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# Measurements of inelastic electron scattering from molecular oxygen at high scattering angles

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Inelastic electron scattering from molecular oxygen has been studied for high scattering angles, from 90° to 180°, at the electron incident energy of 10 eV using magnetic angle-changing technique. Excitation of vibrational levels $v$ = 1–9 of the $X^3\Sigma_g^-$ ground state and $v$ = 0 of the $a^1\Delta_g$ first excited state of oxygen has been observed. From the measured energy loss spectra differential cross-section for excitation of $v$ = 1 vibrational level of the $X^3\Sigma_g^-$ state has been determined in the above scattering angle range. In the measurements a newly constructed double hemispherical electrostatic electron spectrometer has been employed which incorporates a recently designed conical magnetic angle-changer.

Keywords: electron collisions, oxygen, differential cross-sections, magnetic angle changer.

## 1. Introduction

Molecular oxygen has been the subject of intense electron scattering studies since the first swarm experiment carried out by TOWNSEND and BAILEY [1]. These studies provide important cross-section data on elastic and inelastic scattering [2] used to elucidate molecular processes in the Earth's atmosphere and to model processes in laboratory oxygen plasma (see, for example, [3]). Differential and integral cross-sections obtained experimentally create also substantial background for theoretical works to develop adequate models of electron–molecule interactions.

In the present work, we have studied excitation of vibrational levels of the $X^3\Sigma_g^-$ ground state and the $a^1\Delta_g$ state of molecular oxygen at the electron incident energy of 10 eV. The measurements have been carried out at high scattering angles, from 90° to 180°, with a recently constructed double hemispherical electrostatic electron spectrometer which uses the magnetic angle-changing technique [4–6]. From the energy loss spectra measured at fixed scattering angles the differential cross-section of the $v$ = 1 vibrational level of the $X^3\Sigma_g^-$ state in the above scattering angle range has been determined. Previously, differential cross-sections for excitation of the vibrational levels of the $X^3\Sigma_g^-$ state at the energy of 10 eV were measured by BRUNGER *et al.* [7]

in the angular range of 10°–90° and by SHYN and SWEENEY [8] in a wider range of 12°–156°. WONG *et al.* [9] and ALLAN [10] presented cross-sections at single scattering angles of 25° and 90°, respectively. Excitation of the $a^1\Delta_g$ state at the electron energy of 10 eV was previously studied by TRAJMAR *et al.* [11], MIDDLETON *et al.* [12] and by SHYN and SWEENEY [13] in the scattering angle range 10°–90° and 12°–156°, respectively. ALLAN [14] presented measurements for the $a^1\Delta_g$ state at 30° and 90°. The present work extends the angular region of the previous measurements up to 180° for both states under consideration.

## 2. Experimental

The electron spectrometer used in the present measurements consists of a source of incident electrons, an analyzer of scattered electrons and a magnetic angle changer. A schematic diagram of the spectrometer is shown in Fig. 1. In the source of the incident beam, an electron gun produces a beam of electrons which are focused at the entrance of a double hemispherical deflector. Electrons with a narrow energy spread (60 meV), leaving the hemispherical deflector are accelerated and focused on a molecular beam by a triple-electrode cylindrical lens. The molecular beam is formed by effusion of the target gas from a single stainless tube with a 0.6 mm inner diameter. Electrons scattered at a given angle are decelerated by a cylindrical lens and focused on the entrance aperture of a double hemispherical deflector identical to that used in the electron beam source. A two-electrode lens is placed behind the exit aperture of the analyzer, and focuses transmitted electrons into a channel electron multiplier. The electron analyzer can be rotated around the axis of the molecular beam over an angular range from –90° to 90° with respect to the direction of the incident electron

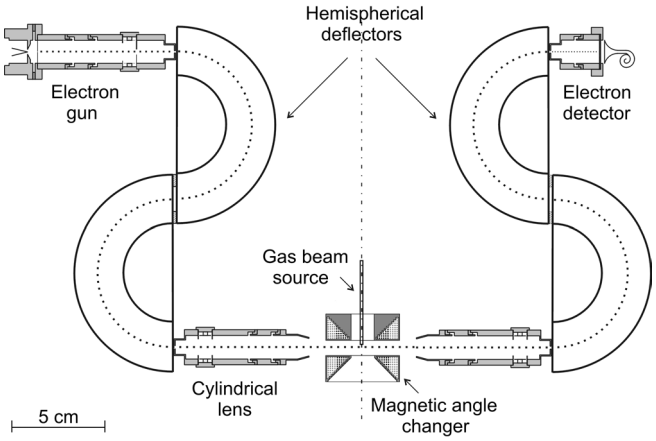


Fig. 1. Diagram (to scale) of double-hemispherical electron spectrometer which incorporates the magnetic angle changer.

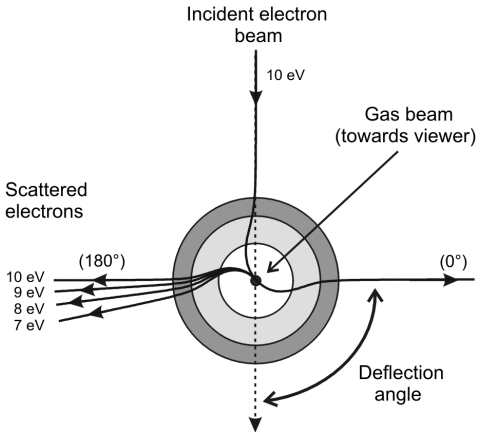


Fig. 2. Deflection of the incident electron beam of energy of 10 eV and of the elastically (10 eV) and inelastically scattered electrons of indicated final energies (7, 8, 9 eV) in the magnetic field of the angle changer. The inner and outer coils are indicated by shaded rings.

beam. This allows studies of electron scattering in the scattering angle region from 0° to 90° without the use of the magnetic angle changer.

The magnetic angle changer consists of two pairs of coils, the inner pair and the outer pair. The coils have conical shapes and each inner coil has 21 turns of wire while the outer coils have 34 turns each [6]. The currents in the inner and outer coils flow in opposite directions and are adjusted to cancel the magnetic dipole moment of the coil arrangement. This is achieved for the ratio of the inner coils current to that of the outer coils equal to 1 : –0.327. This condition ensures that the magnetic field decreases fast enough with radial distance from the scattering center, so that it does not effect the performance of the electron spectrometer. The magnetic field at a distance of 40 mm from the center is equal to 0.1% of its value at the center (1.2 mT). Additionally, the conical shape of the coils allows efficient pumping of the target gas from the target region.

The magnetic angle changer produces a localized, static magnetic field that is perpendicular to the scattering plane. The incident electron beam and the scattered electrons are deflected in the magnetic field [4]. Figure 2 illustrates the motion of electrons of 10 eV energy in the magnetic field produced by the two sets of coils. The electron trajectories shown have been obtained using CPO, a charge particle optics computer program [15]. The unscattered electron beam is deflected by 90°. The electrons scattered elastically at 180° are observed at 90° with respect to the initial incident beam direction, on the opposite side of the molecular beam with respect to the unscattered beam and can thus be detected by the electron analyzer. The electrons scattered inelastically may have different final energies and are deflected in different final directions, as is shown in Fig. 2. The deflection angle depends on the magnetic

field and that dependence when measured at given electron energies can be used to select the required values of scattering angle.

The electron spectrometer is housed in a $\mu$-metal shield in a stainless steel vacuum chamber of about 80 dm$^3$ volume. It is pumped down to $10^{-7}$ mbar by a 2000 dm$^3$/s diffusion pump.

In the present work, electron energy loss spectra have been measured in molecular oxygen at an electron incident energy of 10 eV and at scattering angles from 90° to 180° in 10° steps. The background contributions to these spectra have been measured bypassing the gas line and introducing the target gas directly into the vacuum chamber, maintaining the same gas base pressure as during collection of the energy loss spectra. These contributions have been subtracted from the measured spectra. From the corrected energy loss spectra the intensities of the energy loss peaks corresponding to excitation of vibrational levels of the $X^3\Sigma_g^-$ and $a^1\Delta_g$ states have been determined with respect to the intensity of the elastic peak. The differential cross-sections for the above states have been derived by normalizing their relative intensities to the elastic differential cross-section measured previously [16] in the same scattering angle region, using the relative flow technique. The uncertainties in the differential cross-sections obtained are estimated to be 25%. The scattering angle scale has been calibrated by observing the position of the minimum in the elastic differential cross-section of argon at 117.5° (at 10 eV). The uncertainty in the angular scale calibration is estimated to be 3°. The electron energy is calibrated against the observed position of the doublet $^2P_{3/2,1/2}$ resonances in argon which energies are well established [17].

## 3. Results and discussion

An energy loss spectrum obtained at a scattering angle of 160° is presented in Fig. 3. In the spectrum, vibrational excitation of the $X^3\Sigma_g^-$ ground state of oxygen up to $v = 9$ is clearly identified. The recorded energy loss peaks have been fitted with Gaussian profiles to determine their individual intensities. The energy loss peak of the $v = 0$ level of the $a^1\Delta_g$ state overlaps with that of the $v = 5$ of the $X^3\Sigma_g^-$ state and produces a peak of enhanced width and increased intensity. This peak was fitted with two single energy loss peaks placed at the spectroscopic positions of the $v = 5$ and $v = 0$ levels to determine the intensity of the $a^1\Delta_g$ state peak. The intensity of the $v = 5$ peak has been determined from extrapolation of the intensities measured for $v = 2$–4. These two energy loss peaks obtained from the fitting procedure are also shown in Fig. 3.

Figure 4 presents a differential cross-section obtained in this work for the $v = 1$ vibrational level of the $X^3\Sigma_g^-$ state at an electron energy of 10 eV. This energy corresponds to the center of the $^4\Sigma_u^-$ shape negative ion resonance which decays into the vibrational levels of the $X^3\Sigma_g^-$ state with high decay rate [9, 10]. The present results are shown together with the previous measurements of SHYN and SWEENEY [8] and BRUNGER *et al.* [7]. Experimental points of WONG *et al.* [9] at 25° and ALLAN [10] at

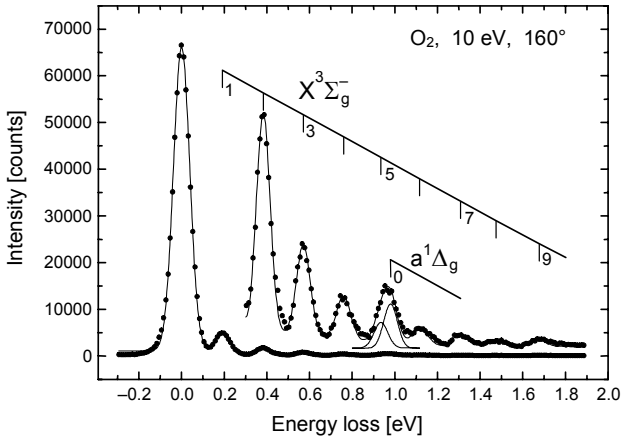


Fig. 3. Energy loss spectrum measured at an incident electron energy of 10 eV and at a scattering angle of 160°. The energy loss peaks corresponding to excitation of vibrational levels of the $X^3\Sigma_g^-$ and $a^1\Delta_g$ states of oxygen were fitted with Gaussian curves shown by solid lines.

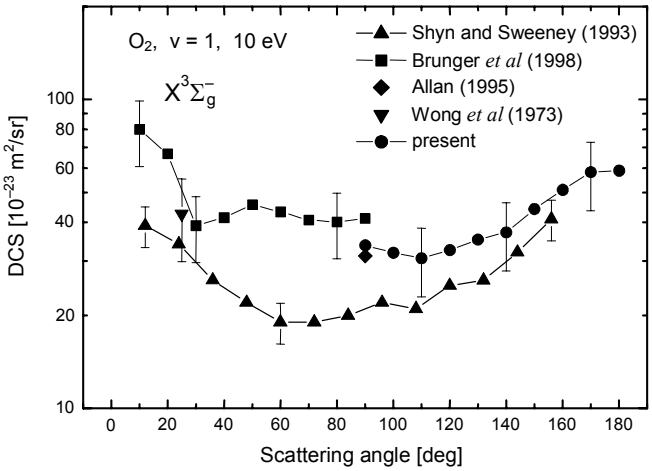


Fig. 4. Differential cross-section (DCS), for excitation of the $v = 1$ vibrational level of the $X^3\Sigma_g^-$ ground state of oxygen measured at an incident electron energy of 10 eV.

90° are also included. In the measured scattering angle range our cross-section increases with scattering angle and in this respect it is in agreement with the results of SHYN and SWEENEY [8]. However, considering the magnitude of the cross-section, it is considerably higher (up to about 50%) than that of SHYN and SWEENEY [8]. At 90° it appears between the values of SHYN and SWEENEY [8] and BRUNGER *et al*. [7], but agrees well with the value reported by ALLAN [10]. The overall angular dependence of the differential cross-section for excitation of the $v = 1$ level over the complete

scattering angle range, 0°–180° implied by the present and previous measurements shows a minimum near 90°. This angular dependence is consistent with the $p\sigma$ wave of the ${}^4\Sigma_u^-$ resonance.

## 4. Conclusions

We have presented results of the first determination of the differential cross-section for excitation of the $v = 1$ vibrational level of the $X^3\Sigma_g^-$ ground state of molecular oxygen in the continuous range of backward scattering, that is, for scattering angles from 90° to 180°. The present studies have been carried out using recently constructed double hemispherical electron spectrometer which employs magnetic angle-changing technique. The measurements have been performed at the electron incident energy of 10 eV that corresponds to the energy region of the resonance vibrational excitation of the oxygen molecule with the formation of the ${}^4\Sigma_u^-$ negative ion resonance. Our results resolve some discrepancies existing in the previous measurements of the $v = 1$ vibrational cross-section.

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