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H^- AND D^- PRODUCTION BY BACKSCATTERING FROM SURFACES

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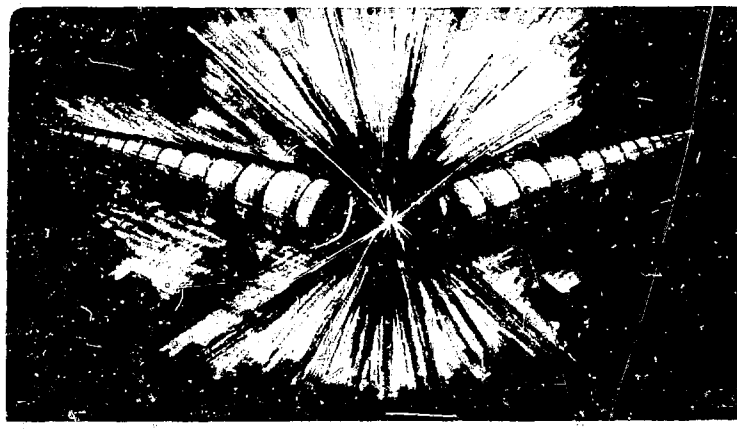
April 1981



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ABSTRACT

We describe three experiments in which H^- or D^- ions have been produced by backscattering from surfaces coated with alkali metals: 1) Backscattering of H^- and D^- produced by 0.15- to 4-keV/nucleus H_2^+, H_3^+, D_2^+, and D_3^+ bombarding clean targets of Cs, Rb, K, Na, and Li. For each target, the H^- and D^- yields were maximized at incident energies between 300 and 1200 eV/nucleus and always at a lower incident energy for H than for D on a given target. At any given incident energy, both the H^- and D^- yields decreased in going from Cs to Li in the order given above. 2) A Mo surface was bombarded by a low-energy flux of H atoms produced in a tungsten furnace. As the surface work function was reduced by evaporating Cs onto the target, a small fraction (10^{-9}) of the incident hydrogen atoms was observed as backscattered H^- ions. 3) Surfaces of Mo, W, Pt, Ni, Cu, Re, Ta, and Pd were bombarded by hydrogen ions produced in a discharge. Two classes of H^- ions were observed when Cs was added to the discharge -- H^- ions leaving the surface with approximately < 10 eV and H^- ions leaving the surface with approximately 50 to 100 eV.

I. Introduction

The weak (0.75 eV) electron affinity of H^- ions makes them ideal for the production of energetic beams of atomic hydrogen: H^- ions are accelerated to the desired energy, and the energetic atomic beam is produced by collisional or photo detachment of the electron. Milliampere beams of H^-, produced by direct extraction from a plasma source or by charge exchange of a proton beam in a gas or metal-vapor target, have been used for many years for negative-ion cyclotrons and polarized ion sources; in the past few years, the need for multi-ampere beam of > 150 keV hydrogen and deuterium atoms for the heating of fusion plasmas has prompted interest in alternate ways of producing negative hydrogen ions.

Several years ago we observed that hydrogen beams transmitted through thin carbon foils contained large fractions of D^- (12 percent for 8 keV D beams) when the exit surface was coated with a clean layer of Mg[1]; "dirty" exit surfaces, or clean coatings of Nb or Au, showed no enhancement of the negative ion component. Because of the large angular spread of a beam emerging from a foil, this was not a practical method for producing D^- beams, but this experiment indicated that electron capture from a properly chosen surface could result in significant negative ion production. Hence, when Belchenko, Dimov, and

Dudnikov[2] reported enhanced H^- yields from an ion source when Cs was added to the discharge, we initiated an experimental program to investigate H^- formation by backscattered particles from substrates coated with clean surfaces of the alkali metals.[3,4] These experiments were limited to backscattered energies above 150 eV/nucleus.

Theoretical work by Belchenko, Dimov, and Dudnikov[2], Hiskes, Karo, and Gardner[5], Hiskes and Karo[6], and Kishinveskii[7], suggested the energy range of interest for surface production of H^- might be lower than that covered by the above experiment. A second experiment, in which thermal hydrogen atoms were produced in a tungsten furnace, was performed to explore the very low energy end of the spectrum.[8]

A third experiment, in which cesiated surfaces were bombarded by ions from a hydrogen discharge[9], is less quantitative than the first two experiments but provides qualitative information on the H^- formation process in the intermediate energy range (tens to hundreds of eV).

In this paper we summarize the results of these three experiments. More detailed information can be obtained from the references.

II. Backscattering of 0.15- to 4- keV/nucleus Hydrogen and Deuterium

A beam of D_2^+ (H_2^+) and D_3^+ (H_3^+) ions was extracted from a hot-filament discharge, accelerated to the desired energy, and momentum selected with a 30° bending magnet before entering the experimental chamber, which is described in greater detail in References 3 and 4. The apparatus within the chamber (Figure 1) was designed around two rectangular plates, perpendicular to the beam line; an aperture in the first plate (the collector) allowed the beam to pass through to the second plate (the target) from which D^- (H^-), D^o (H^o), D^+ (H^+), e^- as well as sputtered particles were emitted. The collector was used to monitor the negative-ion current; therefore, all other charged particles had to be prevented from reaching or leaving it: An electric field between the target and collector plates prevented positive secondary ions from reaching the collector and a transverse magnetic field suppressed secondary electrons. Also, an upbeam collimator shielded the collector from the primary beam. This collimator was the endplate of a Faraday cup (the collimator-Faraday cup) which was used to determine the total current incident onto the target: The total incident current was determined by the difference in current readings from the collimator-Faraday cup when the beam was deflected into the cup and when it was steered through the cup by a pair of upbeam deflection plates. The negative ion secondary emission coefficient (NISEC) was determined by taking the ratio of the collector

current to the total incident current and dividing by the number of deuterons (protons) per incident molecular ion. Clean alkali-metal targets were deposited on a liquid-nitrogen-cooled substrate in the cryopumped experimental chamber, which was maintained at a pressure less than 10^{-9} Torr during the measurements. An S.A.E.S. alkali-metal dispenser, mounted on a bellows, could be positioned between the target and collector plates to coat the target area. The thickness of the alkali-metal layer was controlled by varying the current through the dispenser (6 to 8A) and the evaporation time.

The experiment was divided into two parts: (1) clean, thick, alkali-metal targets (Cs, Rb, K, Na, and Li) and (2) thin coverage of Cs on a Ni substrate. For the thick targets, the incident energy of the hydrogen and deuterium ions ranged from 0.15 to 4 keV/nucleus and for the thin-coverage targets the range was from 0.4 to 0.9 keV/nucleus.

In Figures 2 and 3 we show the measured thick-target H^- and D^- yields for Cs, Rb, K, Na, and Li. The estimated standard uncertainties are $\pm$ 10 percent.

There are several features worth noting:

(1) All the targets show a maximum in the H^- (D^-) yields.

(2) The maximum value of the H^- (D^-) yield decreases in the order Cs, Rb, Na and Li at any incident energy.

(3) The higher the maximum value of the H^- (D^-) yield, the lower the incident energy at which it occurs.

(4) For any given target the maximum in the D^- yield is less than or equal to the maximum in the H^- yield and occurs at a higher incident energy than the H^- maximum.

(5) The H^- yield per incident proton is the same for H_2^+ and H_3^+ ions incident, and the D^- yield per incident deuteron is the same for D_2^+ and D_3^+ incident, but, at a given incident energy, the D^- and H^- yields are not equal.

These results are in good agreement with a model in which the H^- yield is calculated from a product of the probability of reflection of the primary beam, the probability of formation of H^- at the surface, and the probability of survival as the H^- (D^-) ion moves away from the surface.[10]

The thin-coverage measurements were made using cesium on a Ni substrate. This combination of materials was chosen because of the low

value of the minimum work function (1.6 eV)[11] which can be obtained at a fractional Cs monolayer coverage of the Ni surface, and because Ni was a convenient material to work with. In Figure 4, we show the change in the surface work function and the backscattered D^- yield as the Cs coverage is increased on a Ni substrate which was cleaned by abrasion before being installed in the vacuum chamber. The substrate was heated to about 1400K, hot enough to deposit a clearly visible Ni layer on the facing collector plate in about 30 minutes, at a background pressure of 10^{-9} Torr, and was allowed to cool to room temperature over night at a background pressure of 4×10^{-10} Torr before the Cs was evaporated. It can be seen in Figure 4 that the maximum in the backscattered D^- yield occurs at the Cs coverage that produces the minimum work function, for both 170 and 550 eV/d incident energies. The maximum D^- yield of 0.14 for thin coverage is almost twice as high as the maximum of 0.08 for thick Cs. The variation of the backscattered D^- yield with incident energy, as the Cs coverage is increased on a Ni substrate, is illustrated in Figure 5. The backscattered D^- yield curves show a definite change in energy dependence as the Cs coverage is increased: At low Cs coverages the D^- yield decreases as the energy decreases; at optimum Cs coverage (evaporation no. 9) the D^- yield increases with decreasing energy; and at thicker coverage (evaporation no. 11) the D^- yield again decreases with decreasing energy. This change in the energy dependence may be explained by a hypothesis presented by Hiskes and Karo[6] for D^- yields from W with a partial monolayer of Cs coverage: At partial monolayer coverages, near the minimum in the work function,

an electric dipole layer is produced at the Cs -- substrate interface, which greatly enhances the probability of survival of the D^-. The probability of survival dominates the backscattered D^- yield for incident energies below a few hundred eV, so that any change in the survival probability should be apparent in the D^- yield. For higher incident energies, the D^- yield depends more upon the probability of formation than survival, so that the effect of the dipole layer will not be as pronounced.

III. Backscattering of Thermal H Atoms

The apparatus for this experiment is shown in Figure 6. A vacuum chamber was divided into two differentially pumped sections. In one section an atomic hydrogen source (a tungsten tube furnace) was located. The second section of the chamber contained the molybdenum target assembly, the negative ion detector, the cesium dispenser and the workfunction measuring filament. The two latter devices could be alternatively positioned in front of the target. The target region was pumped by a cryopump and a low-magnetic-field ion pump. Ions from the surface were detected with a quadrupole mass spectrometer. A more detailed description of the apparatus is available in Reference 8.

When H atoms were incident on an untreated Mo surface, i.e., one onto which no Cs had been deposited, a background count rate of less than 100 counts/sec was observed, independent of quadrupole voltage. However, when Cs had been evaporated onto the surface a sizeable signal at mass = 1 was obtained. Similar results were obtained with D atoms incident, and the quadrupole mass filter, used to detect the negative ions, showed a peak at mass 2.

The variation of the negative ion yield with successive Cs evaporations was similar for all measurements for both incident

deuterium and hydrogen atoms. In all cases the negative ion signal initially rose rapidly with decreasing workfunction, reached a maximum value, and then started to decrease, even though the workfunction remained constant.

The reason for a pronounced decrease in the negative ion yield at higher Cs coverages is unclear, but could be due to a change in the reflection coefficient for the incident atoms on the surface as the Cs coverage increases. There exists little information at present on reflection coefficient effects at these low energies. For furnace pressure and temperature conditions which would produce a calculated incident hydrogen atom flux of about 10^{14} atoms/sec, the maximum flux of negative ions from the surface was about 4×10^5/sec. The conversion rate to negative ions is clearly extremely small.

The negative ion signal was investigated as the furnace temperature and pressure were varied. It was shown that for a fixed furnace temperature the negative ion signal was proportional to the hydrogen or deuterium gas pressure, whereas the negative ion signal was found to decrease rapidly with decreasing furnace temperature for a given gas pressure.

As the furnace temperature was varied, while the input pressure was kept constant, both the total number of H atoms and the energy distribution of those atoms changed. With a suitably chosen combination of pressure and temperature changes, it was possible to maintain the

same total flux of hydrogen atoms while varying the energy distribution, thus changing the number of atoms in the beam which exceeded particular energies. The calculated variation in the number of atoms with energies exceeding either 1, 2, 3 or 4 eV is shown in Figure 7. Also shown are the measured relative yields of negative hydrogen and deuterium ions produced with the furnace operating under these conditions. Clearly the negative ion yield is strongly dependent on the energy distribution in the atomic beam. Apparently most of the negative ions are produced by atoms in the beam with energies greater than 3 eV.

IV Surface Production in a Hydrogen Discharge

In this experiment targets of Mo, W, Pt, Ni, Re, Ta, or Pd were bombarded by hydrogen ions from a discharge[9]; Cs could be added to the discharge to produce cesiated surfaces. A schematic diagram of the experimental arrangement is shown in Figure 8. The device is a cylindrical multi-cusp ion source (20 cm diam by 14 cm long) with the open end enclosed by a three-grid extraction system. The chamber is surrounded externally by 10 columns of samarium-colbalt magnets (B_{max} approximately 3.6 kG) to form a line-cusp configuration for plasma confinement. A steady-state hydrogen plasma is produced by primary ionizing electrons emitted from two 0.05-cm-diam tungsten filaments which are biased at -60 V with respect to the source chamber wall (anode). No actual source pressure has been measured, but in normal operation the pressure indicated by a gauge located downstream after the mass spectrometer was 2×10^{-4} Torr. In order to generate surface-produced H^- ions, a moveable, concave molybdenum converter (3 cm high by 5 cm long) is inserted into the plasma through a high-voltage insulator mounted on the end flange. By biasing the converter negative with respect to the anode to a potential V_c, positive ions from the plasma are accelerated across the sheath and strike the converter surface. Any H^- ions formed at the surface will then be accelerated

back across the sheath by the same potential. They pass through the plasma and the extraction slot and are focused geometrically at the entrance aperture of the mass spectrometer. In this source, cesium was deposited on the converter surface by evaporating the metal directly into the plasma from two 10-cm-long S.A.E.S. getter dispensers. The amount of cesium introduced could be controlled by adjusting the heater current of the dispenser strips.

With a pure hydrogen discharge, only a very small negative-ion signal was observed; however, when Cs was introduced into the discharge measurable quantities of H^- ions were produced. The H^- yield increased with increasing Cs concentration. The optimum H^- yield was obtained with a bias potential of -200V on the converter (Figure 9).

In order to investigate different converter materials for use with the self-extraction negative ion source, a rotating converter disk with four different materials brazed on the four quadrants was employed. This converter was installed in the multi-cusp ion source (Figure 8) equipped with one exit aperture so that only the negative ions generated by one portion of the converter disk would exit from the source. The source was operated in the presence of cesium and the converter was biased at -200 V with respect to the anode. The energy spectrum of the "self-extracted" H^- ion beam was detected by the mass spectrometer. With this arrangement, the yield of H^- ions for each metal could be compared under identical conditions of gas pressure, discharge power, cesium environment and converter potential.

Figures 10 - 12 show the energy spectrum of the H^- ions produced by Mo, W, Pt, Ni, Cu, Re, Ta, and Pd. The shape of the spectrum differs from one material to the other. In general, two distinct groups of surface-generated H^- ions can be identified. The energy of one group is approximately equal to the sheath potential, indicating that the ions leave the converter surface with little or no energy. One possible explanation is that these H^- ions are produced on the converter by a desorption process.[2,12] The H^- ions can be desorbed from the converter when positive ions enter the surface layer provided the energy transferred in the collision is equal to or greater than the adsorption energy of hydrogen. In this case, the average energy gained by the H^- ions is usually small, and their final energy should be approximately equal to the sheath potential. In addition to reducing the surface work function, which is essential for the efficient production of H^- ions, the Cs^+ ions in the plasma could also serve as a sputtering agent to enhance the hydrogen desorption rate.

An alternate explanation for the H^- ions that leave the surface with very low energy is that they are produced by backscattering of low energy hydrogen atoms produced in the discharge, either Franck-Condon atoms from the dissociation of H_2 or H_2^+ or protons from the discharge that have charge exchanged after falling through some of the ambipolar potential in the plasma.

The second group of H^- ions has a higher energy and appears to be produced by a reflection process. An incoming H^+ ion strikes the converter surface with energy E = 200 eV after falling through the sheath. The molecular species (H_2^+ and H_3^+) are fragmented to form atomic hydrogen particles with energy E/2 (approximately 100 eV) and E/3 (approximately 66 eV) respectively. If the H^- ions are converted from the three groups of backscattered atomic hydrogen particles by capturing the additional electrons, then their average energy at the detector should be close to the limiting values, 2E (approximately 400 eV), E + E/2 (approximately 300 eV), or E + E/3 (approximately 266 eV). In the presence of cesium, the species current distribution H^+ : H_2^+ : H_3^+ was measured to be 7 percent : 33 percent : 60 percent. Thus the dominant species is H_3^+ and most of the H^- ions formed by reflection of positive hydrogen ions should have energy equal to or less than 266 eV; this is consistent with the energy spectra of Figures 10 - 12. (The energy values in these figures are calibrated by using the volume-produced H^- ion peak). In the case of Pd, the group of H^- ions formed by the reflection of H_2^+ ions is distinguishable.

Formation of H^- ions by a reflection process depends partly on the reflectivity of the substrate. The Marlowe code calculations show that, at a given energy, the fraction of reflected particles increases with the Z of the target material.[10] In Figure 10, Pt produced the biggest number of H^- ions formed by reflection and this may be due to the fact

that it has the largest Z of the four materials tested. Both Mo and Re give the highest total H^- yield at optimum conditions with the majority of the H^- ions belonging to the low energy group. Both elements give a maximum H^- yield with a converter bias voltage of about 200 V.

It was not possible to obtain quantitative results for H^- yields from this experiment.

V. Conclusions

It has been demonstrated that negative hydrogen ions can be produced by reflection from a low-work-function surface, at the incident energies used in the present experiments. The fraction of the incident ions or atoms which were converted to negative ions was much lower when the incident energy was a few eV than when the incident energy was greater than 150 eV. There are indications that the negative ions produced in the low energy experiment arise from the high energy tail of the incident energy distribution.

The H^- (D^-) yields for incident energies greater than 150 eV are as high as 0.03 per incident proton (deuteron), and the dependence of the H^- (D^-) yield upon incident energy can be explained in terms of the probability of reflection of the incident particles, the probability of formation of the negative ion at the surface, and the probability of survival of the negative ion as it leaves the surface.

The experiments with plasma-ion bombardment are only qualitative, but indicate that there are at least two mechanisms for the production of H^- at a surface--reflection of ions with energies of 50 to 100 eV and either H^- desorption or reflection of atoms with energy approximately < 10 eV. The substrate material appears to influence both of these mechanisms.

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FOOTNOTES AND REFERENCES

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[+] Max Planck Institute for Plasma Physics, Garching, Federal Republic of Germany.

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FIGURE LEGENDS

Figure 1: Line drawing of the apparatus within the experimental chamber which was used to measure the Negative Ion Secondary Emission Coefficient (NISEC).

Figure 2: H^- yield per incident proton vs. incident energy per proton for H_2^+ and H_3^+ incident on thick alkali-metal targets.

Figure 3: D^- yield per incident deuteron vs. incident energy per deuteron for D_2^+ and D_3^+ incident on thick alkali-metal targets.

Figure 4: Backscattered D^- yield and change in surface work function vs. evaporation number for Cs deposited on a room temperature Ni substrate: Δ, change in work function; ●, 170 eV/d D_3^+ incident; O, 550 eV/d D_3^+ incident.

Figure 5: Variation of the backscattered D^- yield with incident energy as the Cs coverage is increased on a Ni substrate. The numbers to the right of the curves denote the change in the surface work function and those on the left indicate the evaporation number. The Cs thickness increases with evaporation number. The solid circles indicate Cs thickness beyond optimum coverage.

Figure 6: Apparatus for the determination of H^- yields produced by thermal H atoms.

Figure 7: Measured relative D^- yields, ○ , □ , at different oven temperatures. The furnace operating conditions were adjusted so that the calculated total hydrogen atom flux is constant while the energy distribution of the atoms in the beam varies. Closed symbols are for D atoms, open symbols are for H operation. The lines show the calculated variation in the number of atoms with energies exceeding either 1, 2, 3, or 4 eV with different furnace operating conditions.

Figure 8: Schematic diagram of the plasma-ion bombardment experiment.

Figure 9: The energy spectrum of the H^- ions as a function of converter bias voltage at a constant discharge power.

Figure 10: The energy spectrum of the H^- ions produced on Mo, Pt, and Ni at a constant converter potential of -200 V relative to the anode.

Figure 11: The energy spectrum of the H^- ions produced on Cu, Mo, Re and Ta at a constant converter potential of -200 V relative to the anode.

Figure 12: The energy spectrum of the H^- ions produced on Pd, Mo, W and Re at a constant converter voltage of 200 V relative to the anode.

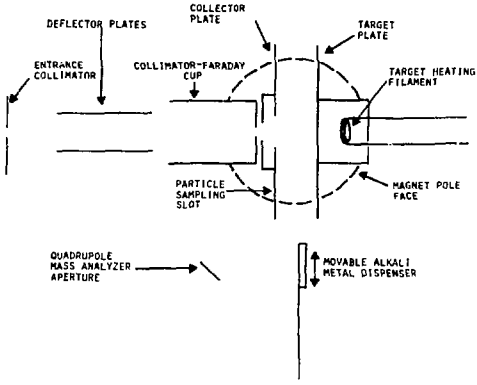
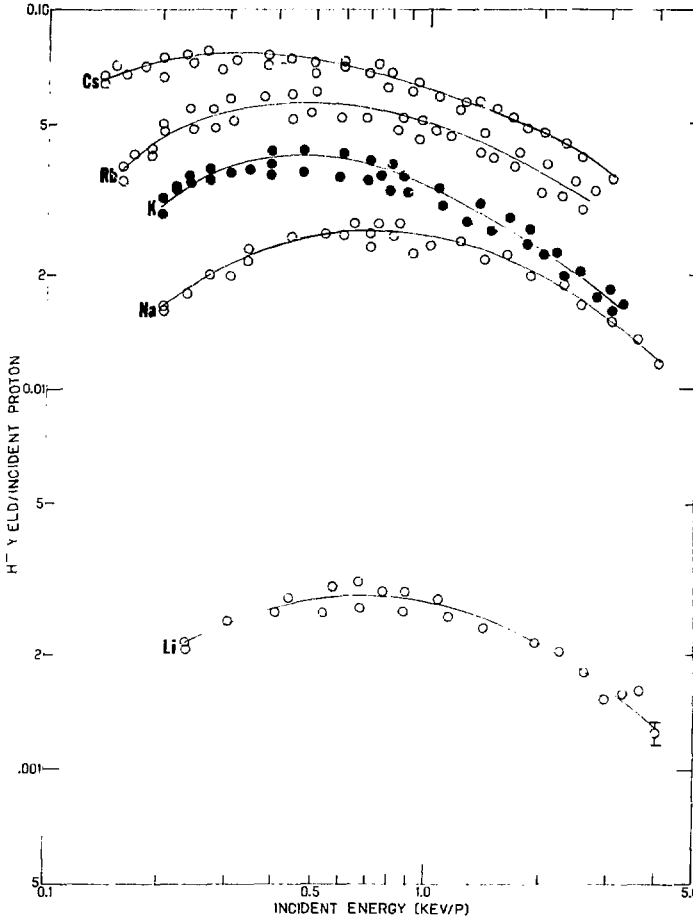

COLLECTOR PLATE
DEFLECTOR PLATES
TARGET PLATE
ENTRANCE COLLIMATOR
COLLIMATOR-FARADAY CUP
TARGET HEATING FILAMENT
PARTICLE SAMPLING SLOT
MAGNET POLE FACE
QUADRUPOLE MASS ANALYZER APERTURE
MOVABLE ALKALI METAL DISPENSER
XBL 779-2487

FIGURE 1



ABL 7910-12272

FIGURE 2

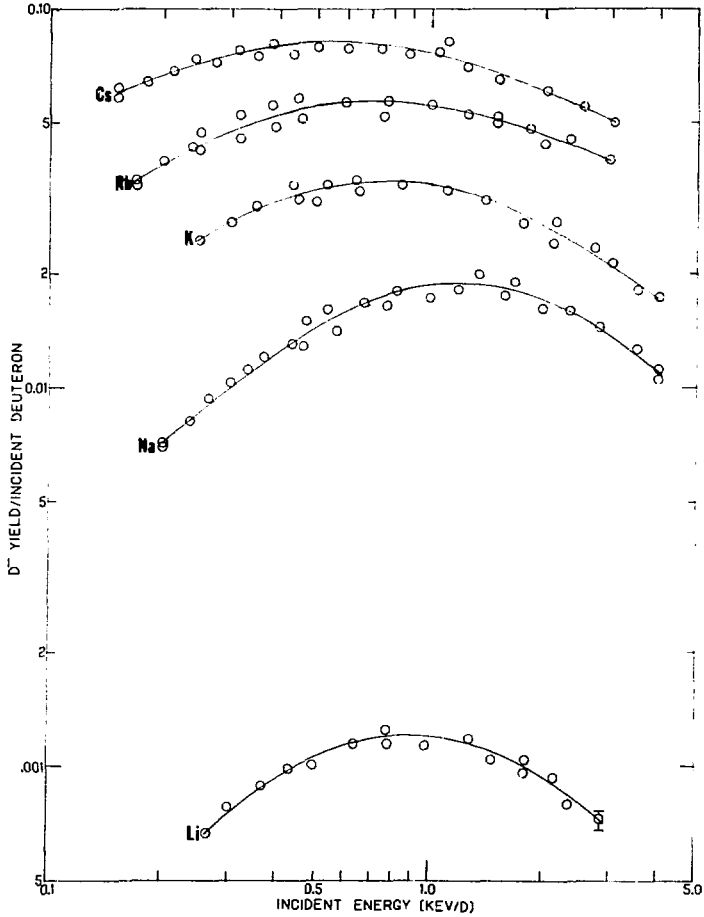


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FIGURE 3

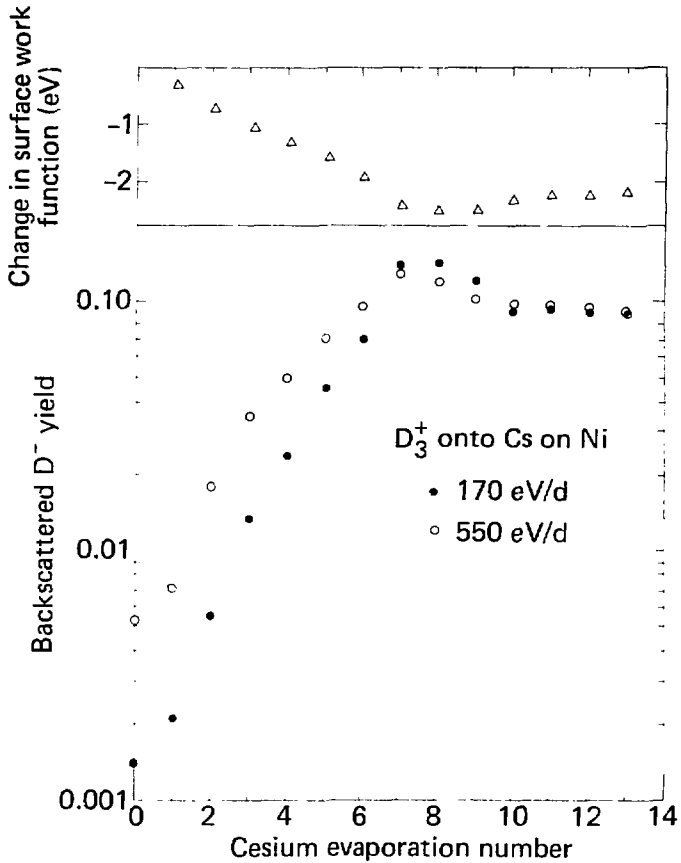
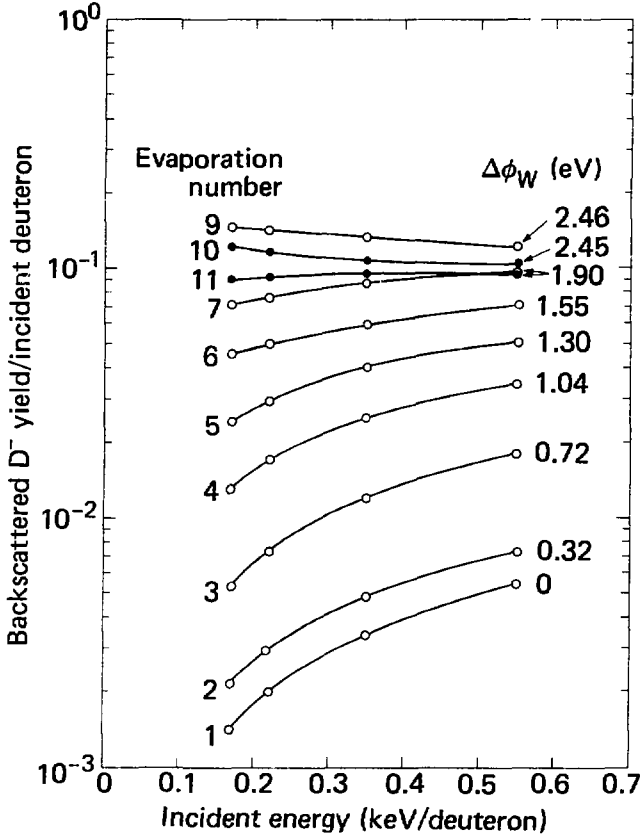

Change in surface work function (eV)
-1
-2
Backscattered D⁻ yield
0.10
0.01
0.001
D_3^+ onto Cs on Ni
• 170 eV/d
○ 550 eV/d
0
2
4
6
8
10
12
14
Cesium evaporation number

FIGURE 4



XBL 806-10361

FIGURE 5

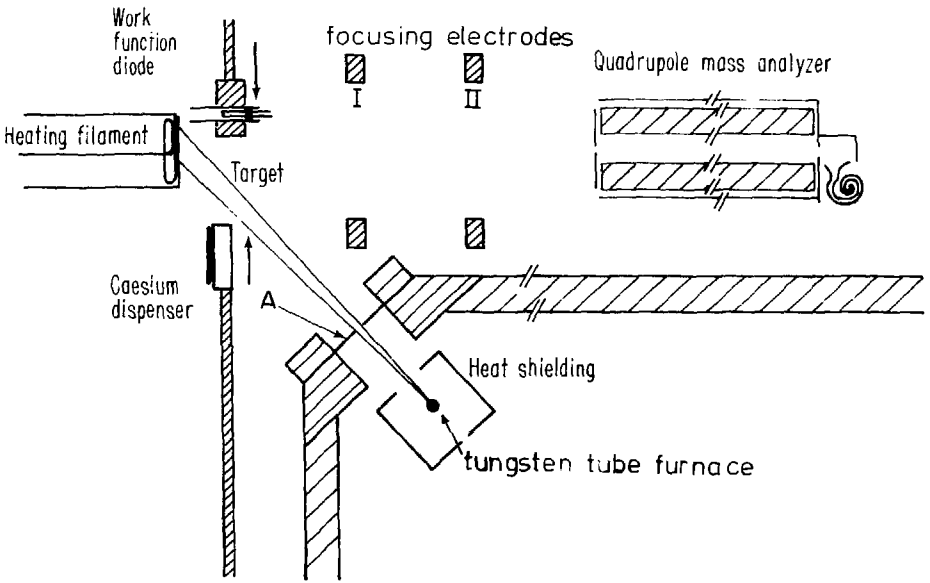


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FIGURE 6

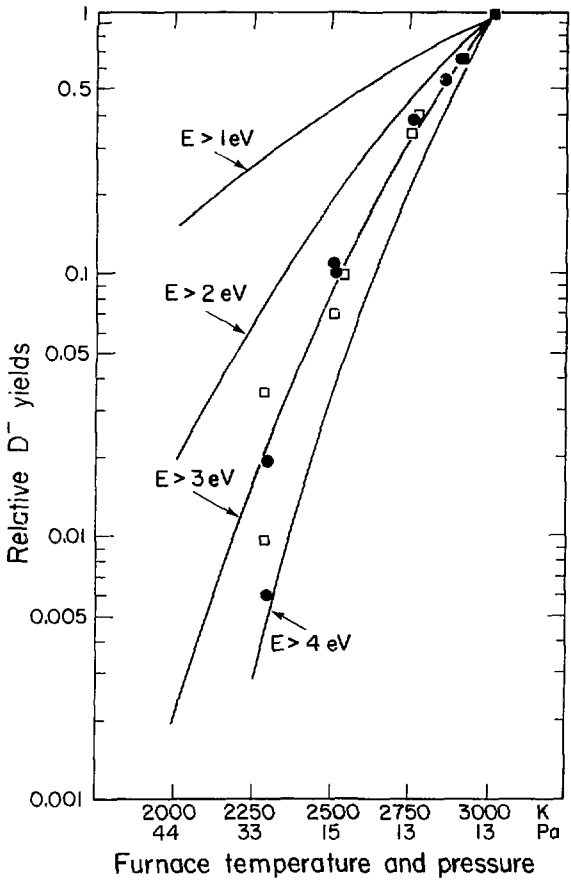

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FIGURE 7

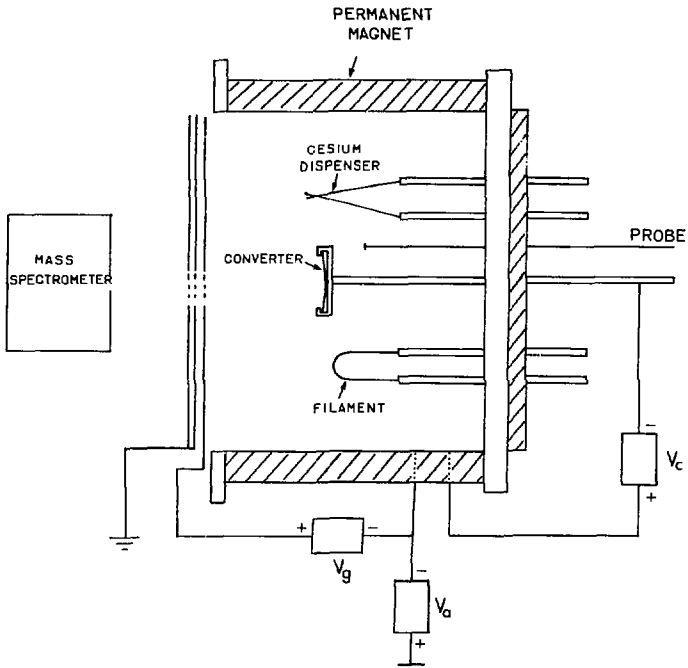

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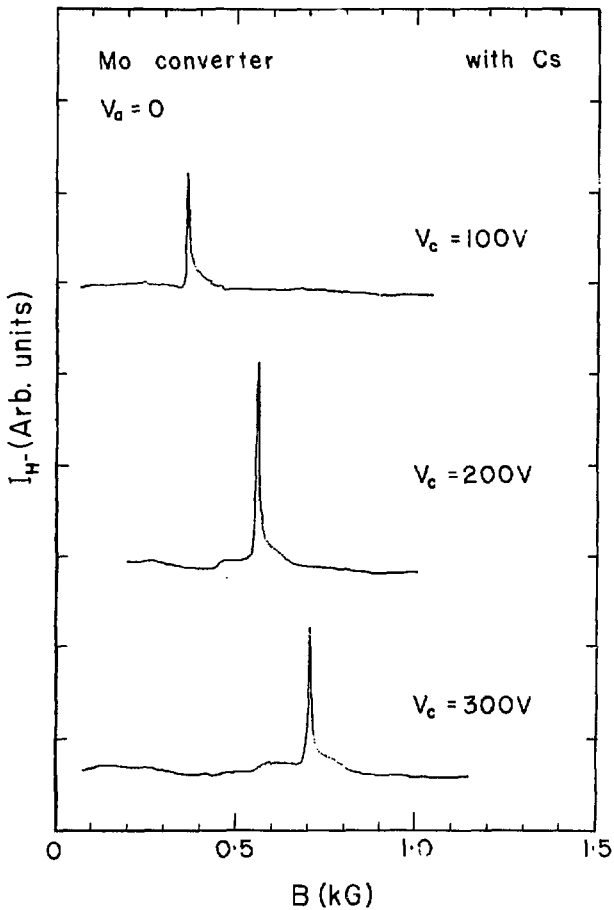
FIGURE 8



XBL 808-11140

FIGURE 9

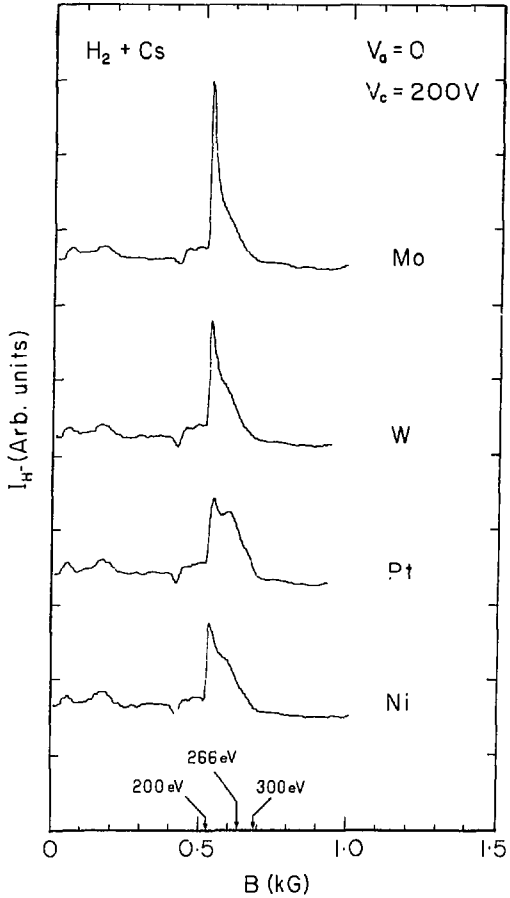


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FIGURE 10

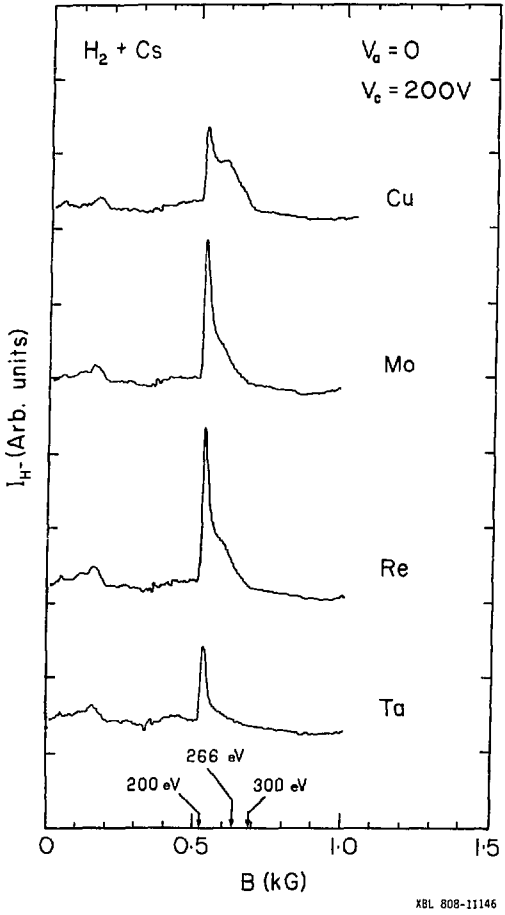
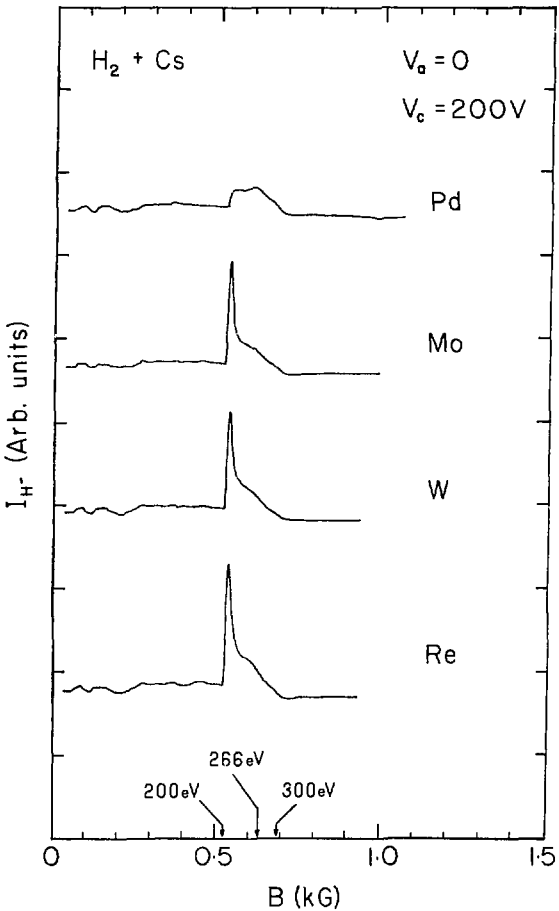

H2 + Cs
Vg = 0
Vc = 200V
Cu
Mo
Re
Ta
IH- (Arb. units)
266 eV
200 eV
300 eV
0
0·5
1·0
1·5
B (kG)
XBL 808-11146

FIGURE 11



XBL 808-11147

FIGURE 12