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# Collisional Electron Detachment from 20-MeV $D^0$ and $D^-$ Ions*

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Cross sections for collisional electron detachment from 20-MeV deuterium atoms and negative ions have been measured in $H_2$, He, $N_2$, and Ar. The cross sections $\sigma_{01}$ per target molecule for the ionization of neutral atoms are 2.2, 1.6, 20, and 36, respectively, in units of $10^{-18}$ cm$^2$. Results for single-electron detachment from $D^-$ ions, $\sigma_{-10}$, are 7.5, 4.7, 58, and 75, respectively. All values have an uncertainty of $\pm 10\%$, chiefly from absolute-pressure calibration uncertainties. The experimental values for atoms in $H_2$ and He are in agreement with calculations that use the Born and free-collision approximations. The measured cross sections for single-electron detachment from negative ions in $H_2$ and He are about one-half of the calculated values. The two-electron detachment cross sections, $\sigma_{-11}$, are approximately 4% of the single-detachment cross sections, $\sigma_{-10}$, in all gases.

## I. INTRODUCTION

THE cross sections for electron loss from fast hydrogen atoms in hydrogen and helium targets have been calculated by using three models: the semiclassical model of Bohr,[1] the "free-collision" (impulse) approximation,[2] and the first Born approximation.[3,4] All of these models predict an $E^{-1}$ energy dependence at high energies (i.e., where $Ze^2/\hbar v \ll 1$). For a hydrogen target, this condition implies energies above a few hundred kilovolts. In this asymptotic region, the Born and free-collision approximations give numerical values that agree with each other and with experiment[5] to within 15%.

For single-electron detachment from fast $H^-$ ions, the evaluation of the cross section by the Born approximation has been considered too cumbersome to carry out with the best available $H^-$ wave function, and the result is so sensitive to the choice of other approximate wave functions that the magnitude of the cross section is very uncertain.[6] The free-collision approximation, on the other hand, permits a simpler calculation; since it has given good results in the case of electron detachment from $H^0$ it might be expected to be fairly reliable in the $H^-$ case. It has been used to calculate $H^-$ cross sections in H and He[2] and in $N_2$ and $O_2$.[7]

We know of only three $H^-$ experiments at energies that are sufficiently high to test the free-collision approximation. Rose *et al.*[8] have made gas-cell measurements at energies up to 1.8 MeV in $H_2$, $O_2$, Ar, and $CO_2$. Fremlin and Spiers[9] and Verba *et al.*[10] have reported measurements in air at higher energies (but under less well-known conditions) by observing the radial attenuation of $H^-$ internal cyclotron beams. In general, the experimental cross sections are well below the calculated values.

In the present work we have measured the cross sections for electron detachment from hydrogen atoms, $\sigma_{01}$, and from negative hydrogen ions, $\sigma_{-10}$ and $\sigma_{-11}$, in a single high-energy experiment under well-controlled conditions.

We note that the magnitudes of these cross sections and the way they extrapolate to higher energies are of interest in certain high-energy-accelerator design considerations.[7,9]

## II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Fig. 1. A beam of 20-MeV $D^-$ ions[11] from the Berkeley heavy-ion linear accelerator was bent 15 deg to remove any possible contaminants. For the measurements of $\sigma_{01}$, the neutral beam was obtained by single-electron stripping in the first gas cell; all ions emerging from the gas cell were swept out by magnet $S1$, which had a field strength of 4 kG. For the measurements of $\sigma_{-10}$ and $\sigma_{-11}$, the first gas cell was evacuated and magnet $S1$ was set at 0 kG.

The collision chamber was a differentially pumped gas cell, consisting of a high-pressure target chamber sandwiched between two intermediate-pressure chambers backed by a 1500-liter/sec oil diffusion pump. The chambers were connected by 6-mm-diam 5-cm-long

* This work done under the auspices of the U. S. Atomic Energy Commission.

[1] N. Bohr, *The Penetration of Atomic Particles Through Matter* (I Kommission Hos E. Munksgaard, København, 1948).

[2] I. S. Dmitriev and V. S. Nikolaev, Zh. Eksperim. i Teor. Fiz. 44, 660 (1963) [English transl.: Soviet Phys.—JETP 17, 447 (1963)].

[3] D. R. Bates, and A. Williams, Proc. Phys. Soc. (London) A70, 306 (1957).

[4] D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) A68, 90 (1955).

[5] C. F. Barnett and H. K. Reynolds, Phys. Rev. 109, 355 (1958).

[6] M. R. McDowell and G. Peach, Proc. Phys. Soc. (London) 74, 463 (1959).

[7] B. T. Wright, Arch. Math. Naturvidenskab. 53, 9 (1957). An asymptotic expression for $\sigma_{-10}$ in Ar is also given; it should be applicable only at energies considerably higher than those discussed here.

[8] P. H. Rose, R. J. Connor, and R. P. Bastide, Bull. Am. Phys. Soc. 3, 40 (1958). Numerical values taken from Allison (Ref. 12). Estimated errors are from a private communication from P. H. Rose.

[9] J. H. Fremlin and V. M. Spiers, Proc. Phys. Soc. (London) A68, 398 (1955).

[10] J. W. Verba, W. Kündig, A. C. Paul, J. R. Richardson, and B. T. Wright, in Proceedings of International Conference on Sector Focused Cyclotrons Meson Factories, CERN, 1963 (unpublished), p. 95.

[11] We used deuterium ions because the Berkeley heavy-ion linear accelerator does not operate stably at the low gradients necessary for hydrogen acceleration.

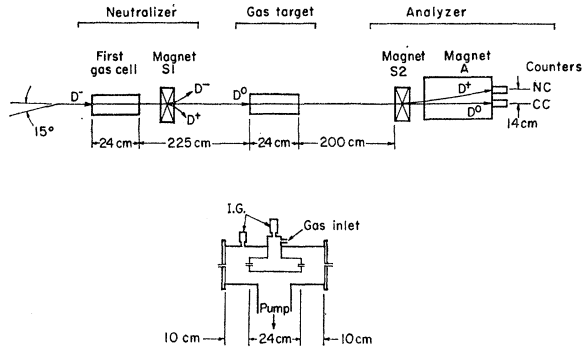


FIG. 1. The experimental arrangement.

tubes (inset Fig. 1). With this cell a base pressure of $5\times10^{-6}$ Torr could be maintained in the drift sections when the pressure in the target chamber was $5\times10^{-2}$ Torr. The effective length of the target chamber was $L=24\pm1$ cm. Integrated target densities ranged from $NL=0.5$ to $30\times10^{15}$ atoms/cm$^2$ for Ar and $N_2$, and $NL=2$ to $200\times10^{15}$ atoms/cm$^2$ for He and $H_2$. The pressure in the target chamber was monitored by a Westinghouse type-7676 high-pressure ionization gauge (Schulz-Phelps gauge) which was cross calibrated with three liquid-nitrogen-trapped McLeod gauges. Fluctuations of the calibration from day to day and uncertainty of the absolute accuracy of the McLeod gauges indicate an uncertainty of $\pm10\%$ in the pressure.

The ions in the beam emerging from the gas target were deflected by magnet $S2$ (3 kG) and steered into the detector CC by magnet A($\approx$8 kG), the neutrals were detected by NC. The detectors NC and CC each consisted of a 5-cm-diam plastic scintillator and photomultiplier. By means of collimating slits it was determined that the ions reaching the detector were well localized in a 5-mm-diam beam spot, which was small compared to the size of the detector. If two species of ions were to be detected, magnet A was used to steer first one and then the other into the detector CC, while the neutral counter was used as a monitor.

### III. RESULTS AND ANALYSIS

Cross sections were calculated at a number of pressures for each target gas according to the following formulas. (We neglect cross sections for electron capture by the fast ions; these are at least three orders of magnitude smaller than the electron loss values considered here.[12])

If $n_0$ is the number of hydrogen atoms at a depth $\pi$ in the target, $\sigma_{01}$ is the cross section for electron detachment, $\Pi\equiv NL$ is the target thickness (atoms/cm$^2$), and $n_+$ is the number of positive ions produced in the thickness $\pi$, then we have

$$dn_0/d\pi=-n_0\sigma_{01}=-dn_+/d\pi\,, \tag{1}$$

[12] S. K. Allison, Rev. Mod. Phys. **30**, 1137 (1958).

with the solution

$$\sigma_{01}=\frac{1}{\Pi}\ln\left[1+\frac{n_+(\Pi)}{n_0(\Pi)}\right]. \tag{2}$$

Similarly, the disappearance rate for negative hydrogen ions due to loss of one electron ($\sigma_{-10}$) and two electrons ($\sigma_{-11}$) in a single collision is given by

$$dn_-/d\pi=-n_-(\sigma_{-10}+\sigma_{-11})\,, \tag{3}$$

with the solution

$$\sigma_{-10}+\sigma_{-11}=\frac{1}{\Pi}\ln\left[1+\frac{n_+(\Pi)+n_0(\Pi)}{n_-(\Pi)}\right]. \tag{4}$$

Using the additional relation

$$dn_0/d\pi=n_-\sigma_{-10}-n_0\sigma_{01}\,, \tag{5}$$

we obtain

$$\sigma_{-10}=\frac{n_0(\Pi)}{n_-(\Pi)}\left[\frac{\sigma_{01}-(\sigma_{-10}+\sigma_{-11})}{1-\exp\Pi(\sigma_{-10}+\sigma_{-11}-\sigma_{01})}\right]. \tag{6}$$

Equations (4) and (6) were solved for $\sigma_{-10}$ and $\sigma_{-11}$, and Eq. (2) was solved for $\sigma_{01}$. Uncertainties in the pressure, cell length, background correction, and counting statistics were propagated through the above equations to obtain the uncertainties in the cross sections.

At sufficiently low pressures, the above equations and the uncertainties in the results can be approximated by relatively simple expressions that demonstrate the correct limiting behavior.

The $\sigma_{01}$ calculations quoted in the text have been carried out for fast hydrogen atoms in the ground state. If an appreciable fraction of the atoms of our beam were in excited states, and if the variation of $\sigma_{01}$ with quantum level, $n$, were sufficiently large, then the experimental values could be considerably greater than the ground-state cross sections. This situation would show up as a decrease in the measured cross sections with increasing gas-cell pressure, closely approaching the ground-state value at the higher pressures. Unfortunately, we did not have time to take $\sigma_{01}$ over a large pressure range (the maximum was a factor of 10 in $H_2$), but no variation of the kind mentioned above occurred in any of the gases.

It is known[13,14] that perhaps 15% of the neutral atoms produced by charge exchange or $H_2^+$ breakup are excited to $n\geqslant3$; the fraction in each state is $f\approx(2-3)n^{-3}$. (The $n=2$ states completely decay in our geometry.) Preliminary measurements by us indi-

[13] A. C. Riviere and D. R. Sweetman, in *Comptes Rendus de la VI$^e$ Conférence Internationale sur les Phénomènes d'Ionisation dans les Gaz* (Paris 1963), Vol. 1, 105.

[14] K. H. Berkner, J. R. Hiskes, S. N. Kaplan, G. A. Paulikas, and R. V. Pyle, in *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions, University College, London, 1963* (North-Holland Publishing Company, Amsterdam, in press).

cate that the excited-state populations are an order of magnitude smaller when the atoms are produced by electron detachment from negative hydrogen ions, as in this experiment. There is also evidence[14,15] that the detachment cross section varies more slowly than $n$. We therefore conclude that the measured cross section is appropriate to the ground state. This question does not arise for the negative-hydrogen-detachment cross sections.

Results for nitrogen are shown in Fig. 2 in order to illustrate the degree of internal consistency. Results for other targets are of similar quality.

The weighted averages of the various cross-section measurements are given in Table I. To aid in the discussion, they are also plotted in Fig. 3 together with lower energy data from other experiments and theoretical estimates. In this figure, and in the following discussion, the ions are treated as if they were 10-MeV hydrogen rather than 20-MeV deuterium particles.

## IV. DISCUSSION AND CONCLUSIONS

### A. Electron Detachment from Neutral Atoms, $\sigma_{01}$

Our measured cross sections for electron detachment from neutral hydrogen in $H_2$ and He are in excellent agreement with the theoretical predictions of the free-collision[2] and Born approximations[3,4] and are consistent with an $E^{-1}$ extrapolation of the lower energy results of Barnett and Reynolds[5] (Fig. 3). For the heavier targets, $N_2$ and Ar, such cross-section calculations have not been reported. A linear extrapolation to the results of Barnett and Reynolds indicates that certainly in Ar, and probably also in $N_2$, the cross section falls off less rapidly than the $E^{-1}$ predicted for and observed in the lighter targets. The semiclassical theory of Bohr,[1] which also predicts the $E^{-1}$ energy dependence in light elements (although it considerably overestimates the magnitudes of the cross sections), predicts a weaker energy dependence, approximately proportional to $E^{-1/2}$ for medium-$Z$ elements. For reference, lines corresponding to $E^{-1}$, $E^{-2/3}$, and $E^{-1/2}$ variations are drawn through our $\sigma_{01}$ point in Ar, but these are not intended to suggest that the asymptotic energy region has been reached.

TABLE I. Measured cross sections per target molecule for 20-MeV deuterium (in units of $10^{-18}$ cm$^2$).

| | $\sigma_{01}$ $\pm10\%$ | $\sigma_{-11}+\sigma_{-10}$ $\pm10\%$ | $\sigma_{-10}$ $\pm10\%$ | $\sigma_{-11}$ $\pm25\%$ | $\sigma_{-11}/\sigma_{-10}$ | $\sigma_{01}/\sigma_{-10}$ |
|---|---|---|---|---|---|---|
| $H_2$ | 2.2 | 7.8 | 7.5 | 0.29 | 0.038 | 0.31 |
| He | 1.6 | 4.9 | 4.7 | 0.14 | 0.029 | 0.34 |
| $N_2$ | 20 | 61 | 58 | 2.7 | 0.046 | 0.34 |
| Ar | 36 | 78 | 75 | 2.5 | 0.033 | 0.48 |

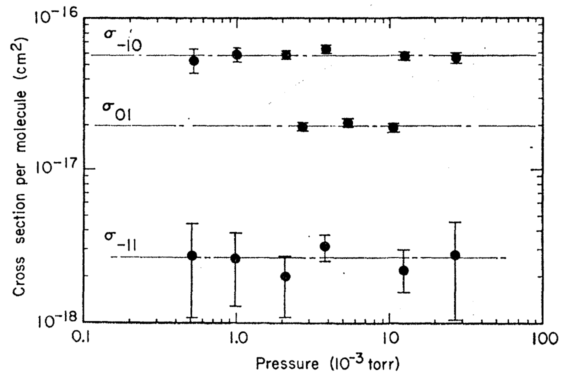


FIG. 2. Cross-section measurements in $N_2$ versus pressure.

### B. Single-Electron Detachment from Negative Hydrogen Ions, $\sigma_{-10}$

The results for single-electron loss from negative hydrogen ions, $\sigma_{-10}$, seem to show the same energy dependence as the $\sigma_{01}$ cross sections at high energies (Fig. 3). The Born-approximation calculation of McDowell and Peach[6] for a hydrogen target predicts a cross section that is $2\frac{1}{2}$ times our experimental value. Moreover, in the 1–10-MeV energy range their calculated cross section has not yet reached the asymptotic dependence and thus varies much more slowly than $E^{-1}$. (The line marked M-P in Fig. 3 is their asymptotic solution.) As mentioned in the introduction, this calculation is extremely sensitive to the choice of the approximation to the $H^-$ wave function. Because of this, they state that their results should not be in error by more than a factor of 5 at high energies.

The free-collision approximation, which requires only a knowledge of the ionization potential, also gives results that are higher than the experimental values for $H_2$,[2] He,[2] and $N_2$.[7]

### C. The Two-Electron Detachment Cross Sections, $\sigma_{-11}$

The cross section for the loss of both electrons from an $H^-$ ion, $\sigma_{-11}$, is approximately 4% of the one-electron detachment cross section, $\sigma_{-10}$, at 10 MeV in all of the target gases. This proportion is similar to that observed by Fogel *et al.* at energies of 40 keV or less.[16] We know of no theoretical predictions for the $\sigma_{-11}$ cross sections; the problem is currently under consideration by McDowell.[17]

[15] A. C. Riviere and D. R. Sweetman, in *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions, University College, London, 1963* (North-Holland Publishing Company, Amsterdam, to be published).

[16] Ia. M. Fogel, V. A. Ankudinov, and R. E. Slabospitskii, Zh. Eksperim. i Teor. Fiz. **32**, 453 (1957) [English transl.: Soviet Phys.—JETP **5**, 382 (1957)].

[17] M. R. McDowell, Royal Holloway College, England (private communication).

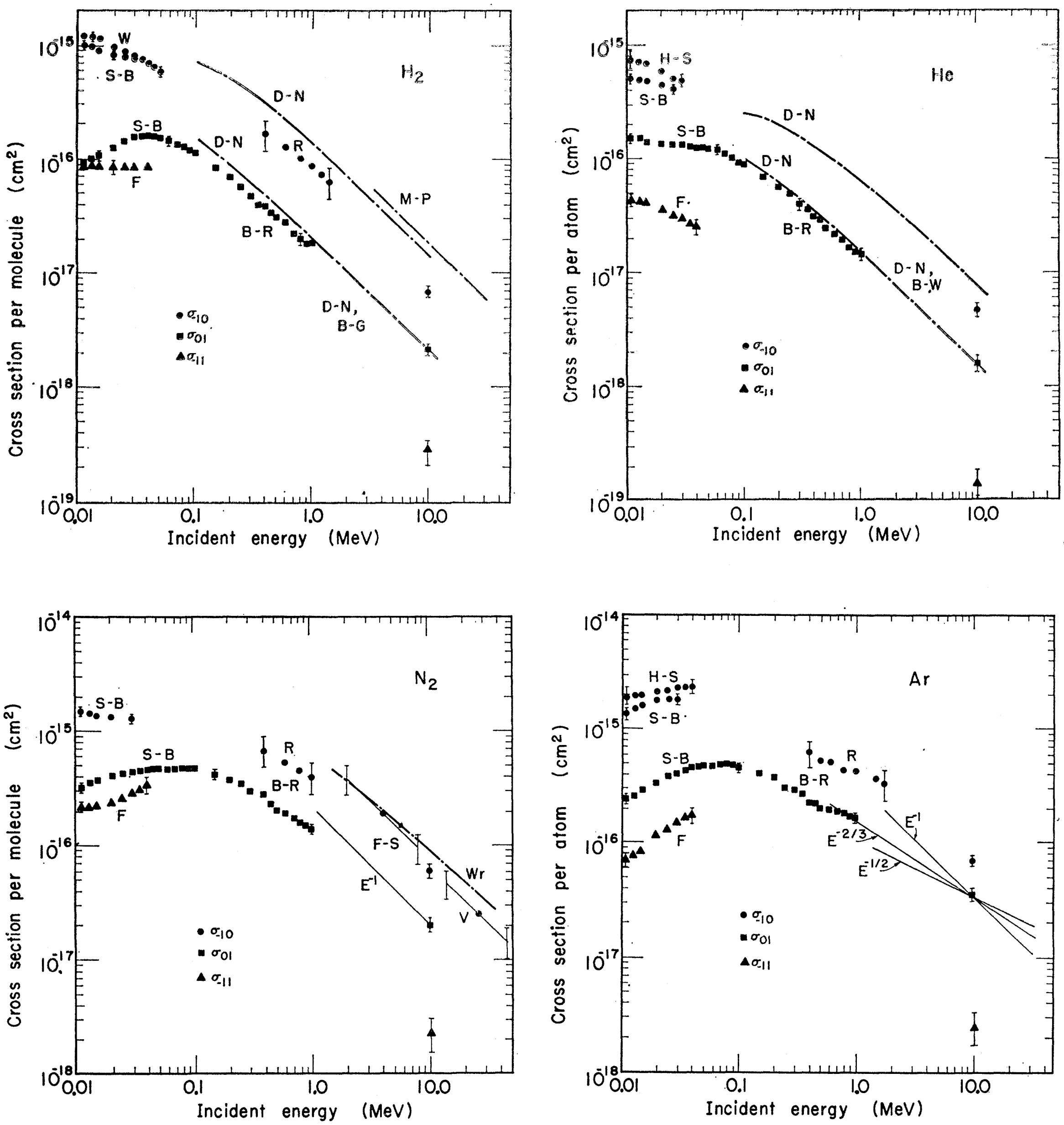


FIG. 3. Energy dependence of the hydrogen cross sections. ●:$\sigma_{-10}$; ■:$\sigma_{01}$; ▲:$\sigma_{-11}$. The "10-MeV" points are the 20-MeV deuterium data of this paper, and the others are from Allison's review article (Ref. 12), which includes measurements by Barnett and Reynolds (B-R), Fogel *et al.* (F), Hasted and Stedeford (H-S), Rose *et al.* (R), Stier and Barnett (S-B), and Whittier (W). The solid lines are internal cyclotron-beam measurements by Fremlin and Spiers (F-S) (Ref. 9) and Verba *et al.* (V) (Ref. 10). The broken lines give Born-approximation calculations by Bates and Williams (B-W) (Ref. 3), Bates and Griffing (B-G) (Ref. 4), and McDowell and Peach (M-P) (Ref. 6), and free-collision-approximation calculations by Dmitriev and Nikolaev (D-N) (Ref. 2) and Wright (Wr) (Ref. 7).

## D. Summary

The measured $\sigma_{01}$ cross sections are in good agreement with theory for $H_2$ and He target gases; calculations are not available in higher $Z$ materials. The $\sigma_{-10}$ cross sections are not in good agreement with theory. As yet, no calculations of $\sigma_{-11}$ have been reported.

Measurements at considerably higher energies are necessary before the asymptotic nature of many of the cross sections can be established.


## ACKNOWLEDGMENTS

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