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PRODUCTION AND DESTRUCTION OF D^- BY CHARGE TRANSFER IN METAL VAPORS

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Experimental studies of D^- collisions are of interest for basic physics, where experimental results can be used to test theoretical models for charge transfer, and for applications to ion sources for accelerators and for heating magnetically confined plasmas of interest for fusion. The high D^- yield from charge transfer in a thick cesium-vapor target is consistent with recent cross-section calculations and measurements. Recent theoretical calculations of cross sections in thick alkaline-earth-vapor targets, leading to prediction of a large D^- yield at low energy, have been partially confirmed in recent measurements, in which a D^- yield of 50% was observed at a D energy of 500 eV.

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I. Introduction

Experimental studies of electron capture and loss in collisions involving D^- ions are of considerable interest for improving our understanding of basic physics, where results of experimental measurements can be used to test theoretical models. In addition, there are important practical applications for intense D^- beams: (1) production of fast D° beams[1-3] for heating magnetically confined plasmas of fusion interest; (2) production of D^- beams for injection into accelerators; (3) conversion of polarized D° to D^- in certain[4] polarized ion sources; and (4) conversion of slow D° to D^- for energy analysis[5] of atoms escaping from confined plasmas. The first application mentioned, heating confined plasmas, is particularly important as fusion plasmas increase in radius, density, and temperature, especially for mirror machines, for which very fast D° beams might be required: the efficiency[1,2] with which D^- can be neutralized exceeds 60% in H_2 (and is still higher in a plasma) even to energies greater than 1 MeV.

Metal vapors are particularly interesting charge-transfer media for D^- production, since D^- production in a metal vapor can be more than an order of magnitude greater than in permanent gases. Collisions of D^- in metal vapors have been reviewed[6,7] in 1977 and in 1980. Although there are still discrepancies between various measurements, much progress was made in the period between the two reviews; we now find more consistent cross sections and yields, and more favorable agreement of experimental and theoretical results. In addition to the 1980 review of D^- production in metal vapors, an extensive discussion of D^- production can be found in a recent article[8] on D^- production by charge transfer in cesium, rubidium, and sodium vapor targets. In the present article I present a comprehensive discussion of those targets which have been studied most extensively and for which new experimental and theoretical results are available, i.e. mainly for cesium and alkaline-earth targets. The reader is referred to my 1980 review[7] for cross sections and yields in other metal vapors.

It is necessary to define two related quantities[8] pertaining to thick-target yields: the equilibrium yield, F_i^{∞}, and the optimum conversion efficiency, $\eta_i^{opt.}$. A highly schematic experiment is shown in Fig. 1. A beam of intensity I_{inc} is incident

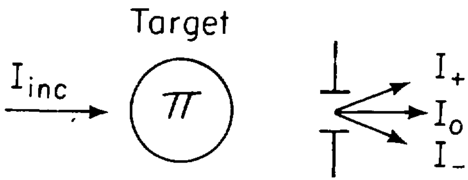

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Fig.1 Schematic diagram of experiment to measure charge-state fractions. A flux I_{inc} is incident on a target of thickness π. Fluxes I_+, I_o, and I_- in charge states +, o, and - leave the target.

on a vapor target of thickness π (target thickness is the integral of target number density over the target length). The beam leaving the target is assumed to have only three charge states (positive, neutral, and negative), the intensities of which are $I_+(\pi)$, $I_o(\pi)$, and $I_-(\tau)$ respectively. The fraction of the total beam leaving the target in charge state i is $F_i(\tau)$:

$$F_i(\tau) = \frac{I_i(\tau)}{\Sigma I_j(\tau)} . \tag{1}$$

Since i and j are +, o, and - in the present case:

$$\Sigma F_i(\tau) = 1. \tag{2}$$

The equilibrium fraction or equilibrium yield in charge state i is:

$$F_i^{\infty} = \lim_{\tau \to \infty} F_i(\tau). \tag{3}$$

F_i^{∞} is independent of target geometry and of target thickness increases beyond a minimum thickness.

The conversion efficiency is:

$$\eta_i(\tau) = \frac{I_i(\tau)}{I_{inc}} . \tag{4}$$

Owing to scattering losses in the target,

$$\Sigma I_i < I_{inc} \tag{5}$$

and

$$\lim_{\tau \to \infty} \eta_i(\tau) = 0 . \tag{6}$$

For a given geometry, there is some optimum value of τ such that $\eta_i(\tau)$ exhibits a maximum, η_i^{opt} . The value of η_i^{opt} depends on target geometry and target thickness. Furthermore,

$$\eta_i^{opt} \leq F_i^{\infty}. \qquad (7)$$

Throughout this paper I show all results as if the experiments had been done with deuterium ions or atoms. Over the present energy range, cross sections and yields measured with hydrogen and deuterium projectiles at the same velocity have been found[9,10] to be the same; therefore results for H projectiles will be treated as if the experiment had been performed with D, but at twice the energy. This is not necessarily true for molecular ions nor for differential scattering, neither of which are discussed in the present paper.

II. Alkali-vapor targets

Cesium-vapor has been the most thoroughly studied charge-transfer medium for D^- production. The situation[6] as of 1977 is shown in Fig. 2, in which η_i^{opt} and F_-^{∞} are shown as a function of D energy, along with D^- yields calculated from previously measured and previously calculated cross sections. The disagreement between various experiments and between the directly measured yield and the yield calculated from experimental and theoretical cross sections is clear.

An apparatus used by the LBL group[8] to study collisions in alkali-vapors is shown in Fig. 3. A charge-state-selected beam passed through a recirculating alkali-vapor target of the heat-pipe type. The beam leaving the target was charge-state analyzed

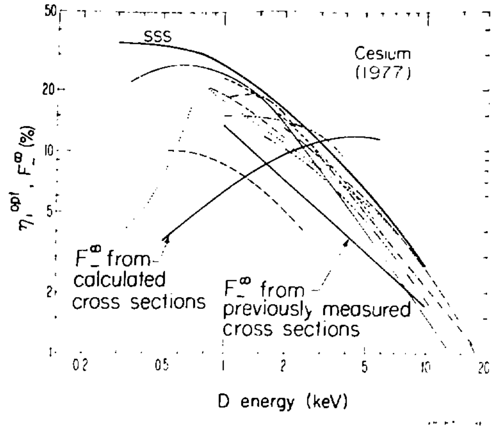


Fig.2 Equilibrium yield F_-^{∞} and optimum conversion efficiency η_-^{opt} for D in cesium vapor: situation as of 1977. Also shown is F_-^{∞} calculated using Eq. 8 for cross sections measured and calculated as of 1977. Identification of the curves can be found in Ref. 6.

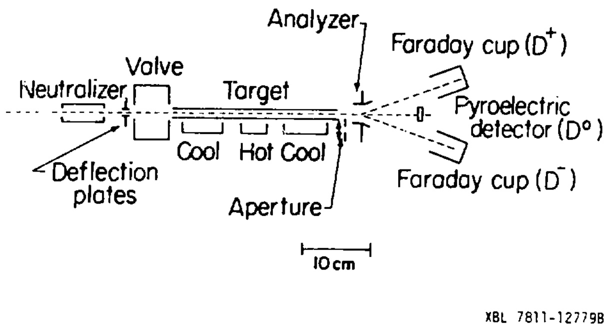


Fig.3 Schematic diagram of the apparatus[8] used by the LBL group to measure charge-state fractions in alkali-vapor targets. The dashed arrow at the left indicates the incident beam. The heat-pipe target and the collimation and scattering geometry are discussed in Ref. 8.

in a transverse electric field. The D^+ and D^- beams were measured with magnetically suppressed Faraday cups, while the D° beam was measured with a pyroelectric detector. Appropriate collimation[8] was used, for cross-section and for equilibrium-yield measurements.

Experimental results[8] for two cases are shown in Figs. 4 and 5. Figure 4 shows charge-state fractions for 1-keV D^+ incident on

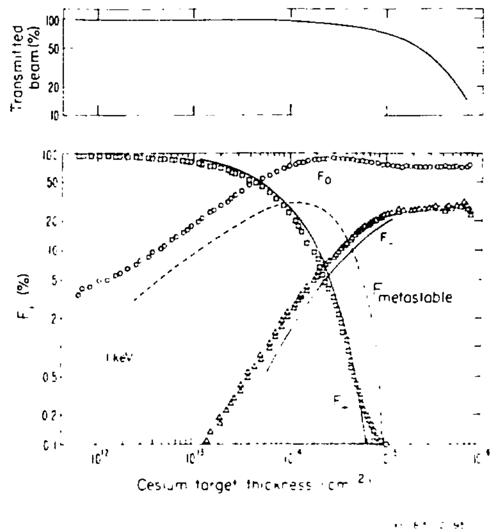


Fig.4 Charge-state fractions,[8] F_1, as a function of target thickness, τ, for 1-keV D^+ incident on cesium vapor. Also shown are charge-state fractions including the fraction in the metastable D(2s) state measured by Pradel et al.[11]

cesium vapor, as a function of cesium target thickness. Shown on the same scale are measurements of charge-state fractions by Pradel et al.,[11] including the fraction of metastable D(2s) atoms in the beam. The collisional de-excitation cross section for

D(2s) in cesium is very large, and D(2s) are generated essentially only by electron capture from D^+, so the metastable fraction is very small in a thick cesium-vapor target. It is clear, therefore, that D(2s) do not play a significant role in D^- formation in a thick cesium-vapor target. Also shown in Fig. 4 is the total beam transmitted through the target. The equilibrium charge-state fractions are independent of the beam transmission, as is to be expected. Figure 5 shows 2.5-keV D^+ and D^- incident on cesium

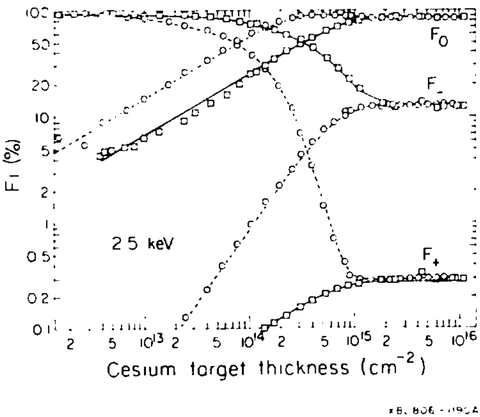
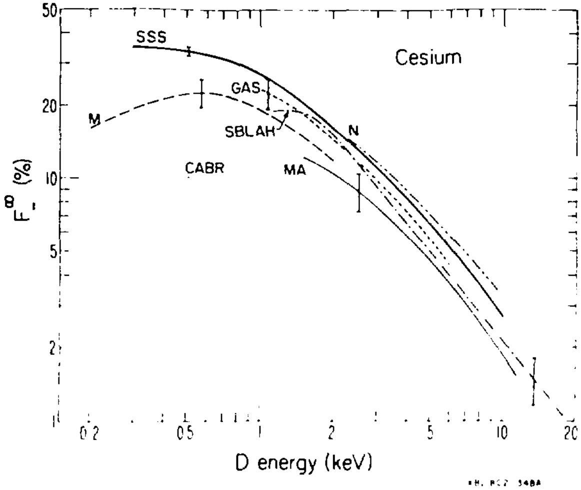


Fig.5 Charge-state fractions,[8] F_i, as a function of target thickness, -, for 2.5 keV D^- (□) and 2.5 keV D^+ (o) incident on cesium vapor.

vapor as a function of target thickness. The equilibrium charge-state fractions are seen to be independent of the charge state of the incident beam, as expected from the solution of the differential equations governing charge transfer: after several collisions, an atom or ion no longer "remembers" the charge state it had when it entered the target.



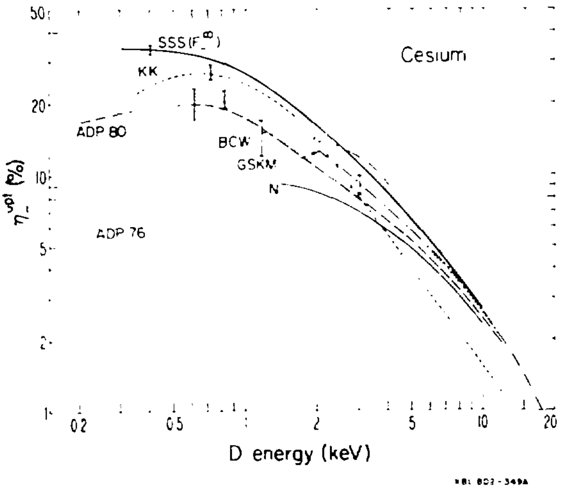
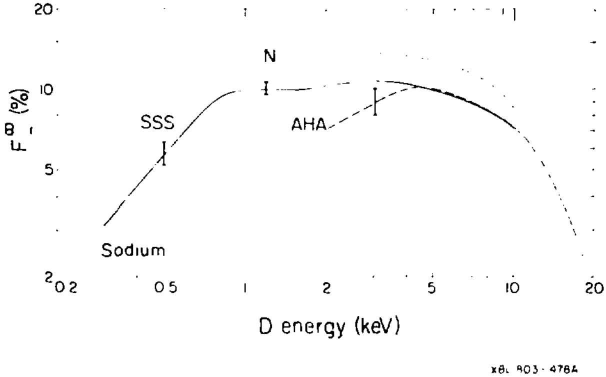


Fig. 6 Equilibrium yield F_-^∞ and optimum conversion efficiency η_-^{opt} for D in cesium vapor.

Thick-target yields[8,12-24] of D^- in cesium and in sodium vapors[8,13,14,21,22,24-27] are shown in Figs. 6 and 7: both the



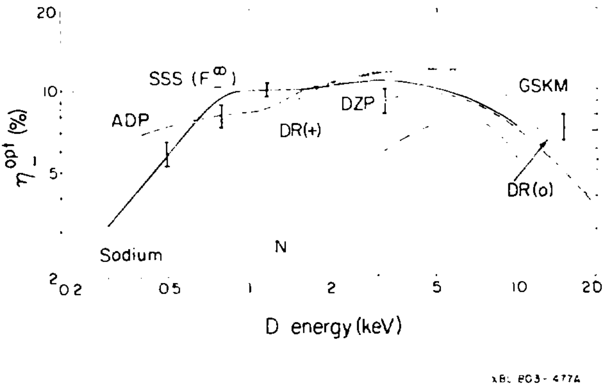
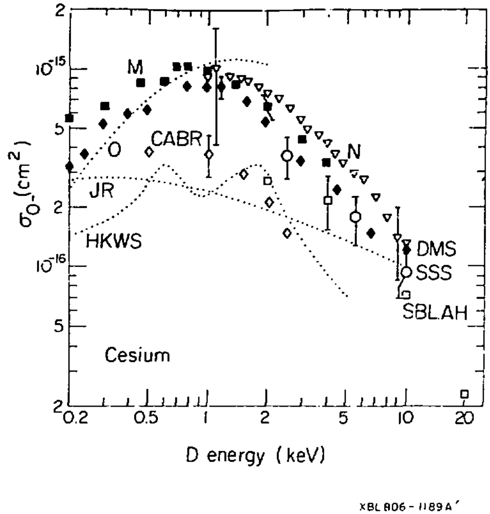


Fig.7 Equilibrium yield F_-^∞ and optimum conversion efficiency η_-^{opt} for D in sodium vapor.

equilibrium yield, F_-^∞, and the optimum conversion efficiency, η_-^{opt}, are shown. Discrepancies in the F_-^∞ results, especially at low energies, are apparent. The discrepancies must be due to errors or to real physical differences in the experiment. Some potential sources of error are probably due to the difficulty of measuring the flux of low-energy atoms leaving the target, insufficient target thickness, impure target material, or different collection efficiencies for different charge-state beams. Physical effects might include beam excitation, target excitation, and target polymerization. These physical effects have been discussed elsewhere,[8] with the conclusion that none are likely to explain the low-energy discrepancies, whose explanation therefore will have to await further investigation. Nothing more can be said about the F_-^{opt} results, since they are geometry dependent; however, they should lie below F_-^{∞} (see eqn. 7), which is not always the case, indicating experimental errors.

There have been several measurements[8,15,19,28-32] of the cross sections for electron capture, σ_{0-}, and for electron loss, σ_{-0}, of D atoms and ions in cesium vapor. Results are shown in Fig. 8. These measurements are, in principle, more difficult than thick-target measurements, because measurement of target thickness (target density and path length) is required. Furthermore, any particles lost from the beam in the target or not collected by the detectors after the target result in erronious cross-section measurements. These losses can arise from both elastic and inelastic scattering, and become more important at lower energies. Olson has recently calculated differential cross sections for such elastic[33] and inelastic[34] processes in cesium vapor. For example, at a D energy of 200 eV, more than 10% of D° are elastically scattered outside an angle of 2°. These effects, in addition to those already discussed for thick-target yields, probably account for the differences in the cross-section results observed.



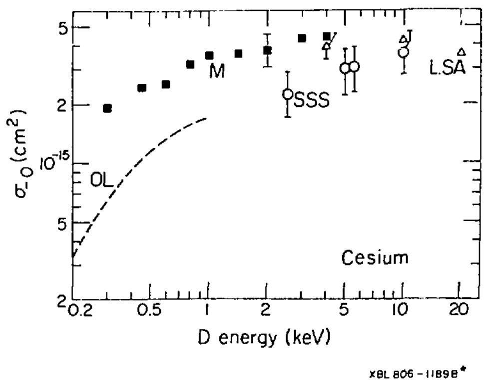


Fig.8 Cross sections σ_{o-} and σ_{-o} for deuterium in cesium vapor. Experimental results are shown as points, calculations as lines.

There have been several recent calculations of σ_{0-} for D^0 in cesium vapor with which experimental results can be compared. These calculations are also shown in Fig. 8. Hiskes et al.[35] made a two-state perturbed stationary state calculation with straight-line trajectories using adiabatic potentials derived from pseudopotential calculations and with coupling matrix elements obtained from ab-initio calculations of Olson, Shipsey, and Browne.[36] Janev and Radulovic[37] used an improved multi-channel Landau-Zener method based on work by Ovchinnikova; they used simple diabatic potentials and coupling matrix elements computed using Janev's asymptotic approximation. Olson[34] has recently performed a quantum-mechanical calculation using diabatic potentials which, when diagonalized with coupling matrix elements, reproduced the RKR (Rydberg-Klein-Rees) spectroscopic values. Higher lying states were added using an approximate Landau-Zener method. Olson and Liu[38] have recently calculated σ_{-0} for D^- in cesium vapor. They used a procedure derived from a two-state perturbed-stationary-state cross-section calculation using ab-initio potential-energy curves for the NaH^- system. They scaled these results to the CsH^- system by correcting for the energy defect and alkali dipole polarization of the CsH^- system. They conclude that electron transfer is the dominant electron-loss mechanism at low energies, with only a small contribution from molecular ionization. At high energies, however, they point out that direct impact ionization is the dominant mechanism of electron loss. They attribute the large value of σ_{-0} to the long-range nature of the interaction, with impact parameters of $15a_0$ contributing to the cross section.

Except at the lowest energies, the most recent experimental measurements of σ_{0-} tend to agree with each other and with the calculation of Olson. For σ_{-0} agreement between experiment and theory is poor at low energies.

Equilibrium charge-state fractions can be compared with cross sections. At low energies, where the small contribution due to D^+ can be neglected, the following relationship can be used:

$$F_-^{\infty} = \frac{\sigma_{0-}}{\sigma_{0-} + \sigma_{-0}} . \qquad (8)$$

For cross sections σ_{0-} and σ_{-0} measured in one experiment, their ratio depends only upon relative uncertainties in the measurements, which are much smaller than the absolute uncertainties. Figure 9

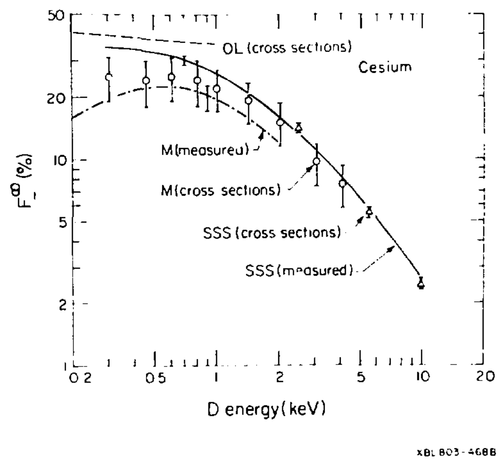


Fig.9 Equilibrium yield F_-^{∞} for D in cesium vapor, from direct measurement and calculated from cross sections using Eq. 8.

shows a comparison of two direct measurements[8,23] of F_-^{∞} with three results for F_-^{∞} obtained using equation 8: the experimental cross sections of Meyer[3] and of Schlach ... et al.[8] were used, along with the calculated cross sections of Olson[37] and of Olson and Liu.[38] The agreement is quite good, although the cross-section ratios are not sufficiently certain to decide between the direct measurements of F_-^{∞}, which are not in good agreement at low energies.

III. Alkaline-earth-vapor targets

Before 1977 the D^- yield from alkaline-earth vapors heavier than magnesium had not been studied. The first measurement of F_-^{∞} in strontium vapor was reported by the LBL group[39] in 1977, and is shown in Fig. 10. A feature to note is the plateau in the F_-^{∞} curve between 5 and 10 keV, and the rise at lower energies.

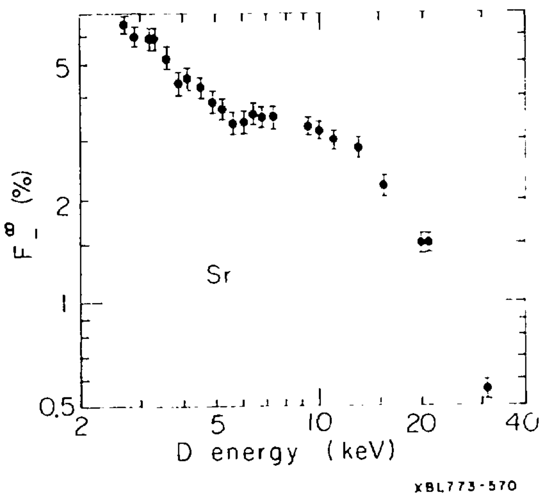


Fig.10 Equilibrium yield F_-^{∞} for D in strontium vapor: situation as of 1977.[39]

Measurements at lower energies were stimulated by a calculation of Olson and Liu.[40] Interaction energies for CaH and CaH^- were calculated using the configuration-interaction method. The CaH system exhibits a deeply-bound well due to the interaction with the Ca^+-H^- ion-pair state. The CaH^- system is calculated to be more tightly bound, and is separated from the neutral system for all interaction distances greater than $2.5a_0$. These calculations led to the prediction[40] that electron detachment in D^- collisions with an alkaline-earth atom would be small at low energies, thus F_-^{∞} would increase with decreasing energy, until the electron-attachment cross section also becomes small.

The heat-pipe target used to measure charge-state fractions in alkali-metal vapors cannot be used for such measurements in alkaline-earth vapors, because recirculation of condensed vapor requires operating the ends of the heat-pipe at a temperature just above the melting point of the metal in the target. Magnesium, strontium, and calcium are solid rather than liquid at the highest temperature (maximum target thickness) used in these measurements; barium melts at 725°C, at which temperature the vapor pressure is too high to provide efficient vapor trapping and to maintain constant effective target length when the target thickness is varied. The LBL group[41] has used the target shown in Fig. 11 for recent measure-

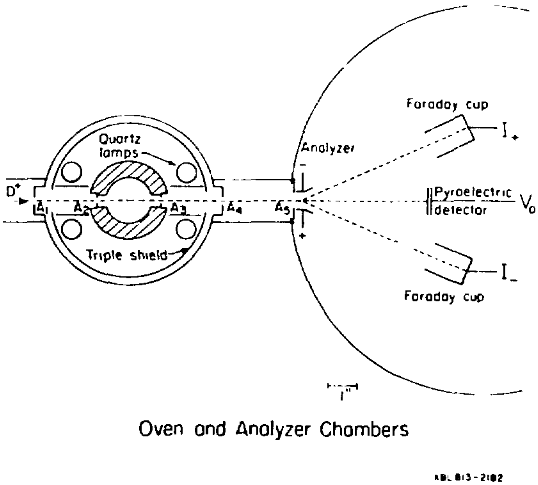


Fig.11 Schematic diagram of the apparatus[41] used by the LBL group to measure charge-state fractions in alkaline-earth-vapor targets.

ments with alkaline-earth targets. Heating of the iron oven is provided by quartz lamps (replacing electrical-resistance heaters used in the previous measurements). Typical data for charge-state fractions measured as a function of target thickness are shown in Fig. 12 for 3-keV D^+ in barium vapor.

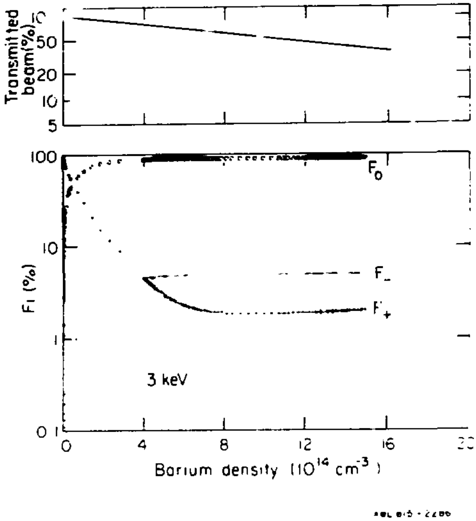


Fig.12 Charge-state fractions,[41] F_i, as a function of target density, for 3-keV D^+ incident on barium vapor.

Results for F_-^{∞} in heavy alkaline earths[41] are shown in Fig. 13. The 1977 results in strontium vapors were reproduced and extended to about 1.5 keV by Morgan et al.,[42] whose results are in excellent agreement with the LBL results. Morgan et al.[42] also found similar behaviour for calcium and barium targets. Also shown in Fig. 13 are the most recent LBL results,[41] in which F_-^{∞} has been measured down to 300 eV. The D^- yield reaches 50% at about 500 eV, making strontium vapor the most efficient conversion medium for D^- formation so far discovered.

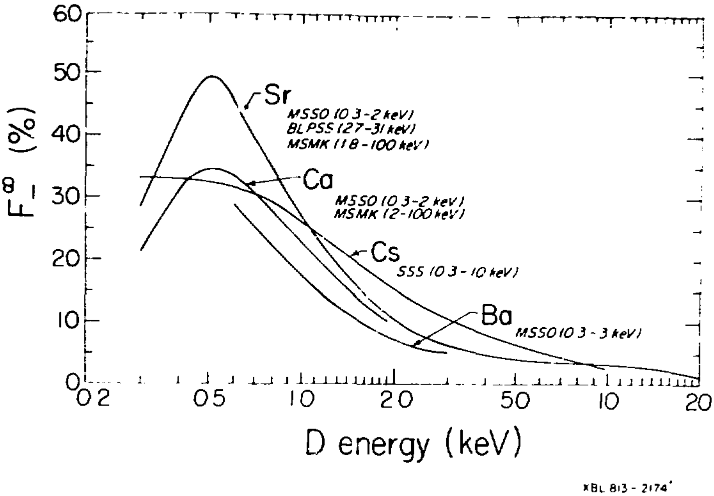


Fig.13 Equilibrium yield F_-^∞ for D in strontium, calcium, and barium vapor. The yield in cesium vapor[8] is shown for comparison.

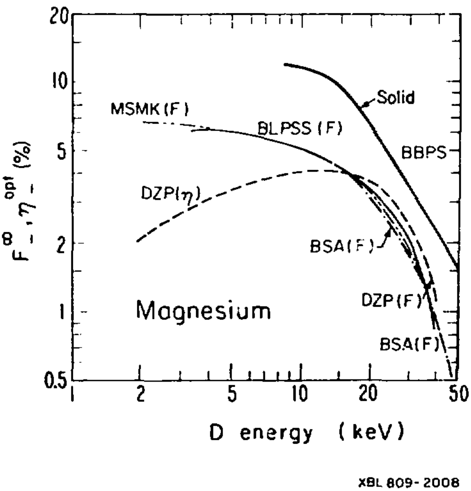


Fig.14 Equilibrium yield F_-^∞ and optimum conversion efficiency η_-^{opt} for D in magnesium vapor. The curve labeled "solid" is the D^- fraction emerging from a solid magnesium target.[46]

Figure 14 shows the thick-target yields of D^- in magnesium vapor.[27,39,41-45] All of the F_-^{∞} results are in good agreement (the one n_-^{opt} result essentially lies below the F_-^{∞} results). Also shown is the yield of D^- formed by passage of a beam through <u>solid</u>[46] magnesium, deposited on the exit side of a foil. This yield is seen to be much larger than that for magnesium vapor.

IV. Conclusion

A summary of the thick-target equilibrium yield, F_-^{∞}, for D^- formation in metal-vapor targets is shown in Fig. 15.

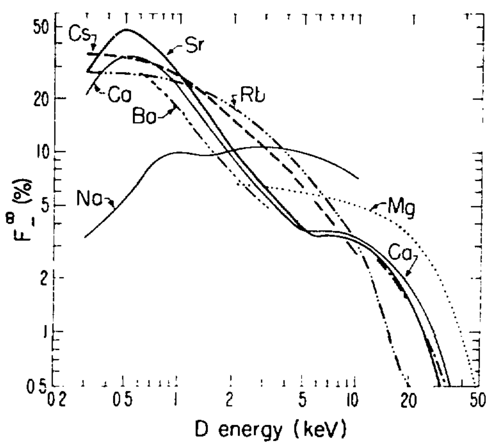


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Fig.15 Equilibrium yield F_-^{∞} for D in various vapor targets.[8]

Recent calculations and measurements of cross sections and equilibrium yields for D^- in cesium vapor are beginning to give a consistent picture, although some discrepancies remain unexplained. Recent measurements of the equilibrium yield in heavy alkaline-earth vapors have partially fulfilled the prediction, based on calculations, of a large yield at low energies. F_-^{∞} was found to reach 50% at a D energy of about 500 eV.

Acknowledgment

The author would like to thank R.H.McFarland and J.W.Stearns for their assistance in providing recent results on D^- formation in alkaline-earth vapors and for their assistance in preparing some of the figures. This work was supported in part by the Office of Fusion Energy of the U.S. Department of Energy under contract W-7405-ENG-48. Support was also provided by NATO (Research Grant 172.80) and by the Alexander von Humboldt-Stiftung.

Key to Figures

ADP76	Agafanov, D'yachkov, and Pavlii (1976)[19]
ADP80	Agafanov, D'yachkov, and Pavlii (1980)[24]
AHA	Anderson, Howald, and Anderson (1979)[25]
BBPS	Berkner, Bornstein, Pyle, and Stearns (1972)[46]
BCW	Bohlen, Clausnitzer, and Wilsch (1968)[12]
BLPSS	Berkner, Leung, Pyle, Schlachter, and Stearns (1977)[39,45]
BSA	Baragiola, Salvatelli, and Alonso (1973)[44]
CABR	Cisneros, Alvarez, Barnett, and Ray (1976)[18]
DMS	Dreiseidler, Miethe, and Salzborn (1981)[32]
DR	Dimov and Roslyakov (1974)[26]
DZP	D'yachkov, Zinenko, and Pavlii (1966-1971)[27,43]
GAS	Girnius, Anderson, and Staab (1977)[20]
GSKM	Grüebler, Schmelzbach, König, and Marmier (1969, 1970)[13,14]
HKWS	Hiskes, Karo, Willman, and Stevens (1978)[35]
JR	Janev and Radulovic (1978)[37]
KK	Khirnyi and Kochemasova (1970)[16]
LSA	Leslie, Sarver, and Anderson (1971)[29]
M	Meyer (1980)[23,30,31]
MA	Meyer and Anderson (1975)[17]
MSMK	Morgan, Stone, Mayo, and Kurose (1979)[42]
MSSO	McFarland, Schlachter, Stearns, and Olson (1981)[41]
N	Nagata (1979-1980)[21,22,28]
O	Olson (1980)[34]
OL	Olson and Liu (1980)[38]
SBLAH	Schlachter, Bjorkholm, Loyd, Anderson, and Haeberli (1969)[15]
SSS	Schlachter, Stalder, and Stearns (1980)[8]

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