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To cite this article: R H J Jansen et al 1976 J. Phys. B: Atom. Mol. Phys. 9 185

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Absolute differential cross sections for elastic scattering of electrons by helium, neon, argon and molecular nitrogen

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Received 9 April 1975, in final form 8 September 1975

Abstract. An electron spectrometer has been constructed for the study of elastic and inelastic electron scattering processes. Up to now the apparatus has been used to measure differential cross sections of electrons elastically scattered by He, Ne, Ar and N₂. Direct absolute cross section measurements were performed on N₂ at 500 eV impact energy and at scattering angles between 5° and 9°. Relative cross section measurements were done on He, Ne, Ar and N₂ at impact energies between 100 and 3000 eV and scattering angles between 5° and 55°. The relative cross sections were put on an absolute scale by means of the apparatus calibration factor derived from the absolute measurements on N₂. The experimental apparatus and procedure are described in detail. The results are discussed and compared with those of other experimental and theoretical groups. Analysis of the exponential behaviour of the differential cross section as a function of momentum transfer yielded apparent polarizabilities of the target.

1. Introduction

One might say that in the last six years in the field of atomic collisions there has been a kind of renaissance with respect to elastic and total scattering of electrons, both experimentally and theoretically. Experimentally, because most data were considered to be not accurate and were only available in a limited energy and angular range. Theoretically, because new methods have been introduced, some of which were already known in nuclear physics. Examples are the Glauber theory, the eikonal Born series, the optical model and the use of second-order potentials. From a fundamental point of view the problem has become even more interesting because of the study of dispersion relations.

In this paper we present absolute differential cross sections for elastic scattering of electrons by He, Ne, Ar and N₂ in the primary energy range of 100–3000 eV and the scattering angle range of 5°–55°. Previously we have reported (Jansen *et al* 1974) our results on relative differential elastic cross sections made absolute by normalization to the absolute N₂ data of Bromberg (1970). The major difference between this report and the present paper is that we have now measured the absolute differential cross section for N₂ at 500 eV between 5° and 9°, and this has enabled

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us to determine an absolute apparatus calibration factor for normalization of the relative cross sections. The absolute data thus obtained supersede the data of Jansen *et al* (1974) and Jansen and de Heer (1973). For an extensive literature survey and a more detailed description of our apparatus and procedures than given below the reader is referred to the thesis of Jansen (1975).

Measurements on the heavier noble gases, krypton and xenon, will be published in a following paper.

2. Experimental apparatus

2.1. Introduction

The apparatus used (see figure 1) is an electron spectrometer consisting of a primary beam source, a gas cell as collision chamber and a rotatable analysing system of the Kuyatt–Simpson type (Simpson 1964, Kuyatt and Simpson 1967). The differential cross section $d\sigma/d\Omega$ is measured by rotating the analysing system around the collision centre in a plane containing the incident beam and the scattered 'beam'. The scattering angle θ is defined as the angle formed by the line through the centres of the collimating apertures for the incident beam and the line through the centres of the acceptance apertures in front of the energy analyser; the collision centre is defined as the intersection of these lines. Having passed the acceptance apertures the scattered electrons are energy analysed by a hemispherical energy analyser and are finally detected.



Figure 1. Electron spectrometer: horizontal cross section (schematically). 1 high-vacuum chamber; 2 collision chamber, consisting of static outer cylinder C_1 with entrance channel A_4 and rotatable inner cylinder C_2 with exit channels A_5 and A'_5 ; 3 electron gun; 4 beam collimating system with pinholes A_1 and A_2 , secondary electron stop A_3 and electric quadrupole Q_1 ; 5 Faraday cup 1 with suppressor ring; 6 rotatable analysing system; 7 spherical analyser; 8 channeltron multiplier replaceable by a Faraday cup 3; 9 Faraday cup 2; A_6 and A_7 acceptance slit–pinhole pair; A_8 secondary electron stop; Q_2 , Q_3 electric quadrupoles; 10 mu-metal shielding; 11 wall of high-vacuum chamber; 12 to gas inlet; 13 to membrane manometer.

2.2. Vacuum system

The electron beam source, collision chamber and analysing system are situated together in one high-vacuum chamber (Hvc). The Hvc is a cylinder 25 cm high with internal diameter 45 cm pumped by a 24001 s⁻¹ NRC oil diffusion pump, backed by a 1751 s⁻¹ oil diffusion pump and a mechanical pump, providing a residual gas pressure of 10^{-7} Torr. The vacuum system is sealed with Viton O-rings.

The collision chamber (cc) in the centre of the HVC is a gas cell consisting of static cylinder C_1 and moving cylinder C_2 , sliding over C_1 so that they form together a kind of gas-tight seal. The support of the analysing system is connected with C_2 . The inner height of the cc is 80 mm and the inner diameter 40 mm. The cc is pumped by way of three channel-shaped apertures A_4 , A_5 and A'_5 allowing the incident and scattered electrons to pass.

The target gas is supplied by a bakeable gas inlet system consisting of a gas reservoir at 5 atm and a needle value to reduce the over pressure to work pressure, usually 10^{-3} Torr. With helium as target gas a molecular sieve is also used to purify the gas in the inlet system.

The electron optical elements and other parts close to the electron path were made of NiCr V and gold plated to prevent the formation of non-conductive layers. All other parts in the HVC were made of stainless steel or copper. The primary beam system and the analysing system are frequently baked out to 100°C by means of quartz lamps and radiation shields mounted above.

The high-vacuum pressure is measured with a calibrated ionization gauge and the target gas pressure in the CC with an MKS-Baratron membrane manometer type 77H-1, calibrated with an apparatus based on the continuous flow method (Bannenberg and Tip 1968, Bannenberg *et al* 1969) to below about 2% accuracy.

2.3. Magnetic fields

A mu-metal shielding inside the HVC and a supplementary pair of Helmholtz coils outside the HVC reduce the earth's magnetic field in this chamber to less than 1 mG in the direction parallel to the rotation axis of the analyser system and to about 5 mG in the plane perpendicular to this axis.

2.4. Primary beam system

A Soa-type electron gun is used to produce the primary electron beam. The oxyde cathode is indirectly heated and gives an energy spread of 0.6 eV (FWHM). A 6 kV John Fluke power supply provides the accelerating voltage for the cathode. A collimating system, consisting of two pinholes (A_1 and A_2 in figure 1) of 0.6 mm diameter at a relative distance of 60 mm, confines the beam divergence half angle to about 0.5°. The gun is adjustable from outside by means of a mechanical device for translation and rotation. This enables us to bring the gun on one line with the line determined by A_1 , A_2 and the collision centre. The beam is additionally adjusted with an electrostatic quadrupole Q_1 behind A_1 . This is done by determining the maximum ratio of elastically scattered intensity and primary beam intensity at the smallest scattering angle used, about 3°.

After collimation the beam passes the secondary electron stop A_3 (a 2 mm diaphragm), enters the collision chamber by way of A_4 , a 15 mm channel of 2 mm internal diameter, and ends opposite to A_4 on the inner wall of C_2 . C_2 is made of copper and coated with aquadag to prevent surface charging.

The primary beam current is measured by a Faraday cup in the collision chamber. The cup is a 23 mm cylinder with 4 mm aperture. In front of the cup is mounted a ring of 14 mm external diameter and 3 mm internal diameter which can be given a negative voltage to suppress secondary electrons coming from the cup when the beam current is measured. The cup is movable up and down, out of and into the beam.

2.5. Scattering angle and geometry

Electrons scattered with scattering angle under $\theta \pm \Delta \theta$, where $\Delta \theta$ is the angular spread due to the finite acceptance apertures A_6 and A_7 , can leave the collision chamber by way of A_5 in C_2 . When C_2 rotates A_5 moves in a slot of C_1 while a slot in C₂ allows the primary beam to enter the collision chamber after it has passed A_4 . This construction limits the range of rotation to 70°. However, the presence of a second exit channel, A'_5 at an angular distance of 70° from A_5 , allows an angular scan between -55° and $+90^{\circ}$ in two stages: $-55^{\circ} < \theta < +15^{\circ}$ and $+20^{\circ} < \theta < -15^{\circ}$ $+90^{\circ}$. In this experiment we measured only in the first interval. The angular rotation is made possible by means of a rotational feed-through. The angular rotation of C_2 together with the analysing system is made possible by a feed-through which is connected with the axis of a highly linear potentiometer. To adjust a particular scattering angle a second potentiometer is set at the desired value; a servo-system measures the voltage difference between the two potentiometers and drives the rotational system until the voltage difference vanishes. The reproducibility of the relative angular adjustment is 10'. A_6 and A_7 are the acceptance apertures of the analysing system. A_6 is a slit of width w = 0.626 mm and height h = 1.387 mm; A_7 is a pinhole of diameter a = 0.538 mm at a distance y = 5.988 cm from A₆ and at a distance R = 10.525 cm from the collision centre. The slit-pinhole pair A₆ and A₇ define an angular resolution $\Delta\theta \simeq 0.5^{\circ}$ in the plane of rotation. The scattering volume is determined by the scattering path length l and the mean diameter d of the primary beam; l varies as a function of θ . The beam diameter d is controlled by focusing and is of the order of 1 mm as determined by beam profile measurements. With the dimensions of the apertures used the smallest scattering angle is about 2.5°. At $\theta < 2.5^\circ$, l becomes larger than the collision diameter and even the primary beam might enter A_6 .

With the analysing system in the zero-angle position A_1 , A_2 , the collision centre, A_6 and A_7 were carefully aligned using a laser beam in the place of the electron gun. With mechanical precision instruments we checked that the analysing system moves correctly in the scattering plane. The determination of the precise zero-angle position is based on the symmetry of the scattering signal in the equivalent intervals $-15^\circ < \theta < -3^\circ$ and $+3^\circ < \theta < +15^\circ$ and is carried out before each measuring run (see also §3.2.1).

2.6. Energy analyser

The analysing system (see Kuyatt and Simpson 1967) consists of two rows of cylinder symmetrical electrodes and a spherical analyser (S) formed by two concentric hemispheres with radii of 2.175 and 2.825 cm. The electrodes of each row are tightened against a pair of parallel ceramic rods in order to centre and isolate each electrode with respect to the others. A field-free region extends from A_1 to A_7 . A_6 and A_7

act respectively as entrance window and entrance pupil of the field lens between A_7 and S, imaging the physical slit A_6 to a virtual slit at the entrance of S. The energy analysis in S is based on the focusing properties of a spherical condenser (Purcell 1938). The elastically scattered electrons filtered out by S are focused by a second field lens from the virtual exit slit of S to the entrance cone of channeltron multiplier M. Secondary electrons are stopped by aperture A_8 (1.2×2.5 mm). Electric quadrupoles Q_2 and Q_3 are used for additional correction of the electrons path. The voltage applied to the Herzog electrode in front of S is electronically derived from the accelerated to the desired analysing energy (E_0), typically 100 eV. The voltages supplied to all other electrodes between A_7 and M are superimposed to the tension of the Herzog electrode. The energy resolution $\Delta E_{1/2}/E_0$ ($\Delta E_{1/2}$ is FWHM of the analyser transmission measured as a function of energy) is equal to w/2r (w is the width of A_6 and r the mean radius of S) and about 1%.

2.7. Detector

The energy-analysed scattered electrons are detected by a channeltron electron multiplier (Mullard, type B318 BL) with a channel of 3 mm internal diameter and an acceptance cone of 5.8 mm internal diameter. The multiplier pulses are inductively coupled from the analysing system at high voltage potential into a pre-amplifier at earth potential; the pulses further pass a pulse-height discriminator, pulse shaper and counter, all connections being triaxial.

The count rate as a function of the overall multiplier voltage showed the characteristic steep rise as the voltage was increased followed by a plateau. To ensure a long multiplier lifetime the multiplier was operated at the lowest plateau voltage, 2200 V. We have the experience that it is necessary to check repeatedly the shape of the plateau curve because in the course of time the starting voltage of the plateau shifts to higher values.

The multiplier efficiency is not uniform over the entrance plane. If eg an electron enters along the channel axis it may penetrate into the multiplier over quite a distance before detaching secondary electrons, resulting in a smaller gain. Using the electric quadrupole Q_3 we scanned the multiplier entrance plane and found an interval of deflection voltages (corresponding to a ring at the entrance plane) where the count rate was constant and maximal. The efficiency as a function of the energy at which the electrons strike the multiplier varies slowly between 50 and 500 eV showing a maximum at about 100 eV.

The dark current is about 0.2 pps. The count rate is not allowed to exceed 3000 pps in order to avoid saturation effects in the multiplier.

3. Experimental procedure

3.1. The differential cross section

The absolute differential cross section for elastic scattering, $d\sigma/d\Omega$, is defined as

$$I_{\rm s} = I_{\rm b} \frac{{\rm d}\sigma}{{\rm d}\Omega} N l \, {\rm d}\Omega, \tag{1}$$

where I_s is the intensity of the electrons elastically scattered into the solid angle $d\Omega$ at scattering angle θ , I_b the primary beam current, N the target gas density and l the length of the scattering volume. In our geometry (see figure 1) $d\Omega$ is the solid angle subtended by the pinhole A_7 . $d\Omega$ is not constant over l and in fact it drops to zero at the ends of the scattering volume. One must therefore average $d\Omega$ over l. This procedure results in an effective value of scattering length times solid angle, $(ld\Omega)_{eff}$. Kuyatt (1968) has reviewed the solutions of this problem for various geometrical situations. If w, a, y, R and d are the geometrical dimensions as given in §2.5 then $ld\Omega$ of (1) may be replaced, to first order, by

$$(l \,\mathrm{d}\Omega)_{\mathrm{eff}} = \int_{I} \mathrm{d}\Omega \,\mathrm{d}x = \frac{\pi a^2 w}{4Ry\sin\theta}.$$
 (2)

In our geometrical set-up we have $w \simeq a \ll y$ and $d \ll R$ so that second-order corrections to (2) are negligible. Substitution of the numerical values of w, a, y and R into (2) yields

$$(l d\Omega)_{\rm eff} = \frac{2 \cdot 258 \times 10^{-6} \,\mathrm{cm}}{\sin \theta}.$$
(3)

The target gas density N is related to the target gas pressure in the collision chamber $P_{\rm c}$ by

$$N = 9.654 \times 10^{18} \frac{P_{\rm c}}{T_{\rm c}} \,\,{\rm cm}^{-3},\tag{4}$$

where T_c is the temperature of the target gas in the collision chamber; N is in units of cm⁻³, P_c in Torr and T_c in K. P_c is related to the actually measured pressure P in the membrane manometer at temperature T_m as

$$P_{\rm c} = \left(\frac{T_{\rm c}}{T_{\rm m}}\right)^{1/2} P.$$
⁽⁵⁾

Combining (1) and (3)–(5) we may express $d\sigma/d\Omega$ into experimental quantities:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = ng \, \frac{(T_{\mathrm{c}}T_{\mathrm{m}})^{1/2} \, I_{\mathrm{s}} \sin\theta}{I_{\mathrm{b}}P},\tag{6}$$

where $d\sigma/d\Omega$ is in units of cm², T_c and T_m in K, I_s and I_b in A, P in Torr, the density factor is $n = 1.036 \times 10^{-19}$ cm³ Torr K⁻¹ and the geometrical factor is $g = 4.429 \times 10^5$ cm⁻¹. Applying the conversion $1 \text{ cm}^2 = 3.5712 \times 10^{16} a_0^2$ we obtain $d\sigma/d\Omega$ in atomic units.

3.2. Relative measurements

3.2.1. General procedure. Let us examine the experimental quantities of (6).

In the relative measurements the pulse count rate S is measured instead of the current I_s :

$$I_{\rm s} = \frac{eS}{\eta\tau},\tag{7}$$

where I_s is in units of A and S in pps; e is the electron charge, η the counting efficiency and τ the analyser transmission.

 $I_{\rm b}$ is measured with the Faraday cup in the collision chamber and has to be replaced by $I_{\rm b}/\epsilon$, where ϵ is the collection efficiency of the cup.

 $T_{\rm c}$ is indirectly measured by three temperature probes in the high-vacuum chamber at positions very close to the collision chamber. The probes consist of a platinum resistor of well known temperature coefficient. The average temperature in °C of the three probes was constant within a few per cent during a complete measurement of the angular distribution of the cross section. With gun and pumps in operation $T_{\rm c}$ was about 10°C above room temperature.

The absolute target gas pressure P is measured with the membrane manometer. The pressure head is connected with the collision chamber by a 120 cm long pipe of 4.7 mm internal diameter. $T_{\rm m}$ is kept constant at 49°C by a thermostat in the pressure head.

Accounting for these considerations (7) has to be replaced by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{e\epsilon n g (T_{\mathrm{c}} T_{\mathrm{m}})^{1/2}}{\eta \tau}\right) \frac{S \sin \theta}{I_{\mathrm{b}} P}.$$
(8)

The factor in brackets contains only constants so that we may write for the absolute differential cross section, at given impact energy E and scattering angle θ , the proportion

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(E,\theta) \propto \frac{S(E,\theta)\sin\theta}{I_{\mathrm{b}}P}.$$
(9)

The right-hand side of (9) is defined as the relative differential cross section. It is measured by scanning the angular dependence of the scattering signal $S(E,\theta)$ at fixed E. In one scan $S(E,\theta)$ was measured many times at each θ and averaged. At each θ the primary beam current I_b is measured before and after the determination of $S(E,\theta)$ and also averaged. A measurement was rejected if I_b had changed more than 1%. Reproduction was checked by performing several angular scans at the same impact energy E. The relative scattering angle is adjusted by setting a ten-turn potentiometer (as discussed in §2.5); 1 division corresponds to 0.36°. The $\theta = 0^{\circ}$ position is roughly known on the relative scale. θ was varied in the intervals + 3° < θ < + 15° and - 3° < θ < - 55°. $S(E,\theta)$ was scanned in steps of 0.36° for 3° < θ < 7°, 1.8° for 7° < θ < 20° and 3.6° for 20° < θ < 55°.

A computer program by Baas and Jansen (1975) was used (a) to determine the exact position of the zero angle from the equivalent areas $\theta > 0$ and $\theta < 0$, (b) to determine the absolute angle from the relative one, (c) to calculate the relative differential cross section from the measured variables according to (9), (d) to fit the best curve through the calculated points by means of a high-order polynomial and (e) to take from this curve the values at angles from 5° to θ_{max} in steps of 1°. θ_{max} was somewhere near 54.5°; the precise value depends on the exact zero angle and maximum relative angle position.

3.2.2. Background correction. In the case of helium it was important to correct both for the background signal due to the background pressure in the collision chamber and for the additional signal due to impurities in the admitted target gas. Therefore we measured the energy-loss spectrum of electrons scattered by the background gas in the collision chamber at several primary energies and angles. We observed an inelastic pattern for energy losses $\Delta E > 6 \text{ eV}$. The same was done with helium gas in the collision chamber. The energy spread of the elastic helium peak was less

than 2 eV (FWHM) and the first inelastic helium contribution would appear at an energy loss $\Delta E \simeq 20 \,\mathrm{eV}$, so one should not expect that the inelastic pattern between $\Delta E = 6 \text{ eV}$ and $\Delta E = 20 \text{ eV}$ as found for the background should change by admitting helium to the collision chamber. We found however that the intensity of this inelastic pattern changed and that the form remained the same. This change was found to be proportional to the helium gas pressure in the collision chamber. From this we concluded that with the helium gas an impurity was also introduced into the collision chamber and that the composition of this impurity must be the same as the background gas. From the angular distribution of the differential elastic cross sections measured for the background gas we know that the background gas and consequently the impurity consists mainly of N_2 and O_2 . The differential elastic cross sections for these gases are at small angles 20 to 50 times larger than for helium. This means that contamination of the target gas and a background pressure too high in the collision chamber may seriously increase the apparent cross sections at small angles. We have made experimental provisions to minimize the contamination and the background applying a molecular sieve in the bakeable gas inlet system (see § 2.2) and increasing the gas-flow conductivity of the collision chamber by removing exit channel A 5.

At small angles we measured the background signal *B* and extrapolated this towards larger angles using the measured angular distribution of the relative differential cross section for N₂. The correction factor $Q_{\rm B}$ for the remaining additional background due to impurities in the helium gas was determined by measuring the signal at a certain energy loss ΔE between 6 and 20 eV both with and without helium gas in the collision chamber and taking the ratio

$$Q_{\rm B} = \frac{S_{\rm B}(P_{\rm Hc})}{S_{\rm B}(P_{\rm Hc}=0)},\tag{10}$$

where $S_{\rm B}(P)$ is the inelastic scattering count rate measured at a certain ΔE as a function of the helium pressure $P_{\rm He}$. Hence in (9) S has to be replaced by $S' - Q_{\rm B}B$, where S' is the uncorrected count rate for He. In practice B was always smaller than 3% of S' at the smallest measuring angle and decreased monotonically towards larger angles. $Q_{\rm B}$ was typically 1.3 at $P_{\rm He} = 10^{-3}$ Torr. For the other gases no background correction was necessary.

3.2.3. Absorption correction. On its way through the collision chamber the primary electron beam is attenuated due to absorption by the target gas. Along the path electrons are continuously scattered out of the beam because of total scattering, ie the sum of all possible elastic and inelastic scattering processes. Electrons scattered from the scattering volume towards the analyser experience the same absorption effect.

According to the scattering analogue of the Lambert–Beer law as given by Bromberg (1969a) we may write the scattered count rate as an exponential function of the target gas pressure:

$$S(P) = A_1 I_b P \exp(-A_2 P L), \tag{11}$$

where A_1 is a constant proportional to the differential elastic cross section, A_2 is a constant related to the total scattering cross section and *PL* the effective product

of target gas pressure P and path length L in the target gas. Equation (11) may be rearranged to

$$\ln\left(\frac{S(P)}{I_{b}P}\right) = \ln A_{1} - A_{2}PL.$$
(12)

Plotting $\ln [S(P)/I_bP]$ against P, where P was varied from 0.5 to 8 mTorr, we found a straight line with intercept $\ln A_1$ and slope $-A_2L$. In the limit $P \rightarrow 0$ where no absorption can take place we find the unaffected relative differential cross section A_1 ; so we take as absorption correction factor

$$F(E, \theta) = \frac{A_1}{S(P_1)/I_b P_1},$$
(13)

where P_1 is the actual target gas pressure during the measurement of the angular distribution of $S(E,\theta)$. To obtain the correct relative differential cross section one has to multiply the measured cross section by $F(E,\theta)$. The latter is a very slowly varying function of θ and in nearly all cases it was sufficient to take one fixed value for all angles. However, $F(E,\theta)$ varied with E as explained by Bromberg (1969a) and was larger for smaller E. For N₂ $F(E,\theta)$ varied over the range 1.02–1.12, for Ar 1.01–1.10 and for Ne 1.01–1.05. For He it was approximately constant at 1.01.

3.3. Absolute measurements

To put the relative cross sections on an absolute scale we need an apparatus calibration factor. We have determined this factor by measuring absolute cross sections for N_2 at 500 eV.

The channeltron used in the relative measurements was replaced by a Faraday cup (cup 3) of the same dimensions as the Faraday cup for the primary beam (cup 1) (see also figure 1). The scattering current collected by cup 3 was measured with a Cary vibrating reed electrometer calibrated according to the instructions of the manufacturer.

Starting from the basic cross section equation, (6), I_s has to be replaced by $(I_s - I_B)/\tau$ where I_s is the scattered current with target gas present in the collision chamber, I_B the background current measured in the absence of target gas and τ the analyser transmission. Because both Faraday cups have identical dimensions the collection efficiencies for primary and scattered current cancel out. Finally we apply the absorption correction factor $F(E,\theta)$ and find for the absolute cross section at impact energy E and scattering angle θ

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(E,\theta) = \left(\frac{ng(T_{\mathrm{c}}T_{\mathrm{m}})^{1/2}}{\tau}\right) \left(\frac{I_{\mathrm{s}}(E,\theta) - I_{\mathrm{B}}(E,\theta)}{I_{\mathrm{b}}}\right) \frac{\sin\theta}{P} F(E,\theta).$$
(14)

The noise level of the vibrating reed electrometer was about 2×10^{-16} A. For a reliable measurement we required that $I_{\rm B} \ll I_{\rm s}$. We chose N₂ as target gas because of its large cross section at small angles and took an impact energy of 500 eV for direct comparison with literature (Bromberg 1970). To keep $I_{\rm s}$ sufficiently above noise level, θ was varied between 3° and 11°. With $I_{\rm b} \simeq 5 \times 10^{-7}$ A and $P = 2 \times 10^{-3}$ Torr, $I_{\rm s}$ varied from 1.5×10^{-13} to 2.5×10^{-14} A as a function of θ . $I_{\rm B}$, containing background scattering and electrometer noise, varied from 7% to 1.5% of $I_{\rm s}$ over the angular range. The transmission τ of the analyser is defined as the ratio of the current entering the spherical analyser and the current entering cup 3 replacing the channeltron M in figure 1. For the determination of τ we measure the beam current in three differently located Faraday cups of identical dimensions: I_1 is the primary beam current collected by cup 1, without target gas in the collision chamber. I_2 is the fraction of I_1 that passes aperture A_7 and is collected in Faraday cup 2 in the wall of the high-vacuum chamber just behind the channel in the outer hemisphere of the analyser at $\theta = 0$. I_3 is the current that passes the analyser and is collected by cup 3. If the appropriate voltages are applied to the hemispheres, I_3 is measured and if the spherical analyser is turned off I_2 is measured. In this way we determined at constant I_1 and E the transmission $\tau = I_3/I_2$ as a function of (a) the deceleration voltage and (b) the voltage of the inner hemisphere in both cases for analysing energies E_0 equal to 50, 100 and 200 eV. In all cases we found trapezium-like transmission curves with a flat top at $\tau = 1.00$, showing an analyser transmission of 100%.

 $(I_{\rm s} - I_{\rm B})/I_{\rm b}$ was measured in angular steps of 0.72°. Applying (14) and using the computer program mentioned in § 3.2.1 we obtained absolute differential cross sections $d\sigma(500,\theta)/d\Omega$ at $\theta = 5^{\circ}$, 6°, 7°, 8° and 9° as shown later in table 11.

3.4. Apparatus calibration factor and normalization

3.4.1. Procedure. To convert our relative cross sections into absolute ones we applied the following procedure.

The relative cross section as a function of angle θ at fixed impact energy E was measured according to (9). Let us indicate that cross section by $\sigma_{rel}(\theta)_E$. Including the absorption correction we obtain as the correct relative cross section $\sigma_{rel}(\theta)_E F(E,\theta)$. In order to obtain a consistent set of relative cross sections we measured for each gas the relative cross section as a function of E at fixed θ (θ was 10° and 30°) according to (8). Let us indicate this cross section as $\sigma_{rel}(E)_{\theta}$. For each gas this energy dependence was measured under completely the same experimental conditions. As discussed in the preceding section we measured for N₂ the absolute cross section according to (14). Let us indicate this direct measured absolute cross section by $\sigma_{abs}(500,\theta)$.

We now define the apparatus calibration factor f_{c} as

$$f_{\rm c} = \frac{1}{5} \sum_{\theta} \left(\frac{\sigma_{\rm abs}(500,\theta)}{\sigma_{\rm rel}(500)_{\theta} F(500,\theta)} \right)_{\rm N_2}, \qquad \theta = 5, 6, 7, 8, 9^{\circ}.$$
(15)

For each gas and energy the absolute cross section at $\theta = 10^{\circ}$, $\sigma_{abs}(E)_{10}$, follows from the relative one by

$$\sigma_{\rm abs}(E)_{1\,0} = f_{\rm c} \,\sigma_{\rm rel}(E)_{1\,0} \,F(E, 10). \tag{16}$$

Since absolute cross sections are concerned we have

$$\sigma_{abs}(10)_E = \sigma_{abs}(E)_{10}.$$
 (17)

The relative cross section $\sigma_{rel}(\theta)_E$ is made an absolute cross section, $\sigma_{abs}(\theta)_E$, by

$$\sigma_{\rm abs}(\theta)_E = \frac{\sigma_{\rm abs}(10)_E}{\sigma_{\rm rel}(10)_E F(E, 10)} \,\sigma_{\rm rel}(\theta)_E F(E, \theta). \tag{18}$$

From (16)–(18) we finally obtain

$$\sigma_{\rm abs}(\theta)_E = f_c \frac{\sigma_{\rm rel}(E)_{10}}{\sigma_{\rm rel}(10)_E} \sigma_{\rm rel}(\theta)_E F(E,\theta).$$
⁽¹⁹⁾

Using (15) we calculated $f_c = 0.0787$ which is only 0.25% larger than the corresponding factor used by Jansen *et al* (1974) normalizing their relative N₂ cross sections on Bromberg's (1970) absolute N₂ cross sections.

Comparing the value of f_c obtained with the proportion constant in (9) between the relative and absolute cross section according to (8), we may estimate the unknown efficiencies ϵ of the primary beam cup and η of the channeltron. Transforming that proportion constant into the same units as f_c and dividing by f_c we find $\epsilon/\eta = 1.04$. The value of this ratio might be explained by the estimation: $\epsilon = 1.00$ and $\eta = 0.96$.

3.5. Error discussion

If, in this section, we speak about errors and the combination of errors we mean fractional errors, respectively the square root of the sum of the squared fractional errors. A survey of the experimental errors involved in the relative and absolute differential cross sections is given in table 1.

The error in the relative cross section corrected for absorption, ie in $\sigma_{rel}(\theta)_E F(E,\theta)$, is the combination of the random errors in I_b , P, $S(E,\theta)$ and $F(E,\theta)$ (see also (9)). The uncertainty in θ has been taken into account in the error of $S(E,\theta)$. The error in the absolute differential cross section $\sigma_{abs}(\theta)_E$ (see (19)) is the combination of the errors in $\sigma_{rel}(\theta)_E F(E,\theta), \sigma_{rel}(E)_{10}/\sigma_{rel}(10)_E$ and f_c . The error in the apparatus calibration factor f_c is the combination of the RMS error of the averaging and the systematic errors involved in $\sigma_{abs}(500,\theta)$ (see (15)). According to (14), the fractional error in $\sigma_{abs}(500,\theta)$ is a combination of both random and systematical errors in I_b , P and $I_s(500,\theta) - I_B(500,\theta)$ and the errors in g, T_c , T_m and $F(500,\theta)$ as given in table 2.

4. Summary of the results

The absolute differential cross sections, obtained according to (19), are summarized in tables 3–6 for respectively He, Ne, Ar and N₂. The cross section data are in units of $10^{-3} a_0^2$ for He and in a_0^2 for the other gases. For convenience the data are only shown at every 5°. The numbers quoted in parentheses behind the cross section values are the plus and minus fractional errors expressed as a percentage of the absolute cross section.

		Fractic	onal error	
Quantity	He	Ne	Ar	N ₂
I _b P		0.0	10	
$ \begin{array}{l} S(E,\theta) \\ F(E,\theta) \\ \sigma_{rel}(\theta)_E F(E,\theta) \end{array} $	0·012–0·021 0·006–0·009 0·019–0·025	0·013-0·020 0·003-0·005 0·018-0·023	0.014-0.024 0.005-0.007 0.019-0.027	0·0140·027 0·0050·008 0·0200·030
$\sigma_{rel}(E)_{10}/\sigma_{rel}(10)_E$ $f_c \begin{cases} random \\ systematic \\ \sigma_{ubs}(\theta)_E \end{cases}$	0·0260·036 0·0590·067	0·027–0·037 0·0 0·0 0·059–0·067	0·032-0·039 19 46 0·062-0·069	0.032-0.045

Table 1. Survey of experimental errors involved in the relative and absolute differential cross sections.

	Frac	tional error
Quantity	Random	Systematic
(w		0.008
a		0.008
g_{v}		0.002
R		0.007
T_c		0.01
Ť,		0.01
$\tilde{F}(500,\theta)$	0.009	
Ib	0.01	0.02
P	0.003	0.03
$I_{\rm s}(500,\theta) - I_{\rm B}(500,\theta)$	0.019-0.027	0.02
$\sigma_{\rm abs}(500,\theta)$	0.021-0.	054

Table 2. Survey of experimental errors involved in the directly measured absolute differential cross section for N₂ at E = 500 eV and $5^\circ \le \theta \le 9^\circ$.

5. Discussion

5.1. Helium

In table 7 we compare the present He results with those of other experimental and theoretical groups.

At energies above 500 eV and angles above 10° the present work is in agreement with the eikonal Born series (EBS) calculations of Byron and Joachain (1973a,b, 1975) which differ very little in this angular and energy range from the pure first Born approximation. This suggests that our absolute scale is correct. Besides scattering by the static potential up to third order, the EBS theory includes also (i) exchange of the incident electron and an atomic electron, (ii) polarization of the target by the incident electron and (iii) absorption; the latter effect arises from the fact that a certain number of incident electrons excite or ionize the target; these electrons are therefore removed from the incident (elastic) channel.

Between 200 and 700 eV, in general the present work and the absolute measurement of Bromberg (1974b, 1975 and private communication) are in agreement with each other and with the EBs theory of Byron and Joachain, except at angles below 10° where our experimental data are 10 to 20% lower than theory. Byron and Joachain estimate their possible theoretical error to be 20% at 100 eV, 5% at 500 eV and 1% at 2000 eV.

Between 200 and 500 eV the *ab initio* optical model (OM) theory of Byron and Joachain (1974, 1976) yields at small angles ($\theta < 20^{\circ}$) values lower than the EBS theory; above 200 eV it is in excellent agreement with the present work and Bromberg. The OM theory also includes scattering by the static field, plus exchange, polarization and absorption.

The experimental error in Bromberg's data is about 3%, where it is about 6% in the present work. The largest deviation between our results and Bromberg is 8% and appears at 700 eV and 5%, where Bromberg is closer to the EBS result. Recently Dillon and Lassettre (1975), of the same group as Bromberg, checked the angular trends of the helium cross section at 400 and 700 eV. They found a less steep rise

5 10	2320(6-0)		W 7	nnc	400	500	700	1000	2000	3000
10	1700/6-0)	2010(6-0)	1680(6-0)	1280(6.1)	1060(6-1)	906(6-1)	706(6.2)	585(6-2)	435(6.4)	(9-9)L9E
	1 1 Mar 1	1360(6-0)	1080(6-0)	787(6-0)	644(6-0)	550(6-0)	436(6-1)	338(6-2)	195(6-4)	127(6-6)
15	1240(6-0)	944(6-0)	739(6-0)	538(6-0)	430(6-0)	355(6-0)	260(6-1)	183(6.7)	81-6(6-3)	12/(0.0) 15/1(6.5)
20	932(5-9)	682(5-9)	528(5-9)	365(6-0)	289(6-0)	229(6-0)	154(6-0)	(20)/01	35-46-3)	19.2(6.5)
25	(0.9)602	503(6-0)	385(6-0)	247(6-0)	192(6-0)	146(6-0)	90.6(6-1)	54-0(c-2)/ 54-0(c-2)	(C 0)F CC	(C.D)C.01
30	549(6-0)	375(6-0)	281(6-0)	169(6-0)	128(6-1)	03:3(6-1)	55-6(6.1)	21.2(C.2)	(+.0)c.71	(0.0)60.0
35	425(6-0)	283(6-0)	205(6-0)	121(6-1)	86.4(6.7)	(1.0)0.07		01 2(0.2)	(+.0)00.4	(0-0)cc.+
10	330(6-1)	215(6-1)	151(6.1)	171(01) 00.5(51)	60.4(0.7)	(7.0)7.10	(7.0)7.00	19-0(6-2)	5-39(6-4)	2-44(6-6)
. Y		(10)(17	(1.0)101	(1.0)0.00	(7-0)/-60	41-2(6-2)	23-0(6-2)	11-9(6-2)	3-33(6-4)	1.46(6.6)
t c	(1.0)007	108(0-1)	114(6.1)	60-1(6-2)	42-2(6-2)	 28-5(6-2) 	15-9(6-2)	7-87(6-3)	2-16(6-5)	0-904(6-6)
00	216(6-2)	135(6·2)	88-5(6-2)	45-0(6-2)	30-6(6-2)	20-3(6-2)	11-1(6-2)	5-59(6-3)	1-40(6-5)	0.584(6.6)
> 20T	189(6-2)	113(6-2)	74-2(6-2)	38-4(6-2)	24-0(6-3)	16-5(6-3)	8-89(6-2)	4.31(6.3)	1-10(6-5)	0-506(6-6)
At θ	= 53.8	54-0	53-8	54-2	54.2	54-2	53-8	53-8	53-8	53-8
) (deg)	E(eV) = 100	150	200	300	400	500	750	1000	2000	3000
	10 4/5 0)	0 17(1 0)								
	(6.0.1-1)	(6-c)/ c-6	9-44(5-9)	8-63(6-0)	8-21(6-0)	7-51(6-0)	6-75(6-0)	6-30(6-1)	5-44(6-4)	5-08(6-6)
0,	7-75(5-9)	6.78(5-9)	6-20(5-9)	5-48(6-0)	4-97(6-0)	4.61(6.0)	3-96(6-0)	3-48(6-1)	2-41(6-3)	1-84(6-5)
5	5-71(5-9)	4-66(5-9)	4-12(5-9)	3-46(6-0)	3-02(6-0)	2.72(6-0)	2.17(6.0)	1-78(6-0)	0-992(6-3)	0-662(6-5)
0	4-15(5-9)	3-21(5-9)	2-75(5-9)	2.19(6.0)	1.84(6.0)	1-60(6-0)	1.19(6-0)	0-908(6-0)	0-442(6-2)	(-0.777(6-4)
5	2.95(6-0)	2.17(6-0)	1.82(6.0)	1.39(6.0)	$1 \cdot 12(6 \cdot 0)$	0-956(6-0)	0.670(6.1)	0-498(6-1)	(-223(6-3))	0.135(6-4)
0 '	2.11(6.0)	1-50(6-0)	1.20(6.0)	0-877(6-0)	0.693(6.0)	0.583(6.0)	0.401(6.1)	$0-293(6\cdot1)$	0.127(6.3)	0-0727(6-5
Ś	1-51(6-0)	1-03(6-0)	0.790(6.0)	0-568(6-0)	0.445(6.1)	0.368(6.1)	0.256(6.2)	0-188(6-2)	0.0784(6.4)	0-0433(6-5
9	1-10(6-0)	0-715(6-0)	0.533(6.0)	0.383(6.0)	0.301(6.1)	0.247(6.1)	0.174(6.2)	(0.128(6.2))	0.0513(6.4)	0-0776(6-5
Ċ,	0-822(6-1)	0.499(6.1)	0-371(6-1)	0.272(6.1)	0-217(6-2)	0.180(6.2)	0.128(6.2)	0-0906(6-2)	0.0354(6.4)	0-0184(6-6
0	0.633(6.1)	0.361(6.1)	0-273(6-1)	0.203(6.1)	0.166(6.2)	0.140(6.2)	0.0978(6.2)	0.0683(6.2)	0.0253(6.4)	0-0132(6-6
> 207	0-516(6-2)	0-284(6-2)	0-218(6-2)	0-160(6-2)	0-137(6-2)	0-116(6-2)	0.0798(6.3)	0-0560(6-3)	0-0207(6-5)	0-0100(6-6
A1 $\theta =$	= \$3.9	53.9	54-0	54-0	54.1	53.0	52.0	54.0		

. ith nite of 10-3 2 Table 3. Absolute differential cross sections of electrons elastically scattered by helium (in Absolute differential cross sections

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0 (dcg)					100					
	E(eV) = 100	150	200	300	400	500	750	1000	2000	3000
5	47-6(6-4)	47-1(6-4)	42.6(6.4)	37-2(6-4)	34-36-41	17-378/6-71	30.515 57	- 11 OC		
10	28-6(6-3)	23-8(6-3)	21-1(6-3)	18.3(6.3)	(1-0)	(+.0)0.76	(C-0)C-0C	(0.9)	24-6(6-7)	19-8(6-9)
15	16-2(6-3)	12.5(6.3)	10.7(6.3)		(+.0)(0.1	(+-9)6-61	12.8(6-4)	11.0(6.4)	6.31(6.6)	3-98(6-8)
20	0.13(6.3)	$(C n)C \neq 1$	(0.0)/ JU	(5-0)12-2	/-42(6-4)	6-59(6-4)	4.87(6.4)	3-88(6-4)	1-86(6-6)	1-17(6-7)
25	(70)(10	(7.0)00.0	(7.9)+5.0	4-18(6-2)	3.40(6.3)	2.94(6.3)	2.07(6.3)	1-64(6-4)	0-781(6-5)	0.4946.61
07	2.11(0.3)	3-49(6-3)	2.71(6.3)	2.08(6.3)	1.72(6.3)	1-48(6-4)	1-09(6-4)	0-865/6.0		0.404(0.0)
05	2-87(6-3)	1-89(6-3)	1-47(6-3)	$1 \cdot 17(6 \cdot 3)$	1-01(6.4)	0-88116-0	0.66916 4)	(+-0)(-0-0)	(0.0)/04-0	0-245(6-6)
35	1.60(6.4)	1-07(6-4)	0-885(6-4)	0-76616-4)	0.69916.4		0.000(0.4)	(1-0)810-0	0-726(6-6)	0.139(6.6)
40	0-899(6-4)	0-66666-4)	0.60016.01	(+ n)nn n	0.000(0.4)	(4-9)(0-0	0.442(6.4)	0.331(6.4)	0.136(6.6)	0-0857(6-7)
45	$(1 \circ) < co \circ$	(+ n)nnn n	0.002(0.4)	(1-0)7/00	0.515(6.4)	0.446(6.4)	0.301(6.4)	0-221(6-4)	0-09306-60	0-0574(6-7)
2 5	(+0)1700	0.407(0.4)	04/2(64)	0.454(6.4)	0.394(6.4)	0-327(6-5)	0-209(6-5)	0-155(6-5)	0-0630(6-6)	
	0.327(6-4)	0-369(6-4)	0.406(6.4)	0.365(6.4)	0-305(6-4)	0.241(6.5)	0-156(6-5)	0.116(6.5)	(0.0)00000	0.0000000
	0-223(6-5)	0-331(6-5)	0.363(6.5)	0-289(6-5)	0-253(6-4)	0-207(6-6)	(-1)4(6-6)	0-002412	0.0410(0.0)	0.0301(6.7)
						(2.2.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2	(n n) = 1 n	(C.0)+7(0.0	(0.0)cn+n.n	0-0230(6-7)
† At θ	= 54.7	54-5	54·1	54-1	54-0	54-0	54-0	53-8	53-8	53-9
Table 6.	. Absolute differential cr	oss sections of e	lectrons elastica	ully scattered by	molecular nitroo	en (in mits of a	² with errors in	4		
							0, with 01015 III	ber cent).		
(gab)	E(eV) = 100	150	200	300	400	500	750	1000	2000	3000
5	61-2(6-3)	58-9(6-3)	54-5(6-4)	47-0(6-4)	42-8(6.4)	30.672 41	22 616 52			
10	35-7(6-3)	30-9(6-3)	27-1(6-3)	71-6(6.4)		(+.0)0.20	(0.0)0.00	(9-9)6-67	20-8(7-0)	12·4(7·4)
15	20.3(6.2)	15.7(6.2)	$(C \alpha) = 12$	(+.0)0.17	18-1(0-4)	15.5(6-4)	10-8(6-5)	8-01(6-6)	3-59(6-9)	2-47(7-2)
20	10-0/0-2	(7 0)/ CT	(0.0)/.71	9-00(6-3)	6.80(6.4)	5-40(6-4)	3-38(6-4)	2-64(6-5)	1-63(6-8)	0-837(7-2)
35	(70)(0.3)	(7.0)+0.1	(7-0)(7-0	3-81(6-3)	2.95(6.3)	2.41(6.4)	1.73(6.4)	1-50(6-4)	0-664(6-7)	0.780/7.0)
5 C2	(6.0)67.6	3 - (4(0-3))	2.82(6.3)	1-88(6-4)	1-61(6-4)	1-44(6-4)	1.15(6.4)	0-886(6-5)	0-278/6-81	(0.7)607.0
25	(5.0)11.0	1-99(6-3)	1.57(6.3)	$1 \cdot 19(6 \cdot 4)$	1.09(6.4)	1-02(6-4)	0-725(6-5)	0-474(6.5)	0 7 7 7 6 0 0	0.120(1.0)
ربر بر	1-83(6-4)	$1 \cdot 22(6 \cdot 4)$	1-04(6-4)	0-917(6-4)	0-822(6-4)	0-740/6-4)	(CO)CZ10	(0.0)+/+0	0.101(0.2)	0-725(7-1)
40	1.18(6.4)	0-845(6-4)	0.778(6.4)	(1-753(6.4))	(1, 2)		(0.0)014.0	(0-0)107-0	0.0994(6.9)	0.0434(7.1)
45	0.833(6.4)	0.662(6.4)	0.630(6.4)	0.570(6.5)	0.475(6.5)	0.498(6.4)	0.242(6.5)	0-176(6-6)	0-0591(6-9)	0-0267(7-1)
50	0.636(6.4)	0-548(6-4)	(-5)(6-4)	0.406655	(2.0)004.0	0.310(6-3)	0.169(6-6)	0.135(6.6)	0.0429(6.9)	0.0183(7.2)
> 50†	0-541(6-5)	0.485(6.5)	(+0)0100	0.261(6.2)	(0.0)067-0	0.209(6.5)	0.137(6-6)	0-0930(6-6)	0-0305(6-9)	0-0125(7-2)
	Anno and a second secon	10 0000 0	0.40704-0	(a.a)rac.n	(9-9)522-()	0.188(6.5)	0-116(6-6)	0.0728(6.7)	0-0224(7-0)	0-0102(7-2)

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53-9

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53-9

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54-0

 $\dagger At \theta =$

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of the cross section for angles below 15° ; at their smallest angle 7° the deviations from Bromberg are -4.4% for 400 eV and -2.2% for 700 eV.

At low energies the present results at 5° are in excellent agreement with Chamberlain *et al* (1970) who measured the absolute cross section only at 5° for energies between 100 and 400 eV. Chamberlain's data are often used as normalization of relative cross sections and also for renormalization of the data of Vriens *et al* (1968). Previously Jansen and de Heer (1973) questioned this procedure because the original data of Vriens *et al* (1968) (normalized by measuring the ratios of the elastic to $2^{1}P$ cross sections) were in agreement with the EBs theory of Byron and Joachain, whereas the data of Chamberlain *et al* (1970) were not. The present results however confirm Chamberlain's data at 5° , and differ in absolute value as well as in slope with the data of Vriens *et al* (1968) and with the renormalized data of Vriens at angles other than 5° .

Compared to our data, the EBS and OM calculations of Byron and Joachain overestimate the small-angle cross sections at 100 eV. At 5° our value is 33% smaller than EBS and 31% smaller than OM.

We also compared with the plane wave approximation of Khare and Shoba (1971) (including polarization and exchange) which shows smaller values than Byron and Joachain at low energies. Khare and Shoba agree quite well with our experiment. Examination of the graphs in LaBahn and Callaway (1969a,b) and Winters *et al* (1974) indicates that the results of these theoretical groups often lie close to our experimental results. Unfortunately we have at this moment no numerical data from these groups and therefore they are not shown in table 7. The recent experimental data of Sethuraman *et al* (1974) seem also to be in favour of the present work.

The absolute data of Crooks (1972) and Kurepa and Vusković (1975) overestimate the cross sections at smaller angles. The absolute data of Oda *et al* (1972) are in excellent agreement with the present work at 500 eV.

Buckley and Walters (1974), applying their so-called static exchange corrected simplified second Born approximation (SESSBA 2), obtained larger values than the EBS theory. At 500 eV however we show their static corrected simplified second Born approximation (SCSSBA 1) which agrees excellently with Bromberg and the present work.

Fink and Yates (1970), applying a partial-wave method to solve the Dirac equation numerically, do *not* include exchange, polarization and absorption effects. Their calculations therefore can never yield correct cross section values at lower energies and small angles. At higher energies and larger angles however the agreement with our experiment is very good.

From the foregoing we may conclude that at the moment Bromberg (1974b, 1975) and the present work yield the best cross sections for He. Above 200 eV the most preferable theory is the OM theory of Byron and Joachain at lower energies and the EBS theory of the same authors at higher energies. The fact that our cross sections below 10° are systematically compared with Bromberg's stresses the need for additional accurate measurements at small angles. We believe that our lower values at angles below 10° result from the fact that we have reduced the N₂ contributions to the He cross section and have corrected for the remaining part, as discussed in § 3.2.

5.2. Neon

In table 8 our results for neon are compared with the results of other groups (again we have omitted the groups from which we do not have numerical data at our disposal).

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: 7. Con	grees and	
Table	in de	

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	lin .	OM BW	3340 4220	2440 2970	1280 1510	707 848	409	251 326							1860 2200	1210 1340	577 650	296 349	- 159	91-4 112	1310	828	378	178	88-2	47-5		1040 1140	1040 1140 658 709	1040 1140 658 709 283 317	1040 1140 658 709 283 317 122 140	1040 1140 658 709 122 3317 122 140 568 -	1040 1140 638 709 283 317 122 140 568 – 292 3337	1040 1140 688 709 283 317 122 140 568 - 29-2 33-7 805 928
Theoretical	on and Joacha	EBS	3480	2510	1260	655	364	218							0661	1250	562	282	152	87-1	1420	854	374	175	87-4	47-3	1120		674	674 283	674 283 122	674 283 122 57-1	674 283 122 57-1 29-6	674 283 122 57-1 29-6 951
	By	B	616	583	476	354	250	174							605	544	373	225	131	0-82	594	508	299	155	6-6L	43-6	583		475	475 245	475 245 112	475 245 112 53-4	475 245 112 534 276	475 245 112 534 276 573
		KS	1	1716	1037	615	377	I		1330	696	365	205	I	I	1115	519	249	133		:	864	336	144	73-0		ļ		713	713 242	713 242 97-0	713 242 97-0 48-3	713 242 97.0 48.3	713 242 97-0
		FΥ		587	484	366	266	192		565	422	287	187	122	ł	543	375	231	138	84-7														(272)
		МР			897	529	268	154																										
		ΚV	3240	2460	1340	740	457	297	2370	1530	758	400	228	140	2000	1230	575	292	162	95-4														
		Br													1729	1122	527	276	152	89.1	1317	810	367	176	88-5	48-1	1097		662	662 277	662 277 123	662 277 123 57-1	662 277 571 571 29-7	662 277 57-1 57-1 29-7 947
ıtal		ſ	2890	2180	1210	(675)	393	247							2360	1500	607	(318)	172	100	1970	1140	500	(218)	107	55-4	1390		893	893 364	893 364 (155)	893 364 (155) 71-5	893 364 (155) 71-5 35-7	893 364 71-5 35-7 35-7
Experime		0																																
		Ċ	i	2440	1350	704	I	269							ì	1930	111	323	I	103							ļ		758	758 315	758 315 141	758 315 141	758 315 141	758 315 141 332
		ę	2340	1730	904	497	i	I	1980	1340	622	311	ļ	i	1660	1040	456	224	İ	-	1250	776	331	131			1040		622	622 237	622 237 95:0	622 237 95-0	622 237 95-0	622 237 95-0
		>	3600	2660	1390	765	ł	I	2590	1750	813	407	i	ł	2040	1280	561	275	ł	ļ	1390	863	368	146		i.	1150		688	688 262	688 262 105	688 262 	888 262 	888 262
		Н	I	I	722	385	236	150							i	1160	443	214	111	64:3														I
	This	work	2320	1700	932	549	330	216	2010	1360	682	375	215	135	1680	1080	528	281	151	88-5	1280	787	365	691	88.5	45-0	1060	144	10	289 289	289 128	0444 128 59:7	044 289 59-7 30-6	289 289 30-6 30-6 906
		0	5	10	20	30	40	50	5	10	20	30	40	50	5	10	20	30	40	50	5	01	20	30	40	50	5	10	10	50 50	30 50 30 50	20 30 40 30 40	20 9 30 50 10 20 9 30 50 10	⁵ 20 30 20 10
		E	100						150						200						300						400							200

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	20	229	198		228	264	226	206	186	204	226	325	400	
	30	93-3	79.3		<i>6.</i> .0	000	91.5	2.7.9	71.6	02:U	277	0.00		
	40	C11	10.7		1	1000			0.17	0.00	0.06	0.06	C.76	
	f i	7.14	1.04		47.8	40-2	41-0	41-6	34-9	38-0	40-2	39-7	41-7	
	20	20-3	20-4		20-5	21-4	20-2	20-3		18-9	20-2	8-61	21-1	
002	v	201												
202	n ș	00/	1				768			553	765			
	0	436	420				461			394	457			
	20	154	130		(148)		157			147	156			
	30	55-6	4 4 -3		46-6		55-7			53.7	5.55			
	40	23-0	7-61		(19-5)		23:3			4 CC	0.00			
	50	11-1	8-22		(9-30)		113			10-4	0-11			
1000	5	585				786		(575)		575				
	9	338				00/		(676)		C7 C	0.50			
	20	L-L6			65.7	(j)		555 200		155	360			
	21 U2	C-112			7.70	333		0.96		7.16	10			
	₹ ₹	710			6.17 C.17	(7.75)		31-5		30-6	31-5			
	₽ 9	6.11			0.11	8-1- 		12-3		11:8	12-2			
	PC PC	6C-C			(5-10)	5-72		5-70		5-40	5-65			
2000	5	435								445	475			
	10	195								2000	306			
	20	35.4								707	007			
	2.6	0.38								5.05	30.8			
	5 5	00.4								9-21	9-35			
	€ 5	0.00 000								3-23	3-30			
	nc	1-40								1-42	1-46			
Н	Hug	hes et al	(1932), re	slative measurement norn	alized b	ov fittino	the 700 eV curve to Mo	tt's theory	hundere	due are	ical interno	lations b	aturon dat	4
	mear	sured at r	nearhy ano	л <u>е</u> с		ρ 		n a moord,	e i anni i anni	are Braph			עושייוו טאו	319
Λ	Vrie	ne <i>at al</i> fi	1068) relat	tive meaniment normal	and to 2	un areas								
- č		ns et ut (.	1700, 10141		7 OI DAZI	CT CTOSS	section.							
5	Cha	mberlam	et al (1970	0), absolute mcasurement	at 5°; re	normaliz	ed values of Vriens et al	1968) at $\theta >$.5°.					
5	Cro	oks (1972,												
0	Oda	et al (19	72): 500 e ¹	V; Oda et al (1973 priva	ite comr	nunicatic	on): 700 and 1000 eV; nu	mbers in pai	rentheses	are graph	nical interne	dations F	otween dat	113
	meat	sured at 1	nearby ang	gles.						-				
ſ	Jost	et al (197	73). relative	'c measurement fitted to t	heory of	. Fink an	d Yates: at 30 [×] oranhicall	v internolate	d hotwee	n data at	28° and 32°			
Br	Brot	nberg (19	74b, 1975).	j.	e.		0							
Kν	Kur	epa and V	Vusković ((1975).										
MD	Mac	Tonley of	ad Denetor	· /1076)·		-		â			•			
		UIINEY AI		(19/3); relative measure.	nent noi	rmalized	at 20° to Vriens et al (190	o8), as renori	nalized b	y Chambe	srlaın <i>et al</i> (1970).		
۲Y	Fink	and Yat	tes (1970);	at 5° linearly interpolated	1 betwee	n data ai	t 4° and 6°.							
KS	Kha	re and Sh	nobha (1971	1).										
в	Borr	l												
EBS	Eiko	mal Born	series	Byron and Joachain (197)	'3a. b. 19	75. 1976)								
OMO	Ah ii	aitio ontic	l lanodel											
DW/	Dund	ando onun Alorenda	Walters (10)	740	1002	-								
ΜQ	DUCI	kley anu v	Wallers (12	7/4) and buckley (12/4); a	DUD EV	SCSSBA 1,	otherwise sessaa 2.							

degree	s and en	ergies in eV).			Experir	nental				Theoretical	
ц.	0	This work	Arnot ^a (1931)	Hughes and McMillen ^b (1933)	Jost et af ^c (1973)	Bromberg (1974b, 1975)	Kurepa et al (1975 private communication)	Gupta and Rees ^d (1975)	Fink and Yates ^e (1970)	Walkcr (1974 private communication)	Byron and Joachain (1974, 1976)
001	5	10.4	·	10-3	(11-3)				(2.98)	4-40	14-3
	2 8	7.75		7-23	7-98		9-33 4-86	8·18 9·16	2.80	4-06 3-07	10-1 4:37
	ର ଜ	61-4 11-6		5.28	-1-4 -1-6		4.60 7-70	2-16 2-16	1-20	5.04 1-94	1-70
	60	1-10		1-12	- 12 1·12		1-36	1.22	1-03	1-15	0-623
	50	0-633		0-530	0.622		0-786	0-679	0.645	0-675	0.240
150	5	9.57		13-3							
	10	6-78		7-39			6.89	7-11			
	20	3-21		2.96			2:75	3-32			
	30	1.50		1-50			1-38	1-54			
	40	0-715		0.773			0-679	0-771			
	50	0-361		0.417			0-357	0-382			
200	5	9-44				9-75				4.96	11-2
	10	6-20	6-01			6.42	6-68	6-32		4.35	7-07
	20	2-75	3-76			2.82	2.64	2.50		2-67	2-68
	30	1-20	1-27			1-17	0-983	1.19		1.35	0-992
	40	0-533	0-553			0-538	0-447	0-523		0-639	0-384
	50	0.273	0-287			0-273	0.220	0-285		0.324	0.177
300	Ś	8-63		i		8-95					9-52
	10	5-48		5-62		5-47		5.65			5-72
	20	2-19		1-97		2-12		2-08			2:05
	30	0-877		0.883		0-839		0-865			0-729
	40	0.383		0.354		0-368		0-386			0.294
	50	0-203		0-195		0-196		0-229			0-153

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400	Ś	8-21			8-48	I		8-53
	10	4-97		6.51	5.16	5-39		5-05
	00	1-84	(2-15)	1.84	1.86	1-96		1.73
	2 0 7	0-693	(0.574)	0.658	0-685	0.729		0-599
	60	0-301	(0.287)	0.309	0-301	0-340		0-251
	50	0.166	(0.157)	0-153	0-165	0.169.		0-138
200	Ŷ	7-51			7.87		(4.94)	7-93
	, 01	4-61			4-65	4.55	3-81	4-66
	20	1-60			1-56	1-53	1-64	1-52
	30	0-583			0.563	0-580	0-632	0.514
	40	0-247			0-246	0-262	0-282	0-221
	50	0.140			0-138	0-127	0.157	0-125
1000	5	6-30					(5-60)	
	10	3-48					3.59	
	20	0-908					1-04	
	30	0-293					0.336	
	40	0.128					0-146	
	50	0.0684					0-0791	

in parentheses are graphical interpolations between data measured at nearby angles. ^b Relative measurement, normalized to the present work at 400 eV and 20° .

 $^{\circ}$ Relative measurement, normalized to the present work at 20 $^{\circ}$; at 5 $^{\circ}$ linearly interpolated between data at 4 $^{\circ}$ and 6 $^{\circ}$.

^d Relative measurement on He-Ne mixture, normalized by comparing with EBS theory of Byron and Joachain (1973b).

 $^{\circ}$ At 5° linearly interpolated between data at 4° and 6°.

ncsic						Frnerime	ntal					heoretical		
											•			
		This	Arnot ^a	Wcbb ^b	Jost et al ^c	Bromberg	DuBois and Rudd	Williams and Willis	Vusković and Kurepa (1975 private	Fink and Yates ^d	Walker (J	[971) [¢]	Lewis et al	Joachain et al
ы	0	work	(1931)	(1935)	(1973)	(1974b)	(1975)	(1974, 1975)	communication	(0/.61) (ΕX	NEX	(19/4)	0/6L (C/6L)
81	s	47-6							43-2	(17-6)	22-0		48.6	59-2
	10	28-6		26-9					27-6	15-3	18.8		33-9	34-5
	20	9-13		9.13			8.33	11-2	8·79	8-73	10-4		0-11	66-8
	30	2.87		3.60			2.59	3.11	2·80	3-65	4-24		2.52	1-95
	40	0.899		1-55			0.815	0-890	0.886	1-14	1-39		0-668	0.549
	50	0-327		0.770			0-284	0-330	0.372	0-314	4-26		0.294	0-289
150	5	47-1							34-7				48-2	
	10	23-8		23-8					21.7				30-0	
	20	6.65		6-65				5-80	6-43				7-47	
	30	1-89		2.47				1.82	1-84				1-43	
	40	0.666		1.08				0-575	0-661				0-515	
	50	0.369		0-668				0-294	0-379				0.292	
200	Ś	42-6			(20-7)	41-3	ļ,				23-3	31-2	45-7	48-5
	10	21-1			21-4	20-7					17-7	22-3	26-4	24·2
	20	5-34			5-34	5-09	4.75	3-98			6-63	7·26	5-32	5-09
	30	1-47			1-50		1-27	1-34			16-1	2.04	0-968	1-08
	40	609-0			0-641		0-532	0-510			0-797	0-852	0.461	0.449
	50	0-406			0-427	Į	0-361	0-313			0-536	0-587	0.278	0-294

Table 9. Comparison of experimental and theoretical differential cross sections for electrons elastically scattered by argon (cross sections in units of a_0^2 , angles in

300	5	37-2			37-0				34·6 21.0	42-1 10.8
	2 8	18:3 4:18			3-87		3.45		21-3 5-46	3-67
	3 8	1.17			, ;		0-936		I-55	0-886
	6	0-572					0-449		0.766	0-447
	50	0.365					0-310		0-501	0-275
400	S	34.3		43-5	34.6		-		36-9	38-3
	10	16-5		18-4	16.2		_		21-0	17-4
	20	3-40		3-40	3-20		2.80		4.36	2.97
5	30	1-01		1-18			0-704		1:30	0-805
	40	0-515		0-547	1		0.284		0-650	0-412
	50	0-305		0-331			0-168		0-387	0-235
500	5	32-8			33-6	I		(26-7)		36-2
	10	15-3			15-2			15.7		15-9
	20	2.94	2:94		2.79	2·83		3-38		2-52
	30	0.881	1-06			0-904		1-02		0-737
	40	0-446	0-529			0.440		0.506		0-365
	50	0.241	0-294		1	0-244		0-289		0-197
1000	5	29-4						(29-0)		
	10	11-0						12-2		
	20	1·64						1.79		
	30	0-518						0-557		
	40	0.221						0-242		
	50	0-116						0.124		
" Rel	ative n	neasuremer	ıt, norma	lized to the pres	ent work at 20°;	actually mea	isured at an energy of 491 e	.V.	od at 510 aV	
a Xer	ative n	neasuremen	of 10f exc	th energy senara	Telv normalizeu	THE DIENEL	I WOLK at ZU ; Uala at JUUS	V WETE ACHIAIIV INCANU	ed al JIVEV.	

P ⁶ Relative measurement, for each energy separately notinatized to the present work at 20°; at 5° linearly interpolated between data at 4° and 6°.
⁶ At 5° linearly interpolated between data at 4° and 6°.
⁶ Ex: with exchange; NEx: non-exchange.

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As in the case of helium (also for neon) our results are in excellent agreement with the absolute data of Bromberg (1974b, 1975), all deviations being smaller than 5%. The recent absolute data of Gupta and Rees (1975) are in agreement with the present work to within 10%. There is less agreement with the absolute results of Kurepa *et al* (1975 private communication).

The preliminary relative measurement of Jost *et al* (1973 and private communications), normalized to the present work, shows good agreement in shape. The early relative data of Arnot (1931) and Hughes and McMillen (1933), also normalized to the present work, show reasonable agreement in shape for some energies.

The theory of Fink and Yates (1970) only agrees to some extent with experiment at higher energies, but fails completely at small angles for the same reason as discussed for helium (§ 5.1). The relativistic exchange calculations of D W Walker (1974 private communication) at 100 and 200 eV show the same picture as Fink and Yates, far too small cross sections at small angles.

On the other hand, between 100 and 300 eV, the *ab initio* optical model theory of Byron and Joachain (1974, 1976), including both exchange and polarization and absorption, overestimates the cross sections at small angles and underestimates those at larger angles. However, at 400 and 500 eV their calculation agrees reasonably well with the experiment of Bromberg and the present work for angles above 30° and even very well for angles below 30° .

5.3. Argon

For argon the situation is similar to that for neon. We are again in excellent agreement with Bromberg (1974b) who has up to now only Ar data available at angles below 25° (see table 9).

At 100 and 200 eV our results are systematically about 12% larger than the absolute data of DuBois and Rudd (1975), whereas at 500 eV they agree excellently. They report an experimental error of 12%.

Williams and Willis (1975) measured relative cross sections above 20° and obtained absolute cross sections by a phaseshift analysis of the relative distributions of electrons elastically scattered from resonant states in Ar. They quote experimental errors between 8 and 12°_{\circ} . Compared with the present work their data at 100 eV agree quite well at large angles but at larger energies their cross section values are substantially smaller than ours, showing besides different angular dependences.

The preliminary absolute results of Vusković and Kurepa (1975, private communication) at 100 and 150 eV are in excellent accordance with the present work except at 150 eV and 5° where their cross section is 26% smaller than ours.

The theory of Fink and Yates (1970) agrees quite well with experiment at 1000 eV. The relativistic non-exchange calculation of Walker (1971) yields better cross section values at small angles than his relativistic exchange calculation.

The calculations of Lewis *et al* (1974), at 100 and 200 eV, are based on the phenomenological optical model theory of Furness and McCarthy (1973), which contains three adjustable parameters and accounts for exchange, polarization and absorption. Lewis *et al* (1974) reported their calculations to be in good shape agreement with the relative measurements of the same authors. Compared with Bromberg's and the present experiment these calculations agree well at 5° but show in general too large values at the smaller angles and too small values at the larger angles. The preliminary *ab initio* optical model results of Joachain *et al* (1975, 1976 and private communication) show a considerably different slope compared to the present work. The optical model overestimates the cross section at smaller angles and underestimates it at larger angles.

5.4. Nitrogen

The comparison with the absolute data of Bromberg (1970) is limited to his energy range from 300 to 500 eV. The agreement is very good. The largest deviations are found at 20° and 40° where our cross sections are 5 to 11% larger than Bromberg's, but we have to take into consideration the experimental errors being about 4% for Bromberg and about 7% for the present work (see table 10).

Kambara and Kuchitsu (1972) report relative measurements between 50 and 500 eV, for each energy separately normalized to their relative cross sections at 30°. They estimate their experimental error to be about 10% for angles smaller than 20° and about 5% for angles between 20° and 50° . We have put their relative cross sections on an absolute scale by multiplying with our absolute cross section value at 30° . The overall agreement with both the present work and Bromberg is quite good. Their cross sections at angles below 10° tend to be too large. For 300 and 500 eV and 40° their cross section is better in agreement with Bromberg.

The relative measurement of Herrmann (1974 and private communication), carried out with the same apparatus as used by Jost *et al*, has been fitted to an independent atom model theory at 90°, using atomic scattering amplitudes of Fink and Yates. Herrmann's results show a similar angular dependence as found by Jost *et al* for the other gases, a too strongly forward peaked cross section in the small angle region. At angles larger than 20° the agreement in shape is very good.

The apparatus calibration factor f_c , as discussed in § 3.4, basically depends on the directly measured absolute differential cross section for N₂ at 500 eV and between 5° and 9°, as described in § 3.3. Table 11 compares our directly measured absolute cross sections with the absolute cross sections obtained from our relative cross sections by applying f_c . In the same table we further compare with the absolute cross sections of Bromberg (1970) and with the relative cross sections of Kambara and Kuchitsu (1972). The latter relative values were normalized to the present absolute cross section value at 30°:1.02 a_0^2 , which equals Bromberg's value at the same angle. In spite of the steep rise of the cross section towards small angles the agreement between the various results is extremely good. Table 11 illustrates the correctness of the calibration procedure used for making our relative cross sections absolute.

6. Apparent polarizabilities

In figure 2 we have made semi-logarithmic plots of $d\sigma/d\Omega$ against K, where K is the momentum transfer, is the difference between the momentum of the incident electron and the momentum of the scattered electron, given by

$$K = (8m E/\hbar^2)^{1/2} \sin \frac{1}{2}\theta = 0.5422 E^{1/2} \sin \frac{1}{2}\theta (au)$$
(20)

where E is the impact energy in eV. In the plots for He, Ne and Ar we have also included the theoretical curve we obtained by calculating the simple first Born approximation which is a uniform function of K and thus independent of E. The atomic form factors for this calculation were taken from the International Tables

Table 10. Comparison of experimental differential cross sections for electrons elastically scattered by *molecular nitrogen* (cross sections in units of a_0^2 , angles in degrees and energies in eV).

Е	θ	This work	Arnot ^a (1931)	Bromberg (1970)	Kambara and Kuchitsu ^b (1972)	Herrmann° (1973)
100	5 10 20 30 40 50	61·2 35·7 10·9 3·11 1·18 0·636			(72·2) 39·2 10·9 3·11 1·17 0·653	114 62·2 17·0 4·54 1·64 0·854
150	5 10 20 30 40 50	58.9 30.9 7.54 1.99 0.845 0.548				99·3 50·7 12·4 3·21 1·33 0·840
200	5 10 20 30 40 50	54·5 27·1 5·75 1·57 0·778 0·516	19·6 4·50 1·53 0·794 0·574			98·3 44·7 8·86 2·32 1·16 0·793
300	5 10 20 30 40 50	47·0 21·6 3·81 1·19 0·753 0·406		47·0 21·0 3·63 1·16 0·680 0·402	(51·2) 22·4 3·69 1·19 0·645 0·364	75-8 32-8 5-36 1-69 1-00 0-582
400	5 10 20 30 40 50	42.8 18.1 2.95 1.09 0.622 0.296	12·1 3·11 1·43 0·689 0·354	43.6 18.1 2.73 1.08 0.580 0.287		75·4 28·8 4·11 1·62 0·847 0·400
500	5 10 20 30 40 50	39·6 15·5 2·41 1·02 0·498 0·209		40.8 15.5 2.23 1.02 0.450 0.211	(39·4) 16·8 2·44 1·02 0·454 0·214	57-9 21-4 3-03 1-33 0-582 0-269
1000	5 10 20 30 40 50	29·9 8·01 1·50 0·474 0·176 0·0930				44-7 10-8 1-98 0-554 0-212 0-110

^a Relative measurement, normalized to the present work at 400 eV and 19°; numbers are graphical interpolations between data at nearby angles; data at 200 eV and 400 eV were actually measured at 205 eV and 410 eV respectively.

 $^{\circ}$ Relative measurement, fitted to independent atom model theory at 90 $^{\circ}$, using atomic scattering amplitudes of Fink and Yates (1970).

^b Relative measurement, for each energy separately normalized to the present work at 30° ; at 5° linearly interpolated between data at 4° and 6° .

Table 11. Comparison of absolute differential cross sections for the elastic scattering of electrons by N₂ at 500 eV impact energy and angles between 5° and 9° (cross sections in units of a_0^2).

θ (deg)	This work		Duombour	Kambara and
	Direct ^a	Using f_{c}^{b}	(1970)	(1972)°
5	39.8	39.6	40.8	(39.4)
6	33.3	34.2	34.4	34.2
7	28.4	28.7	28.4	(29.1)
8	24.1	23.7	23.4	24.0
9	19.5	19.2	19.0	(20.4)
Error ^d (%)	5	6	3	10

^a Directly measured absolute cross section.

^b Relative cross section made absolute using the apparatus calibration factor f_c .

^c Relative measurement, normalized to the present work at 30° ; numbers in parentheses are linear interpolations between data at angles differing 2° .

^d Experimental error as given by the author(s).



Figure 2. Absolute differential cross section for electrons elastically scattered by He, Ne, Ar and N₂ plotted against momentum transfer at impact energies of 100 (\bigcirc), 300 (\square), 1000 (\triangle) and 3000 (\bullet) eV); broken curve: first Born approximation.

for X-ray Crystallography (1962). The effect of exchange between atomic and incident electrons and the effect of charge-cloud polarization of the atoms by the incident electrons have not been included in this simple approximation. For sufficiently high energy this approximation is valid.

The helium plot (see figure 2) indeed confirms the validity of the first Born approximation for $E \ge 1000 \text{ eV}$ at all measured angles and within the experimental accuracy $(\sim 6\%)$ (see also § 5 and table 7). For smaller *E* the curves deviate from the Born curve at small *K*, while the curves for the lower energies lie above those for the higher energies. This deviation from the uniformity in *K* is due to the increasing effects of electron exchange and charge-cloud polarization as *E* decreases. The polarization effect, as it is due to long-range interactions, will dominate in the region of small θ .

The plots for Ne, Ar and N₂ (figure 2) show a K dependence completely different from that for He. Here the curves lie just in reversed order compared with He: the curves for the higher energies lie above those for lower energies. This behaviour for Ne, Ar and N₂, according to van Wingerden *et al* (1975), can be explained by a classical model for scattering. We note that the 3 keV curve for Ne approaches the Born curve at large K, whereas for Ar the Born limit is not yet reached at 3 keV. In contrast to He, the curves for each of the other gases tend to merge in the limit $K \rightarrow 0$.

The curves in the semi-logarithmic plots of $d\sigma/d\Omega$ against K show a very remarkable linear behaviour in the region of small K. This means that the cross section in that area can be described by the expression

$$\sigma(K) = \sigma_0 \exp\left(-\beta K\right),\tag{21}$$

where σ_0 is the cross section at K = 0 and β is the slope of the straight line in the semi-logarithmic plot of $d\sigma/d\Omega$ against K.

Previously Bromberg (1969b, 1970, 1974a) has found that in the case of Hg, N₂, CO, O₂ and CO₂ for 300, 400 and 500 eV the semi-logarithmic plots for each gas show a linear dependence on K and merge for K < 1. From this uniform behaviour he concluded that a Born approximation might be valid in the limit $K \rightarrow 0$. He derived that the quantities σ_0 and β of (21) could then be related to an empirical effective long-range potential (Bromberg 1969b, 1974a):

$$V(r) = \pm \frac{2 CB}{\pi (r^2 + B^2)^2},$$
(22)

where $C = \sigma_0^{1/2}$ and $B = \frac{1}{2}\beta$. In the limit $r \to \infty$ (22) is identical in form to the polarization potential $-\alpha/2r^4$, where α is the apparent polarizability of the target. Based on Bromberg's model α is given by

$$\alpha = \frac{4CB}{\pi}.$$
(23)

For the energy region from 300 to 500 eV Bromberg found the ratio of apparent polarizability α over static polarizability α_0 to be 0.51, 0.97, 1.03, 0.96 and 1.28 for respectively Hg, N₂, O₂, CO and CO₂.

A detailed analysis concerning effective long-range potentials has been done by Huo (1972) who has shown the limitations of Bromberg's model, as well as that under certain conditions $\alpha \simeq 0.5\alpha_0$ and under other conditions $\alpha \simeq \alpha_0$.

E(eV)	Не	Ne	Ar	N ₂
100 150 200 300 400 500 750† 1000 2000	1.57 (20) 1.51 (25) 1.37 (20) 1.15 (30) 0.91 (23) 0.74 (20) 0.57 (10) 0.49 (15) 0.49 (20)	3.09 (20) 2.88 (20) 2.82 (18) 2.62 (16) 2.48 (10) 2.26 (8) 1.98 (8) 1.88 (8) 1.88 (10)	14.8 (12) 13.9 (10) 12.2 (10) 10.6 (10) 9.57 (10) 8.44 (10) 7.77 (10) 7.55 (10) 7.40 (10)	$\begin{array}{c} 17.9 (7) \\ 16.6 (10) \\ 15.6 (10) \\ 13.5 (10) \\ 13.3 (10) \\ 12.6 (10) \\ 11.4 (10) \\ 11.2 (13) \\ 12.1 (20) \\ 12.1 (20) \end{array}$
Static‡	0·49 (18) 1·46	2·69	11·0	12·7 (35) 11·9

Table 12. Apparent and static polarizabilities for He, Ne, Ar and N₂ (in units of a_0^3 , errors, in brackets, in per cent).

† For He: 700 eV.

[‡] Landolt-Börnstein (1950).

The apparent polarizibilities obtained from our cross section measurements are listed in Table 12. The static polarizabilities α_0 obtained from dielectric constants and refractive index measurements (Landolt-Börnstein 1950) are also shown in this table. α decreases with increasing impact energy and becomes a constant above 500 eV, where we find $\alpha \simeq \frac{1}{3}\alpha_0$ for He, $\alpha \simeq \frac{2}{3}\alpha_0$ for Ne and Ar and $\alpha \simeq \alpha_0$ for N₂. We have $\alpha = \alpha_0$ for He at about 170 eV and for Ne and Ar at about 270 eV.

Acknowledgments

We are greatly indebted to Dr L Vriens for the basic design of the apparatus and to Mr R Ch Baas for writing the computer program. We are grateful to Professor F W Byron and Professor Ch J Joachain for the useful discussions concerning theory.

We would like to thank the various investigators for communicating their results prior to publication and for sending tabulated numerical data of their experiments or theories.

This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (Foundation for Fundamental Research on Matter) and was made possible by financial support from the Nederlandse Organisatie voor Zuiver-Wetenschappelijk Onderzoek (Netherlands Organisation for the Advancement of Pure Research).

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