# State-selective differential single-electron-capture cross sections for $O^{2+}$-He collisions

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(Received 27 July 1987)

Energy-gain spectra for single-electron capture by $O^{2+}$ ions colliding with He have been measured at laboratory energies between 60 and 200 eV, and scattering angles between 0° and 4°. The spectra indicate that the predominant exit channel is the $(2p^3\,^2P)$ excited state of $O^+$. Differential cross sections for capture into the $(^2P)$ state were also measured. The data show an oscillatory structure. The measurements are in qualitative agreement with recent theoretical calculations based on a full quantum-mechanical description.

## I. INTRODUCTION

The study of low-energy state-selective electron-capture processes has shown spectacular growth in the last few years. This interest has been stimulated by their relationship to natural atmospheric and physical phenomena such as charge balance in the ionosphere[1] and by instrumental developments including high-energy resolution, translational energy spectrometry, recoil,[2] electron beam ion source (EBIS),[3] and electron cyclotron resonance (ECR)[4] ion sources, and other experimental tools. These processes are of importance in applications to other research fields such as controlled thermonuclear fusion.[5] Measured values of state-selective cross sections for electron capture from H and He by impurity ions present in hot plasmas are needed to estimate radiation losses, and are the basis for spectroscopic measurements of ion transport in plasmas.[6] Finally, electron capture into excited states of multiply charged ions followed by the radiative decay of these states is a well-recognized plasma-cooling mechanism.

Measurements of the angular distribution of the projectile products generally give more information about the nature of the electron-capture process than do measurements of the total cross sections. For example, differential measurements provide the possibility of relating the scattering angle to a classical impact parameter. Establishment of this connection depends on the knowledge of the potential energy curves of the incoming and outgoing channels that participate in the collision, and the avoided crossings at which transitions take place.

The case of capture by $O^{2+}$ from He has received extensive theoretical attention since 1980 because of the importance of this reaction in atmospheric and astrophysical plasmas. This reaction is potentially a very important mechanism for the destruction of $O^{2+}$ in the terrestrial ionosphere and an important source of $He^+$ and metastable $O^+$ ions.[7] The astrophysically interesting incident energy ranges from thermal to about 10 eV/amu, which represents typical low-temperature astrophysical plasmas.

*Ab initio* structure calculations for this system have been carried out by Butler *et al.*[8] State-selective cross sections were calculated from resulting potential curves and coupling matrix elements by Beinstock *et al.*[9] Very recently Heil and Sharma[10] have presented quantal calculations of angular distributions for electron capture by $O^{2+}$ from He at center-of-mass energies from 1 to 100 eV. Their angular distribution at 100 eV is strongly peaked in the forward direction with the first peak near 0.32° and negligible scattering outside 2°. At 10 eV, they calculate that significant amounts of $O^+$ ions are scattered out to a maximum angle of 19°, and that little flux is present inside 1°.

Experimentally, studies of the state-selective single-electron capture by $O^{2+}$ from He have generally been limited to high[11] and thermal energies.[12] Hasted *et al.*[13] have measured angular distributions for single-electron capture in collisions of $C^{2+}$, $N^{2+}$, and $O^{2+}$ with He, Ne, and Ar over the impact energy ranges 1–3 keV and for scattering angles between 0.25° and 2°. Oscillatory structure in inelastic scattering was observed after deconvolution of the data. Their measured probabilities for single-electron capture for collisions of $O^{2+}$ with He were dominated by the presence in the $O^{2+}$ beam of the long-lived $2p^2\,^1S$ and $2p^2\,^1D$ excited states of $O^{2+}$. Makhdis *et al.*[14] have measured the kinetic energy distribution of the product ions and differential single-electron-capture cross sections for $O^{2+}$-He, $C^{2+}$-He, and $C^{2+}$-Ne collisions at 2 keV. The energy-gain spectra for collisions of $O^{2+}$ with He at 2-keV impact energy show a broad peak with a maximum at $Q=5.5$ eV due to capture into $^2P$ state of $O^+$, with contributions from capture into $^4S$ and $^2D$ states. The transition probabilities for $O^{2+}$-He collisions at 3 keV show three groups of oscillations terminating at impact parameters for which avoided crossings arise between the incident channel and the single-capture channels of $He^+$ and $O^+$ $^4S$, $^2D$, and $^2P$ states. Kamber *et al.*[15] have measured the translational energy spectra for single-electron capture by $O^{2+}$ colliding with He, $H_2$, and $N_2$ over energy ranges of 2–8 keV. For the He target they found that capture populates nearly equally the $^2P$ and $^2D$ states of $O^+$ at 2 keV. They also found that, as the collision energy increases, reaction channels with higher energy gain are favored.

We report here on translational energy spectra and differential inelastic cross sections for $O^{2+}$-He collisions.

 

The experimental results in this paper have been obtained on two types of apparatus. First, a differential energy-gain spectrometer was used to measure energy-gain spectra at low angular resolution. This spectrometer was constructed for the measurement of electron-capture cross-section differential in both in angle and energy at very low projectile energy. Second, an angular distribution apparatus was used to record high-resolution angular distributions. The two pieces of experimental apparatus have been previously described respectively by Kamber *et al.*[16] and Tunnell *et al.*[17] and will be only briefly described here.

## II. TRANSLATIONAL ENERGY-GAIN SPECTROSCOPY

### A. Doubly differential energy-gain spectrometer

Ions were produced in a recoil ion source (see Fig. 1). A water vapor target at a pressure of $5\times10^{-4}$ Torr was bombarded by a fast Cu beam from the Kansas State University (KSU) tandem Van de Graaff accelerator. The recoil ions were extracted perpendicular to the pump beam and directed into a 180° double focusing magnet. After momentum analysis the beam passed through a gas cell 3 mm long with 1- and 2-mm diameter entrance and exit apertures, respectively. The scattered ions that had undergone capture were energy analyzed by means of a 90° double focusing electrostatic analyzer (ESA). The ions were then detected by a one-dimensional position-sensitive channel plate detector located at the focal plane of the ESA. The detector device is made of two 3.25-cm microchannel plates followed by a position-sensitive anode. The scattering angle is selected by means of an aperture $A1$ (1mm diameter) in front of the ESA.

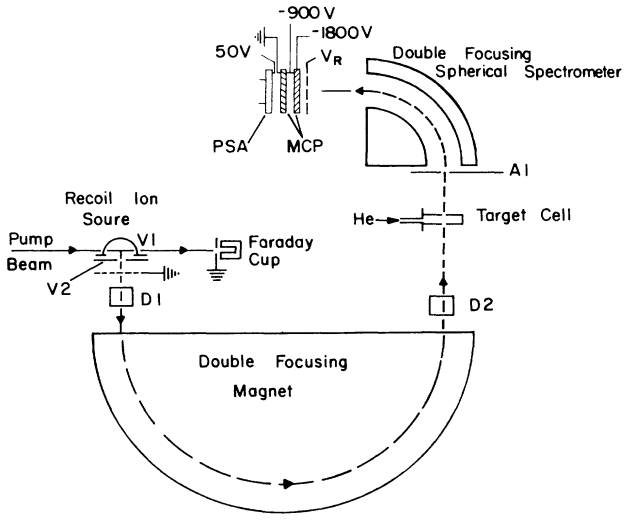


FIG. 1. Schematic diagram of the doubly differential energy-gain spectrometer. $D1$ and $D2$ are electrostatic deflectors, $A1$ is the angular selection aperture, $V_R$ is the retarding grid, MCP labels the microchannel plates, and PSA is the position-sensitive anode.

Giese *et al.*[18] have found experimentally that the best energy resolution occurs when operating with $V_1$ close to $V_2$ (see Fig. 1). In this case, the effective acceleration potential is given by

$$V_{\rm acc}=V_2+0.75(V_1-V_2)\ . \tag{1}$$

In the present experiment $(V_1-V_2)$ was always less than 3 V.

### B. Results

Measurements for $O^{2+}$-He collisions were carried out for impact energies in the range 60–200 eV and scattering angles between 0° and 4°. Figure 2 shows the energy-gain spectra at an impact energy of 80 eV and scattering angles of 0° and 2°. At 0° scattering angle, capture into the $2p^3\,{}^2P$ excited state of $O^+$ from the $O^{2+}(2p^2\,{}^3P)$ ground-state incident ion is overwhelmingly dominant. This process is exothermic by 5.21 eV, with an avoided crossing at $R_c=5.22$ a.u.

When the apparatus is set at 0°, only the largest impact parameter collisions play an important part. Thus avoided crossings at small internuclear separation cannot be reached, and make no contribution to the spectrum. For capture into the $O^+(2p^3\,{}^4S)$ ground state and $O^+(2p^3\,{}^2D)$ excited state, the crossing radii are at 2.57 and 3.75 a.u., respectively. The scattering angles, estimated on the basis of Coulomb potentials, for impact parameters equal to these crossing radii are 4.43° and 2.95°, respectively, substantially outside the angular acceptance (1.6°) of the ESA. Thus one does not expect these channels to give appreciable contributions at this impact energy. No clear evidence of metastable states

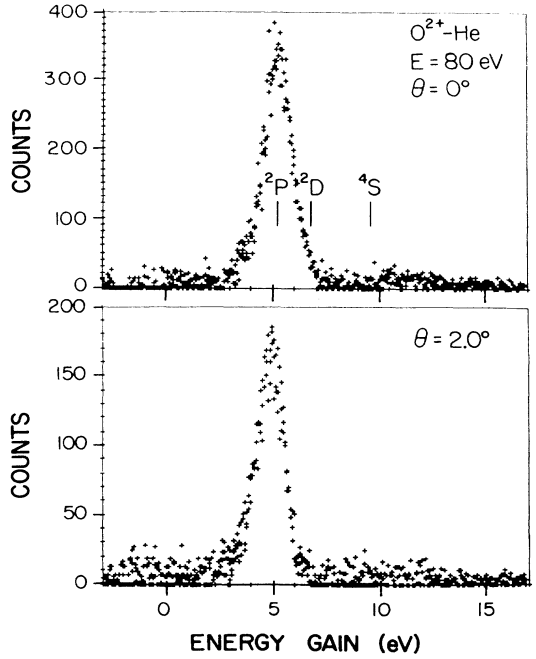


FIG. 2. Energy-gain spectrum for single-electron capture by 80-eV $O^{2+}$ ions from He at scattering angles of 0° and 2.0°.

$^1D$ and $^1S$ in the incident beam was observed.

At a scattering angle of 2° where one might expect contributions from avoided crossings at smaller radii to become important, the dominant reaction channel remains the same. Thus no evidence for population of the $^4S$ and $^2D$ states appears at any angle. A small shift in the energy of the $^2P$ is observed, which is attributable to the kinetic energy transfer to the target. The energy gained by the projectile is equal to $\Delta E - \Delta K$, where $\Delta E$ is the energy defect of the reaction and $\Delta K$ is the translational energy given to the target. From classical two-body kinematics,[19]

$$\Delta K = [m(1-\cos\theta)/(m+M)]\{[2ME_0/(m+M)]-\Delta E\} + [m(\Delta E)^2\cos\theta]/4ME_0 , \quad (2)$$

where $m$ and $M$ are, respectively, the projectile and target masses, $E_0$ is the laboratory energy of the projectile, and $\theta$ is the scattering angle. For zero scattering angle, and at an impact energy of 80 eV, the translational energy given to the target $\Delta K = 0.33$ eV, while at a scattering angle of 2°, $\Delta K = 0.69$ eV. This difference of 0.36 eV was found to be enough to be observed as shift in the energy spectrum.

The calculations of Bienstock *et al.*[9] predict that at our energy, capture preferentially populates the $O^+(2p^3\,^2P)$ state. This is in agreement with the present measurements. The experimentally confirmed result that only the $^2P$ state is populated at these energies allowed us to proceed to the measurement of high-resolution angular distributions without simultaneous selection of the final state.

## III. DIFFERENTIAL SINGLE-ELECTRON-CAPTURE CROSS SECTIONS

### A. Experimental apparatus

The $O^{2+}$ ions, formed in a recoil ion source (see Fig. 3), were extracted and mass analyzed by a 180° magnetic mass separator and directed into a 2.5-cm-long helium gas cell, with entrance and exit apertures, respectively, of 1.5 and 2.5 mm. The target gas pressure in the collision cell was measured by a capacitance monometer, and was typically $<1$ mTorr, to avoid multiple scattering processes. After emerging from this cell, they were detected downstream by a two-dimensional position-sensitive detector. The incident beam was separated from the scattered ions that had undergone capture by means of an electrostatic retarding grid located in front of the detector. The collimation of the ion beam was achieved by the exit aperture of the magnet (2 mm diameter) and the entrance aperture of the gas cell. The detector assembly was composed of two microchannel plates, followed by a two-dimensional resistive anode with four equally spaced contact electrodes. The analog signals were converted to position coordinates using a charge-division technique. For each measurement the grid voltage ($V_R$) was scanned typically over the range $V_{acc}$ to $2V_{acc}$, allowing separated measurements of the direct beam, the $O^+$ product, and the neutral atom. For each event the position information and the grid voltage were recorded by a PDP-11/34 computer with multiparameter data-acquisition capabilities. The data were recorded as an $X$-$Y$ position array, and converted off-line to $d\sigma/d\theta$.

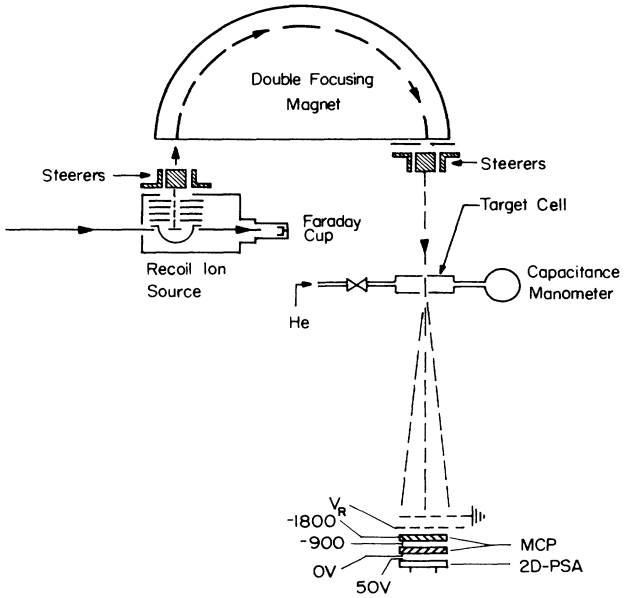


FIG. 3. Schematic of the apparatus used for angular distribution measurements. $V_R$ is the retarding grid, MCP labels the microchannel plate, and 2D-PSA is the two-dimensional resistive anode.

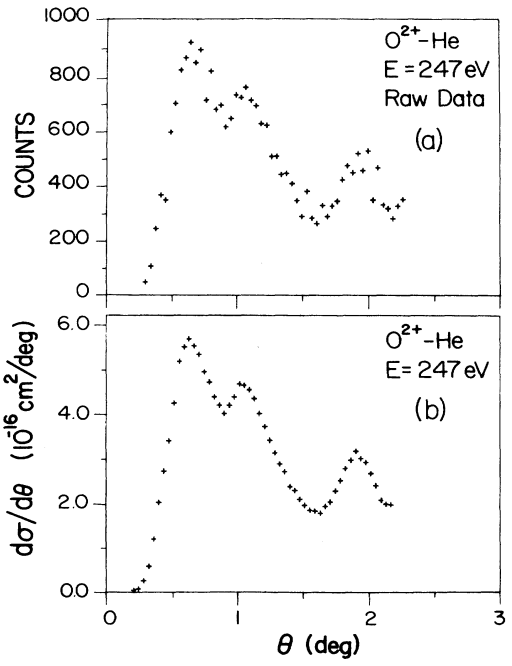


FIG. 4. Typical unsmoothed data (a) and smoothed differential cross sections (b) for single-electron capture by $O^{2+}$ from He at 247 eV.

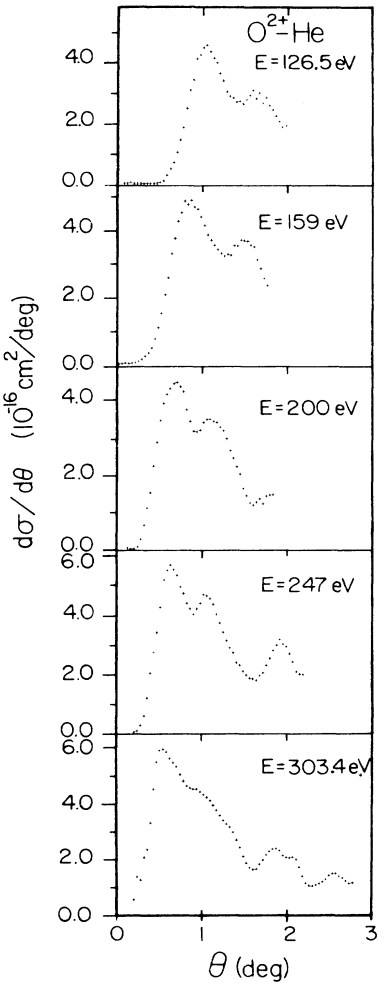


FIG. 5. Differential cross sections for single-electron capture into $^2P$ state of $O^+$, by $O^{2+}$ ions from He, at various laboratory energies.

To check the linearity of the detector and establish a position calibration for the detector, we placed a perforated diaphragm with holes of 1 mm diameter, separated by 3.2 mm, in front of the detector. The recoil beam was then scanned across the detector surface and the resulting hole pattern on the $X$-$Y$ array was used to calibrate the detector. Small changes of linearity were observed near the edges of the microchannel plates. This barrel distortion is expected for a two-dimentional resistive anode.[20] We minimized the effect of this distortion on our data by using only the central portion of the plates. The overall angular resolution of the primary beam with no gas in the collision cell was approximately 0.2° (FWHM).

As an example of the unsmoothed data collected in this experiment, Fig. 4(a) shows the differential cross section for single-electron capture by $O^2$ from He at 247 eV. These data are the result of subtracting from the $O^+$ distribution a background contribution evaluated by diverting the He into the target region near the gas cell but bypassing the cell itself. A somewhat more aesthetically pleasing presentation of the distributions was obtained by a smoothing procedure whereby a running quadratic least-squares fit was done over every seven adjacent data points and each central data point was replaced by the fit result. The result of this smoothing is shown in Fig. 4(b). Absolute cross-section scales were assigned to the data by normalizing our results to the to-

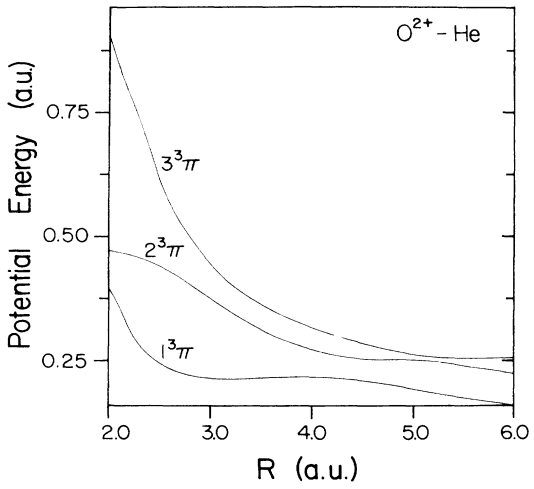


FIG. 6. Adiabatic potential curves of the $1\,^3\Pi$, $2\,^3\Pi$, and $3\,^3\Pi$ states of $HeO^{2+}$ calculated by Butler *et al.* (Ref. 8). At large $R$, states $3\,^3\Pi$, $2\,^3\Pi$, and $1\,^3\Pi$ go to the channels $O^{2+}(2p\,^2P)+He$, $O^+(2p^3\,^2P)+He^+$, and $O^+(2p^3\,^2D)+He^+$, respectively.

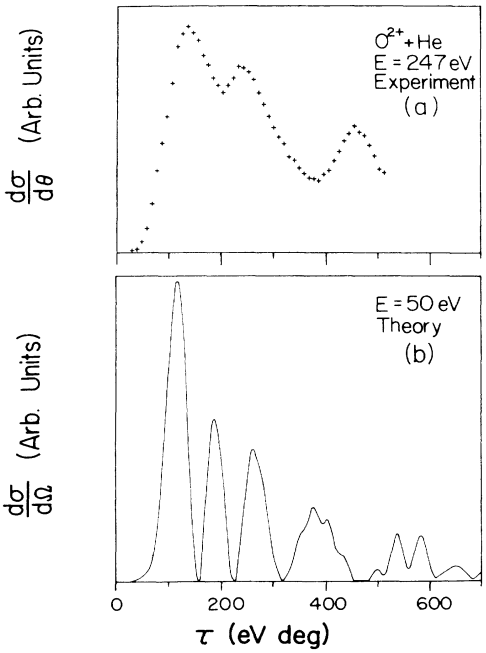


FIG. 7. Differential cross sections for capture from He plotted versus the reduced angle $\tau$. (a) Experimental differential cross section for $E=247$ eV, (b) theoretical differential cross section for $E=50$ eV (Ref. 10).

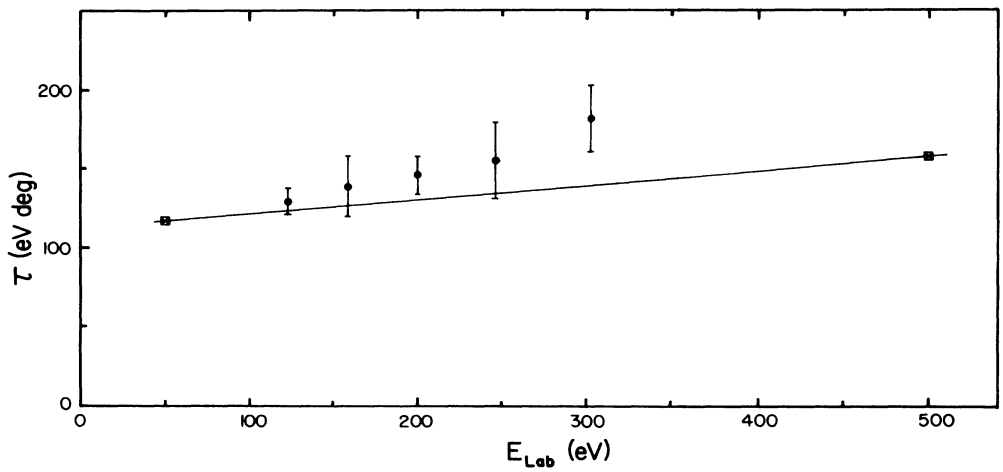


FIG. 8. Energy dependence of the reduced angles for the first maximum in the differential cross sections for single-electron capture in $O^{2+}$-He collisions. Experiment: ●; theory: ⊠——⊠, taken from Heil and Sharma (Ref. 10).

tal cross section measurements of Champion *et al.*[21] This procedure is approximate only, since it can be seen from Fig. 4 that the angular range of our detector is shorter than the range of the angular distribution. Especially at lower collision energies, the detector is not large enough to collect the entire cross sections. Thus the fraction of the cross section occurring outside the region of our measurements was estimated by extrapolation.

### B. Results and discussions

Figure 5 shows the smoothed measured differential cross sections for single-electron capture into $^2P$ state of $O^+$ at laboratory energies between 126.5 and 303.4 eV. The data show an oscillatory structure. Similar electron-capture oscillations by multiply charged ions were observed by Cocke *et al.*[22] in the differential cross sections and by Cederquist *et al.*[23] in the energy gain spectra for double-electron capture by $C^{4+}$ from He. These oscillations were well reproduced and described as Stückelburg oscillations by Barany *et al.*[24] using a two-state curve-crossing model, and most recently by Tan *et al.*,[25] using a quantal two-channel molecular orbital close coupling expansion method and semiclassical approximation.

Calculations of Butler *et al.*[8] demonstrate that the capture takes place when a close approach occurs between the $3\,^3\Pi$ molecular state of $HeO^{2+}$, which correlates to the incident channel, and the $2\,^3\Pi$ which correlates to the $He^+ + O^+\ ^2P$ final state (see Fig. 6). A weaker interaction occurs with the $1\,^3\Pi$ state, which separates into $O^+\ ^2D$ and $He^+$. Heil and Sharma[10] have discussed the difficulty of applying a two-state model to this case, since all three states are involved and the diabatic energy curves do not cross as a two-state model would predict. Over our energy range, however, the problem can be discussed as a two-channel one in the sense that the $1\,^3\Pi$ state is not populated, although this channel does have a strong influence on the $3\,^3\Pi - 2\,^3\Pi$ potentials and couplings. Bearing in mind the limitations of this interpretation, we may use a semiclassical language to identify the observed oscillations as due to interference between scattering amplitudes developed from transitions between the $3\,^3\Pi$ and $2\,^3\Pi$ adiabatic curves, with transitions occurring on the way in or out.

The fully quantal calculations by Heil and Sharma[10] go beyond such qualitative interpretations. Unfortunately, their published calculations do not overlap our bombarding energy range. Thus no direct comparison between experiment and theory can yet be made. A qualitative comparison between our distribution at $E = 247$ eV and the calculations of Heil and Sharma[10] at 50 eV is shown in Fig. 7. In making comparisons, we have plotted the cross sections versus the reduced angle $\tau$, the product of impact energy $E$, and the scattering angle $\theta$, rather than $\theta$. This presentation makes some compensation for the fact that the two distributions correspond to different energies. This comparison clearly must be interpreted as only approximate. A quantitative comparison awaits completion of theoretical calculations for the experimental energies.[26]

A further comparison between experiment and theory is made in Fig. 8. This figure shows the reduced angle $\tau$, for the first maximum in the differential cross sections for different impact energies together with the theoretical predictions of Heil and Sharma.[10] The data show a weak dependence of the reduced angle on the impact energy, and are in good agreement with the theory, particularly at the lower impact energies.

## IV. CONCLUSION

The main objective of the present investigation has been to study single-electron-capture collisions of $O^{2+}$ ions with He by means of translational energy spectroscopy and differential collision cross sections. The experi-

ment confirms the theoretical predictions that, in this collision energy range, single-electron capture into the $2p^3\,^2P$ state of $O^+$ from the ground state $2p^2\,^3P$ of $O^{2+}$ is the dominant process. Oscillatory structure is clearly seen in the differential cross sections, and the rainbow angle appears close to the scattering angle predicted by the theoretical calculations. The theoretical calculations are not yet available for exactly the impact energies we have been able to do in the experiment. The experimental data appear to have their major peak at an angle which is in good agreement with the theory, and the theoretical oscillation frequency similar to that found experimentally.

## ACKNOWLEDGMENTS

The authors would like to thank Professor R. L. Champion of The College of William and Mary in Virginia for providing us with his experimental data prior to publication. The authors are also grateful to Professor T. G. Heil of the University of Georgia for stimulating discussions and communicating the theoretical calculations prior to publication. This work was supported by Division of Chemical Sciences, U.S. Department of Energy. One of us (J.O.K.P.) acknowledges support from the Danish Natural Science Research Council.

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[1]A. Dalgarno, Nucl. Instrum. Methods, **B9**, 655 (1985).

[2]C. L. Cocke, R. Dubois, T. J. Gray, and E. Justiniano, IEEE Trans. Nucl. Sci. **NS-28**, 1023 (1981).

[3]J. Arianer and R. Geller, Annu. Rev. Nucl. Part. Sci. **31**, 19 (1981).

[4]H. Schulte, Gesellschaft für Schwerionenforschung Scientific Report, ISSN No. 0174-0814, 1983 (unpublished).

[5]*Atomic and Molecular Processes in Controlled Thermonuclear Fusion*, edited by C. J. Joachain and D. E. Post (Plenum, New York, 1981).

[6]R. K. Janiv, D. E. Post, W. D. Langer, K. Evans, D. B. Heifetz, and J. C. Weishelt, J. Nucl. Mater. **121**, 10 (1984).

[7]A. Dalgarno, S. E. Butler, and T. G. Heil, J. Geophys. Res. **85**, 6047 (1980).

[8]S. E. Butler, T. G. Heil, and A. Dalgarno, J. Chem. Phys. **80**, 4986 (1984).

[9]S. Beinstock, T. G. Heil, and A. Dalgarno, Phys. Rev. A **29**, 503 (1984).

[10]T. G. Heil and J. B. Sharma, Phys. Rev. A **36**, 3669 (1987).

[11]B. Hird and S. P. Ali, Can. J. Phys. **58**, 772 (1980).

[12]R. Johnsen and M. A. Biondi, Geophys. Res. Lett. **5**, 847 (1978).

[13]J. B. Hasted, S. M. Iqbal, and M. M. Yousif, J. Phys. B **4**, 343 (1971).

[14]Y. Y. Makhdis, K. Birkinshaw, and J. B. Hasted, J. Phys. B **9**, 111 (1976).

[15]E. Y. Kamber, A. G. Brenton, J. H. Beynon, and J. B. Hasted, J. Phys. B **18**, 933 (1985).

[16]E. Y. Kamber, C. L. Cocke, J. P. Giese, J. O. K. Pedersen, W. Waggoner, and S. L. Varghese, Nucl. Instrum. Methods B **24/25**, 288 (1987).

[17]L. N. Tunnell, C. L. Cocke, J. P. Giese, E. Y. Kamber, S. L. Varghese, and W. Waggoner, Phys. Rev. A **35**, 3299 (1987).

[18]J. P. Giese, C. L. Cocke, W. Waggoner, L. N. Tunnell, and S. L. Varghese, Phys. Rev. A **34**, 3770 (1986).

[19]*Collision Spectroscopy*, edited by R. G. Cooks (Plenum, New York, 1978), p. 252.

[20]M. Lampton and C. W. Carlson, Rev. Sci. Instrum. **50**, 1093 (1979).

[21]R. L. Champion (private communication).

[22]C. L. Cocke, J. P. Giese, L. N. Tunnell, W. Waggoner, and S. L. Varghese, in *Electronic and Atomic Collisions*, edited by D. C. Lorents, W. E. Meyerhof, and J. R. Peterson (North-Holland, Amsterdam, 1986), p. 453.

[23]H. Cederquist, L. H. Andersen, A. Barany, P. H. Hvelplund, H. Knudsen, E. H. Nielsen, J. O. K. Pedersen, and J. Sorensen, J. Phys. B **18**, 3951 (1985).

[24]A. Barany, H. Danared, H. Cederquist, P. Hvelplund, H. Knudsen, J. O. K. Pedersen, C. L. Cocke, L. N. Tunnell, W. Waggoner, and J. P. Giese, J. Phys. B **19**, L427 (1986).

[25]J. Tan, C. D. Lin and M. Kimura, J. Phys. B **20**, L91 (1987).

[26]T. G. Heil (unpublished).