Vibrationally elastic scattering cross section of water vapor by electron impact

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Absolute differential cross sections of electrons vibrationally elastically scattered from water vapor have been measured at room temperature by electron impact. A modulated crossed-beam method was used. The energy and angular range covered were from 2.2 to 20 eV and from 15° to 150°, respectively. Strong backward scattering has been observed as predicted by theory. The measured integrated and momentum-transfer cross sections are generally larger than others in the literature by 50%.

I. INTRODUCTION

The interaction of electrons with water vapor is relevant to several fields including radiation biology, planetary and terrestrial aeronomy, and astrophysics. The interaction of electrons with water vapor includes various kinds of scattering processes (elastic, electronic, vibrational and rotational excitations, ionization, and dissociation). As reviewed by Trajmar *et al.*,[1] only fragmentary data are available at low energies. Bruche[2] measured total cross sections and Jung *et al.*[3] measured the differential elastic scattering cross sections at impact energies 2.14 and 6 eV. The angular range covered was from 30°–105°. Recently, Danjo and Nishimura[4] have reported the most extensive measurements of absolute differential cross sections and momentum-transfer cross sections of water vapor. The energy and angular ranges covered were from 4–200 eV and from 10°–120°, respectively. Theoretically, Fujita *et al.*[5] have calculated elastic differential cross sections using the Glauber approximation for energies greater than 50 eV. Very recently, Brescansin *et al.*[6] reported on elastic differential and momentum-transfer cross sections of water vapor by electron impact for collision energies from 2–20 eV. These cross sections were calculated using the fixed nuclei and static-exchange approximation with a multichannel extension of the Schwinger variational method. They predict strong backward-scattering cross sections at energies higher than 10 eV. However, there are no experimental data to confirm their prediction. Gianturco and Thompson[7] and Jain and Thompson[8] both calculated the momentum-transfer cross sections by using a local exchange and a polarization potential.

This paper presents results of measurements of absolute elastic (vibrationally) differential and momentum-transfer cross sections of water vapor by electron impact. The energy and angular ranges covered were from 2.2–20 eV and from 15°–150°, respectively. Indeed, we observed a strong backward scattering above 10 eV impact energy as predicted by Brescansin *et al.*

II. APPARATUS AND PROCEDURE

The schematic diagram of the apparatus used is shown in Fig. 1. A detailed description can be found elsewhere.[9–11] Briefly, the apparatus has two chambers, an upper and lower chamber. These chambers are pumped differentially. In the upper chamber, a modulated neutral beam (30–100 Hz used) by a supersonic beam source is located and the modulated beam from the device enters into the lower chamber through a double skimmer located between two chambers. In the lower chamber, a rotatable electron-beam source, a fixed detector system on the vacuum chamber wall, and a quadrupole mass

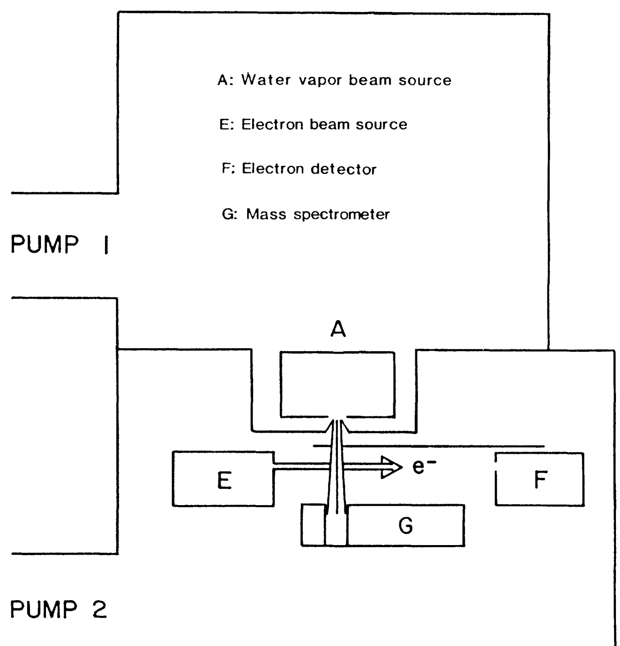


FIG. 1. Schematic diagram of apparatus.

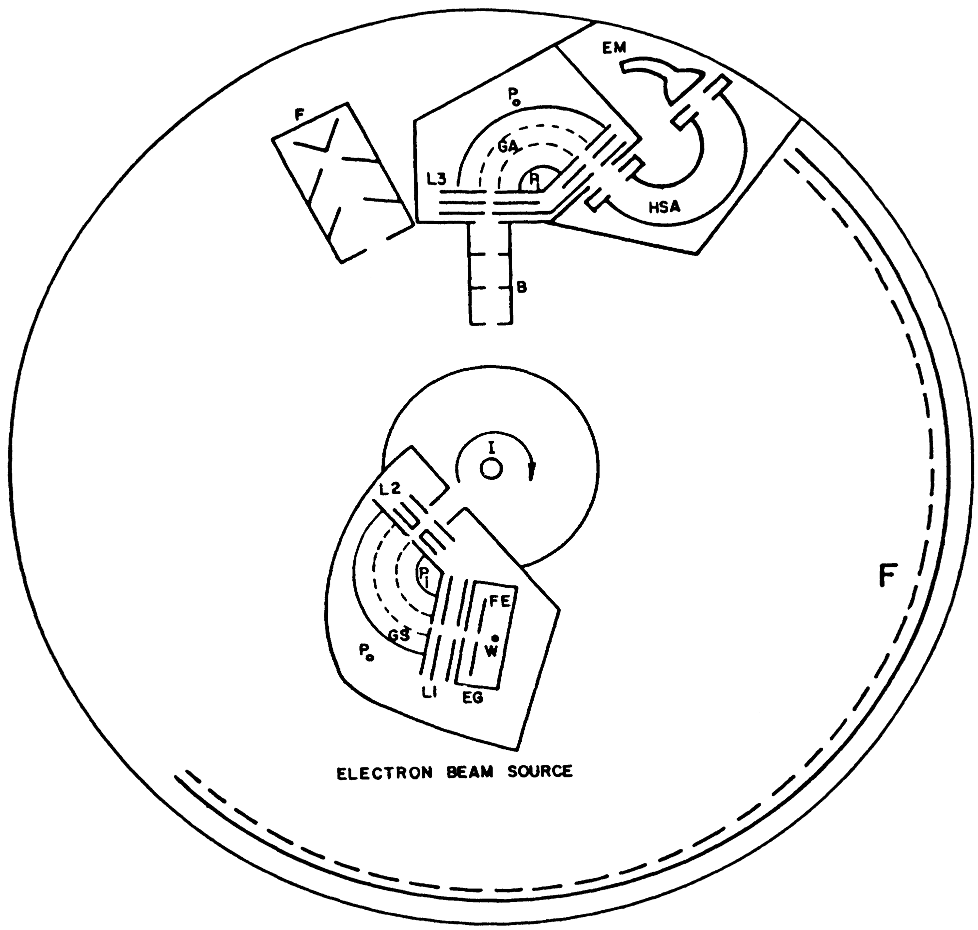
spectrometer are placed in a horizontal plane. A detailed diagram of the apparatus in the lower chamber is shown in Fig. 2.

The purity of the water-vapor beam from the source was checked by a quadrupole mass spectrometer. No dimers and other elements were detected in the beam.

The rotatable electron-beam source shown in Fig. 2 consists of an electron gun, a 127° energy selector, two electron-lens systems, and two electron-beam deflectors. This system produces an electron current of 10^{-9} A with an energy resolution of 80 meV in half-width at 2 eV incident energy and better for higher energies. The divergence angle of the electron beam is $\pm 3°$. This system can be rotated from $-90°-150°$ continuously.

The fixed detector system also shown in Fig. 2 consists of two electrostatic energy analyzers in series, two electron-lens systems, and a channeltron electron multiplier. This double energy analyzer system improves the energy resolution and also reduces background noise by a factor of more than 100 compared to the previously used single energy analyzer system.

Angular distributions of elastic cross sections at various incident energies were obtained as follows: The electron beam in a horizontal plane intersects with a vertically collimated water-vapor beam which is modulated by a supersonic device at the interaction region and vi-



W : FILAMENT
EG : ELECTRON GUN
FE : FOCUS ELECTRODE
L1 : LENS 1
L2 : LENS 2
P_i : INNER PLATE
P_o : OUTER PLATE
GS : GRIDS OF SELECTOR
GA : GRIDS OF ANALYZER
I : INTERACTION REGION
B : BAFFLE
L3 : LENS 3
L4 : LENS 4
EM : ELECTRON MULTIPLIER
F : FARADAY CUP
HSA : HEMISPHERICAL ANALYZER

FIG. 2. Detailed diagram of lower chamber.

TABLE I. Angular distribution of vibrationally elastic cross sections, integrated and momentum-transfer cross sections of water vapor. Numbers in parentheses are extrapolated data points. σ_T: integrated cross section; σ_m: momentum-transfer cross section.

	$d\sigma/d\Omega$ (10^{-17} cm^2/sr)											σ_T	σ_m
E (eV) \ θ(deg)	15	30	45	60	75	90	105	120	135	150	165	(10^{-16} cm^2)	(10^{-16} cm^2)
2.2	74.4	27.7	13.8	7.4	5.8	4.4	3.6	3.5	3.3	4.6	(6.8)	11.8	6.2
4.0	72.1	33.7	14.4	9.9	6.7	4.9	3.1	2.9	3.8	5.8	(8.8)	13.0	6.9
6.0	84.3	33.6	16.0	10.5	7.8	5.5	4.5	3.7	5.0	10.0	(19.5)	15.3	9.5
8.0	90.0	31.7	14.6	11.2	8.2	5.4	4.0	4.2	6.2	12.5	(19.5)	15.7	10.1
10	94.5	30.5	13.8	8.7	7.1	5.3	4.4	4.8	6.8	14.7	(31.0)	16.1	11.4
15	105.0	30.0	16.2	7.9	5.9	3.9	3.3	4.9	8.0	15.8	(31.5)	16.3	11.3
20	97.0	29.7	12.3	5.7	3.4	2.8	2.2	3.3	5.4	11.5	(24.5)	13.2	8.2

brationally elastically scattered electrons from the interaction region were detected at a given angle by a channeltron electron multiplier after energy analysis in the horizontal plane. The procedure was repeated for different angles and different incident energies.

The measured differential cross sections have been placed on an absolute scale by normalizing with measured cross sections of helium[12] at 90° at each energy. In the normalization process, the relative strength of the scattered signal at 90° for each gas was measured in a volume experiment (filled vacuum chamber with uniform density of target gas) and the density of the target gases was measured by a calibrated ion gauge. There are three sets of Helmholtz coils to reduce stray magnetic fields (including the earth's magnetic field) down to less than 20 mG in all directions near the interaction region.

III. EXPERIMENTAL RESULTS

Absolute angular distributions of vibrationally elastic cross sections of water vapor have been measured at room temperature by electron impact. The energies used were 2.2, 4.0, 6, 8, 10, 15, and 20 eV and the angular range covered was from 15°–150° at 15° intervals. A modulated crossed-beam method was used.

There was 5% statistical uncertainty and a 10% uncertainty in the normalization process against the He elastic cross sections. Therefore, the overall uncertainty (in standard deviation) of the present measurements is about 15%, including the uncertainty in the He cross sections (10%). The final results are shown in Table I, including integrated and momentum-transfer cross sections.

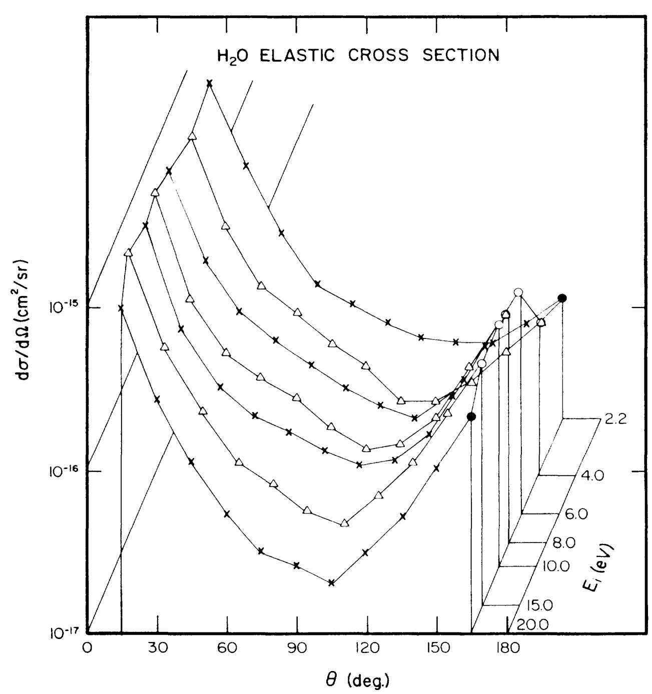


FIG. 3. Three-dimensional spectrograph of elastic cross section.

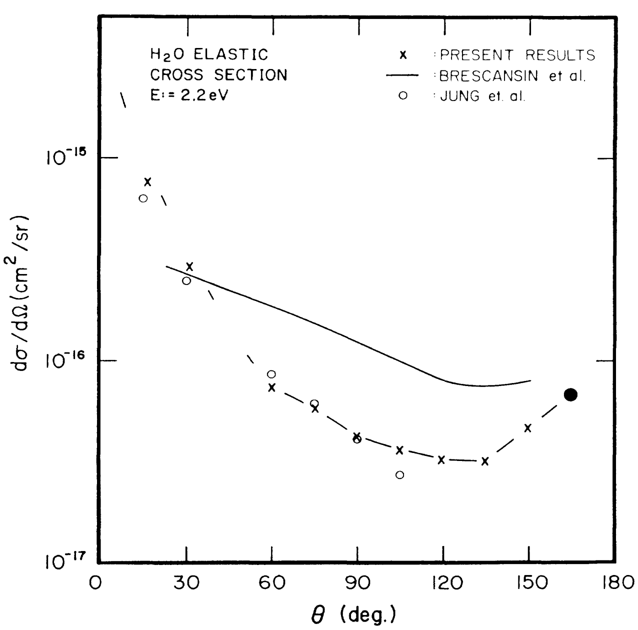


FIG. 4. Angular distribution of elastic cross sections at 2.2 eV impact energy along with the measurements of Jung *et al.* and theoretical results of Brescansin *et al.*

Figure 3 shows a three-dimensional spectrograph of elastic cross sections. It is noted that the forward-scattering cross sections have the same shape for all incident energies, but the backward-scattering cross section has a broad maximum near 15 eV impact energy. The minimum differential cross section moves from large angle ($\sim 130°$) to near 90° as the incident energy increases.

Figure 4 shows the DCS (differential cross section) of electrons vibrationally elastically scattered from water vapor at 2.2 eV along with the results of theoretical calculations (2.0 eV) by Brescansin *et al.* and the experimental results of Jung *et al.* The theoretical results do not agree with the present results. Their results are, in general, larger than the present value by a factor of 2. The results of Jung *et al.* are slightly larger than the present results in the forward scattering.

Figure 5 is the same as Fig. 4, except at 6 eV impact energy, along with the results of Danjo and Nishimura. The theoretical prediction by Brescansin *et al.* agrees with the present results for forward scattering but not for backward scattering. It should be noted that the present results show stronger backward-scattering cross sections than the theoretical calculations. All the measurements are in good agreement near 90°, but the present results have larger forward scattering than other measurements.

Figure 6 is the same as Fig. 4, except at 10 eV impact energy. The results of Danjo and Nishimura agree very well with the present results. A better agreement between theory and experiment is noticed as the incident energy increases. Both measurements show a clear inflection near 60° but the theory does not. Again the present results show a stronger backward scattering than does the theory.

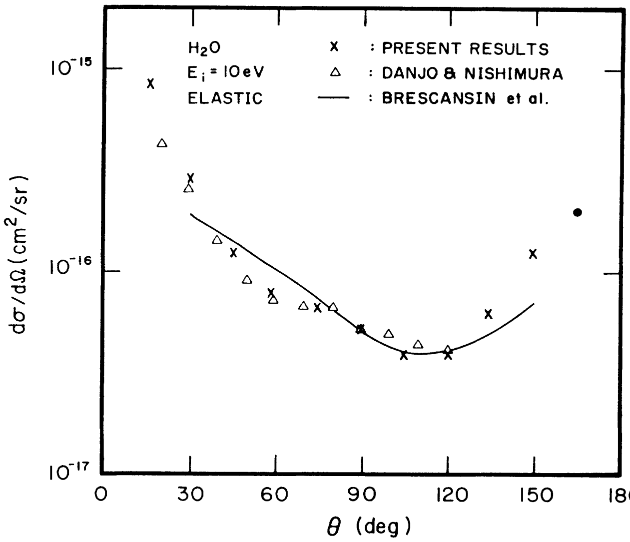


FIG. 6. Same as Fig. 5, except 10 eV impact energy along with measured values of Danjo and Nishimura and theoretical prediction of Brescansin *et al.*

Figure 7 shows the DCS at 20 eV impact along with the results of Danjo and Nishimura and theoretical calculation of Brescansin *et al.* The results of Danjo and Nishimura agree with the present results near 90°, but their values are smaller for forward scattering. Theoretical predictions agree very well with the present results for both forward and backward scattering but larger

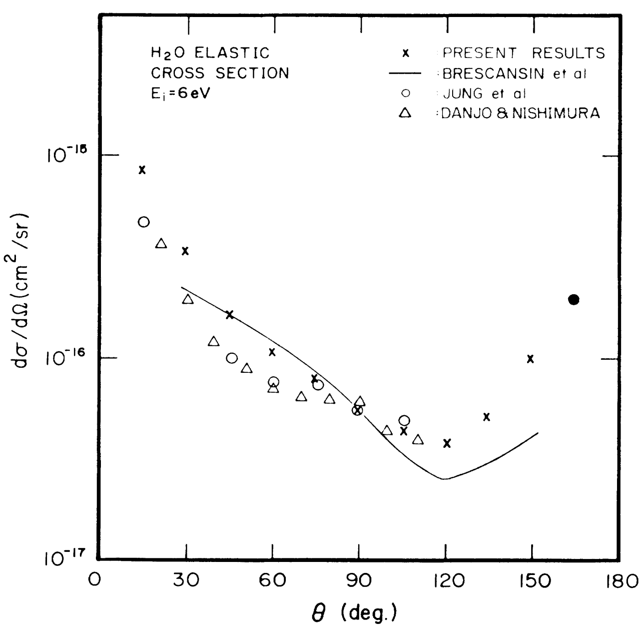


FIG. 5. Same as Fig. 4, except 6 eV impact energy along with measurements of Jung *et al.*, those of Danjo and Nishimura, and theoretical value by Brescansin *et al.*

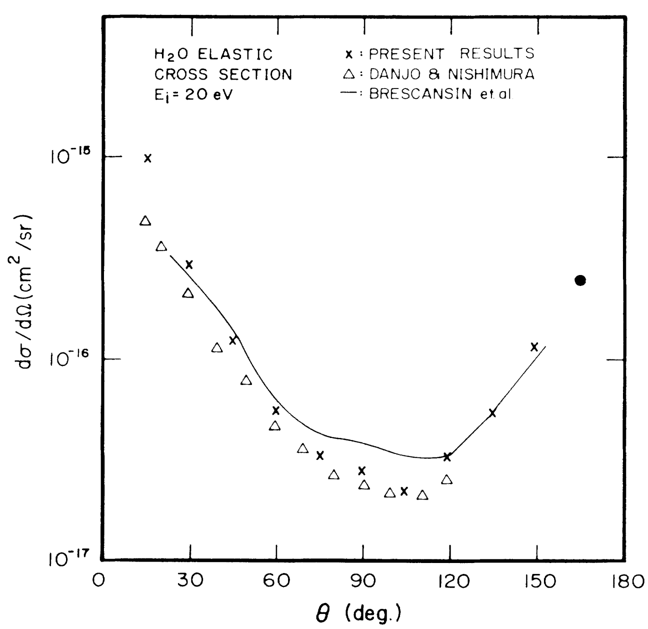


FIG. 7. Same as Fig. 5, except 20 eV impact energy along with measured values of Danjo and Nishimura and theoretical calculation of Brescansin *et al.*

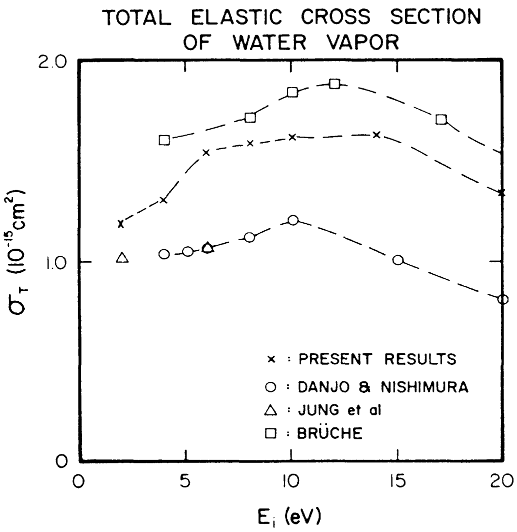


FIG. 8. Integrated cross section of elastic scattering along with total cross section of Bruche, measured values of Danjo and Nishimura, and those of Jung *et al.*

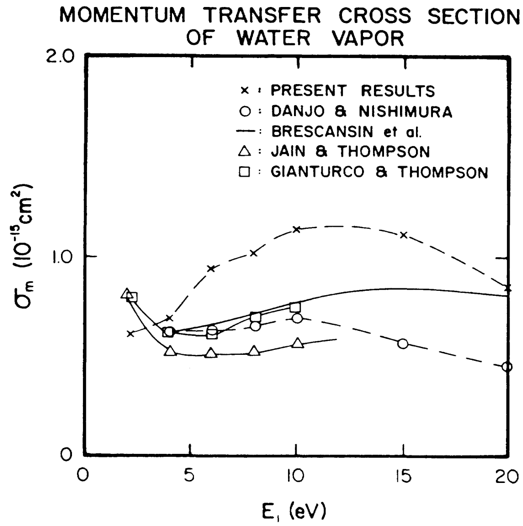


FIG. 9. Momentum-transfer cross section along with theoretical values of Jain and Thompson, those of Brescansin *et al.*, and measured values by Danjo and Nishimura.

than the present results near 90°.

The integrated cross sections are obtained by integrating over scattering angles after exponentially extrapolating to 165° and the results are shown in Fig. 8 along with the results of Jung *et al.*, those of Danjo and Nishimura, and the total cross sections of Bruche. The measured values of Jung *et al.* and those of Danjo and Nishimura are smaller than the present results by about 50% above 5 eV impact energy. This may be due to smaller forward-scattering cross sections and unmeasured backward scattering in their measurements. The present results show a broad maximum around 15 eV and are in a good agreement with those of Bruche. The difference between the total cross section and the present results is the vibrational-excitation cross sections which are expected to be about 10% of the total cross section.

The momentum-transfer cross sections have been calculated from the present measured differential cross sections and they are shown in Fig. 9 along with the theoretical values of Brescansin *et al.*, those of Jain and Thompson, the results of Gianturco and Thompson, and the experimental values of Danjo and Nishimura. There is relatively good agreement among theoretical and experimental values near 5 eV, but the present results are larger than others above 5 eV by approximately 50%. This may be due to the strong backward scattering in the present results. The theoretical cross section of Brescansin *et al.* at 20 eV agrees very well with the present results. The present results do not have a sudden increase in the momentum-transfer cross section below 4 eV as theory predicts.

ACKNOWLEDGMENT

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