LBL-11635

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

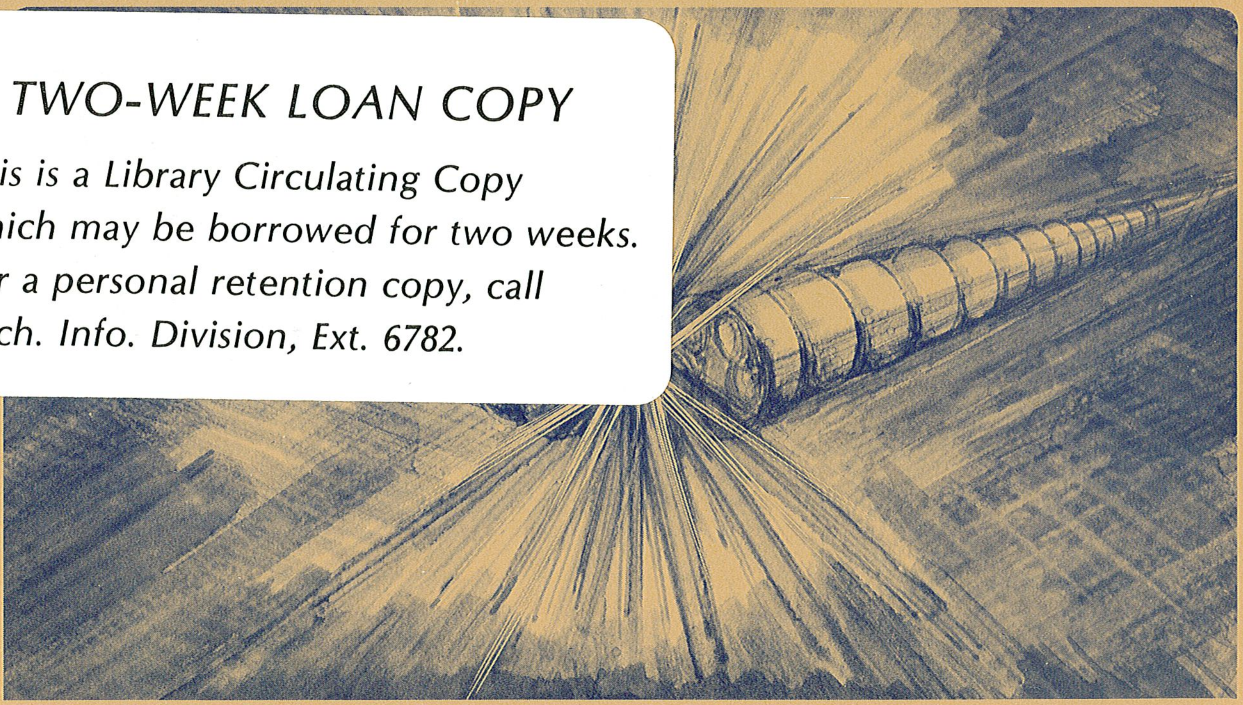
Accelerator & Fusion Research Division

Presented at the Brookhaven National Laboratory
Second International Symposium on the Production
and Neutralization of Negative Ions and Beams,
Upton, NY, October 6-10, 1980

D^- PRODUCTION BY CHARGE TRANSFER IN METAL VAPORS

A.S. Schlachter

October 1980



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

LBL-11635

D^- PRODUCTION BY CHARGE TRANSFER IN METAL VAPORS*

A. S. Schlachter

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Fast D^- ions can be produced from D^+ by multiple charge-transfer collisions in a metal-vapor target. Experimental cross sections and thick-target D^- yields are presented and discussed. The high D^- yield experimentally observed from charge transfer in cesium vapor is consistent with recent low-energy cross-section calculations and measurements.

I. Introduction

Many studies are underway to find methods for producing fast D^- beams which, when neutralized, can be used for heating confined plasmas for fusion. Some of these studies[1] make use of multiple charge transfer of relatively low energy deuterium beams (keV energies) in metal-vapor targets to produce D^- ions which are subsequently accelerated and neutralized to produce high-energy D^0 beams. The atomic physics of D^- formation by charge transfer in metal vapors is the topic of this review. Experimental results for cross sections and D^- yield in thick targets are comprehensively presented, along with some commentary, and certain targets, particularly cesium vapor, are discussed in more detail, including a comparison of experimental and theoretical results.

Considerable progress has been made in understanding D^- formation in metal vapors since this topic was last reviewed[2] in 1977. Although there are still discrepancies between various measurements, consistent cross sections and yields, and more favorable agreement of experimental and theoretical results, have replaced the major discrepancies noted in 1977.

The earliest report of a large D^- yield by charge transfer in a metal vapor was by Drake and Krotkov,[3] who remarked in 1966 that as much as 25% of 1-keV D^+ could be converted to D^- in a thick cesium-vapor target. Grüebler et al.[4] and Schlachter et al.[5] reported more comprehensive results in 1969. We have recently[6] reported comprehensive measurements of D^- formation in cesium, sodium, and rubidium vapors.

There are two related quantities pertaining to thick-target yields: the equilibrium yield (F_i^∞) and the conversion efficiency (η_i^{opt}). Their relationship is discussed in detail in Ref. 6. The fraction of the total beam leaving a target in charge state i is $F_i(\pi)$, where π is the line density or target thickness. If $I_i(\pi)$ is the intensity of the component in charge state i leaving a target of line-density π:

$$F_i(\pi) = \frac{I_i(\pi)}{\sum I_j(\pi)}. \quad (1)$$

Thus,

$$F_i(\pi) = 1. \quad (2)$$

The equilibrium fraction in charge state i is:

$$F_i^\infty = \lim_{\pi \to \infty} F_i(\pi). \quad (3)$$

The conversion efficiency is:

$$\eta_i(\pi) = \frac{I_i(\pi)}{I_0} \quad (4)$$

where I_0 is the intensity of the beam incident on the target. Due to scattering losses in the target,

$$\lim_{\pi \to \infty} \eta_i(\pi) = 0. \quad (5)$$

For a given geometry, there is some optimum value of π such that $\eta(\pi)$ exhibits a maximum, which we call η_i^{opt}. The value of η_i^{opt} is dependent on target geometry.

II. Experimental Considerations

Typical apparatus for measuring thick-target yields or cross sections in a metal vapor generally requires a fast ion or atom beam, a suitable target, and means of detecting the ions and atoms leaving the target. Although these elements are common to both types of measurements, target and detector design considerations are quite different for the two measurements. For equilibrium-yield measurements one assumes that nearly all particles have undergone several scattering and charge-changing collisions. It is important to collimate the beam leaving the target so as to have equal collection effficiency for ions and atoms. For cross-section measurements, where only a small fraction of the incident particles undergo even one charge-changing collision, it is essential that negligibly few scattering

D^- PRODUCTION BY CHARGE TRANSFER IN METAL VAPORS*

A. S. Schlachter

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Fast D^- ions can be produced from D^+ by multiple charge-transfer collisions in a metal-vapor target. Experimental cross sections and thick-target D^- yields are presented and discussed. The high D^- yield experimentally observed from charge transfer in cesium vapor is consistent with recent low-energy cross-section calculations and measurements.

I. Introduction

Many studies are underway to find methods for producing fast D^- beams which, when neutralized, can be used for heating confined plasmas for fusion. Some of these studies[1] make use of multiple charge transfer of relatively low energy deuterium beams (keV energies) in metal-vapor targets to produce D^- ions which are subsequently accelerated and neutralized to produce high-energy D^0 beams. The atomic physics of D^- formation by charge transfer in metal vapors is the topic of this review. Experimental results for cross sections and D^- yield in thick targets are comprehensively presented, along with some commentary, and certain targets, particularly cesium vapor, are discussed in more detail, including a comparison of experimental and theoretical results.

Considerable progress has been made in understanding D^- formation in metal vapors since this topic was last reviewed[2] in 1977. Although there are still discrepancies between various measurements, consistent cross sections and yields, and more favorable agreement of experimental and theoretical results, have replaced the major discrepancies noted in 1977.

The earliest report of a large D^- yield by charge transfer in a metal vapor was by Drake and Krotkov,[3] who remarked in 1966 that as much as 25% of 1-keV D^+ could be converted to D^- in a thick cesium-vapor target. Grüebler et al.[4] and Schlachter et al.[5] reported more comprehensive results in 1969. We have recently[6] reported comprehensive measurements of D^- formation in cesium, sodium, and rubidium vapors.

There are two related quantities pertaining to thick-target yields: the equilibrium yield (F_i^∞) and the conversion efficiency (η_i^{opt}). Their relationship is discussed in detail in Ref. 6. The fraction of the total beam leaving a target in charge state i is $F_i(\pi)$, where π is the line density or target thickness. If $I_i(\pi)$ is the intensity of the component in charge state i leaving a target of line-density π:

$$F_i(\pi) = \frac{I_i(\pi)}{\sum I_j(\pi)}. \qquad (1)$$

Thus,

$$F_i(\pi) = 1. \qquad (2)$$

The equilibrium fraction in charge state i is:

$$F_i^\infty = \lim_{\pi\to\infty} F_i(\pi). \qquad (3)$$

The conversion efficiency is:

$$\eta_i(\pi) = \frac{I_i(\pi)}{I_0} \qquad (4)$$

where I_0 is the intensity of the beam incident on the target. Due to scattering losses in the target,

$$\lim_{\pi\to\infty} \eta_i(\pi) = 0. \qquad (5)$$

For a given geometry, there is some optimum value of π such that $\eta(\pi)$ exhibits a maximum, which we call η_i^{opt}. The value of η_i^{opt} is dependent on target geometry.

II. Experimental Considerations

Typical apparatus for measuring thick-target yields or cross sections in a metal vapor generally requires a fast ion or atom beam, a suitable target, and means of detecting the ions and atoms leaving the target. Although these elements are common to both types of measurements, target and detector design considerations are quite different for the two measurements. For equilibrium-yield measurements one assumes that nearly all particles have undergone several scattering and charge-changing collisions. It is important to collimate the beam leaving the target so as to have equal collection effficiency for ions and atoms. For cross-section measurements, where only a small fraction of the incident particles undergo even one charge-changing collision, it is essential that negligibly few scattering collisions take place which result in loss of particles before reaching the detectors. Scattering collisions include both elastic and inelastic processes. This requirement generally necessitates collimation of the beam incident on the target. Limited angular acceptance sets a lower energy limit for cross-section measurements for a given geometry; this limit can be determined by varying the target exit aperture.

A difficult part of yield or cross-section measurements is measurement of the flux of neutral atoms. Many authors[7] employ a secondary-electron-emission detector for this purpose. Calibration of the detector can be difficult since it requires a known flux of neutral atoms at the appropriate energy. To overcome this difficulty, some experiments invoke previous measurements[8] which show a constant ratio between secondary-electron emission due to incident D^+ as compared to D^0. Whether this assumption is justified or not, a further complication arises as the emitting surface becomes contaminated with the target material, which changes the secondary-electron-emission coefficient[9] during the course of an experiment. Another approach is to use a pyroelectric detector.[6,10] Since this type of detector is not sensitive to the charge state of the beam being detected, it can be calibrated with an ion beam.

Measurement of target thickness is required for cross-section measurements, i.e., target density and path length must be determined. Methods commonly used to determine target density are (1) inferred from temperature by use of known vapor-pressure data,[6,11] (2) surface-ionization gauge,[5,12] and (3) absorption of resonance radiation.[13]

III. Cross-Section Results

Reported cross-section results for D^+, D^0, and D^- in metal vapors are shown in Figs. 1-7. The labels in the figures are identified in a key.[14-43]

Cross sections for charge transfer in cesium vapor are shown in Figs. 1 and 2. The three experimental results[6,33,34] for σ_{-0} in cesium vapor are in fair agreement with each other for energies greater than 2 keV. Also shown is a theoretical calculation of σ_{-0} by Olson and Liu,[40] who 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. Experiment and theory do not agree well at very low energies.

There have been several recent measurements[6,34,38] of σ_{0-} in cesium vapor, which are in fair agreement with each other. There have also been several recent calculations[29,31,39] of σ_{0-}. The experimental results for σ_{0-} fall between the various theoretical calculations.

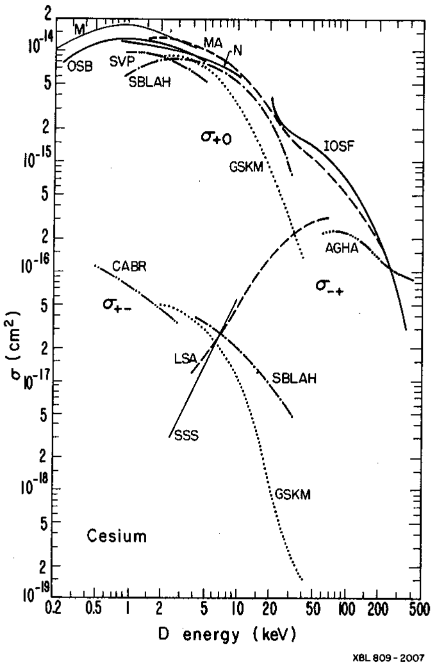


Fig. 1. Cross sections for D ions and atoms in cesium vapor.

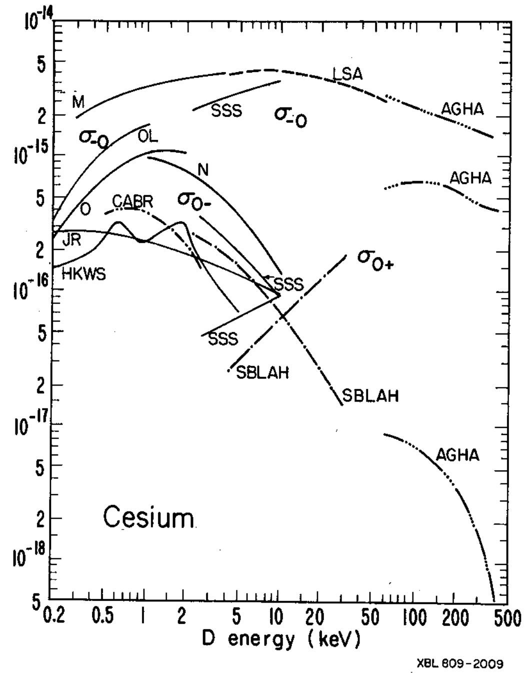


Fig. 2. Cross sections for D ions and atoms in cesium vapor.

Key to Figures

ADP76 Agafanov, D'yachkov, and Pavlii (1976)[14]
ADP80 Agafanov, D'yachkov, and Pavlii (1980)[15]
AGHA Anderson, Girnius, Howald, and Anderson (1977–1980)[16]
AHA Anderson, Howald, and Anderson (1979)[17]
BBPS Berkner, Bornstein, Pyle, and Stearns (1972)[18]
BCKP Berkner, Cooper, Kaplan, and Pyle (1969)[19]
BCW Bohlen, Clausnitzer, and Wilsch (1968)[20]
BLPSS Berkner, Leung, Pyle, Schlachter, and Stearns (1977)[21]
BSA Baragiola, Salvatelli, and Alonso (1973)[22]
CABR Cisneros, Alvarez, Barnett, and Ray (1976)[23]
D D'yachkov (1969)[24]
DR Dimov and Roslyakov (1974)[25]
DZP D'yachkov, Zinenko, and Pavlii (1968–1971)[26]
FM Futch and Moses (1966, 1967)[27]
GAS Girnius, Anderson, and Staab (1977)[28]
GSKM Gruebler, Schmelzbach, Konig, and Marmier (1969, 1970)[4]
HKWS Hiskes, Karo, Willman, and Stevens (1978)[29]
IOSF Il'in, Oparin, Solov'ev and Fedorenki (1965–1971)[30]
JR Janev and Radulovic (1978)[31]
KK Khirnyi and Kochemasova (1970)[32]
LSA Leslie, Sarver, and Anderson (1971)[33]
M Meyer (1980)[34]
MA Meyer and Anderson (1975–1977)[35]
ME Morgan and Ericksen (1978)[36]
MSMK Morgan, Stone, Mayo and Kurose (1979)[37]
N Nagata (1979–1980)[38]
O Olson (1980)[39]
OL Olson and Liu (1980)[40]
OMG O'Hare, McCullough, and Gilbody (1975)[41]
OSB Olson, Shipsey, and Browne (1976)[42]
SBLAH Schlachter, Bjorkholm, Loyd, Anderson, and Haeberli (1969)[5]
SSS Schlachter, Stalder and Stearns (1980)[6]
SVP Spiess, Valance, and Pradel (1972)[43]

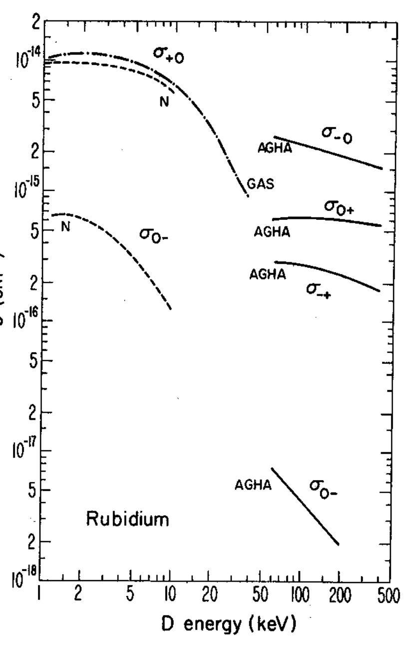


Fig. 3. Cross sections for D ions and atoms in rubidium vapor.

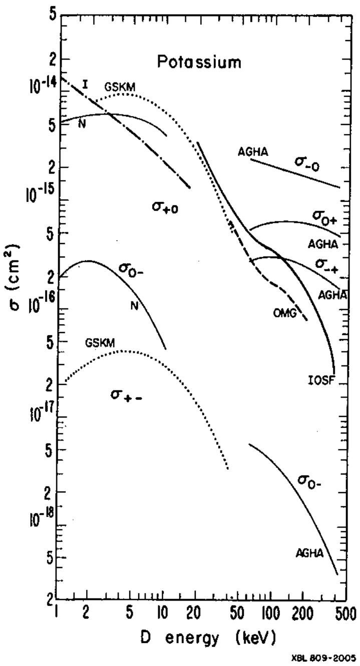
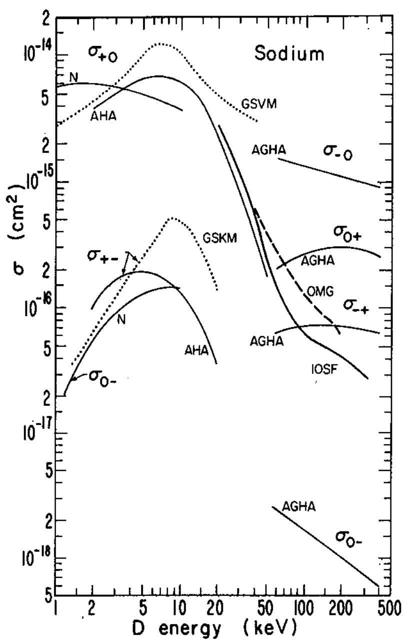


Fig. 4. Cross sections for D ions and atoms in potassium vapor.

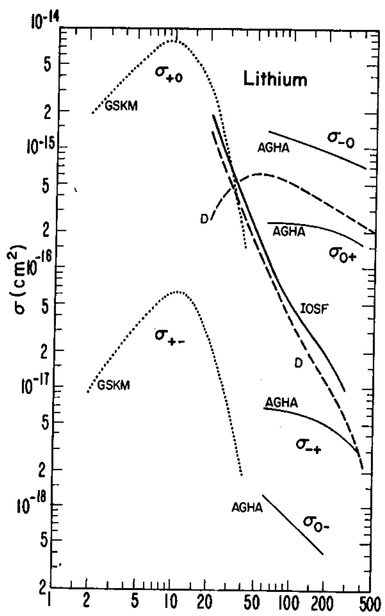
IV. Thick-Target Yields

Thick target yields of D^- in alkali and alkaline-earth vapors are shown in Figs. 8–14. These figures include both the equilibrium yield, F_-^∞, and the optimum conversion efficiency, η^{opt}. Although η^{opt} should always be smaller than F_-^∞, there are some deviations observed in Na and Cs vapors, indicating experimental errors. Some discrepancies between results by different experimenters are probably due to the difficulty of measuring the flux of low-energy atoms leaving the target. Another possibility is failure to achieve sufficient target thickness for equilibrium, which could result from loss of signal due to beam attenuation, or to unwillingness to increase target thickness to avoid excessive loss of target material.



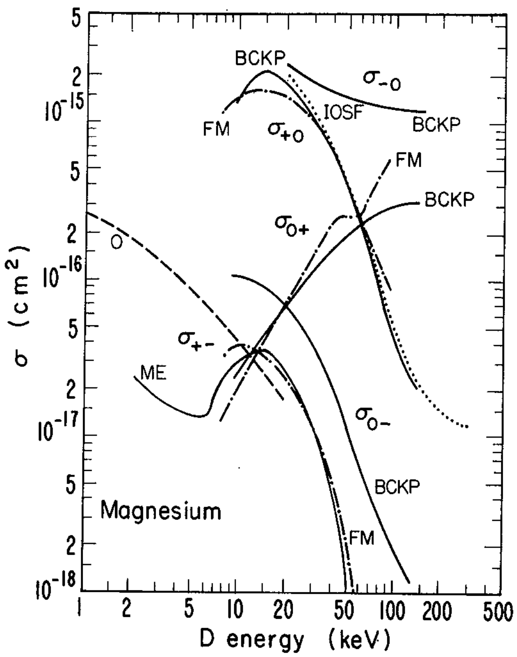
XBL 809-2004

Fig. 5. Cross sections for D ions and atoms in sodium vapor.



XBL 809-2006

Fig. 6. Cross sections for D ions and atoms in lithium vapor.



XBL 809-2010

Fig. 7. Cross sections for D ions and atoms in magnesium vapor.

The possibility that differences in various experimental results might be accounted for by physical effects has been discussed elsewhere.[6] We considered three possible effects: target excitation, beam excitation, and target polymerization. We concluded that, although tantalizing, none of these effects could account for observed discrepancies in thick-target yield measurements. Any of these topics could potentially be a fruitful area for further investigation.

The thick-target yield for D^- in magnesium vapor (Fig. 13) is compared with that for beam transmitted through solid magnesium;[18] the yield from the solid is higher than the yield from the vapor. Further measurements of the negative-ion yield from passage through solids or from collision with large clusters of target atoms would be desirable.

D^- formation in the heavy alkaline earths is shown in Fig. 14. The F_-^∞ yield as a function of decreasing energy was observed in Sr vapor,[21] and later in Ca and Ba vapors,[37] to increase after a plateau. Olson and Liu[44] have recently calculated that the cross section σ_{-0} for H^- in Ca vapor will be extremely small at energies below 500 eV. If the cross section σ_{0-} is not correspondingly small at low energies, a large negative ion yield would be predicted. We are presently beginning such measurements.

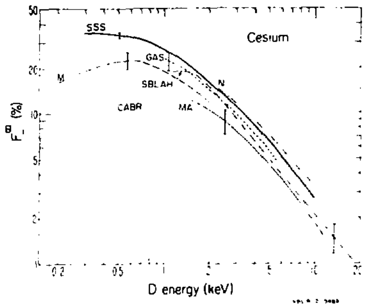


Fig. 8. Equilibrium yield (F_-^∞) for D in cesium vapor.

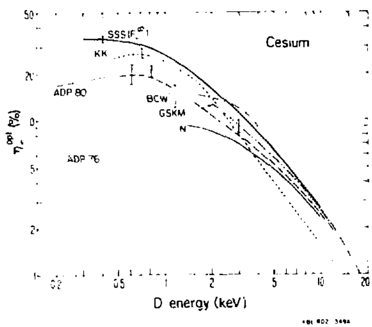


Fig. 9. Optimum conversion efficiency (η_-^{opt}) for D in sodium vapor.

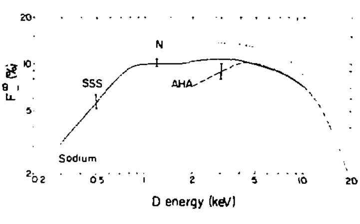


Fig. 10. Equilibrium yield (F_-^∞) for D in sodium vapor.

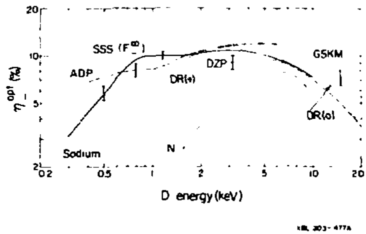


Fig. 11. Optimum conversion efficiency (η_-^{opt}) for D in sodium vapor.

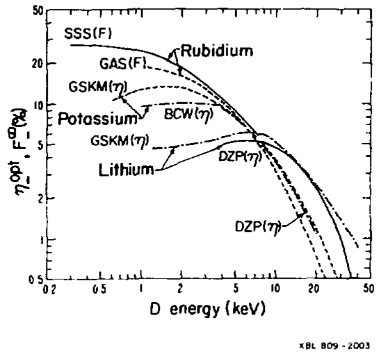


Fig. 12. Equilibrium yield (F_-^∞) and optimum conversion efficiency (η_-^{opt}) for D in rubidium, potassium, and lithium vapors.

We have made a few measurements using D_2^+ and D_3^+ as projectiles incident on cesium and sodium vapor targets, to check whether D_2^+ or D_3^+ might give a greater D^- yield per deuteron at thinner targets than at equilibrium. We discovered no enhancement. F_-^∞ per deuteron is the same for D^+, D^-, D_2^+, and D_3^+ projectiles at the same energy per deuteron. The target thickness required to dissociate D_2^+ or D_3^+ and to reach charge-state equilibrium was an order of magnitude greater than for D^+ or D^- incident, for both cesium and sodium vapor targets.

Equilibrium charge-state fractions can be compared with cross sections, especially for D^- formation at low energies, for which the small D^+ fraction can be neglected. In this case

$$F_-^\infty = \frac{\sigma_{0-}}{\sigma_{0-} + \sigma_{-0}} \qquad (6)$$

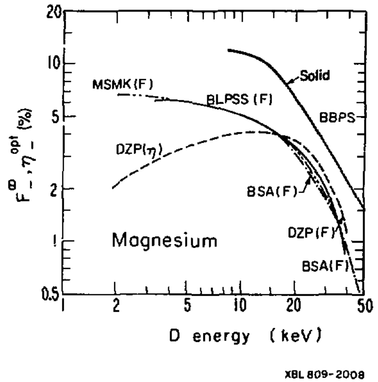


Fig. 13. Equilibrium yield (F_-^∞) and optimum conversion efficiency (η_-^{opt}) for D in magnesium vapor. The curve labeled "solid" is the D⁻ fraction emerging from a solid magnesium target.

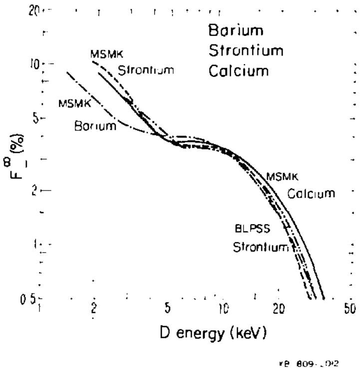


Fig. 14. Equilibrium yield (F_-^∞) for D in barium, strontium, and calcium vapors.

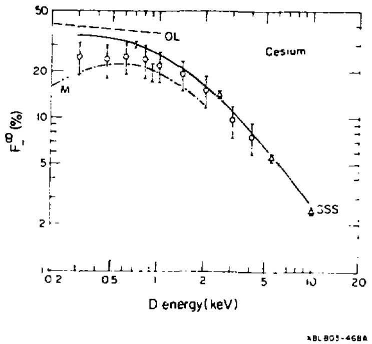


Fig. 15. Equilibrium yield (F_-^∞) for D in cesium vapor measured directly compared with F_-^∞ deduced from calculated and measured cross sections.

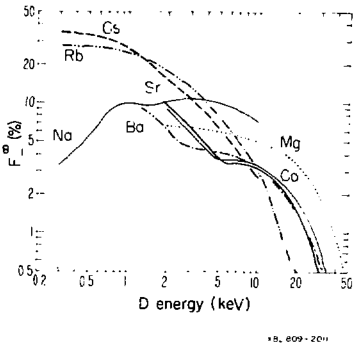


Fig. 16. Equilibrium yield (F_-^∞) for D in various vapor targets.

For cesium vapor we show (Fig. 15) F_-^∞ measured directly,[6,34] deduced from measured cross sections,[6,34] and deduced from calculated cross sections.[39,40] The agreement is fairly good. The large D⁻ yield observed in cesium vapor at low energies is thus essentially consistent with recently measured and calculated cross sections.

V. Conclusion

Recent cross-section measurements and calculations for D^- formation in cesium vapor are consistent with large experimentally observed D^- yields at low energies. Areas where further research is desirable, especially for high-power D^- beam systems, include target excitation, target polymerization, the interaction of a D^- beam with an ionized target, differential cross sections and measurements of scattering, and collisions of molecular ions.

A summary of F_-^{∞} for D in various vapor targets is shown in Fig. 16.

References

* This work was supported by the Fusion Energy Division of the U. S. Department of Energy under contract W-7405-ENG-48.

1. E. B. Hooper, Jr., P. Poulsen, and P. A. Pincosy, submitted to J. Appl. Phys.

2. A. S. Schlachter, in Proceedings of the Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, BNL 50727, edited by K. Prelec (Brookhaven National Laboratory, 1978), pp. 11-23.
3. C. W. Drake and R. Krotkov, Phys. Rev. Lett. 16, 848 (1966).

4. W. Gruebler, P. A. Schmelzbach, V. Konig, and P. Marmier, Phys. Lett. A 29, 440 (1969); Helv. Phys. Acta 43, 254 (1970).

5. A. S. Schlachter, P. J. Bjorkholm, D. H. Loyd, L. W. Anderson, and W. Haeberli, Phys. Rev. 177, 184 (1969).

6. A. S. Schlachter, K. R. Stalder, and J. W. Stearns, Phys. Rev. A. (in press); and unpublished.

7. J. A. Ray, C. F. Barnett, and B. Van Zyl, J. Appl. Phys. 50, 6516 (1979); D. H. Crandall and J. A. Ray, Rev. Sci. Instrum. 41, 1282 (1970).

8. P. M. Stier, C. F. Barnett, and G. E. Evans, Phys. Rev. 96, 973 (1954).

9. J. B. Taylor and I. Langmuir, Phys. Rev. 44, 423 (1933).

10. K. H. Berkner, B. R. Myers, and R. V. Pyle, Rev. Sci. Instrum. 39, 1204 (1968); M. W. Geis, K. A. Smith, and R. D. Rundel, J. Phys. E. 8, 1011 (1975).

11. R. R. Hultgren, P. D. Desai, D. T. Hawkins, M. Gleiser, K. K. Kelley and D. D. Wagman, Selected Values of the Thermodynamic Properties of the Elements, (American Society of Metals, Metals park, Ohio, 1973).

12. J. B. Taylor and I. Langmuir, Phys. Rev. 51, 753 (1937).

13. P. Pradel, F. Roussel, and G. Spiess, Rev. Sci. Instrum. 45, 45 (1974); P. Pradel, F. Roussel, A. S. Schlachter, G. Speiss, and A. Valance, Phys. Rev A 10, 797 (1974).

14. Y. A. Agafonov, B. A. D'yachkov, and M. A. Pavlii, Pisma Zh. Tekh. Fiz. 2, 757 (1976) [Sov. Tech. Phys. Lett. 2, 296 (1976)].

15. Y. A. Agafonov, B. A. D'yachkov, and M. A. Pavlii, to be published in Sov. Phys. - Tech Phys.

16. C. J. Anderson, R. J. Girnius, A. M. Howald, and L. W. Anderson, Phys. Rev. A 22, 822 (1980); R. J. Girnius, C. J. Anderson, and L. W. Anderson, Phys. Rev. A 16, 2225 (1977).

17. C. J. Anderson, A. M. Howald, and L. W. Anderson, Nucl. Instrum. and Methods 165, 583 (1979).

18. K. H. Berkner, I. Bornstein, R. V. Pyle, and J. W. Stearns, Phys. Rev. A 6, 278 (1972).

19. K. H. Berkner, W. S. Cooper, III, S. N. Kaplan, and R. V. Pyle, Phys. Rev. 182, 103 (1969).

20. H. Bohlen, G. Clausnitzer, and H. Wilsch, Z. Phys. 208, 159 (1968).

21. K. H. Berkner, D. Leung, R. V. Pyle, A. S. Schlachter, and J. W. Stearns, Nucl. Instrum. and Methods 143, 157 (1977); Phys. Lett. 64A, 217 (1977).

22. R. A. Baragiola, E. R. Salvatelli and E. Alonso, Nucl. Instrum. and Methods 110, 507 (1973).

23. C. Cisneros, I. Alvarez, C. F. Barnett, and J. A. Ray, Phys. Rev. A 14, 76 (1976).

24. B. A. D'yachkov, At. Energ. 27, 220 (1969) [Sov. At. Energ. 27, 958 (1969)].

25. G. I. Dimov and G. V. Roslyakov, Prib. Tekh. Eksp. 3, 31 (1974) [Instrum. Exp. Tech. 17, 658 (1974)].

26. B. A. D'yachkov and V. I. Zinenko, At. Energ. 24, 18 (1966) [Sov. At. Energ. 24, 16 (1968)]; B. A. D'yachkov, V. I. Zinenko, and M. A. Pavlii, Zh. Tekh. Fiz. 41, 2353 (1971) [Sov. Phys. - Tech. Phys. 16, 1868 (1972)].

27. K. G. Moses and A. H. Futch, Jr., Bull. Am. Phys. Soc. 11, 344 (1966) and private communication; A. H. Futch and K. G. Moses, Proc. V. Intl. Conf. on Phys. of Electronic and Atomic Collisions, Leningrad, 1967, I.

P. Flaks and E. S. Solovyov, Editors (Nauka, Leningrad, 1967), p. 12. These cross sections were renormalized (multiplied by 0.81) as suggested by K. H. Berkner, R. V. Pyle, and J. W. Stearns, Phys. Rev. 178, 248 (1969).

28. R. J. Girnius, L. W. Anderson, and E. Staab, Nucl. Instrum. and Methods 143, 505 (1977).

29. J. R. Hiskes, A. M Karo, P. A. Willman, and W. J. Stevens, Phys. Lett. 68A, 221 (1978).

30. R. N. Il'in, V. A. Oparin, E. S. Solv'ev and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. Pis'ma Red. 2, 310 (1965) [JETP Lett. 2, 197 (1965)]; Zh. Tekh, Fiz. 36, 1241 (1966) [Sov. Phys. - Tech. Phys. 11, 921 (1967)]; R. N. Il'in, V. A. Oparin, I. T. Serenkov, E. S. Solov'ev and N. V. Fedorenko, Proc. VII Intl. Conf. on Phys of Electronic and Atomic Collisions, Amsterdam, 1971, L. M. Branscomb et al, Editors (North-Holland Publishing Co., Amsterdam, 1971), v. 2, p. 793.

31. R. K. Janev and Z. M. Radulovic, Phys. Rev. A 17, 889 (1978).

32. Yu. M. Khirnyi, and L. N. Kochemasova, Prib. Tekh. Eksp. 3, 56 (1970) [Instrum. Exp. Tech. 3, 693 (1970)].

33. T. E. Leslie, K. P. Sarver, and L. W. Anderson, Phys. Rev. A 4, 408 (1971). These results as plotted have been renormalized (multipled by 2.0) to take into account more recent measurements of σ_{+0}.

34. F. W. Meyer, J. Phys. B. (in press).

35. F. W. Meyer, and L. W. Anderson, Phys. Rev. A 11, 589 (1975); Phys. Lett. 54A, 333 (1975); F. W. Meyer, C. J. Anderson, and L. W. Anderson, Phys. Rev. A 15, 455 (1977).

36. T. J. Morgan and F. Ericksen, Phys. Lett. 66A, 198 (1978).

37. T. J. Morgan, J. Stone, M. Mayo, and J. Kurose, Phys. Rev. A. 20, 54 (1979).

38. T. Nagata in Proc. XI Int. Conf. on Phys. of Electronic and Atomic Collisions, edited by K. Takayanagi and N. Oda (Kyoto, Japan, 1979). pp. 512-513; J. Phys. Soc. Japan 46, 919 (1979); to be published in J. Phys. Soc. Japan 48 2068 (1980); and private communication.

39. R. E. Olson, Phys. Lett. 77A, 143 (1980).

40. R. E. Olson and B. Liu, to be published in J. Chem. Phys.

41. B. G. O'Hare, R. W. McCullough, and H. B. Gilbody, J. Phys. B. 8, 2968 (1975).

42. R. E. Olson, E. J. Shipsey, and J. C. Browne, Phys. Rev. A 13, 180 (1976). The results for σ_{0-} and σ_{-0} in this reference have been replaced by those of Refs. 39 and 40.

43. G. Spiess, A. Valance, and P. Pradel, Phys. Rev. A 6, 746 (1972).

44. R. E. Olson and B. Liu, Chem. Phys. Lett. (to be published).