Absolute elastic differential electron scattering cross sections in the intermediate energy region. II.—N_2*†

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Utilizing a recently developed method, the ratios of elastic differential cross sections (DCS) of N_2 to those of He have been measured at electron impact energies of 5, 7, 10, 15, 20, 30, 40, 50, 60 and 75 eV covering an angular range of 20° to 135° at each energy. The absolute values of N_2 DCS (which, in the present work, also include the DCS for pure rotational excitation) have been obtained from these ratios by the use of absolute He DCS of McConkey and Preston. From the differential cross sections, elastic integral and momentum transfer cross sections have been evaluated. The results of the present experiment are compared with some previous measurements.

I. INTRODUCTION

Elastic scattering of electrons from N_2 has been the subject of experimental investigation since 1926. Bruche[1] and Normand[2] measured the absorption coefficient of an electron beam passing through N_2. Kollath[3] obtained absolute elastic cross sections at a scattering angle of 90°. Arnot,[4] Bullard and Massey,[5] and Mohr and Nicholl[6] measured the angular distribution of elastically scattered intensity of electrons at several electron impact energies. Ramsauer and Kollath,[7] Fisk,[8] and Aberth *et al.*[9] determined the absolute values of total scattering cross sections. More recently, differential elastic scattering cross sections (DCS) have been measured by Bromberg,[10] Kambara and Kuchitsu,[11] Comer and Read,[12] Pavlovic *et al.*,[13] Shyn *et al.*,[14] Truhlar *et al.*,[15] DuBois and Rudd,[16] Jansen *et al.*,[17] Finn and Doering,[18] and Herrmann *et al.*[19] Table I summarizes all these earlier measurements on the angular distribution of elastically scattered electrons along with the details on incident electron energies, angular coverage, and the nature of measurements. Theoretical calculations of total and differential elastic cross sections were carried out by Steir,[20] Massey and Bullard,[21] Fisk,[22] Oksyuk,[23] Truhlar *et al.*,[15] Brandt and Truhlar,[24] Sawada *et al.*,[25] and Wedde and Strand.[26]

This paper reports absolute values of DCS for N_2 at electron impact energies of 5 to 75 eV, covering angular range of 20° to 135°, and forms a part of a continuing program in this laboratory on the determination of absolute elastic differential scattering cross sections for gases of interest in lasers, plasmas, and in the Earth's and other planetary atmospheres. Also reported here are the corresponding integral and momentum transfer cross sections. Details of the method, theory, and experimental arrangement used for this purpose have been described in earlier papers.[27,28] Therefore, in Sec. II we only briefly describe the method employed in these measurements. Experimental results are presented in Sec. III and compared with some previous measurements.

II. APPARATUS AND METHOD

A schematic diagram of the experimental arrangement is shown in Fig. 1 of Ref. 27, where further details may be found. Briefly, the apparatus[28] consists of an electron gun which produces a collimated, energy selected beam of electrons of impact energy E_0. The electron beam crosses a target beam of N_2 which is obtained by flowing the gas through a capillary array. Electrons scattered into a solid angle $d\Omega$ ($\simeq 10^{-3}$ sr) at an angle Θ with respect to the incident electron beam are energy analyzed and detected with a spiraltron electron multiplier. A multichannel analyzer is utilized to record the spectrum of scattered electrons. The intensity of elastic scattering is obtained by integrating the area under the elastic peak.

The gas flow system consists of N_2 and He lines, valves, flowmeters, and a pressure gauge, and is shown in Fig. 1 of Ref. 27. By the help of flowmeters F1 and F2, the flow rate of either N_2 or He into the scattering chamber is measured. For either gas, the pressure P in the reservoir F3 is obtained by a calibrated pressure gauge.

The method employs a measurement of the ratio of the elastically scattered intensity of N_2 to that of He. At the same time, the ratio of flowrates of these two gases is measured. Either of the following two relations[27] are then used to obtain the ratio of cross sections

TABLE I. Summary of the experimental work on e-N_2 elastic DCS.

Reference	E_0 (eV)	Θ (deg)	Nature of measurements
Kollath[3]	1–36	90	Absolute
Arnot[4]	30–780	10–120	Relative
Bullard and Massey[5]	7–60	20–130	Relative
Mohr and Nicholl[6]	50, 84, and 100	30–160	Relative
Bromberg[10]	300–500	2–110	Absolute
Kambara and Kuchitsu[11]	50–500	4–150	Relative
Comer and Read[12]	11.5	40 and 85	Normalized
Pavlovic *et al.*[13]	10–40	30	Normalized
Shyn *et al.*[14]	5–90	3–160	Relative
Truhlar *et al.*[15]	20	20–80	Normalized
DuBois and Rudd[16]	20–800	2–150	Absolute
Jansen *et al.*[17]	100–3000	5–55	Normalized
Finn and Doering[18]	13–100	5–90	Relative
Herrmann *et al.*[19]	90–1000	3–135	Normalized
Present	5–75	20–135	Normalized

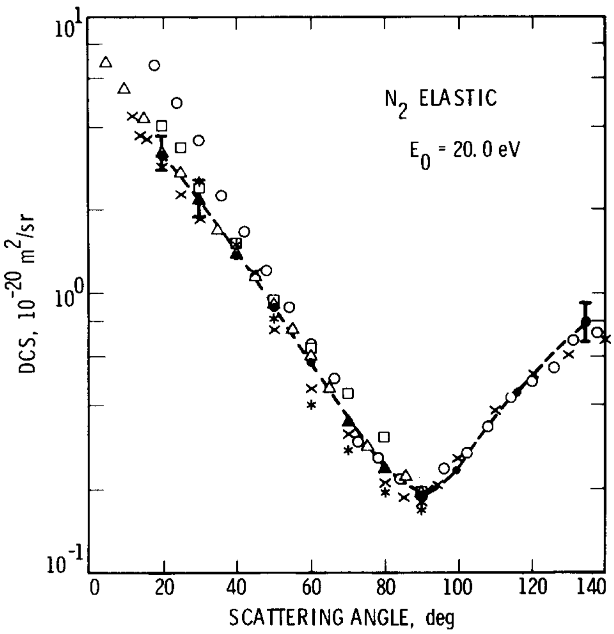

FIG. 1. Elastic DCS at 20 eV electron impact energy. ●— Present measurements. *—Pavlovic *et al.*[13] ○—Shyn *et al.*[14] □—Truhlar *et al.*[15] ×—DuBois and Rudd.[16] Δ—Finn and Doering.[16] The data of Shyn *et al.* and Finn and Doering are normalized to the present measurements at 90° scattering angle. The dotted line shows interpolation between present results. The error bars indicate ±15% uncertainty in the values of elastic DCS reported here.

$$\sigma_{N_2}(\Theta)/\sigma_{He}(\Theta) = [\dot{N}_e(N_2)/\dot{N}_e(He)] \cdot [m(He)/m(N_2)]^{1/2} \cdot [\dot{N}_b(He)/\dot{N}_b(N_2)] , \quad (1)$$

or

$$\sigma_{N_2}(\Theta)/\sigma_{He}(\Theta) = [N_e(N_2)/\dot{N}_e(He)] \cdot [p(He)/p(N_2)] , \quad (2)$$

where $\dot{N}_e(N_2)$ and $\dot{N}_e(He)$ are the rates of elastically scattered electrons which are detected by the analyzer at an angle Θ for N_2 and He, respectively, m(He) and m (N_2) the molecular weights of respective gases, $\dot{N}_b$(He) and $\dot{N}_b(N_2)$ the flow rates, and p(He) and $p(N_2)$ the pressures of these gases in chamber F3 (Fig. 1, Ref. 27). By this method we obtain a ratio of DCS for N_2 to that of He. The absolute value of $\sigma_{N_2}(\Theta)$ is calculated by multiplying this ratio by the absolute value of $\sigma_{He}(\Theta)$.

The following precautions were taken in order to reduce the possible sources of errors in the measurements:

(1) The energy of the incident electron beam was calibrated using the 19.35 eV resonance in He.

(2) The true zero scattering angle was determined from the symmetry of the scattering intensity corresponding to the 2^1P excitation in He.

(3) The incident electron current was monitored by a Faraday cup. It was found that the current was constant to ± 3% over the duration of the experiment. The electron optics are differentially pumped.[28] Therefore, changing N_2 to He did not affect the incident current.

(4) The contribution of the background scattering (both direct beam contribution and scattering by the background gas) to the scattering by the main molecular beam was measured by providing an alternate leak to the vacuum chamber. The flow to the chamber was switched from the capillary array to the alternate gas inlet and the proper background pressure for the desired gas was established. At an impact energy E_0 the angular distribution of elastically scattered electrons was then measured. It was found that for both He and N_2, above 20° scattering angle, the background scattering was between 1% to 2% of the scattering from the beam formed by the capillary array. This error was considered negligible in the ratio of scattered intensities of N_2 to He in comparison with other sources of errors.

III. RESULTS AND DISCUSSION

Using the method described above, the ratios of N_2 DCS to those of He, at incident energies of 5, 7, 10, 15, 20, 30, 40, 50, 60, and 75 eV, were obtained. At each energy, the angular range extended from 20° to 135°. In these measurements the energy resolution of the spectrometer was about 60 meV (FWHM). Therefore, the rotational excitation in N_2 was not resolved and the values of DCS reported here are a sum of elastic and rotational excitation cross sections.

Table II gives results of the present measurements. In brackets are the ratios of N_2 DCS to those of He. The absolute values of N_2 DCS have been obtained by multiplying these ratios by absolute values of He DCS and are also shown in the same table. As our choice of absolute He DCS, we have used values of McConkey and Preston[29] since they are the most recent measurements covering the energy range of interest. The absolute values of N_2 DCS can be renormalized should more accurate He cross sections become available in the future. The measurements of McConkey and Preston cover an angular range of 20° to 90°. In order to obtain elastic He DCS at angles above 90°, we measured in our laboratory their relative values between 60° and 135°. The accuracy of these relative measurements is estimated to be ± 5%. The relative values were then normalized by fitting to the data of McConkey and Preston between 60° and 90°. The details of this method and the results will be presented in a future publication.[30]

At each energy and at each angle at least five sets of data were obtained for the ratio of two differential cross sections. The estimated error for these ratios is about ± 10%. This value has been obtained by considering all possible sources of errors in the measurements. These errors are explained in detail in Table II of Ref. 27. The error in the absolute differential cross sections is estimated to be about ± 15%, which is a square root of the quadratic sum of a ± 10% error in the ratio measurements and a ± 12% error in the results of Mc-McConkey and Preston.[29]

In order to obtain elastic integral cross sections $Q(E)$ and elastic momentum transfer cross sections $Q_m(E)$, the experimental DCS curves had to be extrapolated from 20° to 0° and from 135° to 180°. For this pur-

TABLE II. N_2 differential elastic cross sections $\sigma(E_0, \Theta)(10^{-20}\mathrm{m}^2/\mathrm{Sr})$. In brackets are the ratios σ_{N_2}/σ_{He}.

Θ(deg) \ E_0(eV)	5	7	10	15	20	30	40	50	60	75
20	1.48 (6.49)	1.92 (6.73)	2.32 (7.15)	2.95 (7.85)	3.25 (8.78)	3.60 (9.23)	3.50 (9.33)	3.40 (9.49)	3.15 (9.13)	2.75 (8.57)
30	1.57 (6.49)	1.83 (6.54)	2.10 (6.75)	2.25 (6.50)	2.21 (6.69)	2.00 (6.15)	1.85 (6.17)	1.60 (5.61)	1.40 (5.15)	1.05 (4.88)
40	1.44 (6.00)	1.67 (6.49)	1.77 (6.18)	1.60 (4.98)	1.38 (4.81)	1.04 (3.97)	0.83 (3.58)	0.72 (3.30)	0.60 (2.91)	0.43 (2.81)
50	1.14 (4.84)	1.38 (5.55)	1.41 (5.21)	1.13 (4.33)	0.89 (3.56)	0.60 (2.73)	0.44 (2.35)	0.36 (2.19)	0.29 (2.01)	0.20 (1.98)
60	0.87 (3.69)	1.06 (4.34)	1.08 (4.31)	0.80 (3.43)	0.57 (2.69)	0.36 (1.93)	0.26 (1.83)	0.21 (1.79)	0.18 (1.57)	0.13 (1.71)
70	0.68 (2.58)	0.76 (3.14)	0.75 (3.00)	0.51 (2.28)	0.35 (1.87)	0.21 (1.28)	0.16 (1.45)	0.13 (1.48)	0.11 (1.26)	0.08 (1.48)
80	0.53 (1.89)	0.59 (2.22)	0.50 (2.00)	0.34 (1.46)	0.24 (1.31)	0.15 (1.08)	0.11 (1.16)	0.10 (1.30)	0.09 (1.23)	0.08 (1.74)
90	0.43 (1.45)	0.45 (1.59)	0.36 (1.36)	0.27 (1.13)	0.20 (1.04)	0.13 (1.00)	0.09 (1.06)	0.07 (1.13)	0.08 (1.45)	0.09 (2.81)
100	0.40 (1.23)	0.41 (1.34)	0.40 (1.39)	0.36 (1.57)	0.24 (1.44)	0.14 (1.23)	0.09 (1.20)	0.09 (1.64)	0.10 (2.08)	0.08 (3.10)
115	0.44 (1.08)	0.50 (1.37)	0.56 (1.58)	0.52 (1.87)	0.44 (2.32)	0.26 (2.09)	0.19 (2.47)	0.23 (4.07)	0.26 (5.11)	0.16 (6.40)
135	0.64 (1.06)	0.73 (1.52)	0.95 (1.97)	0.97 (2.61)	0.80 (3.29)	0.68 (4.37)	0.62 (6.60)	0.65 (8.79)	0.58 (9.07)	0.43 (13.46)
Integral ($10^{-20}\mathrm{m}^2$)	9.4	11.0	12.0	12.0	10.1	8.8	8.3	8.0	6.6	5.8
Momentum transfer ($10^{-20}\mathrm{m}^2$)	7.8	8.8	9.7	10.0	7.6	6.4	6.1	5.9	4.4	3.7

pose, we used three methods:

Method (1): Experimental values of Shyn *et al.*[14] (covering the angular range 3° to 160°) and theoretical calculations of Sawada *et al.*[25] showed that there were no sharp maxima or minima in the regions between 20° and 0° and between 135° and 180°. Therefore, our extrapolations between 20° and 0°, and 135° and 160° followed the *shape* of the curves of Shyn *et al.* Between 160° and 180° the extrapolations were made on the basis of the theoretical results of Sawada *et al.* With these extrapolations, $Q(E)$ and $Q_m(E)$ were calculated and the results are shown in Table II.

Method (2): The DCS curves were simply extended as straight lines (on logarithmic scales) whose slopes were determined by the data between 20° and 30° and between 115° and 135°.

Method (3): Here, straight lines parallel to Θ axes were drawn from data points at 20° and 135°.

The results of Methods (2) and (3) represent two extremes of possible extrapolations. They show that up to 20 eV electron impact energy the maximum possible deviations in $Q(E)$ and $Q_m(E)$ from their values obtained from Method (1) are ±7% and ±9%, respectively. However, between 30 and 75 eV the deviations are rather large. At about 40 eV, they rise to $^{+9}_{-25}\%$ for $Q(E)$, and $^{+24}_{-25}\%$ for $Q_m(E)$. This indicates the extent of error that can be caused by an extreme extrapolation. In our opinion, Method (1) is a more reasonable extrapolation and is the basis of the values of $Q(E)$ and $Q_m(E)$ pre-

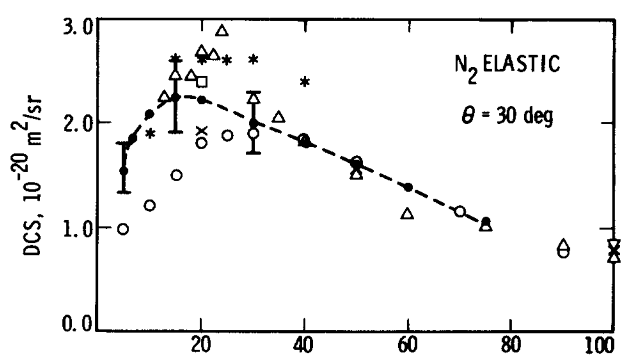

FIG. 2. Elastic DCS at various electron impact energies for the scattering angle of 30°. ●—Present measurements. *—Pavlovic *et al.*[13] ○—Shyn *et al.*[14] (normalized to present results at 40 eV). □—Truhlar *et al.*[15] ×—DuBois and Rudd.[16] ▽—Jansen *et al.*[17] △—Finn and Doering[18] (normalized to present results at 40 eV). The dotted line shows interpolation between the present measurements. The error bars indicate ±15% uncertainty in the results reported here.

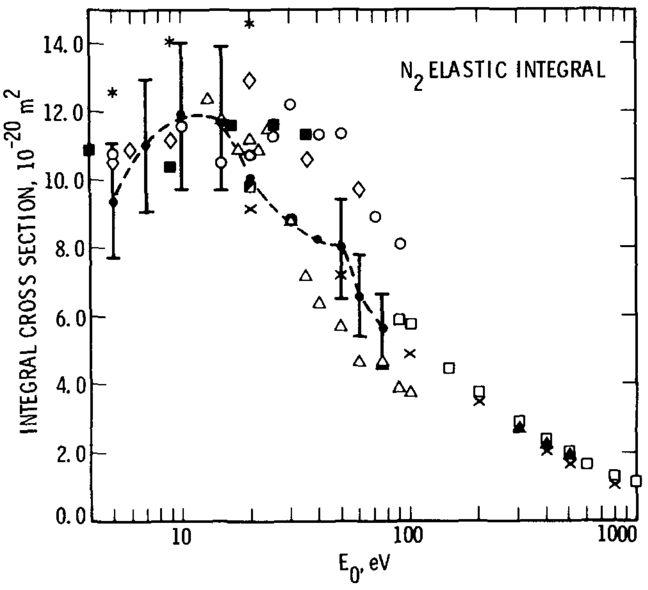

FIG. 3. Integral cross sections. ●—Present measurements. ◇—Bruche.[1] ■—Fisk.[8] *—Aberth *et al.*[9] ○—Shyn *et al.*[14] ⌐—Truhlar *et al.*[15] ×—DuBois and Rudd.[16] △—Finn and Doering.[18] ▲—Bromberg.[10] □—Herrmann *et al.*[19] The dotted line shows interpolation between the present results. The error bars indicate ± 18% uncertainty in the results reported here.

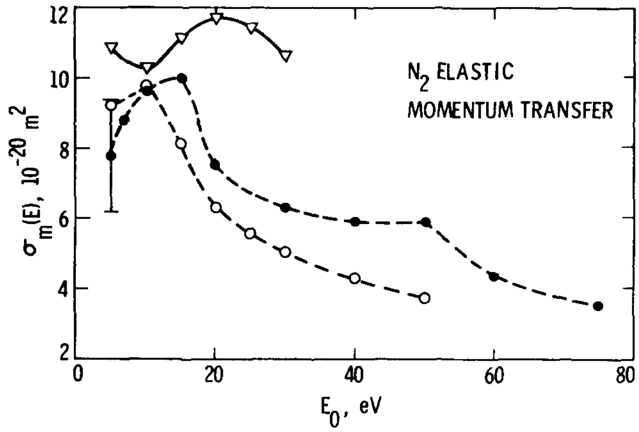

FIG. 4. Elastic momentum transfer cross sections $Q_m(E)$. ●—Present measurements. ○—Shyn *et al.*[14] ▽—Englehardt *et al.*[31] (sum of elastic and inelastic momentum transfer cross sections). The dotted line shows interpolation between the present results. The error bars indicate ± 20% uncertainty in the results.

sented in Table II. An average error of ± 18% has been assigned to $Q(E)$ and ± 20% for $Q_m(E)$. These errors have been arrived at by considering a ± 15% uncertainty in our elastic DCS measurements, a ± 6% error in the shape of elastic DCS curves between 135° and 160° of Shyn *et al.* and a ± 10% error in the extrapolation used between 160° and 180°.

Figures 1 to 4 show our results along with some previous measurements. Comparison of the calculations with the earlier experimental data are given in the theoretical papers[15,24-28] mentioned in Sec. I and are therefore not repeated here. From Table I it is clear that most of the experimental work on angular distribution has been done at an impact energy of 20 eV. Therefore, in Fig. 1 the various measurements have been compared at this energy. Data of Finn and Doering[18] and of Shyn *et al.*[14] are given in arbitrary units. They have been normalized to our result at 90°. Within the limits of experimental errors, the shapes of the DCS are in satisfactory agreement with the present measurements.

In Fig. 2 we compare our DCS at several electron impact energies for 30° scattering angle with the results of other workers.[13-18] Here again the measurements of Finn and Doering[18] and of Shyn *et al.*[14] have been normalized to ours at 40 eV. The agreement of the present work with the results of Truhlar *et al.*[15] and DuBois and Rudd[16] is quite good in view of the fact that the error limits in their measurements are ± 50% and ± 45%, respectively.

Figure 3 compares absolute values of present integral cross sections with previous experiments.[1,8-10,14-16,18,19] It is interesting to note that while above 30 eV impact energy the data of Finn and Doering[18] and of Shyn *et al.*[14] disagree with one another by approximately a factor of 2, both agree with the present results (which lie midway between them) within the combined error limits of the three measurements.

Momentum transfer cross sections have been calculated at each energy for the elastic scattering. These are shown in Fig. 4 along with the results of Englehardt *et al.*[31] and Shyn *et al.*[14] We find that above 10 eV, values of elastic momentum transfer cross sections of Shyn *et al.*[14] are lower than ours. The disagreement is due to the deviation of present angular distributions from those of Shyn *et al.* The momentum transfer cross sections of Englehardt *et al.*[31] are actually a sum of elastic and inelastic momentum transfer cross sections. It seems that the present results will be in a better agreement with their values if the inelastic momentum transfer cross sections are added to the elastic ones. Such inelastic momentum transfer cross sections are not available at present.

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