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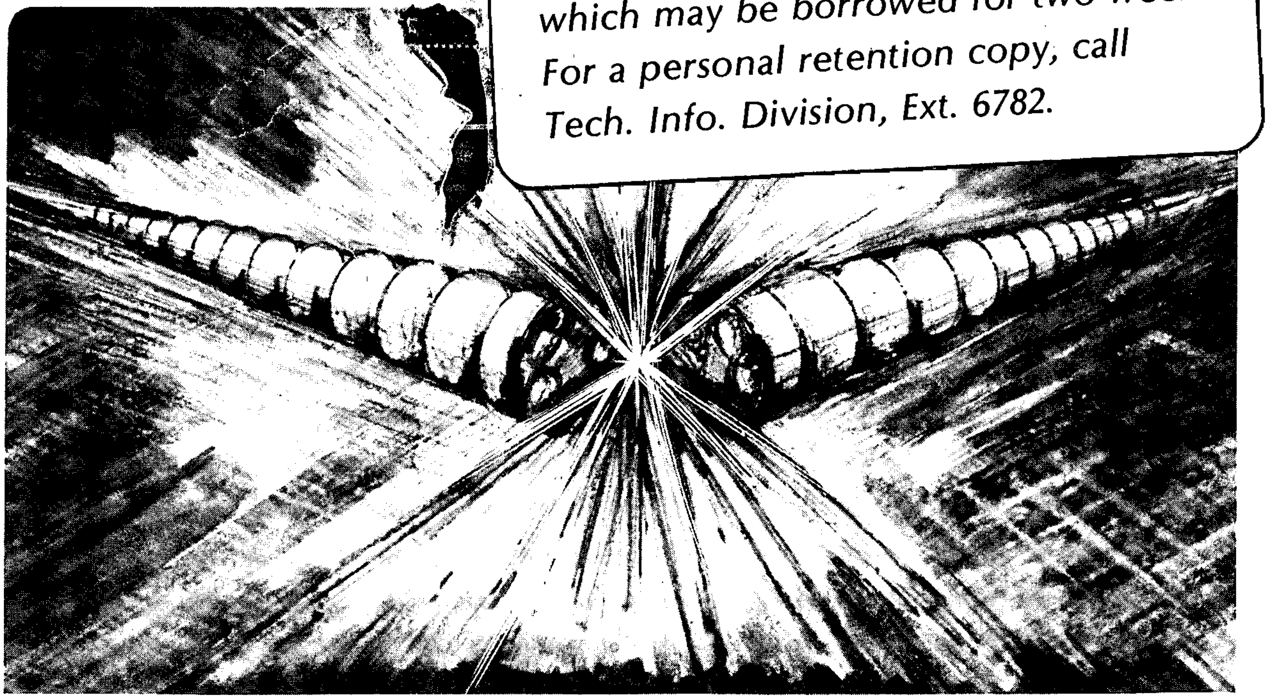

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LBL-16833 REV

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

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

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ABSTRACT

Progress since the last symposium on the study of H$^-$ formation by charge transfer in alkaline-earth vapors is reported. High yields are obtained at low energies, in agreement with theoretical predictions.

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.

Formation of intense beams of D$^-$ by charge transfer has been considered as a means of producing energetic neutral beams of D^0 for heating fusion plasmas. It is not an active candidate in the USA at present because it is considered too complex for fusion applications and because surface and volume production of D^- seem capable of furnishing beams for fusion applications.

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.

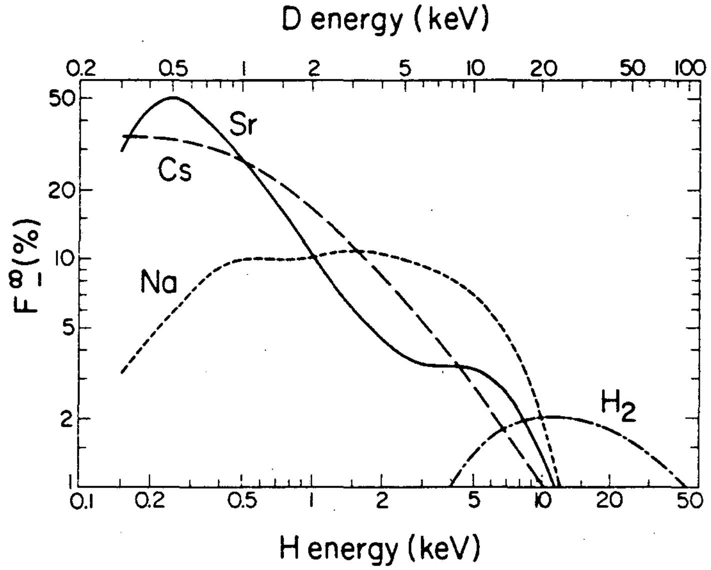
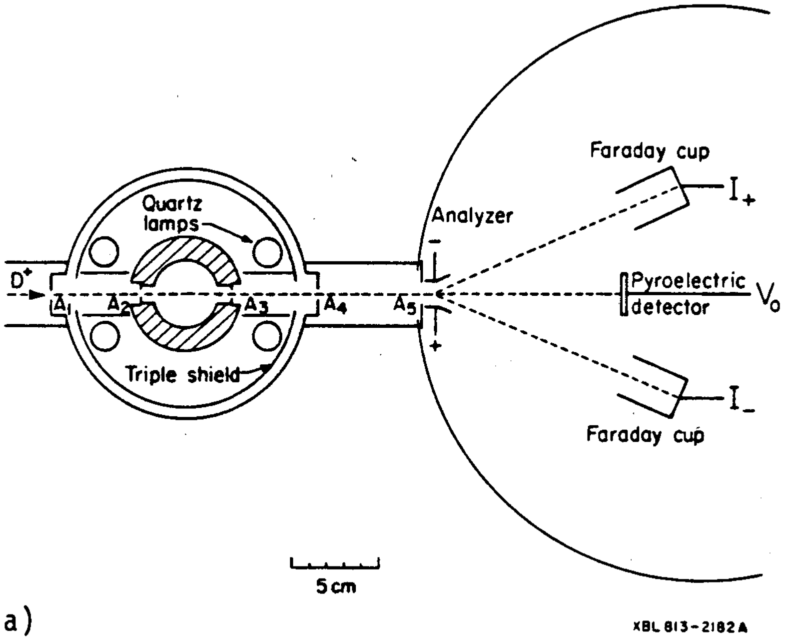


Fig. 1. Summary of equilibrium yields F_-^∞ for H^- formation in typical targets.

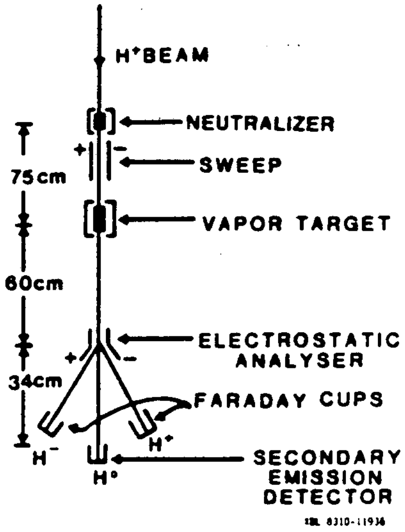
EXPERIMENTAL CONSIDERATIONS

Measurements reported here were made primarily by experimenters at LBL (Lawrence Berkeley Laboratory) and at Wesleyan University over a period of several years.[6] A diagram of the apparatus used[3,4] is shown in Fig. 2. Similar targets were employed: a steel oven heated by electrical resistance or by quartz lamps, with 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 experimenters at LBL used pyroelectric detection. Faraday cups were used for the measurement of H^+ and H^- fluxes. Agreement is good between yields measured in the various experiments.[3,7,8]



a)



b)

Fig. 2. Schematic diagram of apparatus used by McFarland et al.[3] at LBL (2a) and by Mayo et al.[4] at Wesleyan (2b) 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, from measurements by McFarland et al.[3]

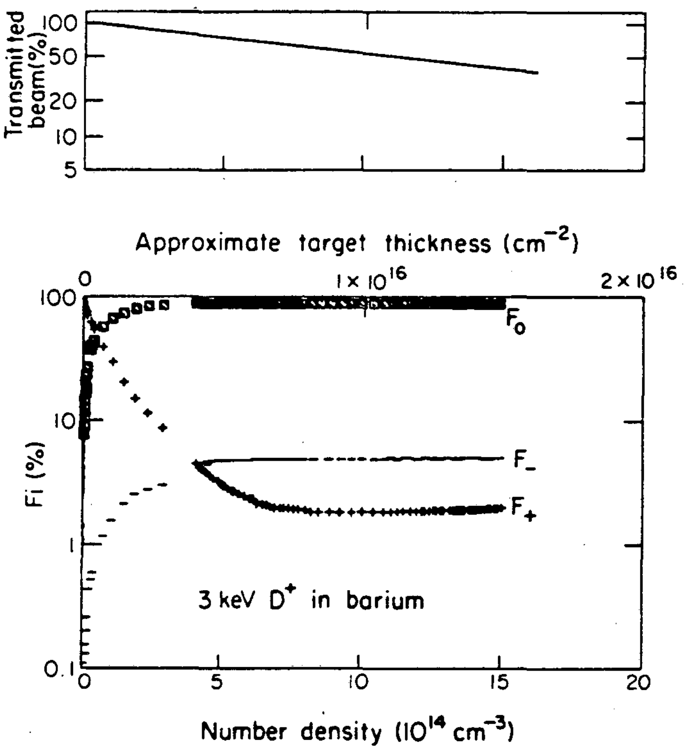


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Fig. 3. Charge-state fractions Fi and total transmitted beam as a function of target number and line densities for 1500 eV/amu D^+ incident on barium vapor, from measurements by McFarland et al.[3]

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

$$H^- + X \rightarrow H^0 + X + e^- \qquad (1)$$

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]

H^- EQUILIBRIUM YIELDS

The equilibrium H^- yield in an alkaline-earth vapor heavier than magnesium was first reported by Berkner et al.[8] in 1977. They measured F_-^∞ for 1.65 to 19.5 keV/amu D^+ in Sr vapor, and noted 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. Morgan et al.[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 McFarland et al. 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 all measurements 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.

Scattering in the target can limit the usefulness of charge transfer in metal vapors as a means of producing H^- beams. Note in Fig. 3 the reduction in total transmitted beam as target thicnkess is increased; this result, of course, is specific to the geometry of the target.

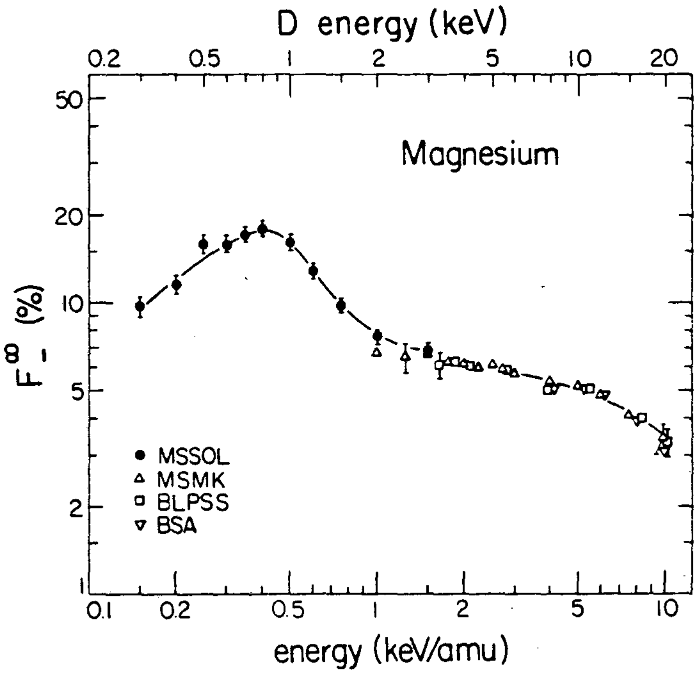

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Fig. 4. Equilibrium yield F_-^∞ for H^- formation in magnesium vapor.

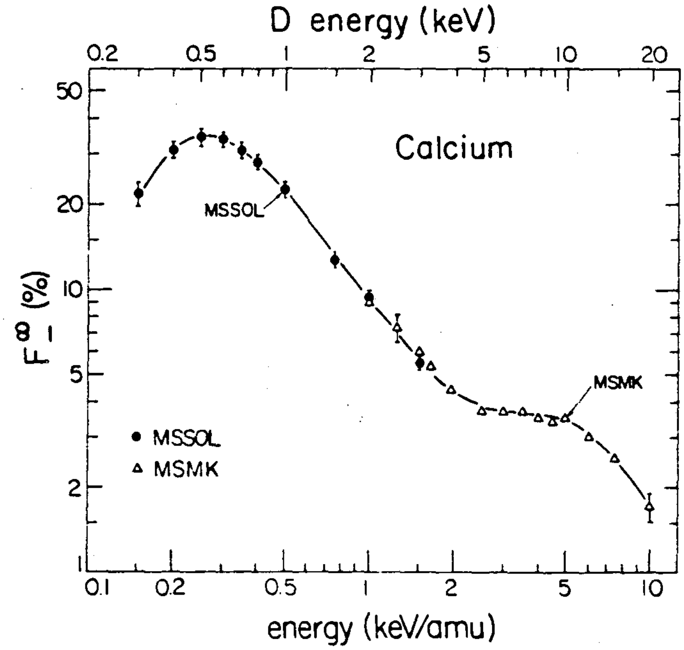

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Fig. 5. Equilibrium yield F_-^∞ for H^- formation in calcium vapor.

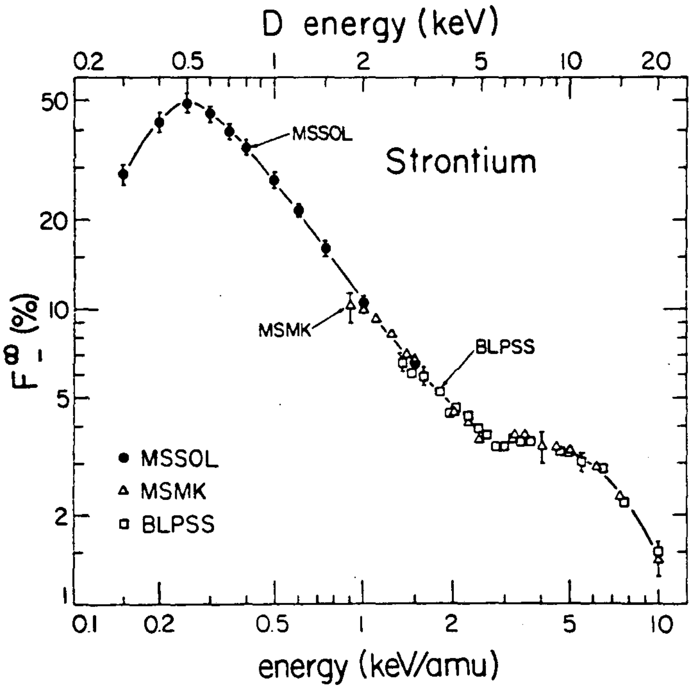

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Fig. 6. Equilibrium yield F_{-}^{∞} for H^- formation in strontium vapor.

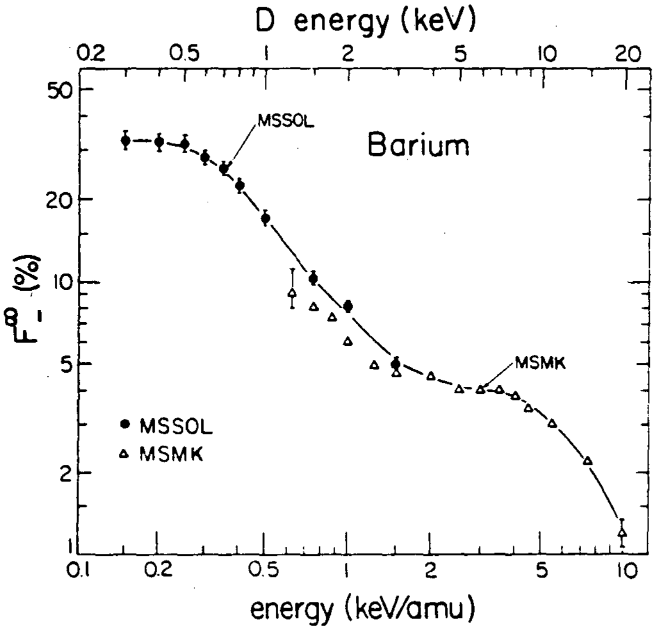

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Fig. 7. Equilibrium yield F_{-}^{∞} for H^- formation in barium vapor.

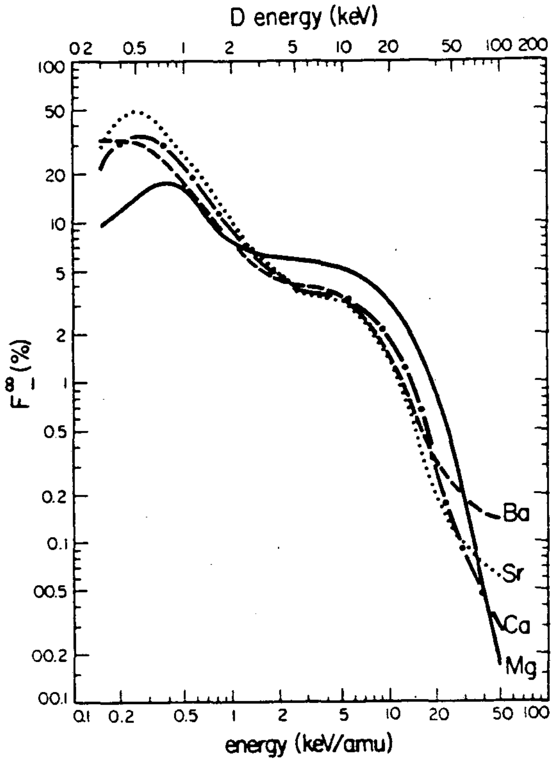

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Fig. 8 Summary of equilibrium yields F_-^∞ for H^- formation in alkaline-earth vapors.

CROSS SECTIONS

Electron-attachment cross sections, σ_{0-1} for H^0 in Ca and Sr vapor targets have recently been published[4] by Mayo et al. 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

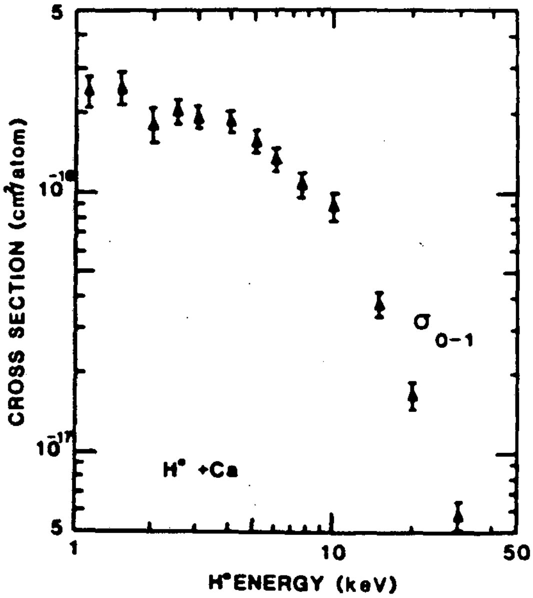

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Fig. 9. Electron-attachment cross section σ_{0-1} for collisions of H^0 with calcium vapor.

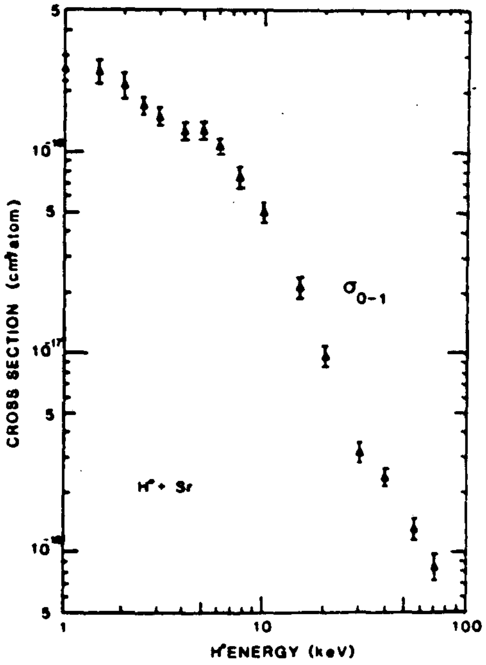

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Fig. 10. Electron-attachment cross section σ_{0-1} for collisions of H^0 with strontium vapor.

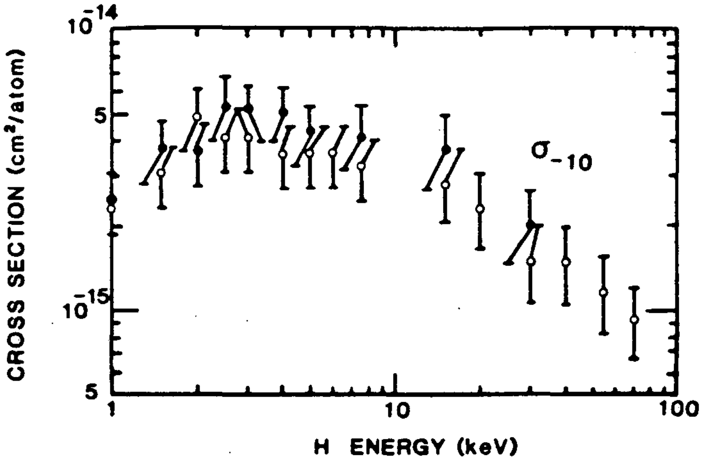

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Fig. 11. Electron-detachment cross section σ_{-10} for collisions of H^- with calcium (●) and strontium (○) vapors, deduced from measured σ_{0-1} and F_{-}^{∞}.

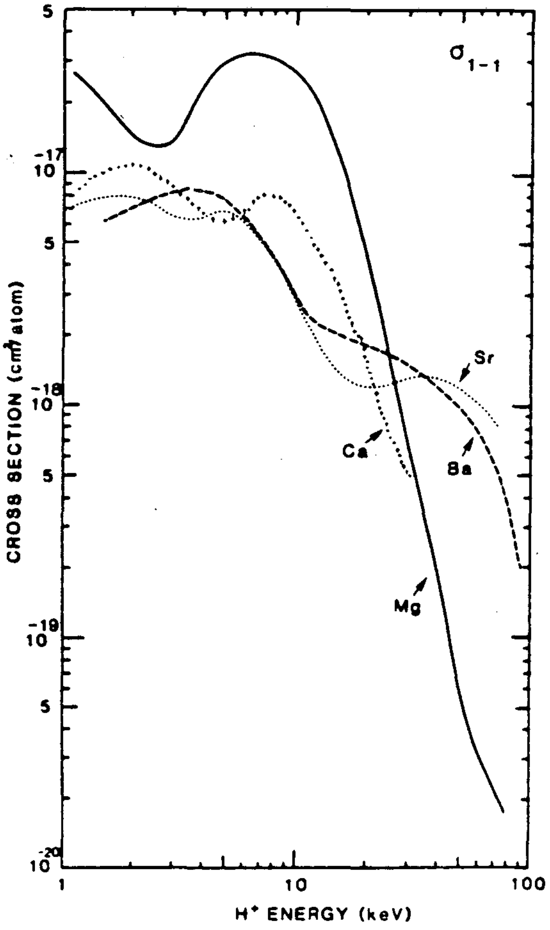

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Fig. 12. Double-electron-capture cross section σ_{1-1} for collisions of H^+ with alkaline-earth-vapor targets.

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 ($H^+ > H^-$). 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^+ H^0, H^+ H^-, and H^0 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 results measured by different experimenters, and there is qualitative agreement between experiment and theory. Heavy alkaline-earth-vapor targets are the most effective media for H^- production by charge transfer, although their usefulness is limited by scattering of a low-energy beam in the target. 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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Symbols in Figures:

MSSOL = McFarland et al.[3]
MSMK = Morgan et al.[7]
BLPSS = Berkner et al.[8]
BSA = Baragiola et al.[11]

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