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Authors

Schlachter, A.S.
Morgan, T.J.

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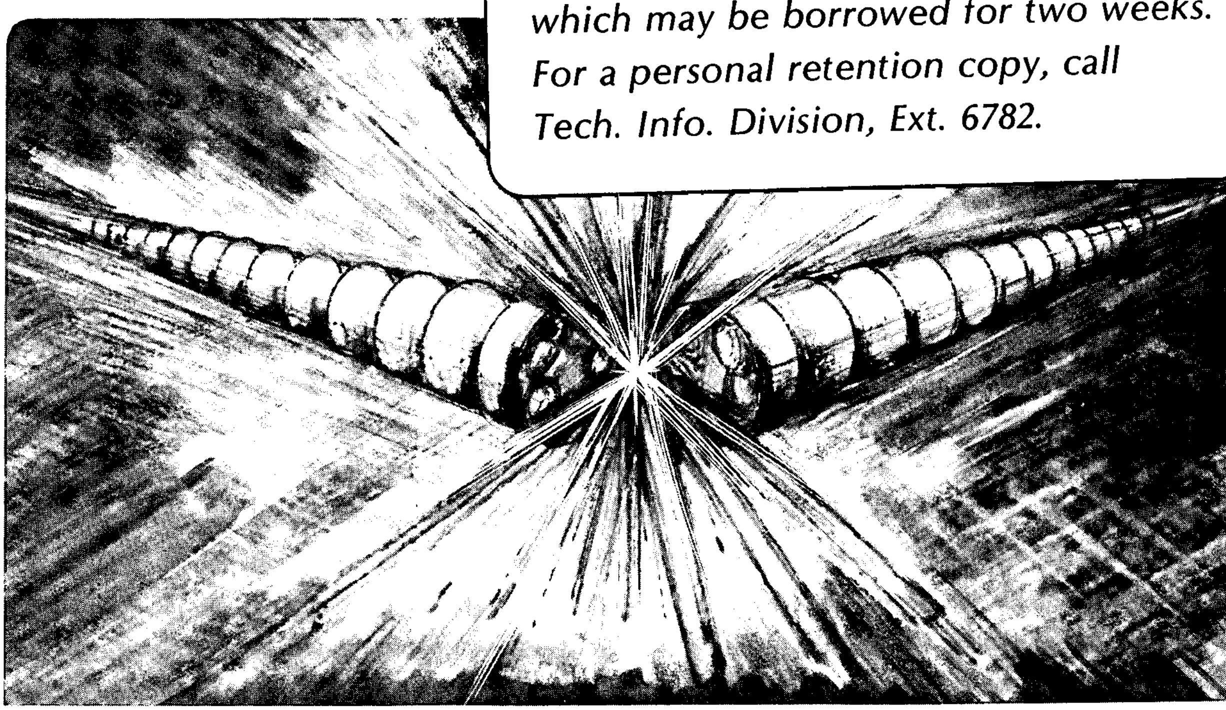

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FORMATION OF H^- BY CHARGE TRANSFER IN ALKALINE-EARTH VAPORS*

A. S. Schlachter+ and T. J. Morgan‡

+Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

‡Wesleyan University
Middletown, CT 06457

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FORMATION OF H^- BY CHARGE TRANSFER IN ALKALINE-EARTH VAPORS

A. S. Schlachter[+] and T. J. Morgan[‡]

[+] Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

[‡] Wesleyan University, Middletown, CT 06457

ABSTRACT

Progress on the study of H^- formation by charge transfer in alkaline-earth vapors is reported. The H^- equilibrium yield in strontium vapor reaches a maximum of 50% at an energy of 250 eV/amu, which is the highest H^- yield reported to date.

I. INTRODUCTION

Considerable progress has been made in the study of H^- formation by charge transfer in alkaline-earth vapors since the 1980 Brookhaven Symposium.[1] Olson[2] wrote at that time:

> ". . . we predict the heavier alkaline earths, and in particular Sr or Ba, will surpass the 35% maximum yield realized using Cs."

Measurements[3] have since confirmed that prediction, showing a maximum H^- equilibrium fraction of 50% for 250 eV/amu H in strontium vapor. The behavior of the cross sections[4] indicates that this large yield at low energies arises because the electron-detachment cross section σ_{-10} is small and the electron-attachment cross section σ_{0-1} is large in heavy alkaline-earth vapors.

The subject of H^- and D^- production by charge transfer in metal vapors was extensively reviewed at the 1980 Brookhaven Symposium.[5] At that time little information was available for alkaline-earth targets, and the review dealt primarily with alkali-vapor targets. During the past 3 years considerable progress has been made on H^- formation by charge transfer in alkaline-earth vapors. The present review discusses and summarizes the progress made during the past 3 years. We limit the discussion to cross sections and equilibrium yields, and assume that results for H and D projectiles are the same at the same velocities. Results are available for the energy range 0.15 to 100 keV/amu.

Figure 1 shows the equilibrium H^- yield, F_-^∞, for H in a variety of targets, to show the energy dependence of an alkaline-earth target (strontium vapor) by comparison with other targets.

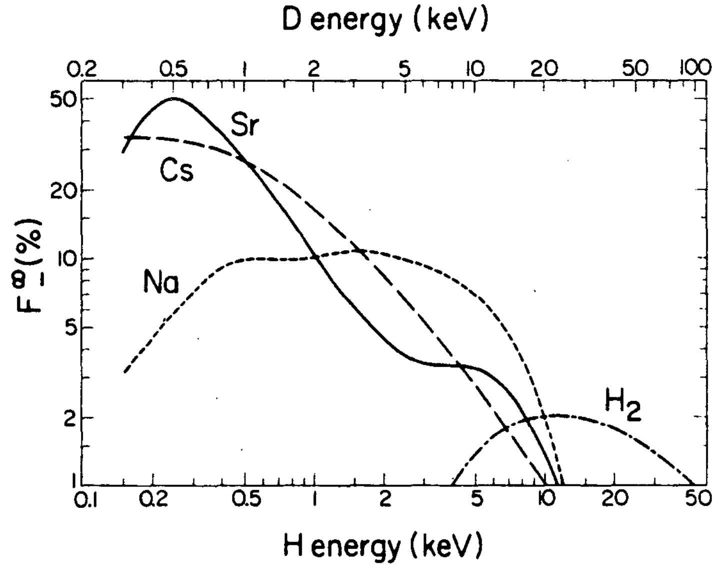
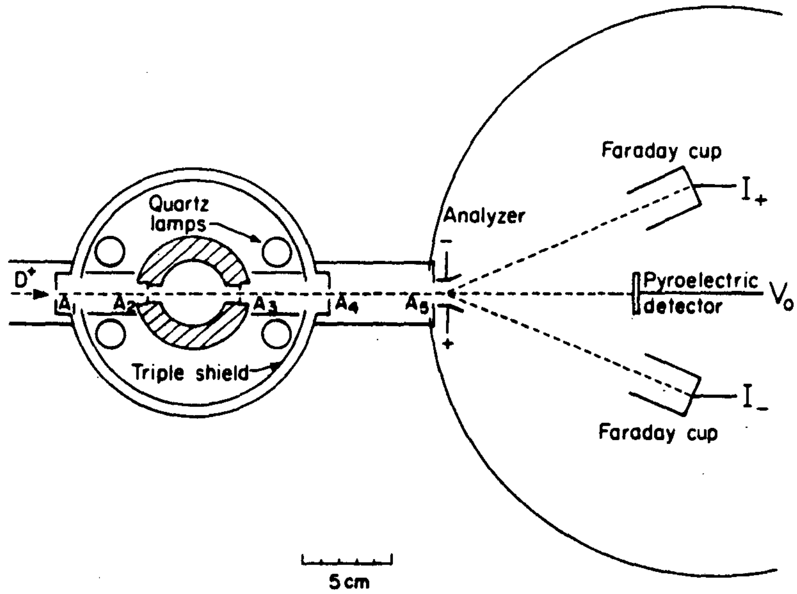


Fig. 1. Summary of equilibrium yields F_-^∞ for H^- formation in typical targets.

II. EXPERIMENTAL CONSIDERATIONS

Measurements reported here were made primarily by two groups, one at LBL (Lawrence Berkeley Laboratory), the other at Wesleyan University, over a period of several years.[6] A diagram of the apparatus used by the two groups[3,4] is shown in Fig. 2. Similar targets were employed by the two groups: a steel oven heated by electrical resistance or by quartz lamps, witn temperature measured by thermocouples, and vapor pressure inferred from the temperature. A heat-pipe target, employed for alkali vapors, is not suitable for use with alkaline earths[3] at the temperatures and pressures usual for charge-transfer measurements.

Two methods have been employed for the measurement of H^0 flux: the Wesleyan group used secondary-electron emission, while the LBL group used pyroelectric detection. Both groups used Faraday cups for the measurement of H^+ and H^- fluxes. Agreement is good between yields measured by the two groups.[3,7,8]



a)

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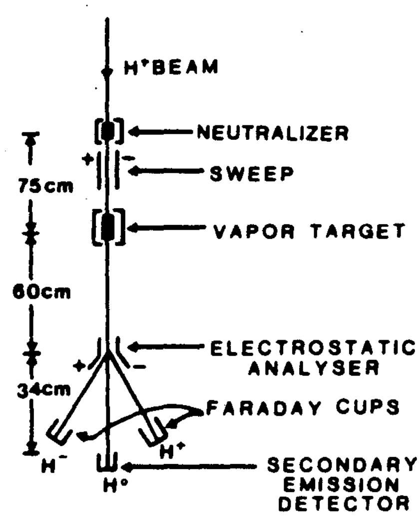

b)

Fig. 2. Schematic diagram of apparatus used by LBL (2a) and Wesleyan (2b) groups to measure charge-state fractions in alkaline-earth vapors.

Measurements of cross sections with an H^{0} beam incident were done by partial neutralization of an H^{+} beam in a gas neutralizer, followed by deflection of residual ions and quenching of H(2s) in a transverse electric field.

Typical data for charge-state fractions as a function of target thickness are shown in Fig. 3: 1500 eV/amu D^{+} incident on barium vapor.

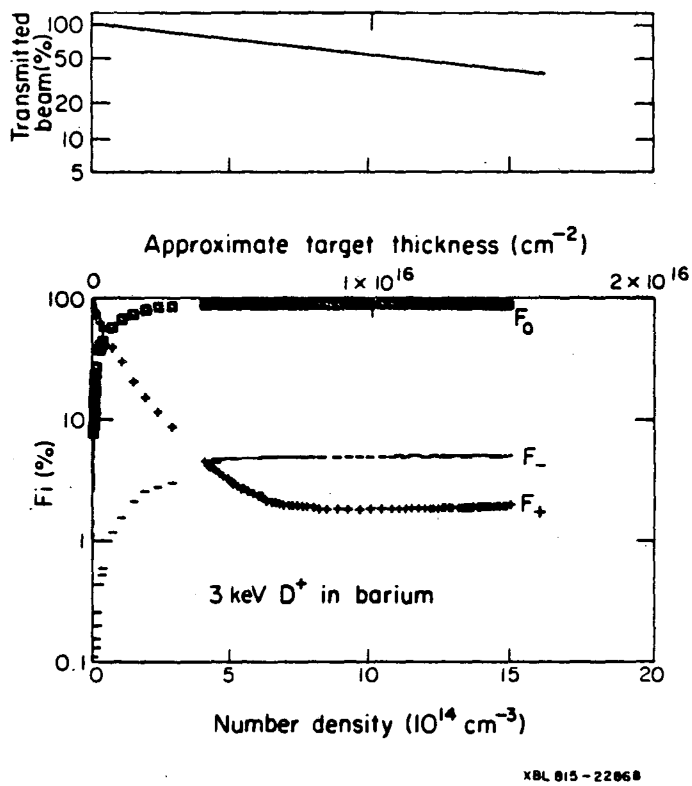

Fig. 3. Charge-state fractions Fi and total transmitted beam as a function of target number and line densities for 1500 eV/amu D^{+} incident on barium vapor.

III. THEORETICAL CONSIDERATIONS

Olson[2] and Liu[3] have provided most of the theoretical calculations for H^{-} formation in alkaline-earth vapors, as well as much of the impetus for the experimental measurements. They pointed out that the alkaline earths do not have a bound and stable negative ion. Electron detachment must therefore be by direct ionization

$$H^- + X \rightarrow H^0 + X + e^-$$

rather than charge transfer (X is an alkaline-earth atom). Olson and Liu used an ab initio molecular-interaction-energy calculation on the neutral and negative-ion CaH system to determine the lack of strong coupling between the negative-ion and neutral molecular states, and to thus predict a small cross section for electron detachment of H^- in Ca at low energies.

For the case of H^- formation by 2-electron capture by a proton in a single collision with a Mg atom, Olson and Liu[9] have employed a Landau-Zener calculation using ab initio potential-energy curves to obtain the cross section σ_{1-1}. The results are in good agreement with the experiment.[10]

IV. H^- EQUILIBRIUM YIELDS

The equilibrium H^- yield in an alkaline-earth vapor heavier than magnesium was first reported by the LBL group[8] in 1977. They measured F_-^∞ for 1.65 to 19.5 keV/amu D^+ in Sr vapor, and mentioned a feature of the energy dependence unlike that observed at low energies for alkali-vapor or gas targets: a plateau between 2.5 and 5 keV/amu and a rise in F_-^∞ for lower energies. The Wesleyan group[7] extended those measurements to several alkaline-earth vapors (Mg, Ca, Sr, Ba) in the energy range 1.25 to 100 keV/amu. They observed the same behavior in all 3 heavy alkaline-earth vapors, with F_-^∞ reaching 10 %, and their results were in excellent agreement with the previous LBL result in Sr. Various hypothesis were advanced to explain the rise in F_-^∞ at low energies.

Measurements were extended to lower energies by the LBL group in 1982: results were published[3] for F_-^∞ in alkaline-earth vapors in the energy range 150 eV/amu to 1.5 keV/amu. The lowest energy was sufficient to observe a maximum in F_-^∞ in all alkaline-earth vapors except Ba; the highest yield observed was 50 % in Sr vapor at 250 eV/amu. D^+ equilibrium yields were also measured, and were found to be negligible (<1 %) at energies below 0.75 keV/amu. Results are in excellent agreement between the LBL and Wesleyan groups at energies where there is overlap. Results for F_-^∞ in Mg, Ca, Sr, and Ba vapors[3,7,8,11] are shown in Figs. 4-7. A composite result is shown in Fig. 8.

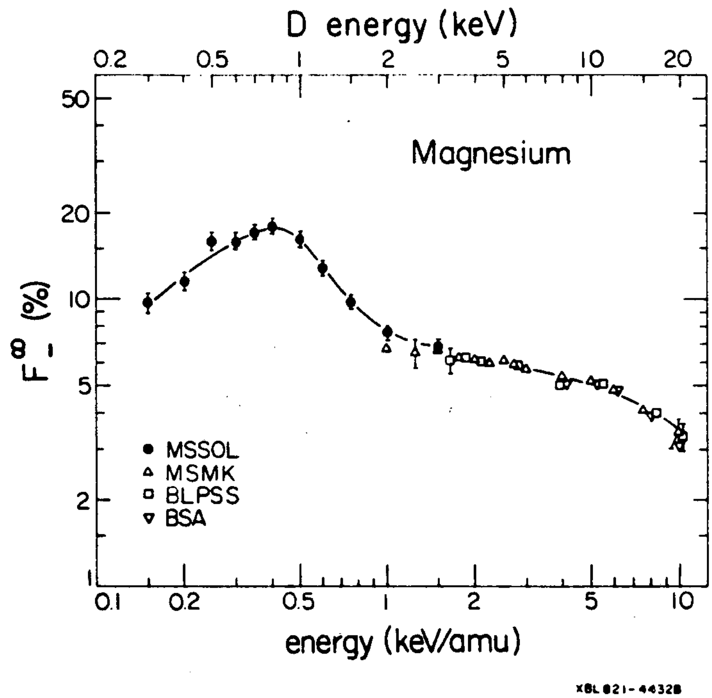

Fig. 4. Equilibrium yield F_-^∞ for H^- formation in magnesium vapor.

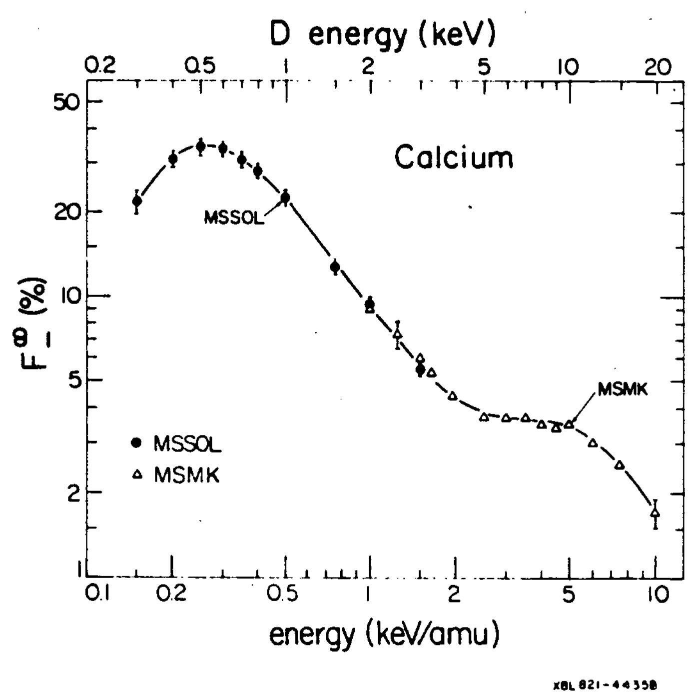

Fig. 5. Equilibrium yield F_-^∞ for H^- formation in calcium vapor.

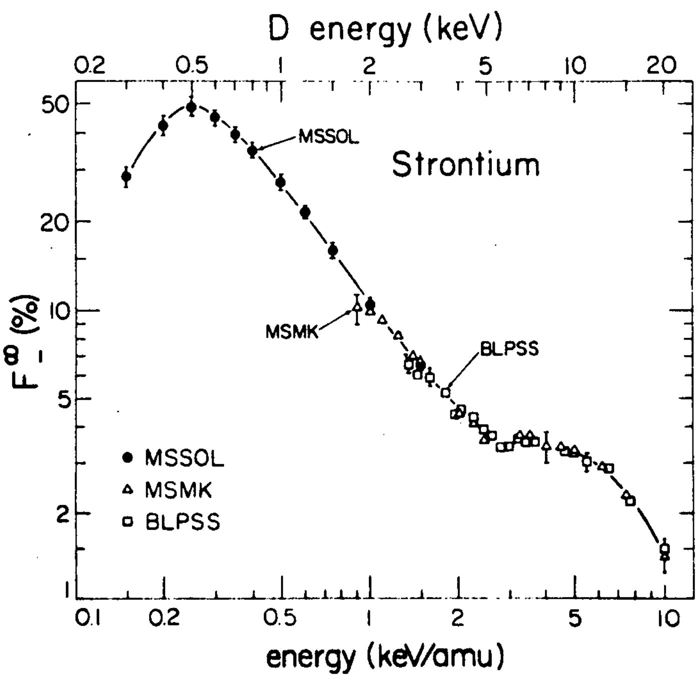

Fig. 6. Equilibrium yield F_-^∞ for H^- formation in strontium vapor.

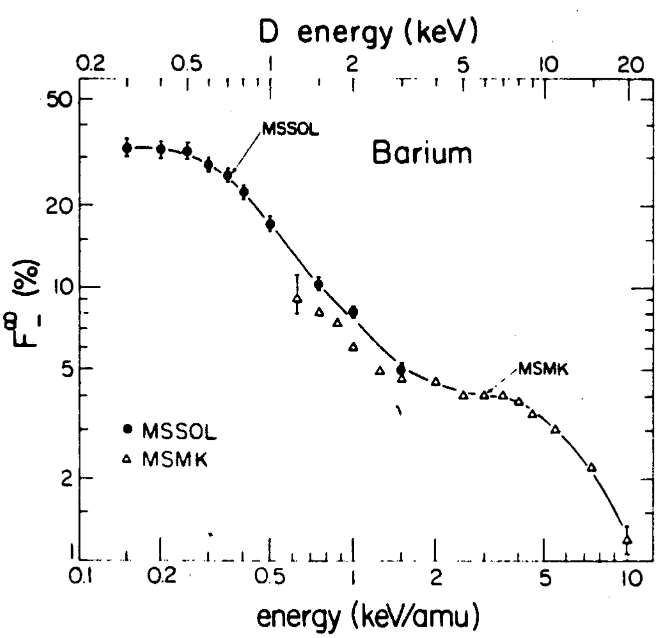

Fig. 7. Equilibrium yield F_-^∞ for H^- formation in barium vapor.

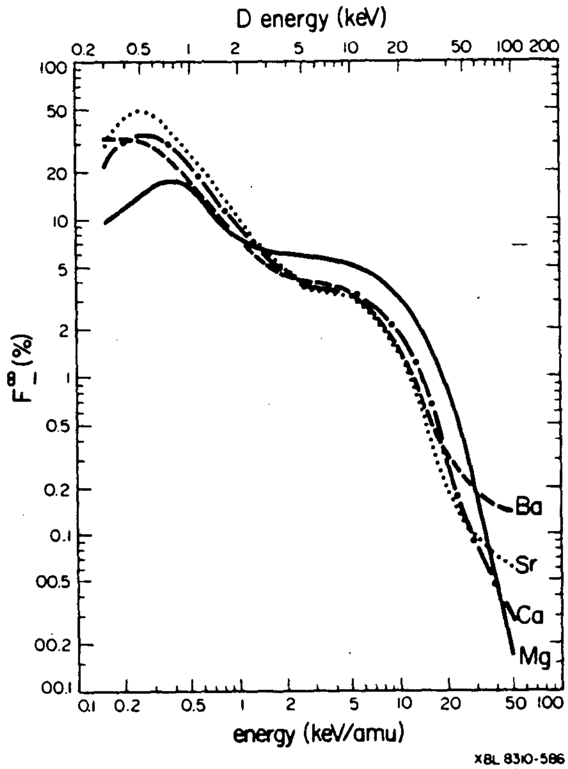

Fig. 8 Summary of equilibrium yields F_-^∞ for H^- formation in alkaline-earth vapors.

V. CROSS SECTIONS

Electron-attachment cross sections, σ_{0-1}, for H^0 in Ca and Sr vapor targets have recently been published[4] by the Wesleyan group, for the energy range 1-70 keV/amu. These cross sections have been used with measured H^- equilibrium yields to infer the electron-loss cross section, σ_{-10}, by use of the formula

$$\sigma_{-10} = \sigma_{0-1} \left[\frac{1}{F_-^\infty} - 1\right]$$

which is true at low energies (H^+ must be small in a thick target and 2-electron transfer processes must be negligible). A more complicated expression is used at higher energies, where those conditions are not met. Results for measurements[4] of the electron-attachment cross section σ_{0-1} in Ca and Sr vapors are shown in Figs. 9 and 10. Figure 11 shows the electron-detachment cross section σ_{-10} inferred from measurements of σ_{0-1} and F_-^∞; this cross section has a

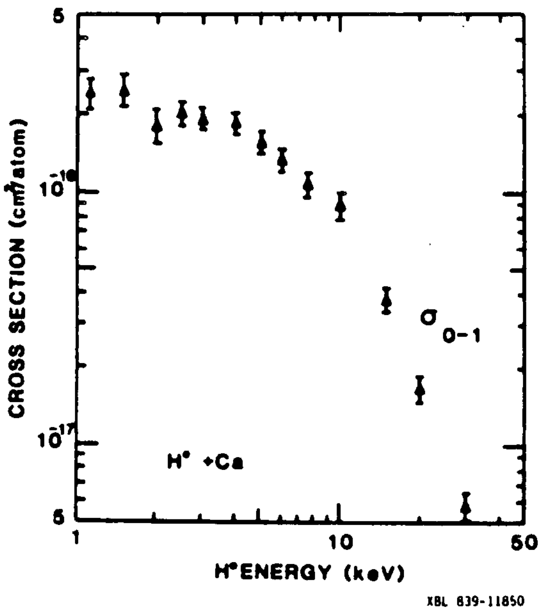

Fig. 9. Electron-attachment cross section σ_{0-1} for collisions of H^0 with calcium vapor.

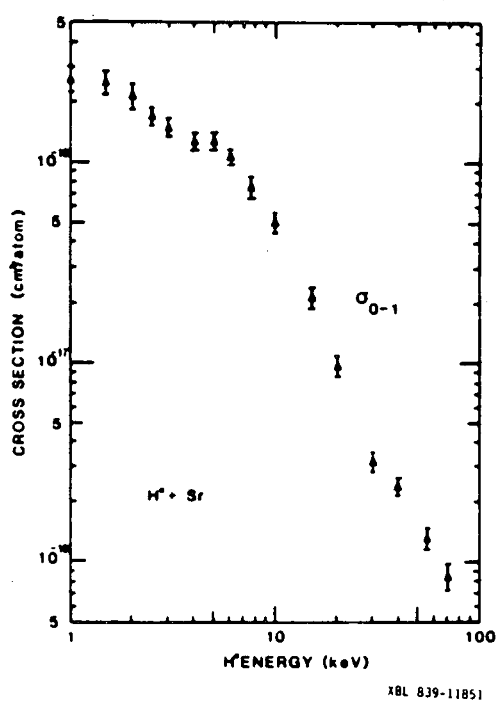

Fig. 10. Electron-attachment cross section σ_{0-1} for collisions of H^0 with strontium vapor.

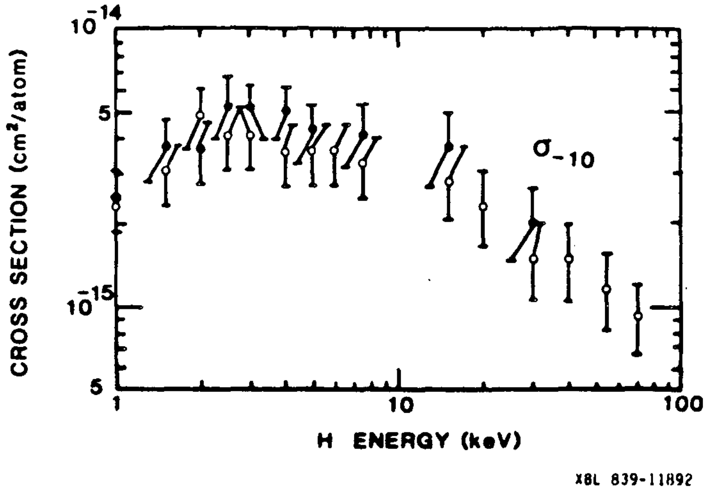

Fig. 11. Electron-detachment cross section σ_{-10} for collisions of H^- with calcium (●) and strontium (○) vapors, deduced from measured σ_{0-1} and F_-^∞.

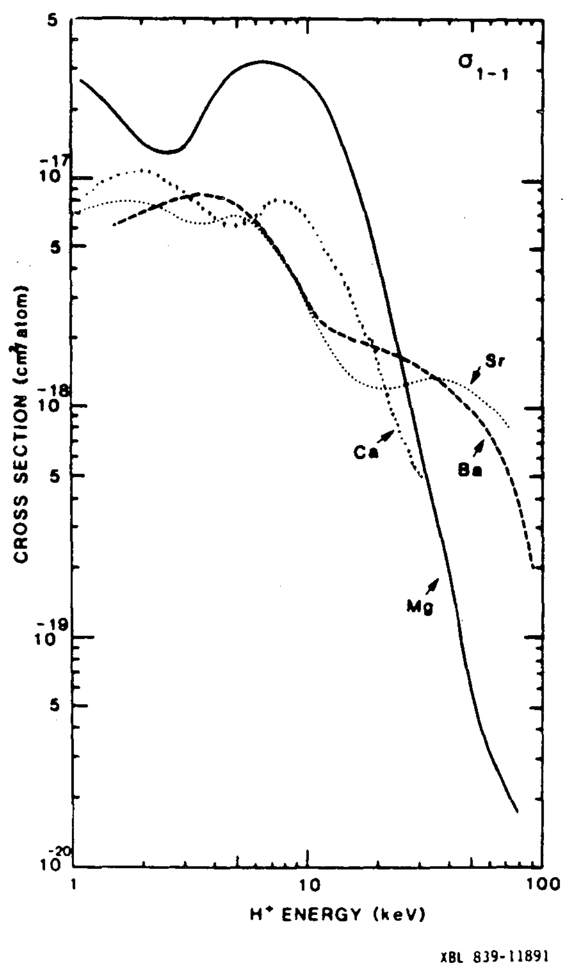

Fig. 12. Double-electron-capture cross section σ_{1-1} for collisions of H^+ with alkaline-earth-vapor targets.

maximum around 2.5 keV/amu, and decreases with decreasing energy for lower energies.

The Wesleyan group has also studied H^- formation by 2-electron capture in a single collision ($H^+ \rightarrow H^-$). Figure 12 shows a summary[4] of their results for alkaline-earth targets. Molecular-curve-crossing effects are important in a Mg-vapor target at low energies.

One measurement of a differential cross section has been reported[12] for hydrogen ions in an alkaline-earth target: $H^+ \rightarrow H^0$, $H^+ \rightarrow H^-$, and $H^0 \rightarrow H^-$ for 0.5 to 5 keV projectiles in Mg vapor. Interference effects are observed in the 2-electron-transfer case.

CONCLUSION

Recent measurements of H^- formation by charge transfer of H^+ in alkaline-earth-vapor targets are reasonably comprehensive; quantitative agreement is found between experimental results of different groups, and there is qualitative agreement between experiment and theory. Heavy alakaline-earth-vapor targets are the most effective media for H^- production by charge transfer, useful for applications in which low-energy beams are appropriate. Cross sections for some charge-transfer processes have been calculated and/or measured; more work is needed, especially for electron attachment and detachment at energies below 1 keV/amu.

ACKNOWLEDGMENTS

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720