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Total Electron Scattering Cross Sections in O_2[†] and Ne[†]

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A modified Ramsauer technique has been used to measure the total low-energy scattering cross sections of electrons in O_2 over an energy range from 2.35 to 21 eV, and in Ne over a range from 0.37 to 20 eV. A broad clearly defined "bump" is observed in the e-O_2 cross section with the maximum occurring between 11 and 12 eV. Both the O_2 and Ne cross-section data are in good agreement with Brüche's measurements at energies above 2 eV. Extrapolation of the low-energy Ne data to zero energy, using modified effective-range theory, yields a zero-energy scattering length of $(0.30 \pm 0.03)a_0$, where a_0 is the Bohr radius.

I. INTRODUCTION

Accurate experimental knowledge of total electron scattering cross section in gases is of importance in atmospheric physics and is needed for comparison with the results of various scattering calculations, particularly in the rare and molecular atmospheric gases. Although a number of microwave and drift-tube experiments have yielded low-energy momentum-transfer cross sections in the last two decades,[1,2] until recently, for many gases of interest the only total scattering cross-section data available for reference were those obtained more than 35 years ago, from Ramsauer-type electron beam-scattering experiments performed in Germany and the United States.[3] An examination of these results for various gases reveals that areas of significant disagreement exist particularly at the lower energies. For the important case of molecular oxygen, comparatively few measurements have been made. Indeed, until the molecular-beam recoil data of Sunshine, Aubrey, and Bederson[4] were published, the only reported e-O_2 cross sections were the results of Brüche[5] and the very-low-energy data (below 2 eV) reported by Ramsauer and Kollath.[6] The molecular-beam results were higher than Brüche's values by as much as 30% at various energies in the range from 1 to 12 eV, and although the disagreements were apparently within the combined errors of both experiments, the need for further e-O_2 scattering measurements is clearly evident.

During the past several years, a program to remeasure the various electron scattering cross sections has been underway in this laboratory using a modernized version of the Ramsauer scattering technique. Results have already been published for He,[7] Ar,[8] H_2,[9] D_2,[9] and N_2.[10] In continuance of this program, we report in this paper measurements of e-O_2 scattering cross sections in the energy range from 2.35 to 21 eV, and e-Ne scattering cross sections in the range from 0.37 to 20 eV.

II. EXPERIMENTAL METHOD

The Ramsauer scattering apparatus and the basic experimental procedures used in obtaining the absolute scattering cross sections have been described in detail elsewhere.[7,8] Because of some minor modifications in apparatus and technique, a summary of the experimental details relevant to the present investigation is given below.

Briefly, electrons are momentum (energy) selected in a 180° magnetic-momentum selector and the resulting beam directed through a gas-scattering chamber before reaching a Faraday cage collector. Because of the deteriorating effect of oxygen on conventional cathodes, the indirectly heated oxide-coated cathode used as the electron source in previous experiments was replaced by a directly heated thoria-coated iridium filament which performs well in the presence of oxygen. This type of source was used both for the e-O_2 and e-Ne measurements.

Two modes of operation were used. In the first, a differential pumping arrangement was utilized in which the gas pressure[11] in the scattering region could be maintained at a level high compared with that in the cathode-magnetic selector region. In this way, gas-cathode interactions and beam attenuation by background scattering were minimized, allowing more precise measurements and operation at lower electron energies.

The second mode of operation utilized a static-volume technique, in which measurements were made at uniform gas pressures throughout the sealed-off Ramsauer chamber. The method was similar to the original Ramsauer technique and was used, mainly, as a check at selected energy points on those measurements made using differential pumping. In general, agreement was excellent (usually to within 2%) except at the very low energies where, in the static mode, insufficient beam current was available for reliable measurements.

Beam energies and energy spreads were obtained from retarding potential measurements on the transmitted beam. These measurements indicate that the beam widths (full width at half-maximum) were about 3.3% of the center beam energy for energies above 3 eV and varied from 3.3 to 9% for energies from 3 eV down to 0.37 eV.

The electron currents to the scattering and collector chambers were measured with Cary Model 31 vibrating-reed electrometers with digitized outputs. Correction factors obtained from comparison measurements of the input resistors allowed determination of current ratios to an accuracy of better than 1%.

The relation used to obtain the cross sections σ_t from the measured beam currents was

$$\ln[1+(I_s/I_c)] = \ln[1+(I_{s0}/I_{c0})] + \sigma_t n x , \qquad (1)$$

where I_s/I_c is the ratio of the currents to the scattering and collector chambers, with gas molecule number density n in the scattering chamber; I_{s0}/I_{c0} is the corresponding ratio at zero pressure; and x is the path length in the scattering chamber. At each electron energy, measurements were made at about 10 pressures (the calibrated Schulz-Phelps gauge outputs were also digitized) and the cross section was obtained from a least-squares fit of the data to Eq. (1). The computer program used also provided for an evaluation of the standard deviation of the calculated cross section and for most of the data, this quantity was smaller than 1% of the cross-section value. Data, for which the standard deviation was greater than 2% of the computed cross section, were automatically rejected. Reproducible cross sections were obtained in this manner down to 0.37 eV for Ne at which point the currents became too low for accurate measurements. For O_2, the measurements could be made down to only 2.35 eV, probably because of the build up of oxidized surface layers, particularly in the vicinity of slits.

The error associated with these cross-section determinations, not including the angular-resolution detection error, is dominated by the uncertainty in the pressure calibration and is estimated to be ±5%. The evaluation of the resolution error for the curved geometry of a magnetic Ramsauer apparatus is difficult and as yet, no general analysis of the problem has been reported. Golden and Bandel[7] have considered an idealized linear analog of the Ramsauer system for which the detection errors, due to scattering into and out of the finite slits of the scattering and collector chambers, may be estimated, provided that differential scattering cross-section data are available. Hoeper, Franzen, and Gupta[12] have published differential cross-section curves for Ne, Ar and He based on a least-squares analysis of the data of Ramsauer and Kollath; and we have used these data to estimate the resolution error for Ne at various energies up to 15.9 eV. It appears that the error is, in general, probably smaller than 4%. In the absence of comparable information for e-O_2 scattering, we have used the rare-gas data to estimate the possible resolution error for this case also. On the basis of these considerations, we estimate the overall uncertainty in the cross-section determinations to be ±8% up to 16 eV, and ±10% at the higher energies.

III. RESULTS AND DISCUSSION

A. e-O_2 Scattering

A plot of the e-O_2 scattering cross sections over the range from 2.35 to 21 eV is presented in Fig. 1. Also, shown in this figure are cross-section curves obtained from the electron beam-

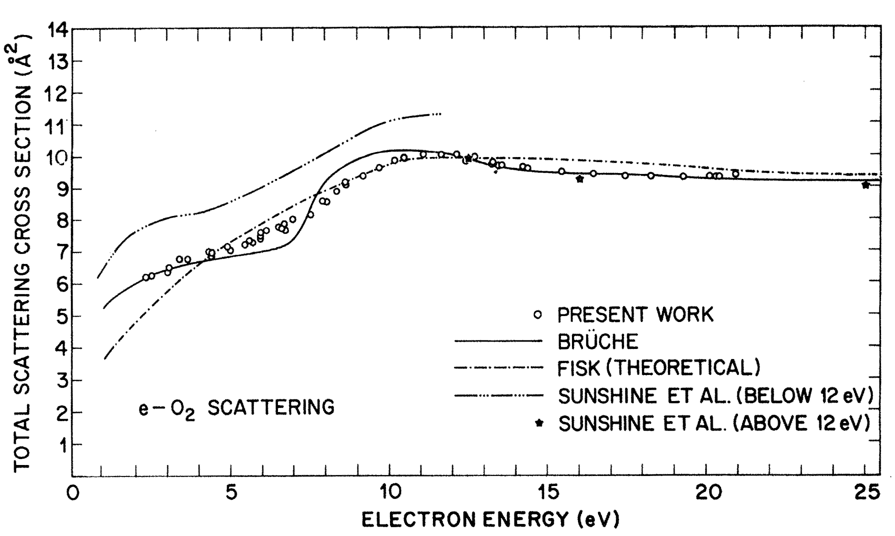

FIG. 1. Total scattering cross sections for electrons in O_2 over the energy range from 0 to 25 eV.

scattering experiments of Brüche,[5] the crossed electron and molecular beam measurements of Sunshine, Aubrey and Bederson[4] and the semiempirical calculations of Fisk.[13] The cross-section curve, obtained in the present experiment, rises gradually from a value of 6.2 Å^2 at 2.35 eV to a broad maximum which peaks at a value of about 10 Å^2 close to 12 eV and very slowly decreases to 9.4 Å^2 at 21 eV.

In Ref. 5, Brüche presents the results of two sets of fairly precise measurements made with his single-cage method ("experiment 1" and "experiment 2") in which a pronounced "bump," with two clearly evident points of inflection, occurs in the cross-section curve, the peak value lying between 10 and 11 eV. These results are in good agreement with those of the present experiment, although our maximum is not as pronounced and our peak value occurs about 1 eV higher in energy. We have, in Fig. 1, reproduced Brüche's "experiment 1" with its pronounced structure rather than his final quantitative cross-section curve, in which the higher-energy inflection point has been eliminated in the process of averaging over several sets of data. The absolute values of the cross section obtained in "experiment 1" are in close agreement (within a few percent) with those of his final curve.

The low-energy scattering cross-section curve given by Sunshine *et al.*[4] has been drawn in over the range from 0.8 to 11.6 eV, as shown in the figure. This curve is a modified straight-line least-squares fit to the experimental data obtained by these investigators in this energy range. In addition, we have plotted in Fig. 1, the three discrete cross-section values reported by Sunshine *et al.* in the higher-energy range from 12.5 to 25 eV. In the lower-energy interval, their cross-section values are 12–25% higher than those of the present investigation, whereas, above 12 eV, the results of the two experiments are in almost exact agreement. An abrupt decrease in the cross section of about 12% is noted between 11.6 and 12.5 eV, which is not observed either in Brüche's results or in the data of the present experiment.

Fisk's[13] theoretical approach to the e-O_2 scattering problem is analogous to the treatment of electron-atom scattering by Allis and Morse.[14] The molecule was represented by a simplified potential function in spheroidal coordinates, and a partial-wave solution for the total cross section for elastic scattering was obtained in terms of two adjustable parameters, whose values were determined from band-spectroscopy data and Slater's rules for atomic-shielding constants. The results, shown in Fig. 1, over the range from 4 to 25 eV are in surprisingly good agreement with the present measurements considering the nature of this approximate semiempirical calculation. Below 4 eV, however, the deviation between Fisk's values and the experimental data becomes appreciable. No "bump" appears in Fisk's curve but it is conceivable, that with different choice of potential, an enhancement of one of the partial cross sections (e.g., q_{02}) could result in such structure.

B. *e*-Ne Scattering

A plot of the e-Ne cross sections over the range from 0.37 to 20 eV as obtained with the

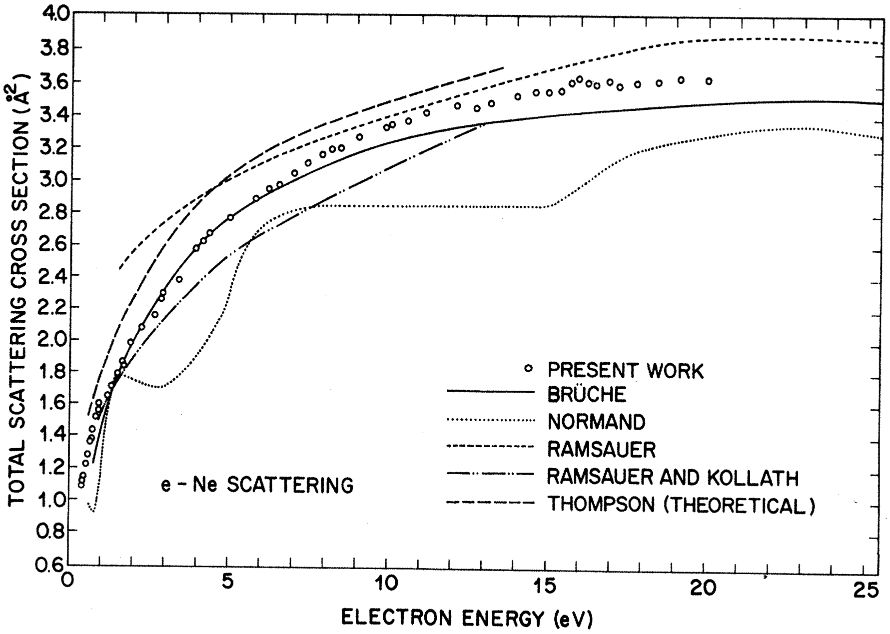

FIG. 2. Total scattering cross sections for electrons in Ne over the energy range from 0 to 25 eV.

Ramsauer apparatus is shown in Fig. 2 along with the experimental beam-scattering curves of Ramsauer,[15] Brüche,[16] Ramsauer and Kollath,[17] and Normand,[18] all of which were obtained more than 35 years ago. The results of the recent calculation of Thompson,[19] which takes into account both exchange and polarization effects using the method of Temkin[20] to estimate the polarization contribution, is also included.

The present data are in good agreement with Brüche's results over the range from 1.3 to 20 eV, the two curves never differing by more than 6%. Below 1.3 eV, the Brüche curve drops away from our curve reaching a value 19% below ours at 0.8 eV.

The Ramsauer-Kollath curve lies below the present data, while the earlier measurements of Ramsauer lie above. Agreement, to within 10% is noted for both sets of data except at the low energies, where the Ramsauer cross sections become 35% higher than our results.

Normand's values are in serious disagreement with the new data and none of the "step" structure, which is prominent in his curve, appears in ours or those obtained by other investigators.

The calculation by Thompson reproduces the shape of the experimental curve quite well, giving cross sections 4–12% higher over its range of energy. The calculation apparently underestimates the effect of long-range (polarization) forces and a fuller treatment would probably give even better agreement with the measurements.

A small but distinct resonance feature, observed as a localized increase in the cross section of about 5×10^{-18} Å^2, is noted near 16 eV and is attributed to the formation of the compound negative-ion state first reported by Simpson[21] and Schulz.[22] (It is to be noted that the energy width of the beam at this energy is about 0.45 eV.)

The e-Ne cross sections in the range from 0.37 to 1.65 eV are shown plotted on an expanded energy scale in Fig. 3. They are compared with the low-energy measurements of Ramsauer and Kollath[23] and the results of Normand.[18] Agreement with the Ramsauer-Kollath values is, in general, closer than 12%, but the new results rise more steeply with energy above 1.0 eV. Major disagreement obviously exists with respect to the Normand data. Using a least-squares method, the data were fitted to the low-energy modified effective range (MERT) expression for the cross section given by O'Malley[24] which for Ne takes the form

$$\sigma_t(E) = A + 2.82E^{1/2} + 0.260AE \ln E - BE . \quad (2)$$

Here $\sigma_t(E)$ is the total scattering cross section in Å^2, $A = 4\pi a^2$, a is the zero-energy scattering length, E is the electron energy in electron volts, and B is a constant. In obtaining this expression, the electric-dipole polarizability for Ne was assumed to be $\alpha = 2.65\, a_0^3$,[25,26] where $a_0 = 0.529$ Å is the Bohr radius.

The fit is shown as the solid line in Fig. 3 and the values obtained for A and B on the basis of this analysis are 0.323 and 0.346, respectively. The calculated scattering length is $(0.30 \pm 0.03)\, a_0$, which compares with the value of $0.24 a_0$ found by O'Malley from the data of Ramsauer and Kollath, and the value of $0.20 a_0$ obtained by Hoffman and Skarsgard[27] from their recent measurements of momentum-transfer cross sections by a microwave technique.

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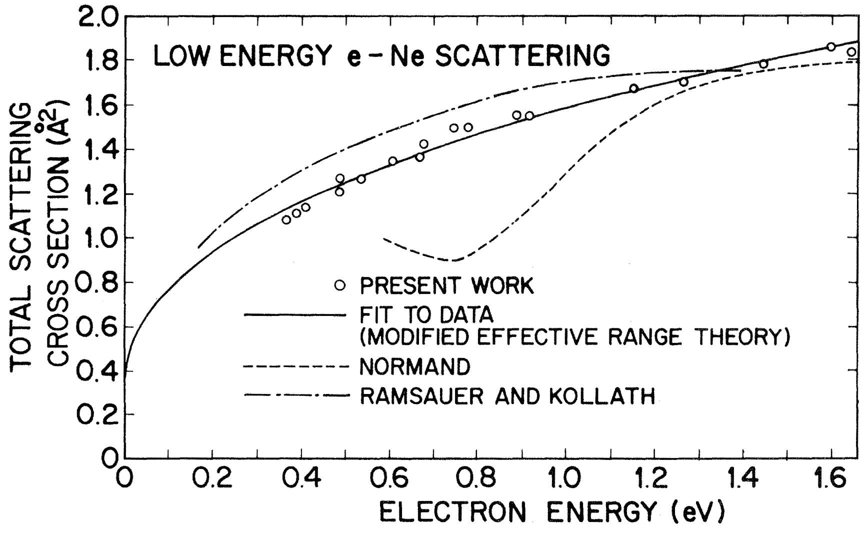

FIG. 3. Total scattering cross sections for electrons in Ne over the energy range from 0 to 1.67 eV.

[†] Work supported by the Lockheed Independent Research Program.

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Cross Sections for Positive-Ion and Electron Production in Collisions of 1–25 keV Hydrogen Atoms with Atomic and Molecular Gases*

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Cross sections are reported for production of positive ions and electrons in collisions of hydrogen atoms in the energy range 1–25 keV with He, Ne, A, Kr, Xe, H_2, and O_2. Slow positive ions are produced by capture of an electron by the fast atom from the target gas and by ionization of the target. Electrons are produced by target-gas ionization and by stripping of the fast atom. Ionization cross sections for each of the target gases are derived from the positive-ion production cross sections and previous measurements of the capture cross sections.

I. INTRODUCTION

Cross sections for charge-changing and ionizing collisions of protons and hydrogen atoms with atomic and molecular gases are useful in many applications. In space physics, for example, they are needed for calculations of ionization produced by proton auroras and for analysis of the interaction of the solar wind with planetary atmospheres. In these applications, protons collide with atmospheric constituents and produce positive ions, electrons, and energetic H^0 and H^-. At low energies, an incident proton flux is rapidly converted to an equilibrium flux of H^+, H^0, and H^- with H^0 being the primary constituent.[1] Subsequent collisions of the fast atoms with atmospheric constituents produce effects comparable in magnitude to those produced by primary protons.

Charge-changing and ionization cross sections for incident H^+ are available from several sets of