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Cross sections for ionization, capture, and loss for 5–450-keV He^+ on water vapor

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Cross sections for the production of positive ions and electrons and for the capture and loss of electrons by 5–450-keV He^+ ions making collisions with water-vapor molecules have been measured. The ionization cross sections σ_+ and σ_- were measured by the transverse-field method and the electron-capture and -loss cross sections σ_{10} and σ_{12} by electrostatic separation of the beam components after passing through a known length of target gas. The four cross sections were adjusted to satisfy the equation $\sigma_+ - \sigma_- = \sigma_{10} - \sigma_{12}$.

I. INTRODUCTION

Basic atomic cross-section data on water vapor are very scarce. For He^+ impact the only measurements are by Koopman[1] for electron capture from 0.1 to 1.4 keV and by Toburen, Wilson, and Popowich,[2] who measured doubly differential cross sections for electron ejection from 300–2000 keV He^+ and He^{2+} impacts. To our knowledge, these fragmentary results are the only cross sections of this kind in the literature, in spite of the importance of water vapor in atmospheric and biological applications.

Here we are reporting on an extension of measurements recently published[3] of the same cross sections for ten different target gases. The present work is for a somewhat smaller energy range since all of the work was done at one laboratory. We have measured the cross sections for production of positive and negative charge σ_+ and σ_-, and the cross sections for capture and loss of one electron by the projectile σ_{10} and σ_{12}.

II. EXPERIMENTAL PROCEDURE

The experimental apparatus was described previously[3] and the description will not be repeated here. The target gas was the vapor from a sample of triply distilled water from which dissolved gases were eliminated by running it through several cycles of freezing, pumping, and thawing. The purity of the target gas was checked using a quadrupole gas analyzer.

Two accelerators, one covering the energy range of 5–100 and the other from 40–350 keV were used. One additional point was obtained at 450 keV equivalent energy by using the isotope $^3He^+$ at 337.5 keV. The cross sections σ_+ and σ_- were measured by the transverse-field or parallel-plate-capacitor method. The target-gas pressure was about 10^{-4} Torr as measured by a capacitance manometer. This was low enough that no correction needed to be made for neutralization of the beam. For the electron-transfer cross sections the charge components of the beam, after passing through a 9.05-cm effective length of target gas in a gas cell, were separated by a transverse electrostatic field. The neutral, singly, and doubly charged components were caught in three separate detectors. The He^+ beam was measured in a Faraday cup while secondary emission detectors were used for the other two beam components. The secondary emission coefficient was measured for the detector of the 2+ beam but for the neutral detector it was measured for a beam of He^+ and assumed to be the same for He^0. Stier, Barnett, and Evans[4] have found the difference between the coefficients for He^0 and He^+ to be only a few percent.

To avoid discontinuities at the points of overlap between the runs, and to smooth out the scatter in the data, a smooth curve was drawn through the average of the points and values read from this curve. As in our previous work, we then utilized the equation

$$\sigma_+ - \sigma_- = \sigma_{10} - \sigma_{12} \tag{1}$$

to make an adjustment of our data. This equation is easily derived from considerations of conservation of charge, assuming that σ_{1-1}, the cross section for capture of two electrons, is negligible. No data are available on this cross section for water, but for the 20–70 keV $He^+ + Ar$ data of Melchior and Papkow[5] the cross sections are about five orders of magnitude smaller than σ_+ and more than a factor

TABLE I. Cross sections for ionization and electron transfer for $^4He^+ + H_2O$ collisions. Units are 10^{-20} m^2.

Energy (keV)	σ_+	σ_-	σ_{10}	σ_{12}
5	6.3 ±1	2.5 ±0.5	3.8 ±0.8	...
6	7.1	2.7	4.4	...
7	7.8	2.9	4.8	...
8.5	8.5	3.2	5.3	...
10	9.4	3.4	6.0	...
12	10	3.7	6.5	...
14	11 ±1	3.9 ±0.5	6.8 ±1	0.0018 ±0.0006
17	11	4.2	7.1	0.0030
20	12	4.5	7.3	0.0046
25	12	4.8	7.4	0.0076
30	13	5.3	7.4	0.011
35	13	5.6	7.3	0.016
40	13 ±1	5.9 ±0.5	7.2 ±1	0.021 ±0.005
50	13	6.3	6.8	0.035
60	13	6.7	6.4	0.052
70	13	6.9	6.0	0.071
85	13	7.2	5.5	0.11
100	12	7.5	4.9	0.14
120	12 ±1	7.9 ±0.6	4.3 ±0.6	0.20 ±0.05
140	12	8.1	3.7	0.26
170	11	8.4	3.1	0.36
200	10	8.5	2.5	0.47
250	9.9	8.6	1.9	0.63
300	9.4	8.7	1.4	0.80
350	8.8 ±0.8	8.6 ±0.6	1.1 ±0.2	0.95 ±0.2
450	7.9	8.5	0.72	1.3

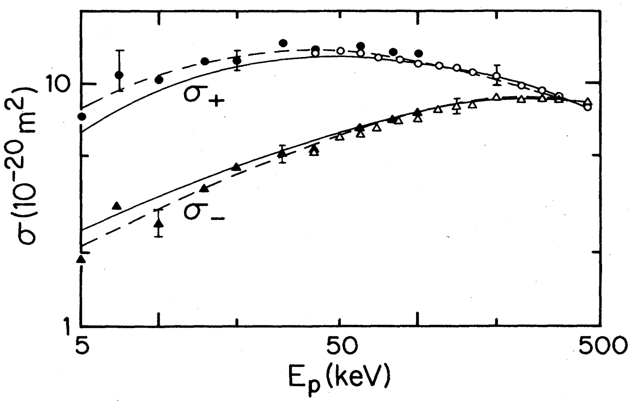

FIG. 1. Values of σ_+ (circles) and σ_- (triangles) for He^+ on water vapor. Filled symbols, data from the low-energy accelerator; open symbols, data from the high-energy accelerator. Dashed line, smooth curve drawn through average of the points; full curve, final adjusted values.

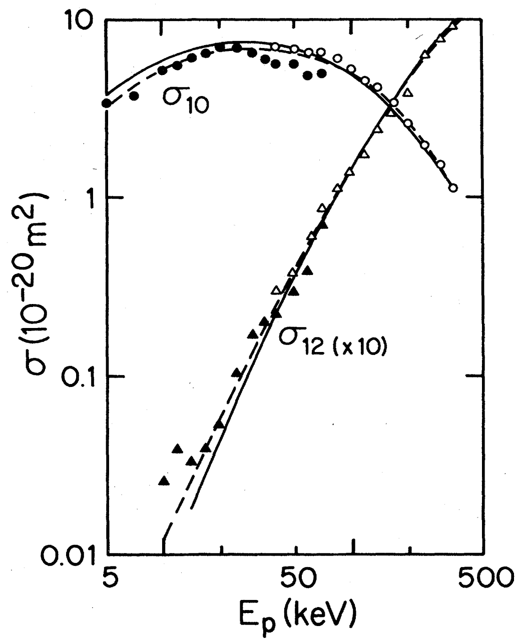

FIG. 2. Values of σ_{10}, circles, and σ_{12}, triangles, for He^+ on water vapor. Legend same as Fig. 1.

of 20 smaller than σ_{12}. Since Eq. (1) is quite rigorously true, it could be used to determine one cross section from measurements on the other three. But in our case we measured all four, and therefore made a least-squares adjustment of the four cross sections to make them satisfy Eq. (1). The adjustments required were all within the uncertainties of the measurements and therefore could have been omitted. However, making the data satisfy Eq. (1) gave the cross sections an internal consistency they would not otherwise have had.

III. UNCERTAINTIES

Since the measurements were all made at one laboratory, the analysis of uncertainties is slightly different from that in the earlier work.[3] The measurement of target-gas density was uncertain by 4%. The effective path length was known to 1% for the ionization measurements but because of the uncertainty in the end corrections only to 7% for the electron-transfer measurements. The primary beam collection and measurement had an uncertainty of 12% at the lowest energies measured, decreasing to 3% at 100 keV and above. Background signal currents decreased from approximately 12% at 5 keV to a negligible amount above about 30 keV for the ionization measurements. The uncertainty in the signal current measurements varied from 8–12% for σ_+, from 5–12% for σ_-, from 13–53% for σ_{12}, and was 11–12% for σ_{10}. The larger uncertainty in each case was for 5 keV and the smaller one for energies of 100 keV and above. These included the uncertainties in the secondary emission coefficients for the electron-transfer cross sections.

The uncertainties in each cross-section measurement were used to calculate the weighting factors for the least-squares adjustment. The algorithm used to approximate the uncertainties discussed above was $F = A + B/E$, where F is the fractional uncertainty and E the beam energy in keV. The values of A were 0.09, 0.07, 0.15, and 0.22 and of B were 0.6, 0.7, 0.25, and 1.65 for σ_+, σ_-, σ_{10}, and σ_{12}, respectively.

IV. EXPERIMENTAL RESULTS

The adjusted values of the cross sections are given in Table I along with the uncertainties calculated from this algorithm. Figures 1 and 2 show plots of the original data, shown as points, the smooth curves drawn as averages of the data, shown as dotted lines, and the final adjusted values, shown as solid lines.

The only previous data[6] on any cross section that we can compare with is the 300-keV σ_- cross section obtained by Toburen *et al.*[2] by integrating their differential cross-section data. Their cross section is within 4% of our value, well within the uncertainty of the measurement. Their higher-energy data fit on smoothly to an extrapolation of our σ_- curve.

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[6] While the data of Koopman (Ref. 1) for σ_{10} are at a lower energy than our graph shows, an extrapolation of our data to lower energies would be generally consistent with his highest-energy point. However, the trend of his data is upward with decreasing energy while ours is downward.