Title
D- PRODUCTION BY MULTIPLE CHARGE-TRANSFER COLLISIONS IN METAL-VAPOR TARGETS

Author
Schlachter, A.S.

Publication Date
1977-09-01

UC-20
LBL-6838
c 1

Presented at the Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven National Laboratory, Upton, LI, New York, September 26-30, 1977

Energy and Environment Division

D$^-$ Production by Multiple Charge-Transfer Collisions in Metal-Vapor Targets

A. S. Schlachter

September 1977

Lawrence Berkeley Laboratory University of California/Berkeley

Prepared for the U.S. Energy Research and Development Administration under Contract No. W-7405-ENG-48

D^- PRODUCTION BY MULTIPLE CHARGE-TRANSFER COLLISIONS IN METAL-VAPOR TARGETS*

A. S. Schlachter

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

A beam of D^- ions can be produced by multiple charge-transfer collisions of a D^+ beam in a thick metal-vapor target. Cross sections and equilibrium charge-state fractions are presented and discussed.

I. Introduction

1. Scope

This paper is intended to be a sometimes-critical summary of cross sections and equilibrium yields relevant to D^- formation by multiple-charge-transfer collisions of D^- ions, atoms and molecules in metal-vapor targets. The projectiles are limited to hydrogen/deuterium because intense beams of D^- are needed for efficient neutral-beam injection into fusion devices at high energies. The targets are limited to metal vapors because the D^- yields obtainable are much larger in metal vapors than in gases. Charge transfer in foils is also mentioned. Experimental results are emphasized in this report. Theoretical calculations are discussed only sporadically.

The available cross-section and equilibrium-yield values are incomplete and often contradictory; there are discrepancies as large as an order of magnitude. It is thus impossible to present a coherent and consistent picture of charge transfer in metal vapors. However, enough is known to provide the designer of a D^- beam system with some ideas of what to expect. Hopefully this report will also serve to indicate the large amount of research to be done.

Section I is an introduction to the topic of D^- formation in metal-vapor targets. Experimental methods are mentioned only to the extent necessary to understand comments on contradictory results. Notation is discussed. Section II presents results for alkali-vapor targets; most thoroughly studied is cesium vapor. Section III presents results for alkaline-earth-vapor targets. Section IV presents results in other targets. Section V discusses design considerations, including choice of target, target thickness, projectile species, and projectile energy. Also discussed in this section are effects which may depend on the intensity of the beam.

Some of the results cited here, as well as results for charge transfer in gases, and a more complete discussion of experimental methods, can be found in Refs. 1-7.

2. Notation

Standard notation is used throughout. The cross section σ_{if} represents the cross section for a particle initially in charge state i and in charge state f after the collision. The symbol 0 is often ambiguous, in that it can refer to D^o in the ground state or in an unknown mixture of excited states. We shall use 0 in the latter sense; the subscript g will be used to refer explicitly to D^o in the ground state; m refers to D(2s), i.e., the deuterium metastable 2s state.

All results referred to here will be for deuterium atoms and ions, unless explicitly stated otherwise, even if the experiment was performed using hydrogen atoms and ions. We assume that H and D projectiles give the same results at the same velocity; therefore H results will be treated as if the experiment were performed using D, but at twice the energy.

The equilibrium yield of atoms or ions in charge state i is denoted by F_i^∞, i.e., the fraction in the charge state i of the total beam emerging from the target such that this fraction no longer changes with increasing target thickness.

3. Experimental Methods

A typical apparatus for charge-transfer measurements in metal vapors consists of an ion source, accelerator and appropriate optics, a metal-vapor target, an analyzing field, and detectors for the charged and neutral beams. Measurements of excited-state formation usually require an optical system, measurements with an incident atomic beam require a neutralizer and sweep field, and so on.

Metal-vapor targets are usually one of three types: an oven, a jet, or a heat pipe. An oven is usually easy to design; the target thickness is the product of the density (usually obtained from vapor pressure tables by measuring the temperature)[8] and the effective path length; high loss rate of target material or limited angular acceptance can be problems. A jet can be designed to recover or recirculate target material; obtaining high densities and determining target thickness

---

*Work done under the auspices of the U.S. Energy Research and Development Administration.

can be difficult. A heat pipe allows high densities, efficient recovery of target material, and large angular acceptance; determining effective path length can be difficult.

The detection of low-energy ions is often done with Faraday cups. The detection of low-energy atoms, however, can be difficult. Methods commonly used include secondary-electron emission, single-particle counting using an electron multiplier, and pyroelectric detectors and bolometers. Lack of space precludes a discussion or comparison of these methods. It should be noted that there is widespread disagreement as to the relative secondary-emission coefficients for D^+, D^0 and D^- incident on a surface.

Problem areas for cross-section measurements include determination of target thickness, incomplete collection of scattered beam, and detection of D^0. Measurements with D^0 incident are further complicated by an unknown admixture of excited states in the beam. Measurements of excited-state formation often require calibration of an optical system.

Difficulties in equilibrium-yield measurements include determination that the target is sufficiently thick, obtaining uniform collection efficiency for all charge states, correction for loss of scattered beam, and D^0 detection.

II. Alkali-Vapor Targets

1. Introduction

References to all articles known to the author dealing with experimental results for collisions of deuterium and hydrogen atoms and ions with alkali-vapor targets are shown in Tables I-V.[9-59] Energies shown are equivalent deuteron energy (hydrogen energies were multiplied by two). Experimental results for F_-^∞ in Cs vapor are shown in Fig. 1; apparatus and charge-state fractions as a function of Cs-target thickness are shown in Figs. 2-4. Cross sections in Cs vapor not involving excited states of the D atom are shown in Figs. 5 and 6. Experimental results in the other alkali-metal vapors for F_-^∞ and for cross sections not involving excited states of the D atom are shown in Figs. 7-14. Although cross sections for n=2 and for highly excited state formation are included in Tables I-V, results are not presented here.

Although there are many results for F_-^∞ in alkali-vapor targets, the results are incomplete and often contradictory. Since collisions of D atoms and ions in cesium vapor have been studied more thoroughly than in other metal-vapor targets, they will be discussed first. Furthermore, the discussion is applicable to other metal-vapor-target measurements.

2. Cesium-Vapor Target

Results for F_-^∞ in Cs vapor are shown in Fig. 1. The obvious questions are (1) to what extent can we have confidence in any given result, and (2) why do the results disagree by more than the stated uncertainties.

TABLE I. Summary of reported measurements of collisions of deuterium atoms and ions in cesium vapor.

	Reference	Measured[a]	(D) Energy Range (keV)
Agafonov *et al.*	9	F_-^∞	0.4 - 12
Bohlen *et al.*	10	F_-^∞	1 - 4
Brouillard *et al.*	11	f	5 - 20
Cesati *et al.*	12	σ_{+m}	1 - 10
Cisneros *et al.*	13	σ_{+-}, σ_{0-}, F_-^∞ [b]	0.5 - 2.5
Cisneros *et al.*	14	[c]	0.5 - 2.5[d]
Cisneros *et al.*	15	[e]	0.5 - 2.5[f]
Donnally *et al.*	16	σ_{+m}	0.32 - 6
Girnius *et al.*	17	σ_{-0}, σ_{-+}, σ_{g+}, σ_{g-}	60 - 400
Girnius *et al.*	18	F_-^∞	1 - 6
Grüebler *et al.*	19,20	σ_{+0}, σ_{+-}, F_+^∞, F_0^∞, F_-^∞	2 - 40
Il'in *et al.*	21,22	σ_{+0}, hes	20 - 360
		F_0^∞	20 - 240
Khirnyi and Kochemasova	23	F_-^∞	0.4 - 12
Leslie *et al.*	24	σ_{-0}, σ_{-+}	4 - 60
Meyer and Anderson	25	σ_{atten}, F_-^∞	1.5 - 11.5[g]
Meyer and Anderson	26	σ_{+0}	1 - 60[h]
Meyer *et al.*	27	σ_{+0}	80 - 240
		σ_{atten}	20 - 160[i]
Osher *et al.*	28	F_-^∞	1.5
Roussel *et al.*	29-31	σ_{+m}, σ_{+g}, f	0.6 - 6
Schlachter *et al.*	32	σ_{+0}, σ_{g+}, σ_{+-}, σ_{g-}, F_+^∞, F_0^∞, F_-^∞	1 - 40
Schlachter *et al.*	33	σ_{+m}, σ_{+g}, σ_{mg}, σ_{m-}, σ_{g-}	1
Schlachter *et al.*	34	F_-^∞	1 - 5
Schlachter *et al.*	35	F_-^∞	0.5 - 3
Schlachter *et al.*	36	F_-^∞	2.5[j]
Schlachter *et al.*	37	F_-^∞	0.3 - 10
Sellin and Granoff	38	σ_{+m}	4 - 60
Spiess *et al.*	39	σ_{+0}	1 - 5
		σ_{+m}, f	4.8
Spiess *et al.*	40	σ_{+0}, σ_{+-}, σ_{-0}, σ_{0-}, F_+^∞, F_0^∞, F_-^∞	5
Tuan *et al.*	41-43	f, σ_{+m}	0.8 - 6

[a] Subscript notation is as follows: +, -, m, g, and 0 refer, respectively, to D^+, D^-, D(2s), D(1s), and D^0 in any state. f is metastable fraction. F_i^∞ is the equilibrium charge fraction for the charge state i. hes is the yield of highly excited states.

[b] Both differential-in-angle cross sections and integrated cross sections.

[c] Differential and integrated cross sections for production of D^-, $D^0 + D_2^0$.

[d] 1 - 5 keV D_2^+ incident beam.

[e] Differential cross section for D^- production.

[f] 1.5 - 7.5 keV D_3^+ incident beam.

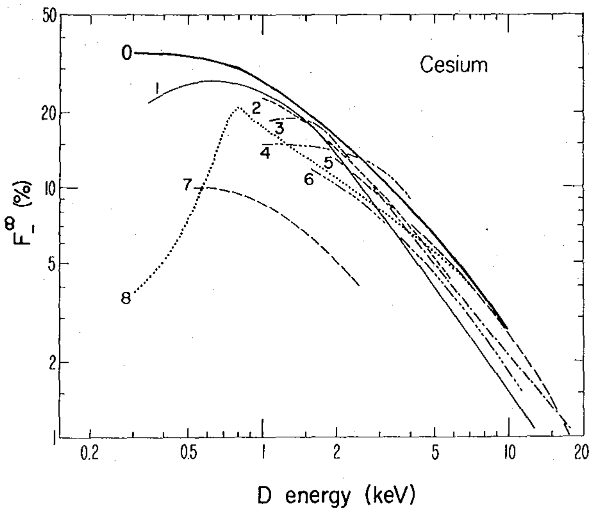
[g] 3 - 23 keV D_2^+ incident beam.

[h] 1 - 30 keV H^+, D^+, H_2^+, D_3^+ incident beams.

[i] 30 - 160 keV H_2^+ and H_3^+ incident beams.

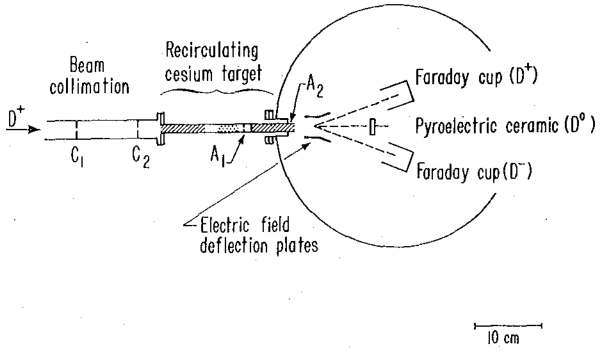
[j] 2.5 keV D^+, 5 keV D_2^+, 7.5 keV D_3^+ incident beams.

A schematic diagram of the apparatus used recently by the LBL group[37] to measure F_-^∞ is shown in Fig. 2, and charge-state fractions as a function of Cs-vapor target thickness are shown in Fig. 3. Also shown in Fig. 3 is the total beam measured after the Cs target (relative units). Two points to note are (1) that the total beam transmitted through the Cs target decreases with increasing target thickness; the decrease is caused by beam loss due to multiple scattering (the loss reaches a factor of ten in the case shown), and (2) that this loss is dependent upon the geometry of the scattering target and detectors.



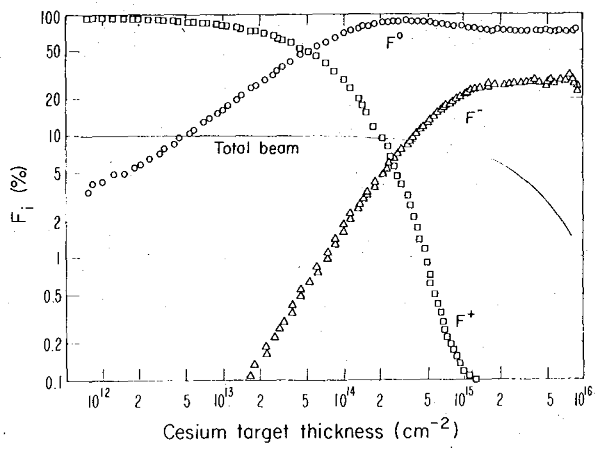
XBL 779-2294

Fig. 1. Equilibrium fraction (F_-^∞) of D^- in Cs vapor.
Curve 0: Schlachter et al.,[35-37] 1976,1977;
Curve 1: Khirnyi and Kochemasova,[23] 1970;
Curve 2: Girnius et al.,[18] 1977;
Curve 3: Schlachter et al.,[32] 1969;
Curve 4: Bohlen et al.,[10] 1968;
Curve 5: Grüebler et al.,[19,20] 1969,1970;
Curve 6: Meyer and Anderson,[25] 1975;
Curve 7: Cisneros et al.,[13] 1976;
Curve 8: Agafonov et al.,[9] 1976.



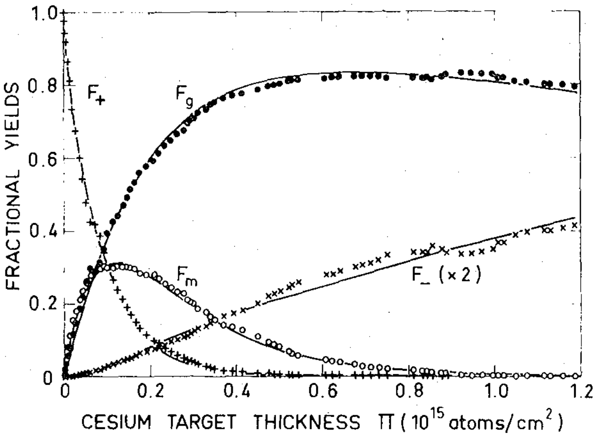
XBL 776-1104

Fig. 2. Schematic diagram of the apparatus used by the LBL group to measure F_-^∞ for D in Cs vapor.[37]



XBL 776-1105

Fig. 3. Charge-state fractions F_i as a function of Cs-target thickness for 1-keV D^+ incident on a Cs-vapor target.[37] Relative total beam intensity is shown by the solid line.



XBL 779-2464

Fig. 4. Charge-state fractions F_i as a function of Cs-target thickness for 1-keV D^+ incident on a Cs-vapor target, for target thicknesses up to 1.2×10^{15} cm^{-2}. F_g and F_m are fractions of D^0 in the ground and metastable 2s states respectively. F_- is shown multiplied by two, i.e., the D^- yield at 1.2×10^{15} cm^{-2} is 20%.[31]

The result of an experiment in which the total beam is not measured after the target is often called the negative-ion conversion efficiency, η^- (the ratio of D^- current emerging from the target to D^+ beam incident upon the target). This conversion efficiency is a convolution of the D^- fraction in the emerging beam, F_-, with the geometry-dependent transmissivity of the target (both functions of target thickness). η^- is often confused with F_-^∞. The difference is that F_-^∞ is independent of both target geometry and target thickness. Such confusion can occur when the product of the increasing D^- fraction and the decreasing target transmissivity remains fairly constant over some range of target thicknesses, leading to an "F_-^∞ apparent"; "F_-^∞ apparent" is often mistaken for F_-^∞, assuming negligible beam loss due to scattering up to that target thickness. Similarly, if the transmissivity decreases faster than F_- increases, for increasing target thickness, an apparent maximum in F_- is observed; beyond some optimum target thickness, F_- decreases with increasing target thickness. This maximum is often called "optimum F_-", assuming a real maximum in F_-. An optimum F_- can indeed occur in some cases (notably in a four- or five-state-component system such as He). However, unless the transmissivity is measured (or the entire beam after the scattering target is measured), it is impossible to measure a geometry-independent F_-^∞. Furthermore, in either of the above two cases ("F_-^∞ apparent" or "optimum F_-") in which transmissivity is not measured, the result is less than F_-^∞, and lower by an unknown amount. Because scattering increases with decreasing energy, the problem becomes more acute as the incident beam energy decreases.

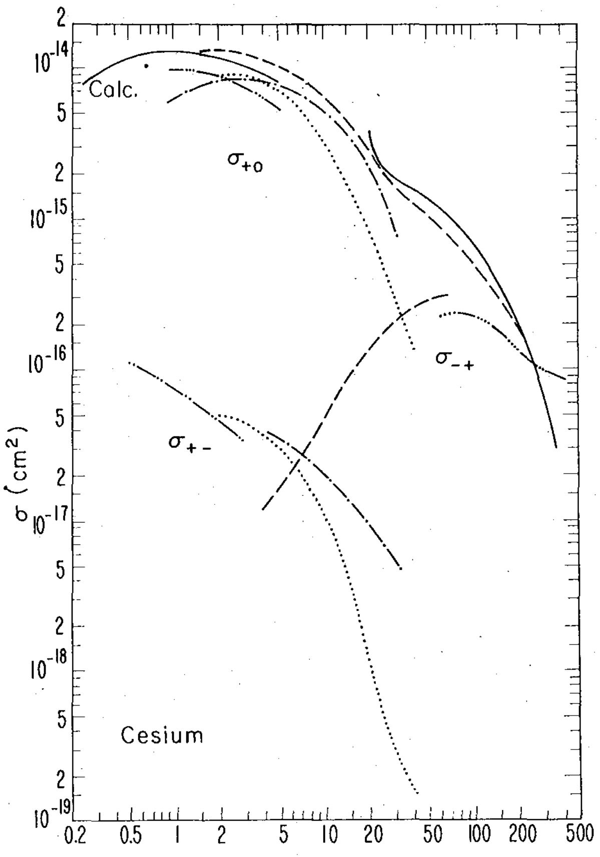
The above discussion probably explains why the results of Bohlen et al.[10] (Curve 4, 1968), Gruebler et al.[19,20] (Curve 5, 1970), and Agafonov et al.[9] (Curve 8, 1976) in Fig. 1 fall below Curve 0 and others at lower energies. The negative-ion yields measured in these experiments are lower than F_-^∞ by an unknown, geometry-dependent amount. Insufficient experimental details are given by Khirnyi and Kochemasova[23] (Curve 1, 1970) to evaluate their results.

The measurements of Meyer and Anderson[25] (Curve 6, 1975), Schlachter et al.[32] (Curve 3, 1969), and Girnius et al.[18] (Curve 2, 1977) were all made on essentially the same apparatus, yet the results of Meyer and Anderson lie considerably below the other two. Meyer and Anderson used both D^+ and D_2^+ as incident beams; "F_-^∞" with D^+ incident is reported to be higher than "F_-^∞" with D_2^+ incident at twice the energy, although within the stated uncertainties. This could indicate that insufficient target thicknesses were used, especially for the D_2^+-incident measurements. A target thickness of about $1\text{-}2 \times 10^{16}$ cm^{-2} is required[36] to dissociate and to charge-state equilibrate a D_2^+ beam incident on a Cs-vapor target at keV energies (as compared to $1\text{-}2 \times 10^{15}$ cm^{-2} for D^+ incident), and beam loss by scattering is one to two orders of magnitude greater. Because most of the D_2^+ incident dissociates in the Cs-vapor target (becoming half energy D^+, D^0, and D^-), one normally expects the same F_-^∞ results for D^+ incident at energy E and D_2^+ at 2E (and D_3^+ at 3E). The above does not explain why Meyer and Anderson's D^+-incident results for F_-^∞ lie below those of Schlachter et al. (1969) and Girnius et al. We can only speculate that the target was not sufficiently thick, that there was some detector problem, or that other unknown effects influenced the results.

Except for the lowest energy point in Curve 3 (Schlachter et al., 1969), which is probably erroneous, three results agree within experimental uncertainties: Schlachter et al. (Curve 3, 1969), Girnius et al. (Curve 2, 1977), both measured on similar apparatus, but by different groups, and the LBL group's recent results (Schlachter et al., Curve 0, 1977), using an entirely different apparatus.

The results of Cisneros[13] et al. (Curve 7, 1976) are much lower than any others, by about a factor of two to three. This experiment was designed primarily to measure differential cross sections, and thus different techniques were used: the scattered D^- beam was scanned with a small detector, and the result was integrated to determine F_-^∞. The total beam was detected by secondary-electron emission (assuming equal coefficients for D^+ and D^0 incident). The D^+ and D^- beams were detected using channel-electron multipliers. Possible sources of uncertainly are the use of a secondary-emission detector in the presence of Cs, the assumption that D^+ and D^0 have equal secondary-electron-emission coefficients at low energies, and the calibration of channel-electron multipliers (also in the presence of Cs). Furthermore there is doubt as to whether the target was sufficiently thick. (Although the authors[13] claim that their quoted equilibrium fractions might be low only by as much as 20%, their results appear to be low by a larger factor.)

It should be possible to calculate F_-^∞ if only two states of deuterium are present in thick targets, i.e., D^- and D^0 (in the ground state), and if the cross sections σ_{g-} and σ_{-0} are known. In this case $F_-^\infty = \sigma_{g-}/(\sigma_{g-} + \sigma_{-0})$. The states D^+ and D^0 (2s) are unimportant for thick Cs targets, as can be seen in Figs. 3 and 4 (Fig. 4, from Ref. 31, includes the metastable state). The cross sections σ_{g-} and σ_{-0} shown in Fig. 6, especially those calculated by Olson et al.[60] at low energies, determine an F_-^∞ which is in total disagreement with experimental results: F_-^∞ calculated this way gives a maximum of 12% at 5 keV, dropping to 3-1/2% at 0.5 keV. Using experimental values for σ_{g-} helps (there are none at low energies for σ_{-0}), but the serious disagreement remains. There are several possible explanations: (a) the cross sections are incorrect; (b) F_-^∞ is incorrect; (c) the D^0 beam in a thick Cs target contains an unknown admixture of higher excited states, having unknown cross sections for D^- formation; (d) the Cs target contains an admixture of dimers, trimers, or heavier polymers (however, the polymer fraction is known to be less than 1% at the highest pressure used)[61]; or (e) the Cs target is excited



XBL779-2307

Fig. 5. Charge-transfer cross sections for D^+ and D^- in Cs vapor.

—— (20 keV and above) Il'in et al.,[21,22] 1965, 1967;

—·— Schlachter et al.,[32] 1969;

– – – (σ_{-+}) Leslie et al.,[24] 1971 (renormalized upward by a factor of two from published values);

—··— Cisneros et al.,[13] 1976;

—...— Spiess et al.,[39] 1972;

—·····— Girnius et al.,[17] 1977;

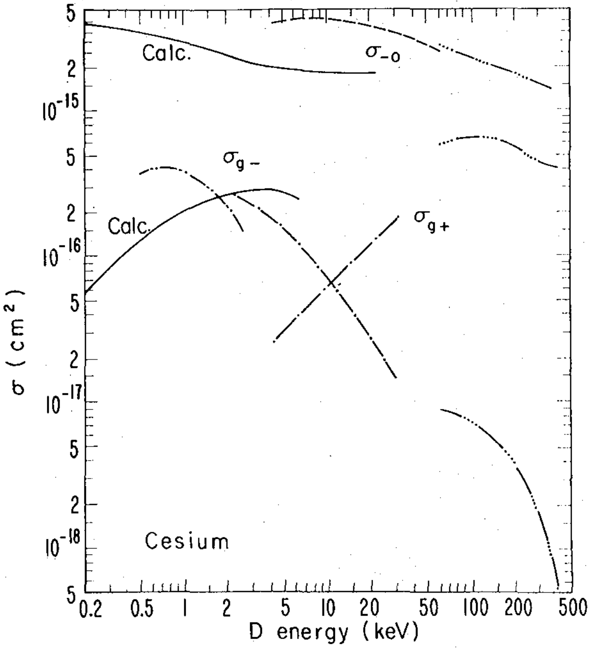
—— (below 5 keV) Olson et al.,[60] 1976 (calculation);

···· Grüebler et al.,[19] 1970;

– – – (σ_{+o}) Meyer et al.,[26,27] 1975,1977.

to the 6p state, from which the cross section for D^- formation could be much larger than from the Cs (6s) state. We have explored the possibility of an effect due to target excitation by varying the intensity of the incident D^+ beam; no variation of F_-^{∞} was observed.

The need for further measurements of cross sections in Cs vapor is evident, especially at low energies. This would perhaps elucidate the D^- formation mechanism which leads to such large values for F_-^{∞}.



XBL779-2304

Fig. 6. Charge-transfer cross sections for D^o and D^- in Cs vapor.

—— Olson et al.,[60] 1976 (calculation -- published values of σ_{g-} have been divided by a factor of four to correct for an error in the original publication);

– – – Leslie et al.,[24] 1971 (renormalized upward by a factor of two from published values);

—·— Schlachter et al.,[32] 1969;

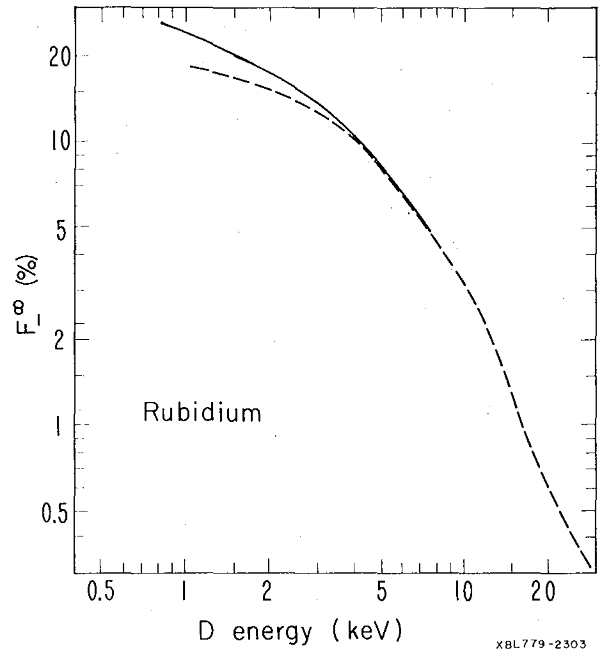
—··— Cisneros et al.,[13] 1976;

—·····— Girnius et al.,[17] 1977.

Two comments about the cross sections shown in Figs. 5 and 6 should be made: (1) the σ_{-o} and σ_{-+} results of Leslie et al.[24] have been multiplied by two to account for renormalization to recent σ_{+o} measurements; (2) the σ_{g-} calculations of Olson et al.[60] have been divided by four to correct an error in the published values.

3. Rubidium-Vapor Target

F_-^{∞} results in a Rb-vapor target are shown in Fig. 7. The results of Stalder et al.[44] are preliminary. The comparison of these results with those of Girnius et al.[18] (1977) shows good agreement at higher energies and slight disagreement at lower energies, which is similar to a comparison of these authors' results for F_-^{∞} in Cs vapor. σ_{+0} (Fig. 8) is the only cross section which has been measured in Rb.

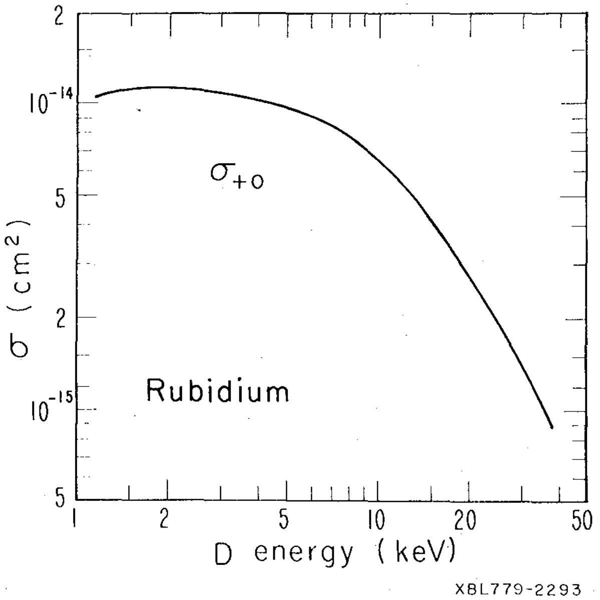


XBL779-2303

Fig. 7. Equilibrium fraction (F_-^∞) of D^- in Rb vapor.

—— Girnius et al.,[18] 1977;

- - - Stalder et al.,[44] 1977.



XBL779-2293

Fig. 8. Charge-transfer cross section for D^+ in Rb vapor.

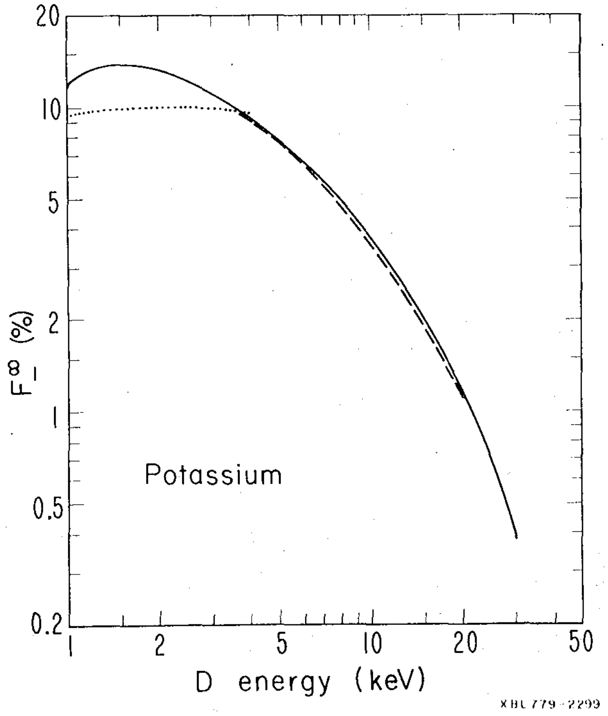
—— Girnius et al.,[18] 1977.

TABLE II. Summary of reported measurements of collisions of deuterium atoms and ions in rubidium vapor.

	Reference	Measured	(D) Energy Range (keV)
Girnius *et al.*	18	σ_{+0}, F_-^∞	1.1 - 40
Sellin & Granoff	38	σ_{+m}	4 - 60
Stalder *et al.*	44	F_-^∞	1 - 7.5

4. Potassium-Vapor, Sodium-Vapor, and Lithium-Vapor Targets.

F_-^∞ results and cross sections in K-vapor, Na-vapor, and Li-vapor targets are shown in Figs. 9-14. It is the author's opinion that all results for F_-^∞ in these vapors should be considered as possibly erroneous, because none of the experiments accounted correctly for target transmissivity (see Cs-target discussion). It is therefore possible that all these results are low, especially at the lower energies. In the case of a Na-vapor target, it is possible that the target thickness was insufficient for the experiment of Dimov and Roslyakov,[53] because they obtained larger F_-^∞ values with D^0 incident than with D^+ incident.



XBL779-2299

Fig. 9. Equilibrium fraction (F_-^∞) of D^- in K vapor.

—— Grüebler et al.,[19,20] 1969,1970;

- - - D'yachkov et al.,[46] 1972;

···· Bohlen et al.,[10] 1968.

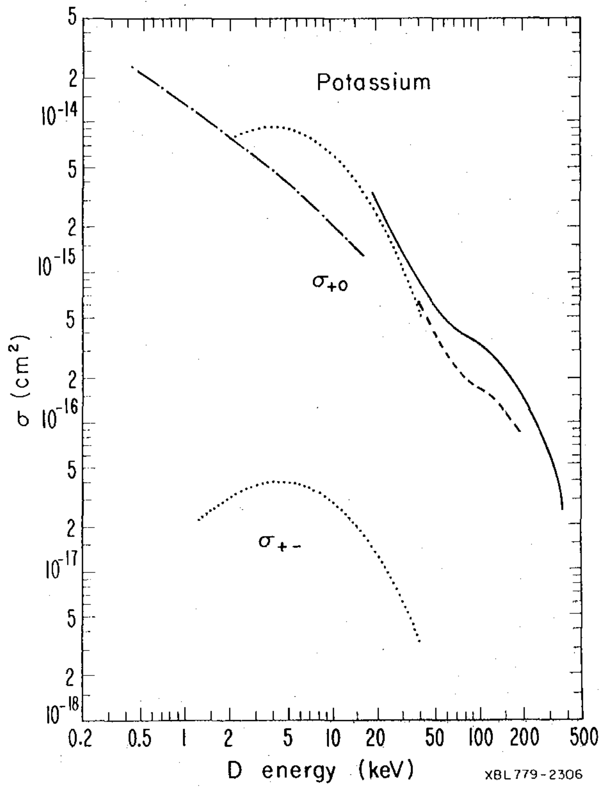


Fig. 10. Charge-transfer cross sections for D^+
—— Il'in et al.,[21,22] 1965,1967;
–·–· O'Hare et al.,[52] 1975;
— — Inoue,[48] 1972 (uncertainty at least a factor of two);
···· Grüebler et al.,[19] 1970.

TABLE III. Summary of reported measurements of collisions of deuterium atoms and ions in potassium vapor.

	Reference	Measured	(D) Energy Range (keV)
Bohlen *et al.*	10	F_-^∞	1 - 4
D'yachkov *et al.*	15,16	F_0^∞, F_-^∞	3 - 80
Futch *et al.*	47	hes	10 - 70
Grüebler *et al.*	19,20	σ_{+0}, σ_{+-}, F_+^∞, F_0^∞, F_-^∞	2 - 40
Il'in *et al.*	21,22	σ_{+0}, hes	20 - 560
Inoue	48	σ_{+0}	0.3 - 16
Nagata	19,50	f	0.8 - 6
Nieman	51	σ_{+0}, F_0^∞	8 - 60
O'Hare *et al.*	52	σ_{+0}	40 - 200
Sellin & Granoff	38	σ_{+m}	4 - 60

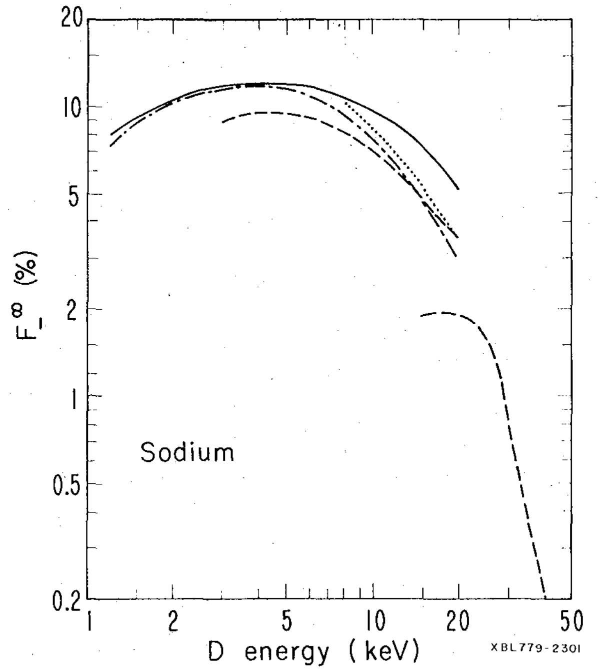


Fig. 11. Equilibrium fraction (F_-^∞) of D^- for D in Na vapor.
—— Grüebler et al.,[19,20] 1969,1970;
– – – D'yachkov et al.,[45,46] 1968,1972;
–·–· Dimov and Roslyakov,[53] 1974 (D^+ incident);
···· Dimov and Roslyakov,[53] 1974 (D^0 incident).

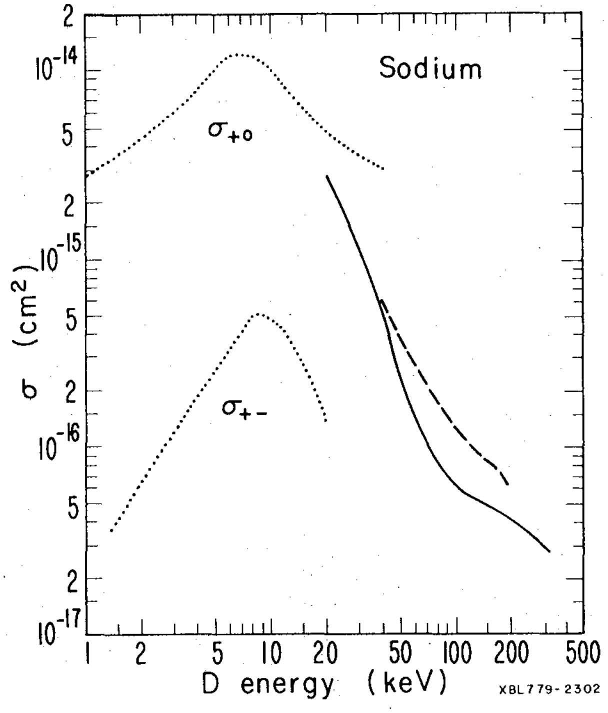


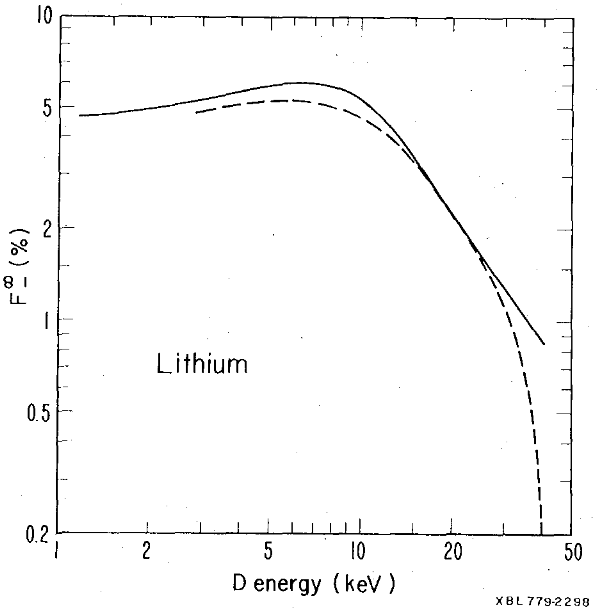
Fig. 12. Charge-transfer cross sections for D^+ in Na vapor.
—— Il'in et al.,[21,22] 1965,1967;
– – – O'Hare et al.,[52] 1975;
···· Grüebler et al.,[19] 1970.

TABLE IV. Summary of reported measurements of collisions of deuterium atoms and ions in sodium vapor.

	Reference	Measured	(D)Energy Range (keV)
Dimov & Roslyakov	53	F_-^∞	2 - 20
D'yachkov *et al.*	45, 46	F_0^∞, F_-^∞	3 - 80
D'yachkov *et al.*	54	F_-^∞	80
Grüebler *et al.*	19, 20	σ_{+0}, σ_{+-}, F_+^∞, F_0^∞, F_-^∞	2 - 40
Il'in *et al.*	21, 22	σ_{+0}, hes	20 - 360
		F_0^∞	20 - 240
Il'in *et al.*	55	σ_{+-}	30 - 360
Nieman	51	σ_{+0}, F_0^∞	8 - 60
O'Hare *et al.*	52	σ_{+0}	40 - 200
Solov'ev *et al.*	56	hes[a]	13 - 180[b]

[a] Also cross section for formation of fast atomic ions and atoms.

[b] 20 - 180 keV H_2^+ and H_3^+ incident beam.

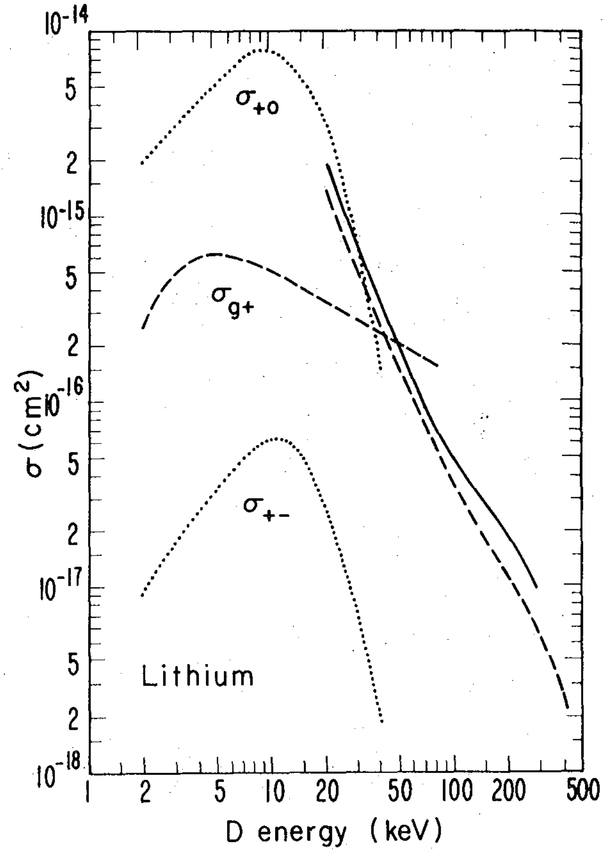


XBL 779-2298

Fig. 13. Equilibrium fraction (F_-^∞) of D^- for D in Li vapor.

—— Grüebler et al.,[19,20] 1969,1970;

---- D'yachkov et al.,[45,46] 1968,1972.



XBL 779-2300

Fig. 14. Charge-transfer cross sections for D^+ and D^o in Li vapor.

—— Il'in et al.,[21,22] 1965,1967;

---- D'yachkov,[58] 1969;

.... Grüebler et al.,[19] 1970.

TABLE V. Summary of reported measurements of collisions of deuterium atoms and ions in lithium vapor.

	Reference	Measured	(D) Energy Range (keV)
Berkner *et al.*	57	σ_{dissoc}	270 - 1200[a]
D'yachkov *et al.*	45, 46	F_0^∞, F_-^∞	3 - 80
D'yachkov	58	σ_{+0}, σ_{0+}	80 - 800
D'yachkov	59	σ_{dissoc}, F_0^{max}[b]	67 - 800[c]
Futch *et al.*	47	hes	10 - 70
Grüebler *et al.*	19, 20	σ_{+0}, σ_{+-}, F_+^∞, F_0^∞, F_-^∞	2 - 40
Il'in *et al.*	21, 22	σ_{+0}, hes	20 - 360
Il'in *et al.*	55	σ_{+-}	30 - 360

[a] 400- 1800 keV H_3^+ incident beam.

[b] F_0^{max} is maximum D^0 yield (or optimum D^o yield).

[c] 100 - 400 keV H^-, H_2^+, H_3^+ incident beams.

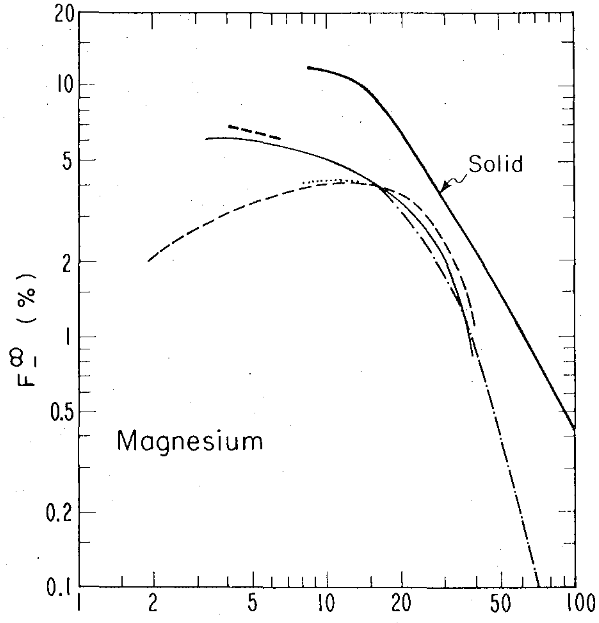
III. Alkaline-Earth-Vapor Targets

1. Introduction

References to all articles known to the author dealing with experimental results for collisions of deuterium and hydrogen atoms and ions with alkaline-earth-vapor targets are shown in Tables VI and VII.[62-76] Energies shown are equivalent deuteron energy (hydrogen energies were multiplied by 2). Experimental results for F_-^∞ and for cross sections not involving excited states of the D atom are shown in Figs. 15-17.

Trends in cross sections[77] indicate that alkaline earths might be useful targets for D^- formation. The only alkaline earths which have been studied as charge-exchange targets for D^- formation are Mg vapor and Sr vapor. No measurements have yet been reported in thick Ca- or Ba-vapor targets.

Measurements of D^- formation in solid Mg have been reported[78]; the D^- yield is a factor of two larger than in Mg vapor.



XBL779-2295

Fig. 15. Equilibrium fraction (F_-^∞) of D^- in Mg vapor.

—— (unlabeled) Berkner et al.,[63] 1977;

– – – D'yachkov et al.,[45,46] 1968,1972;

–·–· Baragiola et al.,[62] 1973;

···· Moses and Futch,[67] 1967;

– – – Morgan,[69] 1977 (unpublished);

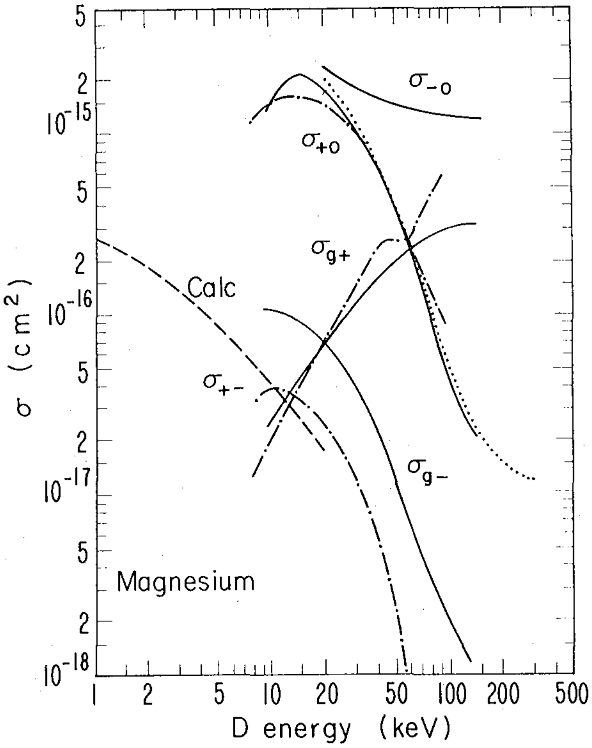
The solid line labeled "solid" shows the D^- fraction emerging from a solid Mg target.[78]

2. Magnesium-Vapor Target

Results for F_-^∞ in Mg vapor are shown in Fig. 15. The results of Baragiola et al.[62] and Berkner et al.[63] are in excellent agreement over the entire energy range where there is overlap (8-39 keV). Agreement is also good with recent results of Morgan[69] and with the higher-energy results of Futch and Moses.[67]. The results of D'yachkov et al.[45,46] are in serious disagreement with the others over most of the energy range. This discrepancy might arise because the target transmissivity was not measured in their experiment.

Cross sections in Mg vapor are shown in Fig. 16. The results of Futch and Moses[67] have been renormalized (multiplied by 0.81) as suggested by Berkner et al.[65] Calculated values[79] for σ_{+-} are are also shown in Fig. 16.

F_-^∞ calculated at 20 keV using cross sections agrees fairly well with the experimental value.[63] It is, however, necessary to take into account the stripping cross section from excited D atoms to obtain agreement between calculated and experimental results for F_+^∞.



XBL779-2305

Fig. 16. Charge-transfer cross sections for D^+, D^0, and D^- in Mg vapor.

– – Berkner et al.,[65] 1969;

–·–· Futch and Moses,[67] 1967 (renormalized downward by a factor of 1.23 from published values, as suggested by Berkner et al.[65]);

···· Il'in et al.,[21] 1965;

—— Olson,[79] 1975 (calculation).

TABLE VI. Summary of reported measurements of collisions of deuterium atoms and ions in magnesium vapor.

	Reference	Measured	(D) Energy Range (keV)
Baragiola *et al.*	62	F_+^∞, F_0^∞, F_-^∞	8 - 80
Berkner *et al.*	63	F_+^∞, F_0^∞, F_-^∞	3.3 - 39
Berkner *et al.*	64	hes	10 - 140
Berkner *et al.*	65	σ_{+0}, σ_{g+}, σ_{g-}, σ_{-0}	10 - 140
Butusov *et al.*	66	F_0^∞	50
		F_o^{max}	40 - 100[a]
D'yachkov *et al.*	45,46	F_0^∞, F_-^∞	2 - 80
Futch & Moses	67	F_+^∞, F_0^∞, F_-^∞, σ_{+0}, σ_{0+}, σ_{+-}	8 - 88
		hes	20 - 100
Il'in *et al.*	21	σ_{+0}, hes	20 - 360
Il'in *et al.*	55	σ_{+-}	30 - 360
Kingdo *et al.*	68	hes	10 - 80[b]
McFarland & Futch	47	hes	10 - 70
Morgan	69	F_+^∞, F_-^∞	4.2 - 6.3
Morgan *et al.*	70,71	*c*	2 - 84[d]
Oparin *et al.*	72	F_0^∞	20 - 240
		hes	20 - 360
Pansenkov & Semashko	73	F_0^∞	20 - 60
Solov'ev *et al.*	56	hes[e]	13 - 180[f]
Stewart & Forsen	74	hes	20[g]

[a] 40 - 100 keV H_2^+ incident beam

[b] 10 - 80 keV D^+, D_2^+, H_2^+ incident beams.

[c] Cross section for formation of ${}^1\Sigma_g^+$ and ${}^3\Pi_u^-$ states of molecule.

[d] 1 - 40 keV/nucleon H_2^+ or D_2^+ incident beam.

[e] Also cross section for formation of fast atomic ions and atoms.

[f] 20 - 180 keV H_2^+ and H_3^+ incident beams.

[g] 10 keV H^+, 20 keV H_2^+ incident beams.

3. Strontium-Vapor Target

The only measurements reported in Sr vapor[75] are equilibrium charge-state fractions. Results for F_-^∞ are shown in Fig. 17. A feature to note is the plateau in the F_-^∞ curve between 5 and 10 keV and the rise at lower energies. This could perhaps arise from oscillations in the electron-attachment cross section σ_{0-}. Measurements of F_-^∞ at lower energies might show further structure. Cross-section measurements would also be of great interest.

TABLE VII. Summary of reported measurements of collisions of deuterium atoms and ions in calcium, strontium and barium vapors.

	Reference	Measured	Target	(D) Energy Range (keV)
Berkner *et al.*	75	F_+^∞, F_0^∞, F_-^∞	Sr	2.7 - 31
McFarland and Futch	47	hes	Ba	10 - 70
Morgan *et al.*	76	σ_{+0}, σ_{+-}, σ_{+m}	Ba	20 - 120
Oparin *et al.*	72	hes	Ca	20 - 360

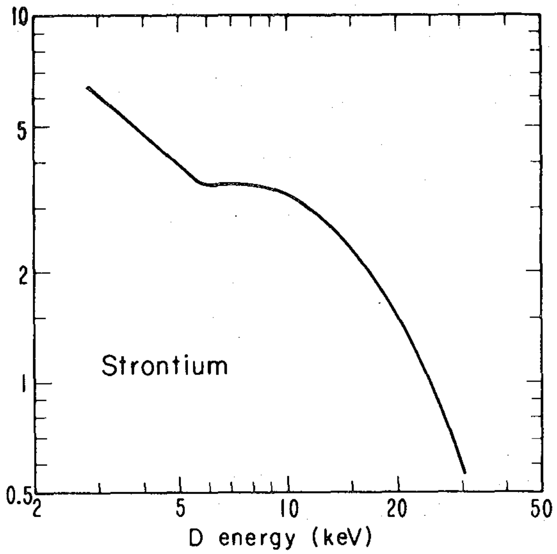


Fig. 17. Equilibrium fraction (F_-^∞) of D^- in Sr vapor.

—— Berkner et al.,[75] 1977.

IV. Other Targets

"Other targets" includes metal vapors such as Pb, Zn, and Hg, which are not discussed in this article; some references are to be found, however, in Table VIII.[80-83]

Also included in "other targets" are solid foils. The reader is referred to Berkner et al.[78] (1972) and the references therein. Although large D^- yields can be obtained from clean metals deposited on a thin foil (see Fig. 15 of the present report for a comparison of the D^- yield from the passage of a D^+ beam through Mg vapor and solid Mg), the application to intense beams is not apparent.

When an intense deuterium beam passes through a metal-vapor target, a plasma can be formed in the target. D^- yields and cross sections for charge transfer are not known at present in plasma targets.

Another category of targets about which little is known is electronically excited targets, i.e., targets excited by passage of the beam through the target or perhaps excited with photons from a laser.

TABLE VIII. Summary of reported measurements of collisions of deuterium atoms and ions in other metal vapors.

	Reference	Measured	Target	(D) Energy Range (keV)
Baragiola & Salvatelli	80	σ_{+0}, σ_{+-}, σ_{0+}, σ_{0-}	Pb	15 - 18
Brooks *et al.*	81	F^∞	Hg	20 - 60[a]
D'yachkov *et al.*	45	F_-^∞	Zn	20 - 60
Fogel *et al.*	82	F_-^∞	Hg	20 - 60
Masuda *et al.*	83	F_-^∞	Hg	12 - 48[a]
Oparin *et al.*	72	F_0^∞, hes	Zn, Cd	20 - 360

[a] Also H_2^+ and H_3^+ incident.

A final category of targets about which very little is known is polymer targets and clusters. A Cs jet created by passage of high-pressure Cs vapor through a nozzle could contain a large fraction of polymers (dimers, trimers, etc.) or even clusters. Since jets are in use for D^- formation, measurements of cross sections and D^- yields in cluster targets would be very interesting.

V. Design Considerations for the Production of D^- Beams

A beam of D^- ions can be obtained by multiple charge-transfer collisons of D^+ in a vapor target. (Direct-extraction D^- sources also exist. This topic is discussed elsewhere in these proceedings.) The options available to the designer include choice of D^+ source, D^+ energy, choice of incident beam species (normally a mixture of D^+, D_2^+ and D_3^+ in some ratio), choice of target material, target thickness (line density), and type of target (jet, oven, heat pipe, etc).

Factors to consider are intensity of the D^+ beam available from the source as a function of extraction voltage, transport of the D^+ beam, efficiency of conversion of the D^+ beam to a D^- beam, loss of beam intensity due to multiple scattering in the charge-transfer target, and space-charge effects on the D^+ and D^- beams before acceleration. Further considerations are deleterious effects of metal vapors on ion-source operation, on the accelerating structure, and eventual contamination of a tokamak or mirror machine by heavy-metal atoms if the D^- beam is used for neutral injection. Further practical problems concern the safe handling of large quantities of liquid metal, and pumping and/or recirculation in the target.

This article addresses only one aspect of these considerations, namely the efficiency of the D^- formation process. Only partial and sometimes contradictory results are available, and then only with low-intensity beams. More reliable measurements of cross sections, equilibrium yields, and angular distributions of D^- formed in thick targets are required. Furthermore, although F_-^∞ in Cs vapor reaches 35% at energies below 500 eV, beam transport and source intensity may be unsatisfactory for some applications. Other targets with a lower D^- formation efficiency, but with a maximum D^- yield at a higher, more convenient energy, might be more suitable for many applications. Furthermore, a target material with a lower atomic number might help reduce high-Z contamination in certain MFE applications.

All of the experiments cited in this paper have been done with low-intensity beams (usually microamperes or less). A practical D^- system will use multiampere beams. Target excitation and ionization might seriously alter the D^- yield compared to that obtained with a low-intensity beam, in which target ionization is not a factor.

Acknowledgements

I would like to thank J. Warren Stearns for stimulating conversations and for his comments on the manuscript. I would like to thank L. W. Anderson and T. J. Morgan for giving me their results prior to publication.

References

1. S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).
2. N. V. Fedorenko, Zh. Tekh. Fiz. 40, 2481 (1970) [Sov. Phys. - Tech. Phys. 15, 1947 (1971)].
3. R. C. Dehmel, H. K. Chau, and H. H. Fleischmann, Atomic Data 5, 231 (1973).
4. H. Tawara and A. Russek, Rev. Mod. Phys. 45, 178 (1973).
5. R. J. McNeal and J. H. Birely, Rev. Geophys. and Space Phys. 11, 633 (1973).
6. C. F. Barnett, J. A. Ray, E. Ricci, M. I. Wiker, E. W. McDaniel, E. W. Thomas, and H. B. Gilbody, "Atomic Data for Controlled Fusion Research," Oak Ridge National Laboratory Report ORNL-5206 (1977).
7. M. A. Abroyan, V. P. Golubev, V. L. Komarov, and G. V. Chemyakin, "Negative Ion Sources," Efremov Institute (Leningrad) Report OD-4, (1974). Available in translation as ERDA-tr-150.
8. R. R. Hultgren, *Selected Values of the Thermodynamic Properties of the Elements* (American Society of Metals, Metals Park, Ohio, 1973).
9. 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)].
10. H. Bohlen, G. Clausnitzer, and H. Wilsch, Z. Phys. 208, 159 (1968).
11. F. Brouillard, W. Claeys, and G. Van Wassenhove, J. Phys. B 10, 687 (1977).
12. A. Cesati, F. Cristofori, L. Millazo Colli, and P. G. Sona, Ener. Nucl. 13, 649 (1966).
13. C. Cisneros, I. Alvarez, C. F. Barnett, and J. A. Ray, Phys. Rev. A 14, 76 (1976).
14. C. Cisneros, I. Alvarez, C. F. Barnett, J. A. Ray, and A. Russek, Phys. Rev. A 14, 88 (1977).
15. C. Cisneros, I. Alvarez, R. Garcia, C. F. Barnett, and A. Russek, *Proc. X Int. Conf. on Phys. of Electronic and Atomic Collisions, Paris, 1977*, G. Watel, Editor (Commissariat a l'Energie, Paris, 1977), v. 2, p. 884.
16. B. L. Donnally, T. Clapp, W. Sawyer, and M. Schultz, Phys. Rev. Lett. 12, 502 (1964).
17. R. J. Girnius, C. J. Anderson, and L. W. Anderson, to be published in Phys. Rev. A.
18. R. J. Girnius, L. W. Anderson, and E. Staab, Nucl. Instrum. Methods 143, 505 (1977).

19. W. Grüebler, P. A. Schmelzbach, V. Konig, and P. Marmier, Helv. Phys. Acta 43, 254 (1970).

20. W. Grüebler, P. A. Schmelzbach, V. Konig, and P. Marmier, Phys. Lett. 29A, 440 (1969).

21. R. N. Il`in, V. A. Oparin, E. S. Solov`ev, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. Pis`ma Red. 2, 310 (1965) [JETP Lett. 2, 197 (1965)].

22. R. N. Il`in, V. A. Oparin, E. S. Solov`ev, and N. V. Fedorenko, Zh. Tekh. Fiz. 36, 1241 (1966) [Sov. Phys. - Tech. Phys. 11, 921 (1967)]. See also E. S. Solov`ev, R. N. Il`in, V. A. Oparin and N. V. Fedorenko, Proc. V Int. Conf. on Phys. of Electronic and Atomic Collisions, Leningrad, 1967, I. P. Flaks and E. S. Solovyov, Editors (Nauka, Leningrad, 1967), p. 6.

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

24. T. E. Leslie, K. P. Sarver, and L. W. Anderson, Phys. Rev. A 4, 408 (1971).

25. F. W. Meyer and L. W. Anderson, Phys. Rev. A 11, 589 (1975).

26. F. W.Meyer and L. W. Anderson, Phys. Lett. 54A, 33 (1975).

27. F. W. Meyer, C. J. Anderson, and L. W. Anderson, Phys. Rev. A 15, 455 (1977). See also L. W. Anderson and F. W. Meyer, Proc. IX Int. Conf. On Phys. of Electronic and Atomic Collisions, Seattle, 1975, John S. Risley and R. Geballe, Editors (Univ. of Washington Press, Seattle, 1975), v. 1., p. 97.

28. J. E. Osher, F. J. Gordon, and G. W. Hamilton, Proc. 2nd Int. Ion Source Conf., Vienna, 1972, p. 876.

29. F. Roussel, P. Pradel, and A. Valance, Proc. VIII Int. Conf. on Phys. of Electronic and Atomic Collisions, Beograd, 1973, B. C. Cobic and M. V. Kurepa, Editors (Institute of Physics, Beograd, 1973), v. 2, p. 747.

30. F. Roussel, thesis (University of Paris-VI, 1973) (unpublished).

31. P. Pradel, F. Roussel, A. S. Schlachter, G. Spiess, and A. Valance, Phys. Rev. A 10, 797 (1974).

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

33. A. S. Schlachter, G. Spiess, and P. Pradel, Proc. VIII Int. Conf. on Phys. of Electronic and Atomic Collisions, Beograd, 1973, B. C. Cobic and M. V. Kurepa, Editors (Institute of Physics, Beograd, 1973), v. 2, p. 749.

34. A. S. Schlachter, J. W. Stearns, F. Roussel, P. Pradel, and G. Spiess, Bull. Am. Phys. Soc. 21, 818 (1976).

35. A. S. Schlachter and J. W. Stearns, Bull. Am. Phys. Soc. 21, 1135 (1976).

36. A. S. Schlachter, J. W. Stearns, D. L. Kagan, and K. R. Stalder, Bull. Am. Phys. Soc. 21, 1265 (1976).

37. A. S. Schlachter, K. R. Stalder, and J. W. Stearns, Proc. X Int. Conf. on Phys. of Electronic and Atomic Collisions, Paris, 1977, G. Watel, Editor (Commissariat a l`Energie, Paris, 1977), v. 2, p. 870.

38. I. A. Sellin and L. Granoff, Phys. Lett. 25A, 484 (1967).

39. G. Spiess, A. Valance, and P. Pradel, Phys. Rev. A 6, 764 (1972).

40. G. Spiess, A. Valance, and P. Pradel, Phys. Lett. 31A, 434 (1970).

41. A. S. Schlachter, Vu Ngoc Tuan, and G. Gautherin, Proc. VIII Int. Conf. on Phys. of Electronic and Atomic Collisions, Beograd, 1973, B. C. Cobic and M. V. Kurepa, Editors (Institute of Physics, Beograd, 1973), v. 2, p. 751; and Vu Ngoc Tuan, thesis (University of Paris-Sud, 1972) (unpublished).

42. Vu Ngoc Tuan, A. S. Schlachter, and G. Gautherin, Nucl. Instrum. Methods 114, 499 (1974).

43. Vu Ngoc Tuan, G. Gautherin, and A. S. Schlachter, Phys. Rev. A 9, 1242 (1974).

44. K. R. Stalder, J. W. Stearns, A. S. Schlachter, J. S. Demboski, and S. J. Proctor, to be published in Bull. Am. Phys. Soc. (APS Mtg. Knoxville, TN., Dec. 1977).

45. B. A. D`yachkov, V. I. Zinenko, At. Ener. 24, 18 (1966) [Sov. At. Ener. 24, 16 (1968)].

46. B. A. D`yachkov, V. I. Zinenko, and M. A. Pavlii, Zh. Tekh. Fiz. 41, 2353 (1971) [Sov. Phys. - Tech. Phys. 16, 1868 (1972)].

47. A. H. Futch, Jr. and C. C. Damm, Nucl. Fusion 3, 124 (1963); R. H. McFarland and A. H. Futch, Jr., Phys. Rev. A 2, 1975 (1970). See also R. H. McFarland and A. H. Futch, Jr. Proc. VI Int. Conf. on Phys. of Electronic and Atomic Collisions, Cambridge, 1969, I. Amdur, Editor (MIT Press, Cambridge, Mass., 1969), p. 441.

48. N. Inoue, Nucl. Fusion 12, 130 (1972).

49. T. Nagata, J. Phys. Soc. Jap. 39, 1334 (1975).

50. T. Nagata, Phys. Lett. 56A, 261 (1976).

51. R. A. Nieman, thesis (University of Pittsburgh, 1971) (unpublished). See also R. Nieman, K. Lulla, and T. M. Donahue, Proc. V Int. Conf. on Phys. of Electronic and Atomic Collisions, Leningrad, 1967, I. P. Flaks and E. S. Solovyov, Editors (Nauka, Leningrad, 1967), p. 18.

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

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

54. B. A. D`yachkov, A. I. Krylov, V. V. Kuznetsov, B. P. Maksimenko, and N. N. Semashko, ERDA-tr-41 (1975).

55. R. N. Il`in, V. A. Oparin, I. T. Serenkov, E. S. Solov`ev and N. V. Fedorenko, Proc. VII Int. 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.

56. E. S. Solov`ev, R. N. Il`in, V. A. Oparin, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. 53, 1933 (1967) [Sov. Phys. - JETP 26, 1097 (1968)].

57. K. H. Berkner, T. J. Morgan, R. V. Pyle, and J. W. Stearns, Phys. Rev. A 8, 2870 (1973).

58. B. A. D`yachkov, At. Ener. 27, 220 (1969) [Sov. At. Ener. 27, 958 (1969)].

59. B. A. D`yachkov, Zh. Tekh. Fiz. 38, 1259 (1968) [Sov. Phys. - Tech. Phys. 13, 1036 (1969)].

60. R. E. Olson, E. J. Shipsey, and J. C. Browne, Phys. Rev. A 13, 180 (1976). The values for σ_{g-} cited should be divided by four (R. E. Olson, private communication).

61. C. S. Lee, D. I. Lee, and C. F. Bonilla, Nucl. Eng. Design 10, 83 (1969).

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

63. K. H. Berkner, D. Leung, R. V. Pyle, A. S. Schlachter, and J. W. Stearns, Nucl. Instrum. Methods 143, 157 (1977).

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

65. K. H. Berkner, R. V. Pyle, and J. W. Stearns, Phys. Rev. 178, 248 (1969).

66. V. I. Butusov, P. A. Mukchin, and V. S. Svishchev, Zh. Tekh. Fiz. 37, 1818 (1967) [Sov. Phys. - Tech. Phys. 12, 1331 (1968)].

67. K. G. Moses and A. H. Futch, Jr., Bull. Am. Phys. Soc. 11, 344 (1966) and private communication. See also A. H. Futch and K. G. Moses, Proc. V Int. Conf. on Phys. of Electronic and Atomic Collisions, Leningrad, 1967, I. P. Flaks and E. S. Solovyov, Editors (Nauka, Leningrad, 1967), p. 12.

68. J. Kingdon, M. F. Payne, and A. C. Riviere, J. Phys. B 3, 552 (1970).

69. T. J. Morgan, (private communication).

70. T. J. Morgan, K. H. Berkner, and R. V. Pyle Phys. Rev. A 5, 1591 (1972).

71. K. H. Berkner, T. J. Morgan, R. V. Pyle, and J. W. Stearns, Nucl. Fusion 13, 27 (1973).

72. V. A. Oparin, R. N. Il`in and E. S. Solov`ev, Zh. Eksp. Teor. Fiz. 52, 369 (1967) [Sov. Phys. JETP 25, 240 (1967)].

73. A. A. Panasenkov and N. N. Semashko, Sov. Phys. - Tech. Phys. 15, 1979 (1971).

74. L. D. Stewart and H. K. Forsen, Phys. Rev. A 8, 184 (1973).

75. K. H. Berkner, D. Leung, R. V. Pyle, A. S. Schlachter, and J. W. Stearns, to be published in Phys. Lett. A.

76. T. J. Morgan, F. J. Eriksen, and D. Mariani, Proc. X Int. Conf. on Phys. of Electronic and Atomic Collisions, Paris, 1977, G. Watel, Editor (Commissariat a l`Energie, Paris, 1977), v. 2, p. 868.

77. J. R. Hiskes, Lawrence Livermore Laboratory Report UCID-853 (1975).

78. K. H. Berkner, I. Bornstein, R. V. Pyle, and J. W. Stearns, Phys. Rev. A6, 278 (1972).

79. R. E. Olson, Phys. Lett. 55A, 83 (1975).

80. R. A. Baragiola and F. R. Salvatelli, Nucl. Instrum. and Methods 110, 503 (1973).

81. Ya. M. Fogel`, L. I. Krupnik, and V. A. Ankudinov, Zh. Tekh. Fiz. 26, 1208 (1956) [Sov. Phys. - Tech. Phys. 1, 1181 (1956)].