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Angular distribution of electrons elastically scattered from O_2: 2.0–200-eV impact energy

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Angular distributions of electrons elastically scattered from O_2 have been measured by a crossed-beam method. The energy and angular range measured were from 2.0 to 200 eV and from $-96°$ to $+156°$, respectively. Total elastic and momentum-transfer cross sections have been obtained and compared with the previous measurements. It is found that there are discrepancies among the measurements in the total elastic cross sections and a serious discrepancy with previous measurements in the momentum-transfer cross sections.

I. INTRODUCTION

Total elastic scattering cross sections of molecular oxygen have been measured by a number of authors. Brüche[1] has measured the total cross section from 1 to 50 eV by an attenuation method. Sunshine *et al.*[2] have measured the total cross section from 1 to 25 eV by a recoil method. Salop and Nakano[3] have measured the cross section from 2.35 to 21 eV by a modified Ramsauer method. There is a discrepancy in the total-cross-section measurements below 15 eV, especially between those of Sunshine *et al.* and Salop and Nakano.

Trajmar *et al.*[4] have measured the absolute differential cross section (DCS) in the energy and angular range of 4 to 45 eV and 10° to 90°, respectively, using a crossed-beam method. Linder and Schmidt[5] have measured the relative DCS in the energy and angular range from 0.74 to 4.0 eV and from 20° to 110°, respectively, utilizing a crossed-beam method. These relative DCS's were normalized to the total cross section measured by Salop and Nakano. Recently, Dehmel *et al.*[6] measured the DCS at 5 and 15 eV for the angular range from 15° to 150° by a modulated crossed-beam method. The results of Dehmel *et al.* differed from those of Trajmar *et al.*, primarily in the forward direction.

There is a paucity of theoretical calculations for O_2. Fisk[7] has calculated the scattering cross sections by a semiempirical method (two-center potential). Wedde and Strande[8] have calculated the DCS and total elastic cross sections of N_2, N, O_2, and O by a phase-amplitude method for the energy range from 40 eV to 1 keV. These theoretical predictions are not in good agreement with the measurements.

This paper presents extensive experimental results from which the DCS of electrons elastically scattered from the zeroth vibrational level of O_2 have been measured by a crossed-beam method. The angular and energy range measured were from 2.0 to 200 eV and from $-96°$ to $+156°$, respectively.

II. APPARATUS AND PROCEDURE

The apparatus used for the present measurements is the same as that used for the previous measurements.[9,10] The detailed description can be found in these references. Briefly, a rotatable electron beam which is produced by an electron monochromator at a desired energy (the full width at half maximum is equal to 0.06 eV) intersects with a collimated neutral beam at 90°. The scattered electrons from the neutral beam are detected by a channeltron electron multiplier after energy analysis.

The stray magnetic fields have been reduced to less than 10 mG in all directions by three sets of Helmholz coils. The absolute energy scale was determined to within 0.05 eV using the He resonance at 19.3 eV.

The procedure used for the present measurements was as follows: The collimated beam of O_2 was turned on at the background pressure of 2×10^{-5} Torr and the signal count was integrated for 10 sec for each angle from $-96°$ to $+156°$ in 12° increments for an incident energy. The measurements were repeated with the O_2 beam off to obtain the background count. The difference between the two signals yields the DCS electrons elastically scattered from the O_2 beam. With the O_2 beam on, the density in the interaction region where the electron beam and neutral beam met was approximately five times larger than the overall background density. The ratio of the beam-on signal to the beam-off signal was typically of the order of 100 except for scattering angles below 24° at low incident energies (<10 eV), where the ratio was about 10.

Since the halfwidth of the electron beam ($\pm2°$) of

TABLE I. Angular distribution, $d\sigma/d\Omega$ (in units of 10^{-18} cm^2/sr). (The numbers in parentheses represent extrapolated data points.)

$\theta°$ \ E (eV)	2.0	3.0	5.0	7.0	10.0	15	20	30	40	50	70	100	150	200
6														
12	34.5	59.2	95.9	154.3	250.1	373.8	488.2	655.4	760.4	773.3	755.6	633.3	443.9	422.9
18														
24	44.0	63.3	103.9	149.0	200.0	243.7	263.3	301.3	300.0	275.0	217.6	145.2	104.0	68.2
30														
36	48.7	70.0	108.9	138.8	157.8	171.5	157.7	129.6	109.4	85.7	55.9	34.2	25.3	20.9
48	52.3	77.1	110.0	127.6	131.1	120.7	100.3	63.0	44.2	32.5	20.9	13.6	12.6	11.6
60	54.7	72.2	101.2	93.2	99.9	82.1	61.0	34.4	22.2	16.4	11.5	8.45	7.64	5.89
72	51.1	70.0	87.1	73.6	73.8	53.0	35.6	19.7	14.1	10.7	6.96	5.30	4.93	3.57
84	51.1	62.5	65.9	59.0	57.1	35.1	23.2	13.1	8.95	6.21	4.51	3.68	3.57	3.03
96	48.7	58.4	58.2	49.4	49.3	30.1	20.5	10.1	5.19	3.73	3.76	4.00	3.57	3.03
108	48.7	53.6	50.4	46.9	51.4	32.8	24.3	12.0	6.45	5.46	6.21	5.01	4.59	3.21
120	52.3	57.6	50.8	50.3	57.9	39.9	31.8	20.9	15.9	15.6	13.4	7.95	6.46	3.93
132	57.0	60.0	51.8	58.7	65.9	52.5	45.5	39.0	34.4	31.3	20.9	11.8	7.81	4.10
144	60.5	63.3	61.7	68.9	72.8	70.7	66.5	66.6	63.0	50.7	33.3	17.1	9.00	5.00
156	59.5	63.3	66.6	80.7	80.7	89.4	90.3	100.4	93.5	69.8	45.5	24.6	10.5	5.71
168	(60.5)	(68.2)	(72.3)	(95:0)	(89.7)	(113.2)	(122.4)	(151.5)	(138.8)	(96.4)	(62.2)	(35.3)	(12.6)	(6.60)
σ_{el}[a]	6.5	8.0	9.3	9.9	10.9	10.0	9.1	8.2	7.5	6.6	5.3	3.8	2.7	2.2
σ_{MT}[a]	6.7	7.7	8.0	8.2	8.6	7.2	6.1	5.2	4.5	3.5	2.5	1.5	0.95	0.62

[a]σ_{el} and σ_{MT} are in units of 10^{-16} cm^2.

the present apparatus is inside the halfwidth of the collimated neutral beam, and the halfwidth of the neutral beam is well inside the field of view of the detector system, as shown in a previous paper (Ref. 9), the angular dependence of the effective path length can be expressed as a simple linear superposition of a static-gas experiment and a pure-beam experiment. This may introduce an uncertainty in the differential cross section for angles less than 12° due to the departure from the $\sin\theta$ correction as Trajmar *et al.*[11] and Vuskovic *et al.*[12] have pointed out. The volume correction for the final data has been made accordingly.

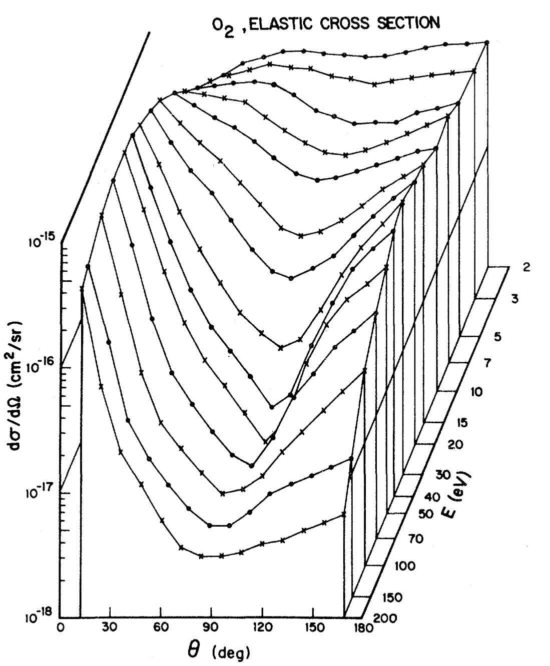

FIG. 1. Three-dimensional perspective diagram of electrons elastically scattered from O_2.

III. EXPERIMENTAL RESULTS

The DCS of vibrationally elastic electrons scattered from O_2 has been measured for 14 incident energies (2.0, 3.0, 5.0, 7.0, 10, 15, 20, 30, 40, 50, 70, 100, 150, and 200 eV). The angular range covered was from $-96°$ to $+156°$.

Five sets of data for each incident energy below 30 eV and four sets for the rest of the incident energies have been taken and averaged to produce the shape of the angular distribution at each incident energy. For these measurements, there are electron lens effects through the deceleration and acceleration of the scattered electrons before and after energy analysis by 127° analyzer, which discriminates between $v'=0$ and 1 vibrational excitation. These angular distributions have been calibrated among themselves at two angles by normalizing them to the energy distribution at a fixed angle. Here the ratio of the signal to the incident electron intensity and target density at each energy is obtained without the use of any electron lens system in the detector in order to ensure a constant transmission of electrons over all energies. This calibration has been performed at 36° and 60° where the contribution of vibrational excitation is expected to be minimal (less than 1%) for all incident energies. Five calibrations have been averaged to give a final normalization among the incident energies. These normalized results have been placed on an absolute scale using the elastic cross section[10] of He at 10 eV which was normalized to the theoretical value at 10 eV calculated by Nesbet.[13] The inter-gas (He-O_2) calibration has been done by a static-gas experiment with a Bayard-Albert gauge which was calibrated by MTS Baratron within 5% uncertainty. The results of angular distributions, total elastic cross sections for $v'=0$, and momentum transfer cross sections derived from the angular distributions are shown on Table I.

The statistical uncertainty (in standard deriva-tion) in the shape for low incident energies (<100 eV) is less than 2% and less than 3% for higher energies (>150 eV). There is 2% uncertainty in the path-length correction except at 12° (5% uncertainty) and 5% in transmission of electrons through the detector system. The uncertainties among the incident energies and between the two gases (He-O_2) are 7% and 10%, respectively. Therefore, the resultant uncertainty of the present results including the uncertainty of Nesbet's theoretical calculation (3%) is $\pm 14\%$.

Figure 1 shows the three-dimensional perspective diagram of DCS of electrons elastically scattered from O_2. Below 7 eV, a broad maximum is near 60° with smaller forward scattering than backward scattering. The forward scattering increases as the incident energy increases, eventually dominating the cross sections. The backward scattering is nearly constant from 2.0- to 30-eV incident energy, whereupon it begins to decrease for higher energies. The minimum between 95° and 105° in the angular distribution is present at 5 eV and becomes well defined as the energy increases.

Figure 2 shows DCS of vibrationally elastic electrons scattered from O_2 at 2.0 eV along with the results of Linder and Schmidt.[5] The results of Linder and Schmidt agree very well above 60° with the present results, but their results are systematically smaller than the present results below 60°.

Figure 3 shows a DCS at 5.0 eV along with those of Trajmar *et al.* and Dehmel *et al.* The results of Trajmar *et al.* show a monotonic increase in the

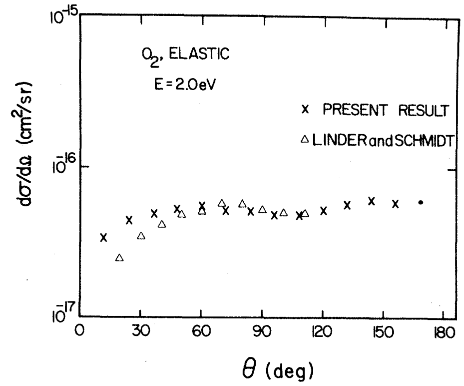

FIG. 2. Angular distribution of electrons elastically scattered from O_2 at 2.0 eV with the results of Linder and Schmidt. Dot is extrapolated data point.

scattering as the angle decreases. The results of Dehmel *et al.* are in fair agreement with the present results except at 30°. In general, their results are smaller than the present results at extreme angles. This may be owing to an overcorrection of path length on their data. As the energy increases, the agreement among the measurements, in general, improves.

These angular distributions were used to calculate the total elastic cross section. The results along with those of Trajmar *et al.*, Salop and Nakano, and total cross sections of Sunshine *et al.* are shown in Fig. 4. The results of Trajmar *et al.* are systematically smaller than the present results by about 20%. However, the shape of the energy dependence is in good agreement with the present results. The results measured by Sunshine *et al.* and Salop and Nakano above 20 eV agree very well with the present results. However, the results of Salop and

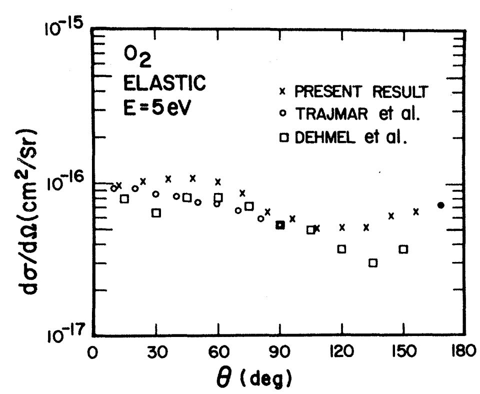

FIG. 3. Angular distribution of electrons elastically scattered from O_2 at 5.0 eV along with those results of Trajmar *et al.* and Dehmel *et al.* Dot is extrapolated data point.

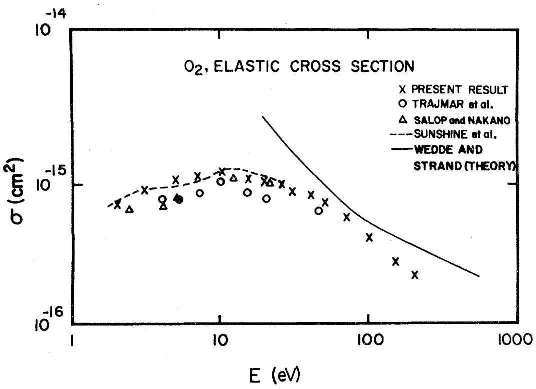

FIG. 4. Total elastic scattering cross sections of O_2 along with other measurements.

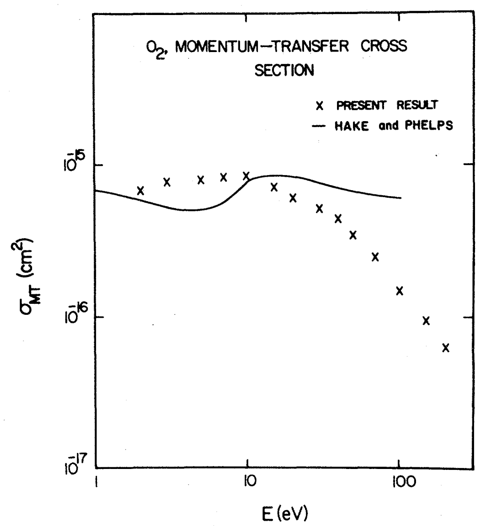

FIG. 5. Momentum-transfer cross sections of O_2 with the results of Hake and Phelps.

Nakano below 20 eV are smaller than the present results by approximately 20%. The results of Sunshine *et al.* agree very well with the present results even below 10 eV.

Finally, Fig. 5 shows the momentum transfer cross sections derived from the present results along with the results of swarm experiments measured by Hake and Phelps.[14] There is serious disagreement in the shape of the energy distribution. This can seriously affect calculations of electron scattering in O_2. The assumptions used to derive the momentum-transfer cross sections from transport coefficients in swarm experiments may be responsible for the disagreement.

ACKNOWLEDGMENTS

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