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CROSS SECTIONS FOR ELECTRON CAPTURE BY 0.3- TO 70-keV DEUTERONS IN H_2, H_2O, CO, CH_4, AND C_8F_{16} GASES*

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Berkeley, California

June 2, 1969

ABSTRACT

Electron-capture cross-section measurements are reported for 0.3- to 70-keV deuterons in H_2, H_2O, CO, CH_4, and C_8F_{16} gases.

I. INTRODUCTION

The containment time for plasmas of interest in controlled thermonuclear fusion research (CTR) is determined in part by charge-exchange collisions with background gas in the confinement region. Some of the background-gas constituents found in high-vacuum systems are H_2, H_2O, CO, and CH_4, and the cross sections σ_{10} for electron capture by protons or deuterons in these gases are required for interpretation of data from CTR plasmas. Cross-section measurements in these gases have been reported in the literature for proton energies in the 100-eV to 2.5-MeV range.[1-19] There are, however, gaps in the energy range and some large discrepancies in magnitudes. We have measured σ_{10} in these gases with 0.3- to 70-keV deuterons, the lower energy limit being set by our experimental arrangement, and the upper limit being chosen to provide a good overlap with other experiments that have been performed using different techniques. The measurements with molecular hydrogen, which

unlike the other gases has a small cross section at low energies where our uncertainties are greatest, were made as a check on our technique.

We also measured σ_{10} in C_8F_{16}, a fluorocarbon vapor used as the change exchange medium in the Phoenix experiment.

II. EXPERIMENTAL APPARATUS AND METHOD

We used the well-known technique of slow-ion collection[20] (Fig. 1). A beam of momentum-analyzed deuterons, collimated to a diameter of 2.2 mm, passed through a target chamber and was collected on a Faraday cup (small permanent magnets provided electron suppression). Slow ions produced by charge-exchange collisions were swept from a well-defined length of the target chamber by a variable, weak electric field applied between a pair of 3-cm-long plates spaced 1 cm apart, and collected on one of these plates. Guard plates were used to provide a uniform electric field in the collection region. Contributions to the plate current from ion-electron pairs produced by ionization, or from secondary electrons produced at the plates, were eliminated by measuring the net current to the two plates.

Large-angle elastic scattering of the primary beam could contribute to the net positive current to the collection plates, especially at the lower energies, and it was necessary to determine the current due to energetic ions. This was done as follows: A magnetic field of 100 gauss along the beam direction was applied to prevent electrons produced by ionization from reaching the plates. A weak electric field was then applied between the plates, and the current to the positive plate was monitored. Without an electric field, both fast (elastically scattered) and slow (produced by ionization and charge-exchange) ions

reached the plate. As the electric field was increased, the current to the positive plate decreased (the slow ions were repelled) until it reached a plateau beyond about 1 V/cm, when only elastically scattered ions of the primary beam reached the plate. At much higher electric fields, the electrons reached the plate and the current again decreased. The total fast-ion current was determined by repeating this procedure for the other plate when the electric field was reversed.

At each energy the sweeping electric field was increased until the collected plate current was independent of the field. The currents from the plates and the Faraday cup were measured with electrometers and integrated for at least six different pressures. Both the net plate current in the absence of a magnetic field and the total fast-ion current, expressed as fractions of the total beam (Faraday cup) current, were linear functions of the target thickness, indicating that the pressures were low enough that two-step processes (e.g., $H^+ \rightarrow H^0 \rightarrow H^+$) were negligible. The difference in the slopes of these two functions yielded the electron-capture cross section.[21] The elastic-scattering contribution was negligible (less than 5%), except for measurements in H_2 and C_8F_{16} at the lower energies, for which the correction was (30 ±10)% at 300 eV.

The pressure in the collision chamber was measured with an ionization gauge which was frequently calibrated against a capacitance manometer. Day-to-day variations in the calibration were ±5% for H_2, CO, and CH_4 and ±10% for H_2O and C_8F_{16}. Pressures were varied from a background of 2×10^{-7} Torr to approximately 5×10^{-5} Torr. For each

gas and energy, the maximum pressure was chosen such that the plate current never exceeded 0.5% of the primary current collected by the Faraday cup. A mass spectrometer attached to the target chamber was used to check for impurities. Corrections due to gas impurities were negligible, except for our two low-energy measurements in H_2, where 0.3% H_2O contamination led to a 10% correction on the cross section.

The deuteron energy was determined by retracting the Faraday cup and passing the beam through an electrostatic analyzer. A retarding-grid analyzer was also used for energies below 3 keV. The two energy measurements agreed within 1.5%. The fractional energy spread in the beam was approximately 0.1% FWHM.

The electrostatic analyzer was also used to check on H_2^+ contamination in the dueteron beam: With a relatively high pressure in the target chamber (approximately 5×10^{13} N_2 molecules/cm^2) the electrostatic analyzer was set to look for protons when a beam tuned for deuterons was incident on the target chamber. We then switched to hydrogen gas in the source and checked our sensitivity by recording protons produced by dissociation of an H_2^+ beam under the same target conditions. From these experiments we determined that the maximum H_2^+ contamination in our D^+ beam was less than 0.1%.

Another possible beam contaminant was D^0, which could be produced by charge exchange in the beam line ahead of the target chamber. Although deuterium atoms in the beam would not be detected by the Faraday cup, they could cause a pressure-dependent negative contribution to the net plate current via electron-loss collisions in the target chamber. To determine the magnitude of this effect, we

magnetically deflected the charged particles of the primary beam so that they could not enter the target chamber, and observed the plate current as gas was admitted to the target chamber. We found that the contribution to the plate current from D^0 in the primary beam was less than 1% of the current produced by D^+.

III. RESULTS AND DISCUSSION

Our electron-capture cross sections for H_2, CO, CH_4, and H_2O are shown in Figs. 2 through 5 along with others reported in the literature.[1-19] Since most of the other results are for electron capture by protons, we have plotted our deuteron cross sections at the equivalent proton energy, i.e., at one-half the deuteron energy.

The C_8F_{16} results are shown in Fig. 6. We know of no other measurements for this target.[22]

Our results are summarized in Table I for convenience. To keep the table simple we do not list the individual data points shown in the figures. Instead we have taken cross-section values at convenient energy intervals from the dashed lines drawn in the figures to represent our results. Since H_2 is well documented in the literature[1-12] and was used mainly to check our technique, these results are not listed in Table I. Also given in the table are our estimates of the standard errors of our measurements, based on uncertainties in pressure determination, electrometer and integrator calibration, slow-ion collection efficiency, and corrections for elastic scattering of the primary beam and gas impurities.

IV. CONCLUSIONS

We note that the electron-capture cross sections per molecule of the substances reported here are nearly identical at low energies, except for the case of molecular hydrogen. The existence of a maximum in the H_2 cross section at a proton energy of about 6 keV has been explained qualitatively with the aid of the Massey adiabatic criterion;[23] for this case the energy defect (the ionization potential of H minus the ionization potential of H_2) is 1.8 eV. The ionization potentials of CH_4, CO, and H_2O are 13.0, 14.0, and 12.6 eV, respectively;[24] the corresponding energy defects are 0.6, 0.5, and 1.0 eV. (We do not know of any value for C_8F_{16}.) Therefore, we would expect these charge-exchange processes to be more nearly resonant than for H_2, and the cross-section maximum for each of the other gases would occur at lower energies than for H_2. Our data indicate that if a cross-section maximum exists in these gases, it must occur near or below a proton energy of 150 eV.

ACKNOWLEDGMENTS

We wish to thank Dr. F. H. Coensgen for calling to our attention the need for these measurements, Dr. C. M. Van Atta for his support of this research, and Dr. A. H. Futch, Jr. for permission to use his unpublished electron-capture cross sections in H_2O. The valuable assistance given by V. J. Honey in the construction and maintenance of much of the electronic equipment is gratefully acknowledged.

FOOTNOTES AND REFERENCES

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

1. Numerous measurements of the electron-capture cross section in H_2 for this energy range have been reported in the literature. A representative sample is given in References 2 through 12.

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20. See, for example, Refs. 8, 9, or 13.

21. The net slow-ion current results from both single- and double-electron capture. Experimental evidence in other gases [see, for example, ALLISON, S. K., GARCIA-MUNOZ, M., in Atomic and Molecular Collision Processes, D. R. Bates, ed., Academic Press, New York (1962)] indicates that double-electron capture cross sections are typically 1% of those for single-electron capture. We have, therefore, assumed that double-electron capture is negligible.

22. Two types of C_8F_{16} were used: Fluorocarbon Liquid PP3 obtained from the Imperial Smelting Corporation, Bristol, England, and Perfluoro-octane obtained from Peninsular Chemresearch, Inc., Gainesville, Fla. We could detect no difference in the cross sections for vapors of the two fluids.

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TABLE I. ELECTRON-CAPTURE CROSS SECTIONS (IN 10^{-16} cm^2/MOLECULE) FOR D^+ IN CO, CH_4, H_2O, AND C_8F_{16}, OBTAINED FROM THE DASHED LINES IN FIGS. 3 THROUGH 6.

Deuteron energy (keV)	Target Gas			
	CO	CH_4	H_2O	C_8F_{16}
0.3	19 ±1.9	27 ±2.7	25.5 ±3.9	29 ±5.8
0.6	19 ±1.9	26 ±2.6	24 ±3.6	31.5 ±6.3
1	18.5 ±1.9	25 ±2.5	22.5 ±3.4	33 ±6.6
2	18 ±1.8	23 ±2.3	20.5 ±3.1	35 ±7.0
4	17 ±1.7	21.5 ±2.2	18 ±2.7	36 ±5.4
6	16 ±1.6	20 ±2.0	16.5 ±2.5	36 ±5.4
10	14.5 ±1.5	18 ±1.8	14 ±2.1	36 ±5.4
20	12 ±1.2	14.5 ±1.5	11 ±1.7	33.5 ±5.1
40	7.8 ±0.8	10.5 ±1.1	7.4 ±1.1	29 ±4.4
70	4.5 ±0.5	6.7 ±0.7	4.7 ±0.7	23.5 ±3.6

FIGURE LEGENDS

FIG. 1. Experimental arrangement (top) and wiring schematic (bottom).

FIG. 2. Electron-capture cross section for protons in H_2: ○, present work for deuterons plotted at the equivalent proton energy; ◑ and ◐, Ref. 2; ■, Ref. 3; ◆, Ref. 4; ▼, Ref. 5; △, Ref. 6; ◆, Ref. 7; ◇, Ref. 8; –, Ref. 9; □, Refs. 10 and 11; and ▲, Ref. 12.

FIG. 3. Electron-capture cross section for protons in CO: ○, present work for deuterons plotted at the equivalent proton energy; ■, Ref. 3; ▼, Ref. 5; ◆, Ref. 7; ◇, Ref. 13; ▽, Ref. 14, and ▲, Ref. 12. The dashed line drawn through our results was used to obtain the cross sections listed in Table I.

FIG. 4. Electron-capture cross section for protons in CH_4: ○, present work for deuterons plotted at the equivalent proton energy; ■, Ref. 3; C-K, Ref. 18; ▼, Ref. 5; K, Ref. 19; and ▲, Ref. 12. The dashed line drawn through our results was used to obtain the cross sections listed in Table I.

FIG. 5. Electron-capture cross section for protons in H_2O: ○, present work for deuterons plotted at the equivalent proton energy; △, Ref. 15; ■, Ref. 3; F-D, Ref. 16; K, Ref. 17; and ▲, Ref. 12. The dashed line drawn through our results was used to obtain the cross sections listed in Table I.

FIG. 6. Electron-capture cross section for deuterons in C_8F_{16} plotted at the equivalent proton energy. The dashed line drawn through our results was used to obtain the cross sections listed in Table I.

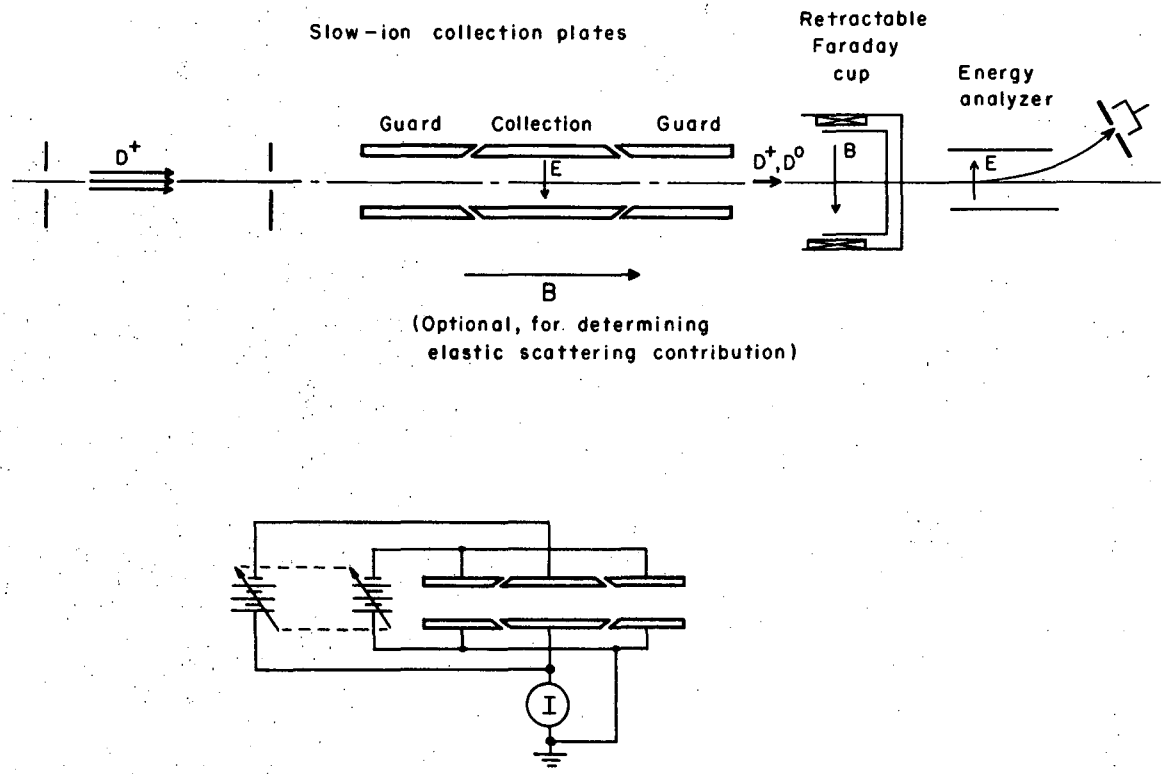
Slow-ion collection plates
Retractable Faraday cup
Energy analyzer
Guard
Collection
Guard
D+
E
D+,D0
B
E
B
(Optional, for determining elastic scattering contribution)
I
XBL696-2926

Fig. 1.

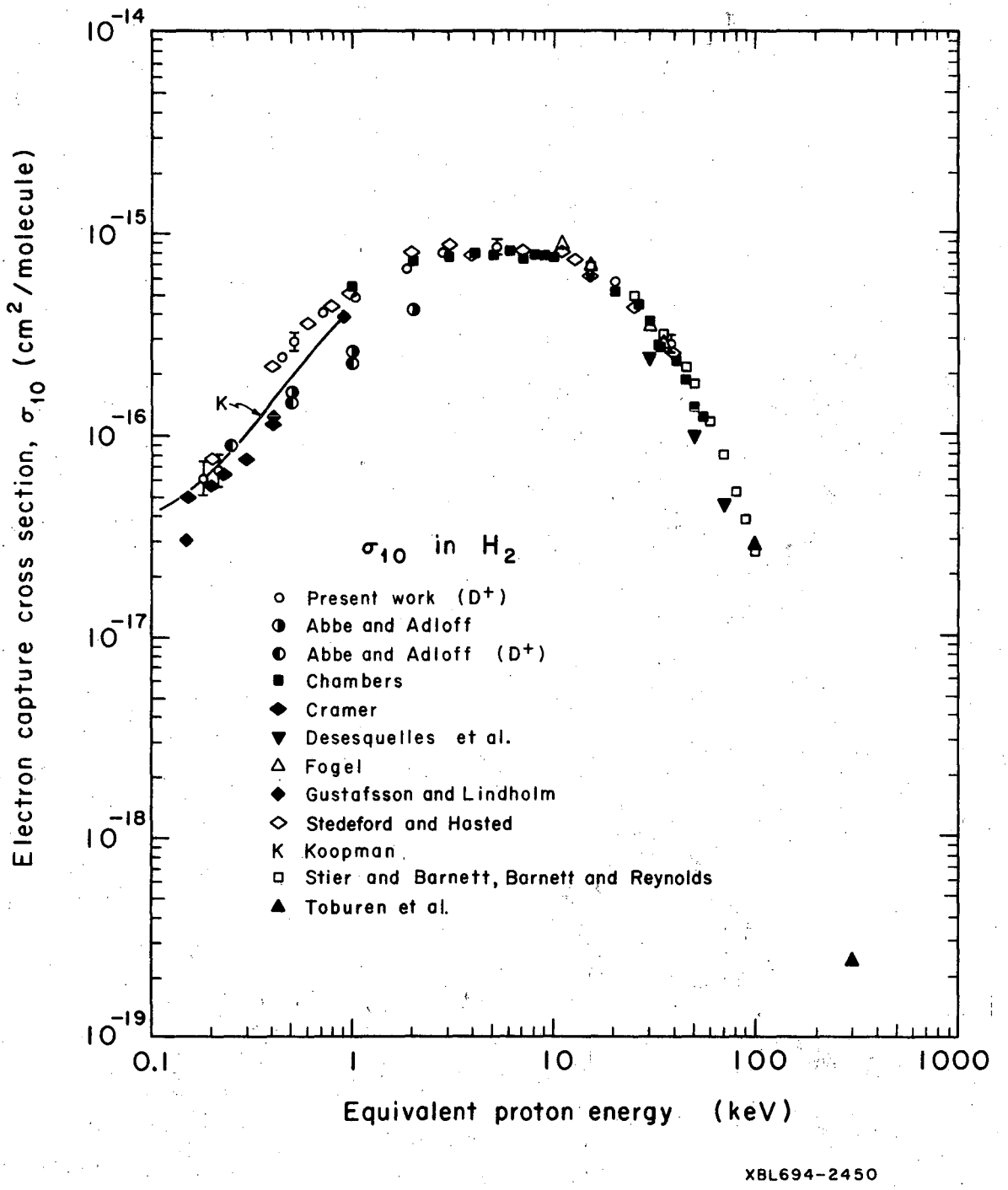
Electron capture cross section, σ_{10} (cm^2/molecule)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
0.1
1
10
100
1000
Equivalent proton energy (keV)
σ_{10} in H_2
Present work (D^+)
Abbe and Adloff
Abbe and Adloff (D^+)
Chambers
Cramer
Desesquelles et al.
Fogel
Gustafsson and Lindholm
Stedeford and Hasted
K Koopman
Stier and Barnett, Barnett and Reynolds
Toburen et al.
K
XBL694-2450

Fig. 2.

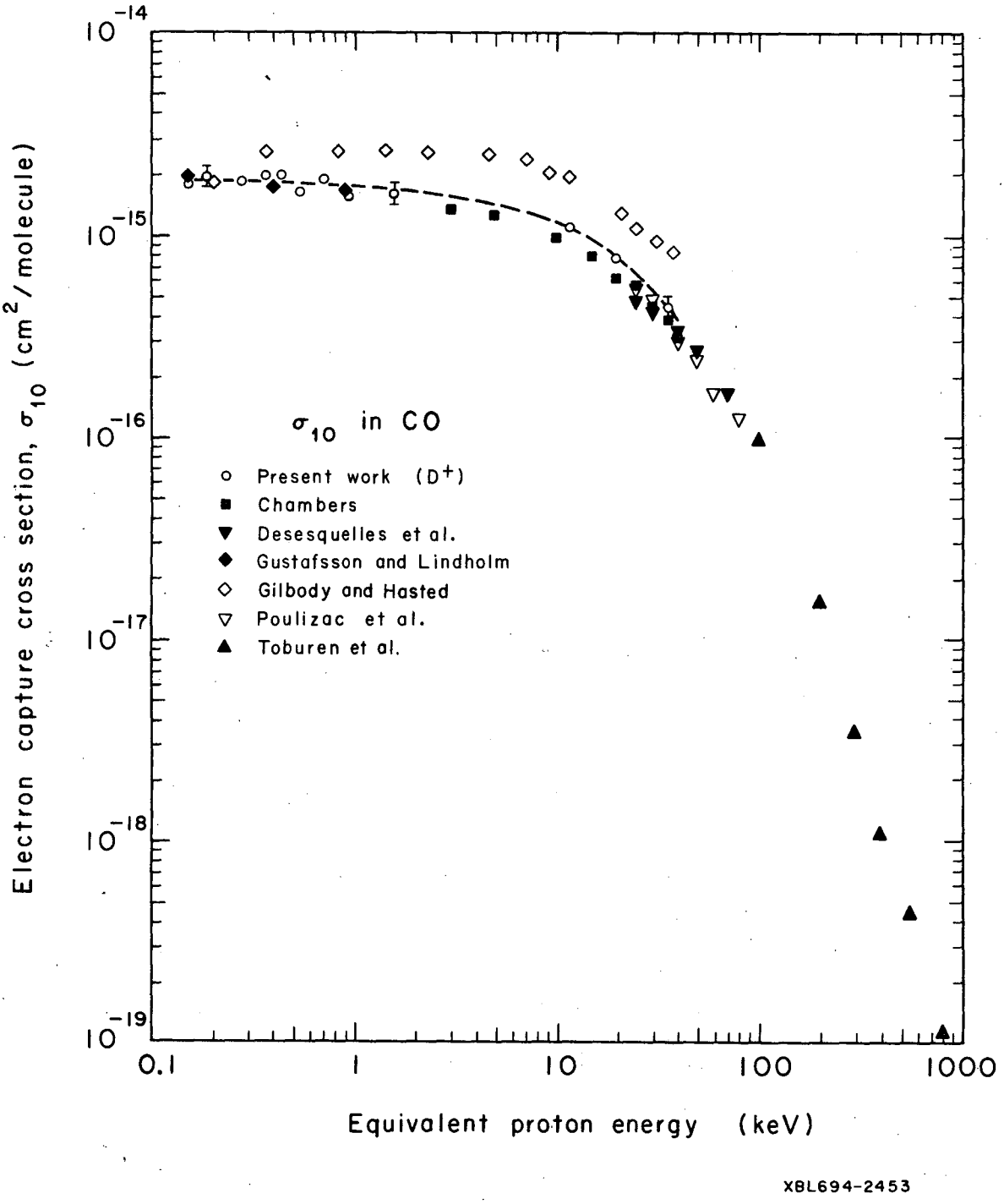
Electron capture cross section, σ_{10} (cm^2/molecule)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
σ_{10} in CO
Present work (D^+)
Chambers
Desesquelles et al.
Gustafsson and Lindholm
Gilbody and Hasted
Poulizac et al.
Toburen et al.
0.1
1
10
100
1000
Equivalent proton energy (keV)
XBL694-2453

Fig. 3.

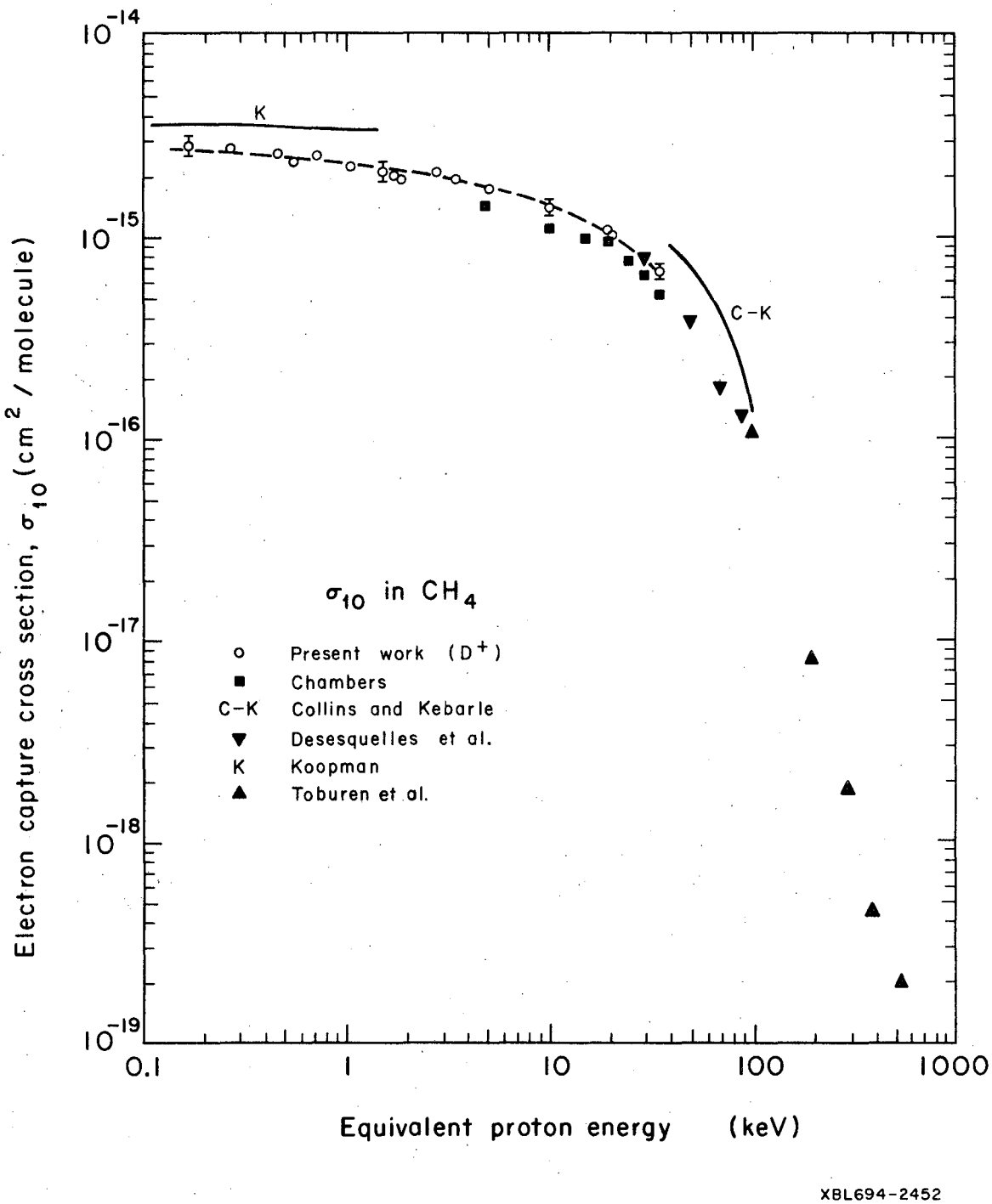
Electron capture cross section, σ_{10} (cm^2 / molecule)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
K
C-K
σ_{10} in CH_4
o Present work (D^+)
■ Chambers
C-K Collins and Kebarle
▼ Desesquelles et al.
K Koopman
▲ Toburen et al.
0.1
1
10
100
1000
Equivalent proton energy (keV)
XBL694-2452

Fig. 4.

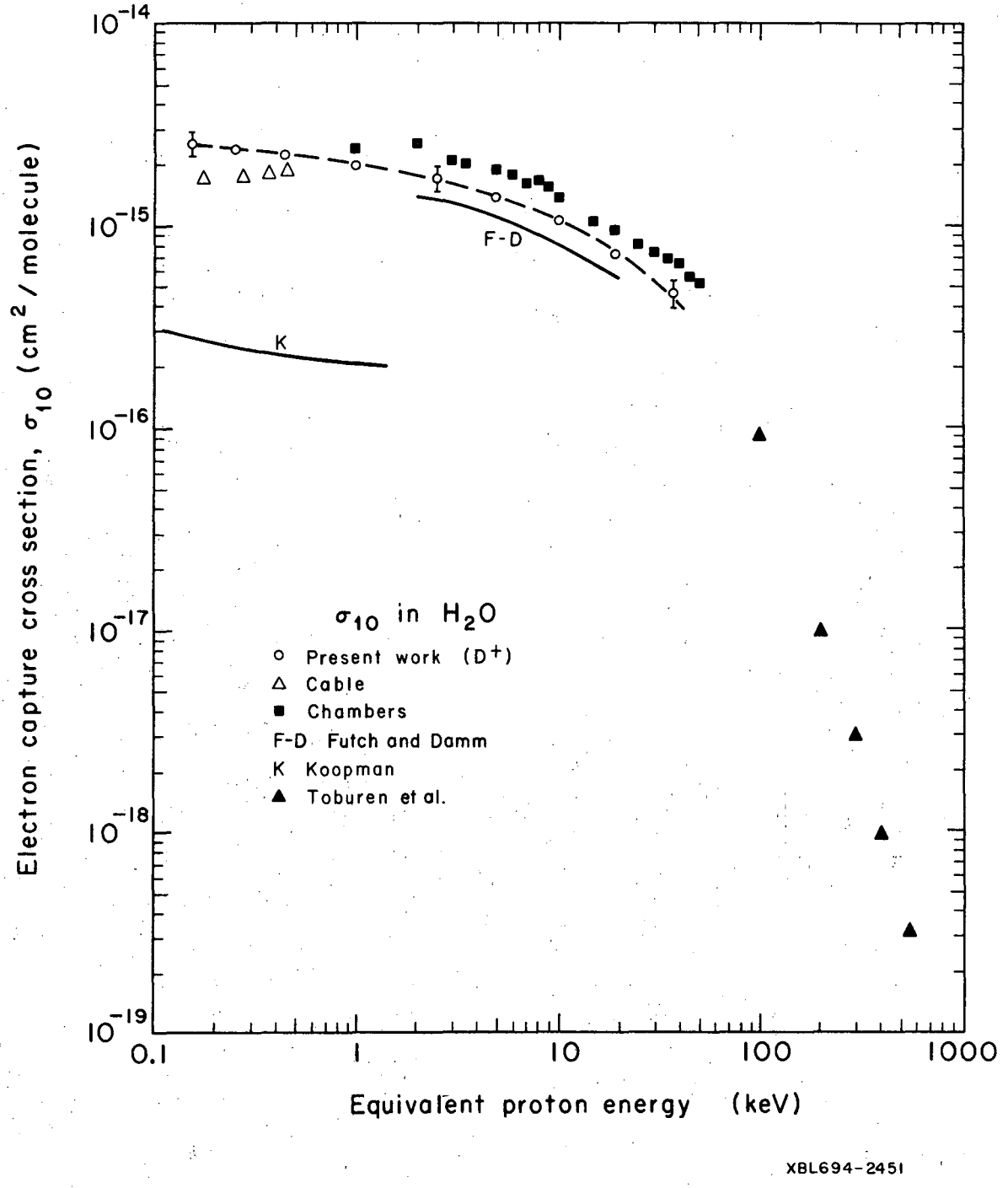
Electron capture cross section, σ_{10} (cm^2 / molecule)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
0.1
1
10
100
1000
Equivalent proton energy (keV)
F-D
K
σ_{10} in H_2O
Present work (D^+)
Cable
Chambers
F-D Futch and Damm
K Koopman
Toburen et al.
XBL694-2451

Fig. 5.

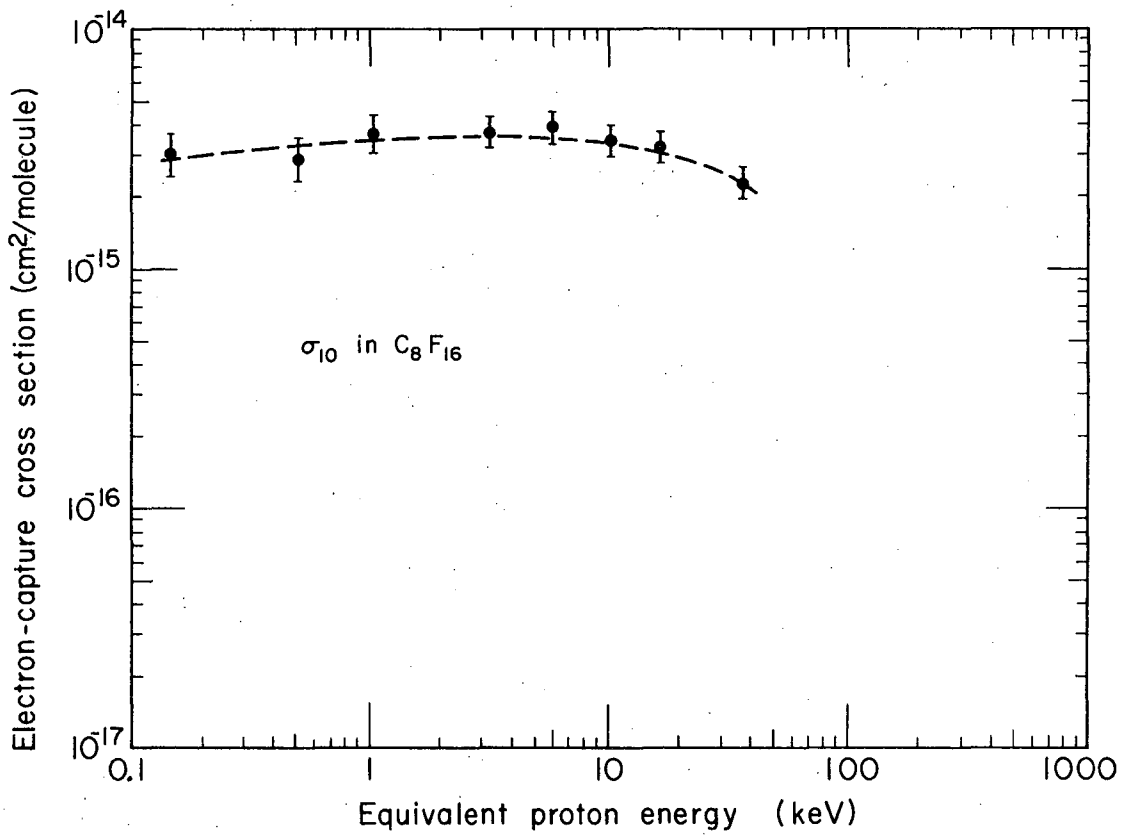
Electron-capture cross section (cm²/molecule)
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
σ10 in C8 F16
0.1
1
10
100
1000
Equivalent proton energy (keV)
XBL696-2925

Fig. 6.

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