plate with two stainless steel wedges on top of it, used to focus the sputtered ions and electrons through the anode extraction slot. Only a small central part of the cathode of a 4×4 mm^2 area is hit by the Cs^+ beam which passes through an aperture in the shield surrounding the anode. The temperature of the cathode can be maintained from -85 to 20 °C
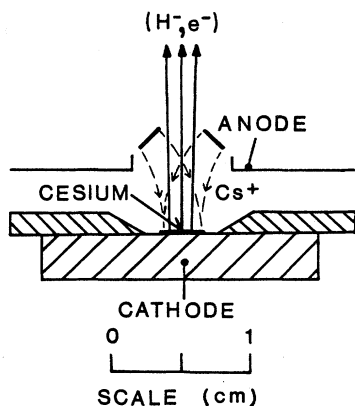
using refrigerated methanol as coolant.

In order to reduce the work function of the cathode, cesium vapor is produced in the cesium oven and directed onto the surface of the cathode by means of a heated feeder tube. The orientation of the feeder tube from the cesium oven with respect to the cathode is shown in Fig. 2. The feeder tube is heated to above 300 °C so that $\phi(Cs)$ can be controlled by varying only the temperature of the cesium oven. The cesium oven is a stainless-steel chamber into which is placed a glass ampoule containing two grams of cesium. After the oven has been evacuated, the ampoule is crushed using a plunger mounted onto the oven with bellows. The cesium flux used was about 2 orders of magnitude larger than the flux of residual water vapor so that we would not have our results affected by the presence of CsOH. A typical cesium atom flux at the cathode is $\phi(Cs) = 10^{15}$ atoms cm^{-2} s^{-1} for an oven temperature of 150 °C.

Hydrogen is supplied to the molybdenum surface of the cathode by chemisorption of hydrogen gas. The hydrogen gas is admitted into the vacuum chamber by means of a needle valve. The hydrogen pressure was varied from 10^{-7} to 10^{-3} Torr. The vacuum system is evacuated by a six inch oil diffusion pump to a background pressure in the 10^{-8}-Torr range. The residual gas was observed by a Veeco SPI-10 residual gas analyzer to be predominantly water vapor.

The cathode surface is kept clean of impurities such as water vapor by continuously bombarding it with Cs^+ ions with energies above 250 eV and current densities greater than 100 μA cm^{-2}. This is a flux of $\phi(Cs^+) \simeq 63 \times 10^{13}$ ions cm^{-2} s^{-1},

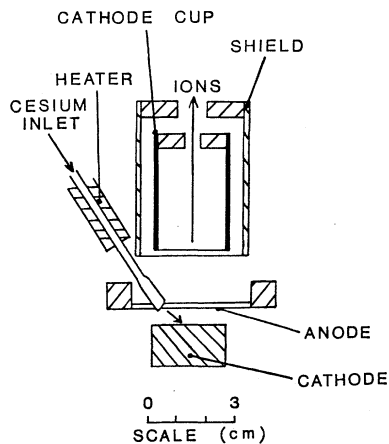FIG. 1. Schematic diagram of the vacuum diode.

FIG. 2. View of the vacuum diode with location of cesium feeder tube.
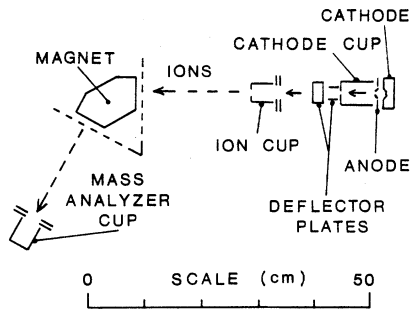
FIG. 3. Experimental setup for measuring secondary emission yields.

which is much larger than the water vapor flux of $\phi(H_2O) \simeq 5 \times 10^{13}$ molecules cm^{-2} s^{-1} obtained for a background pressure of 10^{-7} Torr.[17]

The anode is grounded and the cathode is negatively biased from 0 to -2 kV. More than 95% of the sputtered negatively charged particles originating on the cathode are extracted through the extraction slot in the anode.

Figure 3 shows the experimental apparatus used to measure the fraction of ions to electrons in the extracted beam. The sputtered electrons and negative ions pass through the extraction slot in the anode and are collected by the "cathode cup," a Faraday cup located directly behind the anode. A guard ring biased at -50 V is between the anode and the cathode cup and prevents low-energy, stray electrons from reaching the cathode cup, and also suppresses secondary electrons generated inside the cup. The current measured by the cathode cup is the total secondary current I_s.

About 1% of the beam exits through a small aperture in the back of the cathode cup and is collected by the "ion cup," another Faraday cup with guard ring located about 20 cm behind the cathode cup. A transverse magnetic field of about 20 G applied along the path between the two cups deflects the electrons out of the ion beam so that the ion fraction of the beam, I_I'/I_I, can be measured. I_I' is the ion current and I_I is the total current to the ion cup.

About one percent of the remaining beam exits through a small aperture in the rear of the ion cup and enters the mass analyzer. The mass analyzer consists of a 60° magnetic sector used to deflect negative ions of different masses into a Faraday cup. For H$^-$ ions, the mass analyzer measures the ratio of H$^-$ ions to all ions, I_{H^-}/I_-.

The total negative hydrogen ion yield γ_{H^-} can be determined from the above measurements and

the primary bombarding Cs$^+$-ion current I_p. This gives the H$^-$-ion sputtering yield

$$\gamma_{H^-} = \left[\frac{I_s}{I_p} \right] \left[\frac{I_I'}{I_I} \right] \left[\frac{I_{H^-}}{I_-} \right] \qquad (1)$$

where the various ratios have been described above. The cathode current I_k is also measured in order to determine the extraction efficiency of the secondary negative particles from the cathode. I_k is within 95% of the difference between the total secondary current and the primary current $I_s - I_p$.

An example of using Eq. (1) is given for 750-eV Cs$^+$ ions incident on the molybdenum surface. For a cathode-cup current of $I_s = 11.0 \ \mu$A and an incident Cs$^+$-ion current of $I_p = 21 \ \mu$A, the total secondary yield is $I_s/I_p = 0.53$. The ion fraction of the beam is determined from $I_I' = 0.15 \ \mu$A and $I_I = 0.22 \ \mu$A which gives the ion fraction $I_I'/I_I = 0.68$. The mass analyzer showed the negative ions to be at least 95% H$^-$ ions, with a negligible O$^-$ and OH$^-$ component. Using Eq. (1) gives the H$^-$-ion sputtering yield $\gamma_{H^-} \simeq 0.36$. This was with a hydrogen pressure of 2.2×10^{-4} Torr in the system and a cesium flux of 1×10^{15} atoms cm^{-2} s^{-1} directed onto the cathode by the feeder tube. The electron yield is $\gamma_{e^-} \simeq 0.17$, which is about half the H$^-$-ion yield for these parameters.

III. CESIUM AND HYDROGEN ADSORPTION

Since the cathode is exposed to cesium atoms and ions, the molybdenum surface will be partially covered with cesium. Taylor and Langmuir[18] investigated the cesium coverage on a tungsten surface exposed to cesium vapor. Their results could be explained by the Langmuir adsorption model for coverages less than a monolayer.

The coverage is determined in equilibrium by equating the adsorption rate of cesium on the surface to the desorption rate. There are two contributions to the adsorption term. The first contribution is the adsorption of neutral cesium given by $\alpha_0 \phi(Cs)(1 - \Theta_{Cs})$, where α_0 is the condensation coefficient or fraction of cesium atoms sticking to the molybdenum surface, $\phi(Cs)$ is the neutral cesium flux, and $(1 - \Theta_{Cs})$ is the fraction of the surface not yet covered with cesium. The sticking coefficient α_0 was shown[19] to be unity for temperatures of the surface from 300 to 700 K and cesium coverages less than 0.98 monolayers. We operated within this regime. The second contribution is the adsorption of cesium ions given by $\alpha_+ \phi(Cs^+)$

$\times(1-\Theta_{Cs})$, where α_+ is the sticking coefficient of cesium ions and $\phi(Cs^+)$ is the positive cesium-ion flux. The sticking coefficient α_+ is approximately one for the low-energy ions[18] but in general depends on the energy of the incident cesium ions. The value for α_+ drops to a minimum of about 0.35 at 150 eV as discussed by Arifov,[20] and then rises again to about 0.9 for incident cesium ions with energies above 900 eV.

The desorption rate is given by $\gamma_c\phi(Cs^+)\Theta_{Cs}$, where γ_c is the sputtering yield of neutral cesiums from the surface. We shall assume γ_c to be unity in later discussions by considering the interaction between an incident cesium ion and an adsorbed cesium atom to be a binary collision. In addition, there is thermal desorption.[18] However, this is much less than the desorption due to sputtering since our cathode is at temperatures below 400 K. Equating the adsorption and desorption rates gives

$$[\alpha_0\phi(Cs)+\alpha_+\phi(Cs^+)](1-\Theta_{Cs})$$
$$=\gamma_c\phi(Cs^+)\Theta_{Cs}\ . \quad (2)$$

This can be solved for the cesium coverage giving

$$\Theta_{Cs}=\{1+\gamma_c/[\alpha_++\alpha_0\phi(Cs)/\phi(Cs^+)]\}^{-1}\ ,$$
$$(3)$$

which is always less than one. Therefore, the cesium coverage of the molybdenum surface can be varied by changing the ratio of incident cesium ions to cesium atoms, $\phi(Cs^+)/\phi(Cs)$.

As an example, Eq. (3) gives a coverage of $\Theta_{Cs}\simeq0.67$ for 750-eV incident Cs^+ ions with $\phi(Cs^+)=8.4\times10^{14}$ atoms cm^{-2} s^{-1}, $\phi(Cs)$ $=1\times10^{15}$ atoms cm^{-2} s^{-1}, $\gamma_c=1$, $\alpha_0=1$, and $\alpha_+=0.87$.

It is known that hydrogen adsorbs onto clean molybdenum as atomic hydrogen.[21] As for cesium adsorption, the hydrogen coverage Θ_H can be estimated using a Langmuir adsorption model. The rate of adsorption is $\alpha_H\phi(H)(1-\Theta_H)$, where α_H is the sticking probability of hydrogen on molybdenum partially covered with cesium and

$$\phi(H)=3\times10^{21}P(273/T)^{1/2} \quad (4)$$

is the number of hydrogen atoms cm^{-2} s^{-1} for a molecular hydrogen pressure given in Torr and a temperature given in K. It is shown later in Sec. V that α_H depends on the cesium coverage Θ_{Cs}. The rate of desorption by incident Cs^+ ions is $\phi(Cs^+)\gamma_H\Theta_H$, where γ_H is the sputtering yield of hydrogen atoms and ions from a completely covered surface when $\Theta_H=1$. Equating the ad-

sorption and desorption rates gives as the equilibrium hydrogen coverage

$$\Theta_H=[1+\phi(Cs^+)\gamma_H/\phi(H)\alpha_H]^{-1}\ , \quad (5)$$

which is always less than one. The hydrogen coverage can be varied by changing the ratio of $\phi(Cs^+)/\phi(H)$, which is easily done by changing the hydrogen pressure in the vacuum system.

IV. SPUTTERING OF NEGATIVE HYDROGEN IONS

The H^--ion yield γ_{H^-} is measured as a function of hydrogen gas pressure for a particular cesium voltage and cesium coverage. This dependence is shown in Fig. 4 where γ_{H^-} is observed to increase with hydrogen pressure until it saturates at hydrogen pressures approaching 10^{-3} Torr.

We develop a model that explains these observations and determines two important parameters that yield additional information on the adsorption of hydrogen and the desorption of H^- ions. The desorption rate of H^- ions is given by $\phi(Cs^+)\ \gamma_H\Theta_H P^-$, where $\phi(Cs^+)\gamma_H\Theta_H$ is the desorption rate of all hydrogen atoms and ions and P^- is the probability that the hydrogen atom leaves the surface as a negative ion. Dividing the H^--ion desorption rate by $\phi(Cs^+)$ gives the negative hydrogen-ion yield

$$\gamma_{H^-}=\gamma_H\Theta_H P^-\ , \quad (6)$$

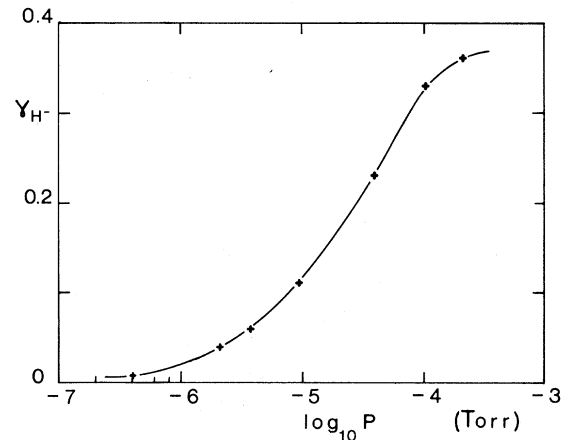which is the number of H^- ions sputtered per incident Cs^+ ion.

FIG. 4. Yield of H^- ions as a function of hydrogen gas pressure. Cesium coverage is 0.65 monolayers and Cs^+ ions have 750-eV energies.

Substituting for Θ_H the expression given in Eq. (5), we obtain

$$\frac{\gamma_{H-}}{P^-\gamma_H} = \frac{1}{1+[\phi(Cs^+)/\phi(H)](\gamma_H/\alpha_H)} = \Theta_H \ .$$

(7)

In this equation, $\phi(H)/\phi(Cs^+)$ is proportional to the hydrogen gas pressure P, and γ_{H-} is the measured H^- yield. The two unknown parameters are $P^-\gamma_H$ and α_H/γ_H, where P^- is the probability that the hydrogen atom is a negative ion and α_H is the sticking coefficient of hydrogen to the cesiated molybdenum surface. For each Cs^+-ion energy U and cesium coverage on the molybdenum surface Θ_{Cs}, the above two unknown parameters can be determined as follows.

The values of γ_{H-} and $\phi(Cs^+)/\phi(H)$ are stored in a computer and the two parameters, $P^-\gamma_H$ and α_H/γ_H, are then determined by fitting the data to the curve described by Eq. (7) using the least-squares method. Figure 5 shows that the data can be fit to this universal curve for different cesium coverages. This curve was obtained for 750-eV Cs^+-ion energies. Similar curves were obtained for the voltage range from 500 to 1250 eV.

Each set of data taken for a particular cesium coverage gives one pair of values, $P^-\gamma_H$ and α_H/γ_H, which are plotted as a function of cesium coverage Θ_{Cs} in Fig. 6 for 750-eV Cs^+ ions incident on the surface. If γ_H is assumed to be a constant close to unity (to be discussed in Sec. VI), then for a cesium coverage of 0.65 monolayers, P^- reaches an optimum value of 0.4. The value of 0.65 for Θ_{Cs} is close to the cesium coverage resulting in a minimum work function reported by Fehrs and Stickney.[22] They investigated the adsorption of cesium on monocrystals of both tantalum and tungsten. Arifov[23] reviews many works where the minimum work function occurs for a coverage of 0.7 monolayers for alkali metals on many different polycrystalline targets, including molybdenum. Taylor and Langmuir[24] report the optimum cesium coverage of polycrystalline tungsten to be 0.67 monolayers.

Also shown in Fig. 6 are the sticking coefficients α_H for different cesium coverages Θ_{Cs}. The hydrogen sticks readily to bare molybdenum but does not stick well to cesium. This was investigated by Papageorgopoulos and Chen.[25] They report that molecular hydrogen does not stick at all to a cesium coverage greater than about a monolayer.

The variation of $P^-\gamma_H$ for different Cs^+-ion energies is shown in Fig. 7. Curves of $P^-\gamma_H$ vs Θ_{Cs} are shown for Cs^+-ion energies ranging from 500 to 1250 eV. The optimum value for $P^-\gamma_H$ occurs at the same coverage of 0.65 monolayers of cesium for all voltages. Also shown in Fig. 7 are the values of α_H/γ_H for different voltages. One can see that α_H/γ_H depends on the cesium coverage only, and is independent of Cs^+-ion energy.
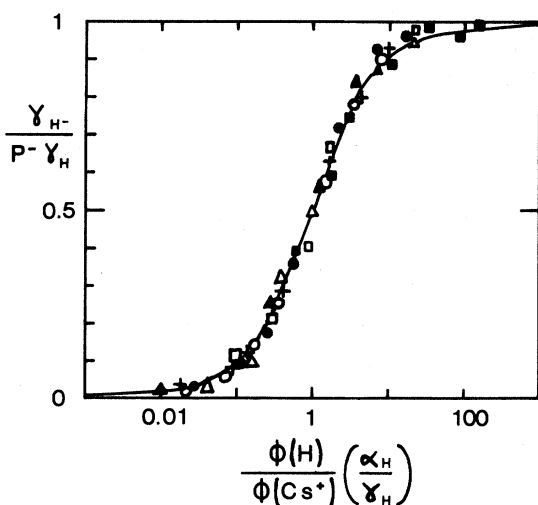

FIG. 5. H^--ion yields as a function of $\phi(H)/\phi(Cs^+)$, fitted to the universal curve for 750-eV Cs^+ ions incident on cesium coverages ranging from 0.50 to 0.80 monolayers.
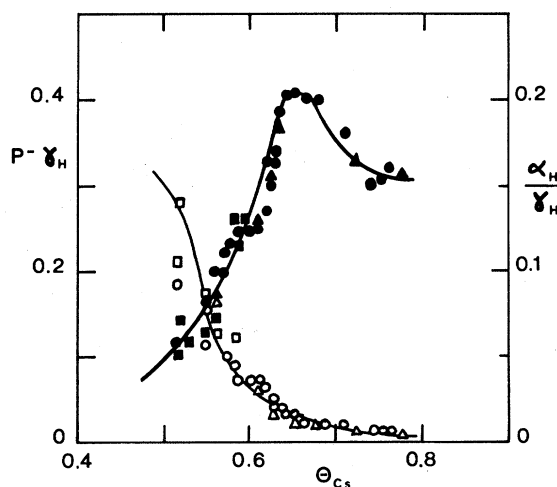

FIG. 6. Production probability P^- and sticking coefficient α_H as a function of cesium coverage for 750-eV Cs^+ ions. The solid symbols refer to P^- and the open symbols refer to α_H.
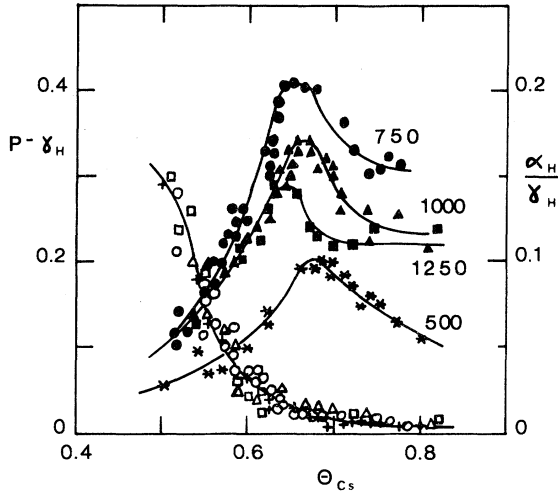
FIG. 7. Production probability P^- and sticking coefficient α_H as a function of cesium coverage for different Cs^+-ion energies shown on each curve. The solid symbols refer to P^- and the open symbols refer to α_H.

V. ENERGY DISTRIBUTION OF NEGATIVE HYDROGEN IONS

Some insight into the dependence of $P^-\gamma_H$ on Cs^+-ion energy can be obtained by measuring the velocity distribution for the H^- ions as they leave the cathode surface. This is interesting both from theoretical and practical considerations. The exit velocity is a major parameter determining the H^--ion production discussed by various authors.[3,7,11-13] The velocity spread is also important for producing well-focused H^- ion beams. The spread in velocities originates at the surface of the cathode as the energetic Cs^+ ions desorb the H^- ions.

The energy distribution of H^- ions was measured with a retarding voltage energy analyzer. In front of the ion cup is placed a biased tungsten grid. The wires of radius $r = 0.0017$ cm are a distance (center to center) $a = 0.018$ cm apart. At a distance $d = 1.32$ cm in front of the mesh is a plate with a 1-mm-diameter aperture in it. The energy resolution can be estimated using the formula[26]

$$\frac{\delta V}{V} = \frac{-\ln 2 + \ln(2\sin\pi r/a)}{\dfrac{\pi d}{a} - \ln(2\sin\pi r/a)} , \qquad (8)$$

where the values for r, a, and d are given above. This gives a resolution $\delta V/V \simeq 0.5\%$. The transverse magnetic field mentioned in Sec. II is used to remove electrons from the H^--ion beam. The
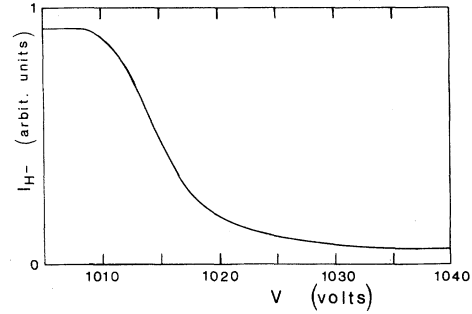

FIG. 8. H^--ion current to the ion cup as the retarding voltage on the grid is increased. Cs^+-ion energy is 1000 eV. Hydrogen pressure is 2.4×10^{-4} Torr.

H^--ion current to the ion cup is measured as a function of voltage V applied to the retarding grid. This dependence is shown in Fig. 8 for 1000-eV Cs^+ ions incident on the cathode. The magnetic mass analyzer showed the negative ions to be at least 95% H^- ions, the rest being predominantly O^- and OH^-.

The energy distribution $f(E)$ is determined by differentiating the curve in Fig. 8. The distribution $f(E)=dI_{H^-}/dE$ is then normalized and plotted in Fig. 9. The abscissa is the ratio E/U, where E is the initial energy of the H^- ions at the cathode surface and U is the incident Cs^+-ion energy. Data are shown for Cs^+-ion energies ranging from 500 to 2000 eV. The data shows that a universal relationship exists between $f(E)$ and E/U, independent of incident Cs^+-ion energy. The slight deviation from the universal curve for the two lowest Cs^+-ion energies measured, 500 and 625 eV, is probably due to scattering of the H^- ions in the background hydrogen gas. The
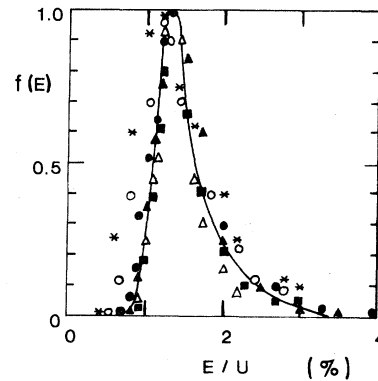

FIG. 9. Energy distribution of H^- ions for Cs^+-ion energies ranging from 500 to 2000 eV. The abscissa is the H^--ion energy divided by the Cs^+-ion energy. Hydrogen pressure is 2.4×10^{-4} Torr in all cases.

peak in the energy distribution occurs for
$E/U \simeq 0.013$. The full width at half maximum
(FWHM) of the energy distribution is
$E/U \simeq 0.005$. Practically all ions have energies
below the maximum energy transferable to an H^-
ion due to a head-on elastic collision with an in-
cident Cs^+ ion. Conservation of momentum and
energy show that this energy is $E/U \simeq 0.03$. As an
example, for 500-eV Cs^+ ions incident on the
cathode, the peak in the energy distribution for the
H^- ions occurs at about 6.5 eV and the maximum
transferable energy is about 15 eV. The FWHM is
about 2.5 eV. This compares favorably with ener-
gy spreads obtained in discharge ion sources.

VI. DISCUSSION

Figure 7 showed that for each voltage, the prod-
uct $P^-\gamma_H$ reached a maximum at the same cesium
coverage, about 0.65 monolayers. These maxima
depend on the Cs^+-ion energy and reach a max-
imum of 0.4 for 750-eV Cs^+ ions. P^- is the pro-
bability that the desorbed hydrogen atom is a nega-
tive ion. It is equivalent to the production proba-
bility used in the theory of Hiskes.[12] In Sec. IV we
mentioned that we assume the total hydrogen yield
of atoms and ions, γ_H, close to unity. We think
this is a reasonable assumption for the following
reason. Since the hydrogen coverage of the surface
is always less than a monolayer [see Eq. (5)] and
the penetration depth of the incident Cs^+ ion is
only a few monolayers, then the momentum
transfer from a Cs^+ ion to a hydrogen atom on the
surface should be due to a binary collision. As
shown previously in Fig. 9, the maximum energy
of the desorbed H^- ions is 3% of the incident
Cs^+-ion energy, supporting the assumption of
binary collisions.

To compare our results with theory,[3] we replot
P^- versus the initial velocity of the H^- ions at the
cathode surface using the results of the preceding
section. Figure 9 showed that the most probable
energy of the H^- ions is 1.3% of the incident
Cs^+-ion energy. This information is used to ob-
tain the H^--ion velocities. P^- versus the H^--ion
velocity is plotted in Fig. 10. Theory[12] indicates
that P^- should be given by an equation of the
form

$$P^- = [1 - \exp(-\alpha/v_\perp)][\exp(-\beta/v_\perp)] \qquad (9)$$

where α and β are unknown parameters depending
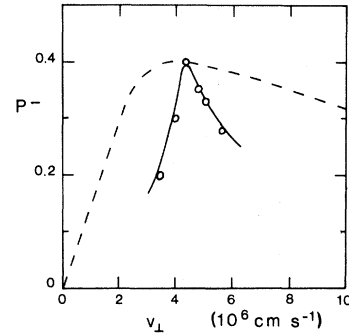on the cathode surface and $v_\perp$ is the normal com-

FIG. 10. Production probability as a function of exit-
ing H^- ion velocity for H^- ions at the peak in the ener-
gy distribution. Cs^+-ion energies range from 500 to
1250 eV. The dashed curve is Eq. (9) with the same
maximum for P^- as the data.

ponent of the H^--ion velocity at the surface.
Equation (9) has been used previously for thick
cesium targets. Hiskes and Schneider[3] investigated
the reflection of high-energy hydrogen atoms from
a thick cesium target using incident energies from
120 eV up to 3 keV. Pargellis and Seidl[6] investi-
gated the reflection of low-energy hydrogen atoms
from thick cesium using energies of about 1 eV.
In both cases the experimental data could be fitted
to Eq. (9) when the two parameters were taken to
be $\alpha = 7.7 \times 10^6$ cm s^{-1} and $\beta = 9.5 \times 10^6$ cm s^{-1}.
The optimum value of P^- was 0.22 for 85-eV H^-
ions.[27]

We can compare our results shown in Fig. 10
with the predictions for P^- given by Eq. (9) as fol-
lows. The optimum value for P^- is taken to be
0.4 for H^- ions with a velocity of 4.2×10^6
cm s^{-1}, obtained from our data. Setting the
derivative of P^- with respect to $v_\perp$ equal to zero
gives a second equation and the two unknown
parameters are determined to be $\alpha = 4.6 \times 10^6$
cm s^{-1} and $\beta = 2.4 \times 10^6$ cm s^{-1}. The resultant
values of P^- as a function of $v_\perp$ are shown by the
dashed line in Fig. 10. Our experimental data are
steeper than the curve given by Eq. (9) and the
values of α and β are lower than those for a thick
cesium target. The optimum production probabili-
ty $P^- = 0.4$ occurs for 10-eV H^- ions. Table I
compares our results with those of Hiskes and
Schneider.[27] The differences are most likely due to
different cesium coverages.

VII. CONCLUSION

We have investigated the sputtering of negative
hydrogen ions from a cesiated molybdenum sur-

TABLE I. Comparison of the data obtained by
Hiskes and Schneider with this work. α and β are
parameters in Eq. (9). P^- is the production probability
and E_{H^-} is the H^- ion energy corresponding to op-
timum production probability.

	Thick Cs target Hiskes, Schneider (Ref. 3)	Optimum Cs coverage This work
α	7.7×10^6 cm s^{-1}	4.6×10^6 cm s^{-1}
β	9.5×10^6 cm s^{-1}	2.4×10^6 cm s^{-1}
P^-_{opt}	0.22	0.4
E_{H^-}	85 eV	10 eV

face. The negative hydrogen ions were sputtered
by positive cesium ions with energies in the range
500−1250 eV. The number of H^- ions produced
per incident Cs^+ ion is defined as the yield. We
investigated the dependence of the H^--ion yield as
a function of hydrogen gas pressure, cesium cover-
age on the cathode surface, and energy of the in-
cident Cs^+ ions.

The H^--ion yields increase with hydrogen pres-
sure until they saturate for pressures of about 10^{-3}
Torr. The H^--ion yields can be fitted to a univer-
sal curve, Eq. (7), by means of two parameters,
$P^-\gamma_H$ and α_H/γ_H. P^- is the probability that a
desorbed hydrogen atom is a negative ion, γ_H is the
total sputtering yield of hydrogen atoms and ions,
and α_H is the sticking coefficient of hydrogen
atoms to the cesiated molybdenum surface. The
universal curve applies for all Cs^+-ion energies and
all cesium coverages. The two fitting parameters
$P^-\gamma_H$ and α_H/γ_H depend on cesium coverage and
cesium-ion energy. The optimum values of $P^-\gamma_H$
occur for a cesium coverage close to 0.65 mono-
layers for all voltages. This cesium coverage is
close to the coverage resulting in a minimum work

function, as discussed by several authors. The
maximum value for $P^-\gamma_H$ is 0.4 and occurs for
750-eV Cs^+ ions. The parameter α_H/γ_H decreases
as the cesium coverage increases, in agreement
with the observations of Papageorgopoulos and
Chen. This dependence is the same for all volt-
ages.

The energy spread in the H^--ion beam has been
measured with a retarding grid energy analyzer.
Most H^- ions are desorbed from the cathode with
1.3% of the incident Cs^+-ion energy. The spread
in energies is about 0.5% and the maximum H^--
ion energy is 3.0% of the Cs^+-ion energy.

In Fig. 10 the optimum values of P^- are plotted
versus the initial velocity of the hydrogen ions at
the cathode surface assuming $\gamma_H \approx 1$. The values
of P^- are compared with the theoretical curve, Eq.
(9), for the production probability according to the
theory of Hiskes,[12]

$$P^- = [1 - \exp(-\alpha/v_\perp)][\exp(-\beta/v_\perp)] .$$

Matching the peaks of the experimental and theo-
retical curves provides the following values for the
two constants: $\alpha = 4.6 \times 10^6$ cm s^{-1}, $\beta = 2.4 \times 10^6$
cm s^{-1}. Table I compares our results with the pre-
vious work by Hiskes and Schneider,[3] who studied
H^- production by backscattering energetic hydro-
gen atoms from a thick cesium target.

ACKNOWLEDGMENTS

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