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Measurements of total scattering cross sections for low-energy positrons and electrons colliding with helium and neon atoms

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Total scattering cross sections have been measured for 0.3–31 eV positrons colliding with helium atoms and for 0.25–24 eV positrons colliding with neon atoms using a beam-transmission technique. These measurements have resulted in the first direct observations of Ramsauer-Townsend effects for positrons colliding wih helium and neon, and also provide clear indications of the onset of positronium formation in each of these gases. As an overall check of the reliability of the experimental approach for measuring total scattering cross sections for positrons, electron-atom scattering cross sections have been measured in the identical apparatus, using the same target gases, and the same technique as was used for the positron measurements.

I. INTRODUCTION

Sensitive tests of approximate theories developed for the scattering of low-energy electrons by atoms and molecules can be provided by applying such theories to the corresponding cases of low-energy positron-atom (molecule) collisions.[1] As an example, one of the difficult problems in the theory of the scattering of low-energy electrons by atoms is assessing the relative importance of the polarization interaction (the distortion of the atom by the projectile). For electrons the potential due to polarization, being attractive, tends to add to the static interaction (the Coulomb interaction between the projectile and the undistorted atom) which is also attractive. For positrons the polarization interaction is still attractive, whereas the static interaction is repulsive, and so these interactions tend to cancel each other. For these reasons comparisons between experimental studies of positron- and electron-atom collisions might provide useful information in assessing the relative importance of the polarization interaction. The absence of the exchange interaction in positron-atom scattering is also an important incentive for making experimental comparisons between positron- and electron-atom collisions.

There has been considerable effort devoted to theoretical studies of positrons scattering from atoms and molecules, in particular to the calculation of total scattering cross sections for such collisions. Although there is a broad range of values of total cross sections predicted by different theories for positrons colliding with a given target, there is nearly universal agreement on one interesting qualitative feature; the total cross section is predicted to pass through a minimum (Ramsauer-Townsend effect) at a well-defined positron energy for each of the inert gases which has been studied thus far (He, Ne, Ar, and Kr). The Ramsauer-Townsend effect refers to the observations of Ramsauer[2] and of Townsend and Bailey[3] of pronounced minima in the total scattering cross sections for electrons colliding with argon, krypton, and xenon at energies of about 1 eV. The first direct observation of a Ramsauer-Townsend effect in positron-atom collisions was recently reported for positrons colliding with argon by Kauppila *et al.*[4] In the present article, cross-section measurements are described for positrons of 0.3–31 eV and 0.25–24 eV scattering from helium and neon, respectively, which have revealed the first direct observations of Ramsauer-Townsend effects in these gases.

Total cross sections have been measured for low-energy positrons colliding with helium[5-7] and neon[5,8] by several different experimental groups, but none of these groups have made direct measurements of total cross sections at sufficiently low energy to test the theoretical predictions of Ramsauer-Townsend effects in helium and neon. In the case of helium there is very good agreement between the recent calculations of Campeanu and Humberston[9,10] and the measurements of Canter *et al.*[5] Referring to this agreement Massey[1] has recently indicated that the theory appears to give accurate results over the energy range of comparison. Yet, as was recently pointed out by Campeanu and Humberston,[9] there is a significant discrepancy between their calculated cross sections and the preliminary results[11] of the present experiment for energies less than 6 eV, and they have concluded that this discrepancy cannot be resolved by further improvements in the theory.[9] We have conducted a number of tests for possible systematic errors since making the original measurements, have applied a small correction to these results related to thermal transpiration effects (described in the present article), and have taken considerably more data.

The results of these efforts indicate that a significant discrepancy still exists in the region of the Ramsauer-Townsend minimum.

II. APPARATUS AND EXPERIMENTAL APPROACH

The experimental approach which we use for measuring total scattering cross sections for positrons colliding with gases is based on a transmission technique in which the attenuation of a beam of low-energy positrons passing through a gas-scattering region is measured (see Ref. 12 for a detailed discussion). For single scattering, the beam current I transmitted through the scattering region containing a gas of number density n is given by

$$I = I_0 e^{-n Q_T L}, \tag{1}$$

where I_0 is the beam current transmitted through the scattering region when it is evacuated, Q_T is the total scattering cross section, and L is the path length of the beam through the gas-scattering region.

A schematic diagram of our experimental apparatus is shown in Fig. 1. The production and detection of our low-energy positron beam has been described by Stein *et al.*[13,14] A radioactive ^{11}C positron source is generated by the reaction $^{11}B(p,n)$ ^{11}C, where a 4.75-MeV proton beam from a Van de Graaff accelerator is used to bombard a water-cooled boron target. Roughly one in 10^6 of the high-energy positrons produced in the boron target results in a detected low-energy positron. The measured intrinsic energy width of our low-energy positron beam is less than 0.1 eV.[14] The positron beam is focused by an electrostatic lens system, guided by an axial magnetic field through a curved, differentially pumped gas-scattering region, and is detected with a Channeltron electron multiplier (CEM).

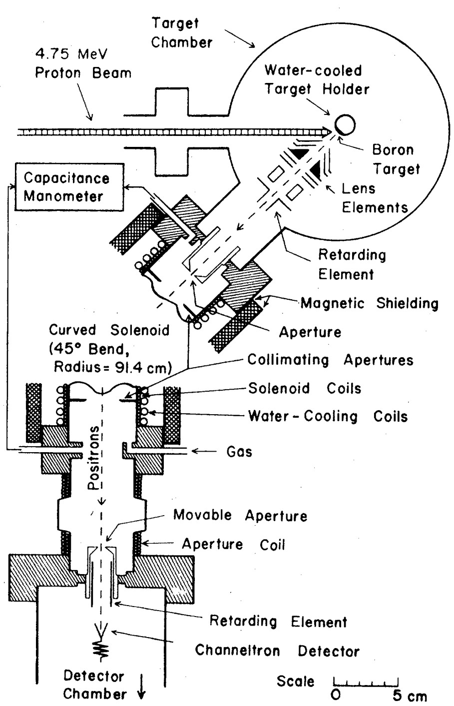

FIG. 1. Schematic diagram of the apparatus.

The gas-scattering region consists primarily of a curved solenoid (45° bend, radius of curvature 91.4 cm). The target gases (research grade) are admitted into this region near the detector end and are simultaneously pumped out through small apertures (0.24 cm diameter at the source end and 0.48 cm diameter at the detector end), establishing pressure differentials of approximately 220 : 1 and 90 : 1 between the gas-scattering region, and the source and detector vacuum chambers, respectively. The pressure measured at the detector end of the scattering region is 10% higher than at the source end. The average of the pressures measured at both ends of the gas-scattering region is used to determine the target-gas number density, given by the ideal-gas expression

$$n_s = P_s / kT_s, \tag{2}$$

where P_s and T_s are the pressure and temperature of the gas in the scattering region, and k is Boltzmann's constant. Since T_s depends on the current passing through the water-cooled solenoid, the temperature of the gas-scattering region is monitored during cross-section measurements with thermocouples placed on the solenoid and the measured temperature is used in determining n_s.

The pressure P_s of the target gas in the scattering region is determined with a capacitance manometer.[15] Since the temperature of the manometer head T_m is regulated at (49 ± 1)°C, which is generally different from the temperature of the gas-scattering region, the pressure P_m measured by the manometer head is different from the pressure P_s in the scattering region due to thermal transpiration, which is accounted for by the relation

$$P_s = P_m (T_s / T_m)^{1/2}. \tag{3}$$

The correct path length to be used in determining Q_T in Eq. (1) should take into account not only the axial distance between the gas-confining apertures of the scattering region, but should also account for any spiralling of the positrons in the curved axial magnetic field, and the vertical drift of the guiding center of the spiral path (due to motion in the curved magnetic field) followed by the positrons. Both of these effects have been found (see Ref. 12) to increase the path length by less than 1% above 2 eV (and 2% at 1 eV), so that the axial distance between the apertures is very close to the actual distance traversed by the positrons through the scattering region. For this reason the axial distance between the gas-confining apertures, 109 cm, has been used as L in Eq. (1). The last gas-confining aperture (shown in Fig. 1) is movable and is positioned to allow for the small vertical drift of the positrons in the curved magnetic field of the scattering region.

A. Energy calibration

The energy of the positrons is determined by the voltage applied to the boron target since the scattering region is at ground potential. A stainless-steel (type 304) retarding potential element in the source chamber (Fig. 1) and a second retarding element (oxygen-free-high-conductivity copper) in the detector chamber have been used to determine the energy width of the beam and its absolute energy with respect to the type-304 stainless-steel scattering region. Details of these energy measurements are provided elsewhere.[12,14] We have checked the retarding potential technique for measuring the positron beam energy by observing the cross-section resonance at 19.3 eV for electrons colliding with helium in the identical apparatus as we use for positrons.[12] A comparison of the location of this resonance as measured by Golden and Bandel[16] with the retarding potential measurements indicates an agreement of the energy calibrations to within 0.1 eV. As an additional check on the accuracy of the retarding potential technique we have observed the shape of the envelope of the cross-section peaks in the vicinity of 2 eV for e^--N_2 collisions, and our energy calibration agrees to within 0.2 eV with the measurements of Golden.[17] The retarding potential measurements have been used to assign the positron and electron energies in the present experiment, and the calibrations described above indicate that these energy assignments should be accurate to within a few tenths of an eV.

B. Discrimination against projectiles which have undergone small-angle forward scattering

In beam transmission measurements of total scattering cross sections, if particles are detected which have undergone small-angle forward scattering the measured cross sections will be smaller than the actual cross sections. In order to enhance discrimination against beam particles scattered through small angles in the forward direction we have made use of the retarding potential element (shown in Fig. 1) located between the movable gas-confining aperture and the CEM detector. For each projectile energy studied the potential applied to this retarding element is set (with the scattering region evacuated) so as to decrease the beam intensity to 80% of the beam intensity with no applied retarding potential. As described elsewhere,[12] the steepest portion of the retarding potential curve is at the next higher voltages above this "80%" retarding potential. When a particle undergoes scattering some energy associated with axial motion is transferred to energy associated with transverse motion. Since the retarding potential element only retards the axial component of velocity, a particle which scatters through a small angle in the forward direction may lose sufficient energy associated with axial motion that it will no longer be able to surmount the retarding potential barrier and consequently it will not reach the detector. As a result of the narrowness of the energy distribution of the positrons (measured energy width less than 0.1 eV), the angular discrimination at an energy of the order of 1 eV is better than 13° and at about 30 eV is better than 7°. These results rely solely on the "80%" detector retarding potential for discrimination.[12] However, there is evidence (discussed below) indicating that the angular discrimination is considerably better than the above estimates which are based upon the assumption that the detector retarding element is the only means of discriminating against scattered particles.

It should also be noted that positrons which undergo inelastic scattering lose several eV of energy, and essentially none of these particles should be detected when the "80%" detector retarding potential is used.

C. Procedure for determining total scattering cross sections

A typical measurement of a total scattering cross section at a given energy proceeds in the following manner for positrons. The boron target is bombarded for approximately 45 min with a 40-μA, 4.75-MeV proton beam, yielding an ^{11}C source activity of about 0.1 Ci. The proton beam is then turned off to reduce background noise, and with the scattering region evacuated the detected positron beam current is maximized by adjusting the lens-element voltages and magnetic fields which guide the beam.[12] The 80% retarding potential is then applied to the detector retarding element as described above. A background count is taken while applying a potential (the cut-off potential) to the retarding element in the target chamber (the lens retarding element) which is typically about 1 V above the voltage applied to the boron target. However, this depends in general upon how rapidly the total cross section varies as a function of energy at the projectile energy being studied. This retarding potential cuts off most of the positrons in the well-defined low-energy peak, and only spurious CEM counts and a small number of higher-energy positrons which manage to reach the CEM contribute to the so-called "background" or "noise" level. The lens retarding voltage is then set at zero and detected positrons are counted for 40 sec with the scattering region still evacuated providing the first "gas-out" count, I_{01}. The target gas is then admitted into the gas-scattering region allowing sufficient time for the pressure to come to equilibrium (typically 20 sec) before the next 40-sec counting interval commences. The pressure of the target gas is continuously monitored while the "gas-in" counts (I) are accumulated during the next 40-sec counting interval. The scattering region is then evacuated (allowing the same equilibration time, i.e., 20 sec) and a third 40-sec counting interval begins, yielding the second gas-out count, I_{02}. This completes one cycle of a cross-section measurement, which generally includes several such cycles with different target-gas pressures. At the end of the last cycle another background count is taken as described above. For energies above 1 eV, the signal-to-noise (background) ratio is generally larger than 100 and is often a few hundred. In such cases the cross-section determination is not measurably affected by the background counts, and can be determined to a very good approximation for each cycle by using the relation

$$Q_T = (1/nL)\ln[(I_{01}+I_{02})/(2I)]. \quad (4)$$

When the signal-to noise ratio is less than 100 (typically the case for energies less than 1 eV) a correction for background counts becomes more important in determining the total cross section. In such cases, a cross section Q_B is measured for the background counts, with the cut-off lens retarding voltage left on during each cycle. The background counts at the beginning and end of the normal (i.e., nonbackground) run are then used to obtain a background count corresponding to each 40-sec counting interval of the normal run, e.g., B_{01} for I_{01}, B for I, and B_{02} for I_{02}. The measured cross section, corrected for the background counts, is obtained by using the relation

$$Q_T(\text{corrected}) = \frac{1}{nL}\ln\left(\frac{(I_{01}-B_{01})+(I_{02}-B_{02})}{2(I-Be^{-nQ_B L})}\right). \quad (5)$$

For both helium and neon, Eqs. (4) and (5) gave results which were the same (within statistical uncertainties) when the signal-to-noise ratio was greater than 100. As the energy approaches closer to zero, the correction due to the background counts becomes much more significant and contributes to larger uncertainties at the lowest energies studied.

III. RESULTS AND DISCUSSION

A. Positron-helium total cross-section measurements

The present measurements of total cross sections for positrons scattered by helium atoms are shown in Fig. 2 where they are compared with the prior experimental results[5-7] and with several theoretical calculations.[9,18-23] The present results represent the first direct observation of a Ramsauer-Townsend effect for positrons colliding with helium atoms. The minimum in the cross section is about 5×10^{-18} cm^2 and occurs in the vicinity of 2 eV. Noticeable changes in the shape of the cross-section curve occur at the thresholds for positronium formation (17.8 eV) and for excitation of the atom by positron impact (20.6 eV).

The cross sections measured by Jaduszliwer and Paul[6] are (30–70)% higher than the present results below 17 eV, show no change in shape near the positronium formation threshold, and are in reasonably good agreement with the present results above 22 eV. The measurements of Canter *et al.*[5] for e^+–He collisions are in reasonable agreement with the present results for energies above 6 eV, but are (15–30)% higher than the present measurements below 6 eV.

The calculation of Callaway *et al.*[19] shown in Fig. 2 (an adiabatic approximation using a dipole polar-

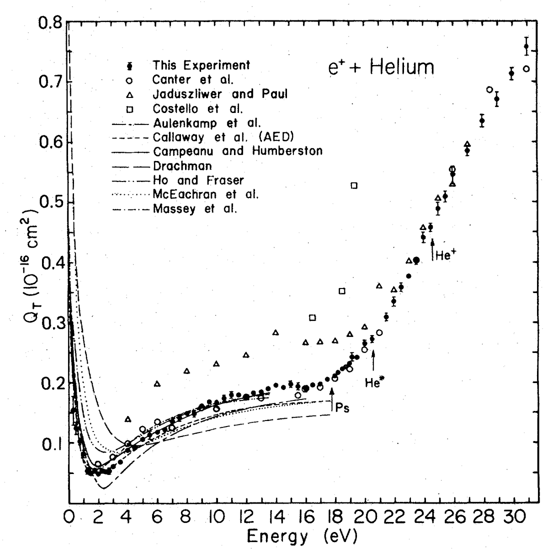

FIG. 2. Total positron-helium scattering cross-section results. The energy thresholds for positronium formation, excitation, and ionization are indicated by arrows. The indicated threshold for excitation (20.6 eV) corresponds to the first excited singlet state for helium (which is above the threshold for excitation by an electron, i.e., the first excited triplet state at 19.8 eV). Statistical uncertainties of the present results are represented by error bars except where they are encompassed by the size of the dot.

ization potential) is in good agreement with the present measured cross sections below 4 eV, but gives results which are below the present ones at energies above 4 eV. Some of this discrepancy at higher energies could be due to the fact that virtual positronium formation is not taken into account in this calculation. The calculations of Massey *et al.*[23] (an exchange adiabatic approximation) and of Ho and Fraser[21] (who use a method of models in an optical-potential formulation to calculate s-wave phase shifts, and use Drachman's[20] p- and d-wave phase shifts) are in reasonable agreement with the present results above 7 eV. Between 7 and 2.5 eV the Massey *et al.* calculation remains higher than the present measurements, but it seems to come quite close to our measured cross sections again in the region of the minimum (near 2 eV) and remains quite close to the present measured values down to the lowest energy of overlap (about 0.3 eV). (It should be noted that if the energy calibration in the present measurements is off by as little as a few tenths of an eV, this could make a substantial difference in how these measurements agree with the various theories below 1 eV because the cross section is rising very steeply in this region.) The calculated cross sections of Ho and Fraser below 7 eV remain considerably higher than the present results. The calculation of Campeanu and Humberston[9] (using variational calculations to obtain s- and p-wave phase shifts and using Drachman's[20] d-wave phase shifts) gives results which are in very good agreement with the present results above 5 eV, but are 20% higher in the vicinity of the minimum. The discrepancy between the present measurements and the results of the Campeanu and Humberston calculation in the region of the minimum is of particular interest in view of the expected accuracy of their calculation.[9] The other calculations shown in Fig. 2 give significantly different shapes and absolute values than indicated by the present measurements.

If it is assumed that the elastic scattering cross section continues above 17.8 eV (the positronium formation threshold) along an extrapolation based upon cross-section values below 17.8 eV, then the increase in the total cross section above the extrapolation from 17.8 to 20.6 eV (the threshold for excitation of the helium atom by a positron) can be attributed to positronium formation. An estimate of the cross section for positronium formation, based on this assumption and the present measurements for helium, would suggest a value which increases roughly linearly from 0 at 17.8 eV to approximately 7×10^{-18} cm^2 at 20.6 eV. Above 20.6 eV other inelastic processes may contribute to the total cross section, making it somewhat more difficult to extract information on the cross section for positronium formation.

It is interesting to compare the above estimate of the cross section for positronium formation with the theoretical results for positronium formation in helium obtained by Massey and Moussa[24] using a Born approximation, and by Fels and Mittleman[25] using a projection-operator technique. The value of the positronium formation cross section (Q_{Ps}) calculated by Massey and Moussa at 20.6 eV is roughly 0.32×10^{-16} cm^2, which is more than four times as large as that obtained from the present measurements. The value of Q_{Ps} obtained by Fels and Mittleman at 20.6 eV is roughly 1.6×10^{-19} cm^2, which is less than $\frac{1}{40}$ the value obtained from the present measurements. There is therefore, an enormous discrepancy between available theoretical estimates of Q_{Ps} and the value of Q_{Ps} obtained from the present experiment. The present estimates are supported by the observations and estimates of positronium formation by Coleman *et al.*[26]

B. Positron-neon total cross-section measurements

The present measurements of positron-neon total scattering cross sections are shown in Fig. 3 with the experimental results of Canter *et al.*[5], Jaduszliwer and Paul,[8] and results of theoretical calculations by Montgomery and LaBahn[27] (polarized orbital approximations), Massey *et al.*[23] (an exchange adiabatic approximation), and Ryman *et al.*[28] (a polarized orbital approximation). The present results shown in Fig. 3 represent the first observation of a Ramsauer-Townsend effect for positrons colliding with neon and exhibit the most dramatic minimum yet observed for positrons colliding with gases. The minimum occurs in the vicinity of 0.6 eV and has a value of 1×10^{-17} cm^2. Above 1 eV

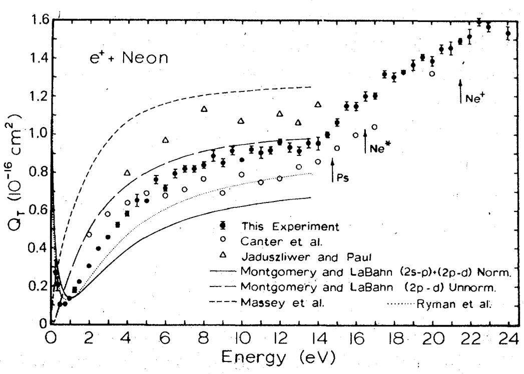

FIG. 3. Total positron-neon scattering cross-section results. The energy thresholds for positronium formation, excitation, and ionization are indicated by arrows. Statistical uncertainties of the present results are represented by error bars except where they are encompassed by the size of the dot.

the cross section rises sharply and then begins to level off in the vicinity of 6 eV. Near the predicted threshold for positronium formation (14.8 eV) there is an abrupt increase in the total cross section, providing a clear indication of the onset of positronium formation. Using a procedure similar to that used above for e^+–He collisions, the cross section for positronium formation for e^+– Ne collisions at 16.6 eV (the threshold for excitation of the neon atom) is estimated to be 2×10^{-17} cm^2. Above 16.6 eV possible competing inelastic scattering effects could contribute to the total scattering cross section, making it more difficult to extract information on Q_{Ps}.

The measurements of Jaduszliwer and Paul[8] range from 35% higher than the present results at 4 eV to 20% higher at 14 eV. The results of Canter *et al.*[5] do not plunge as steeply as the present results do below 5 eV, thus bearing some similarity to the situation in helium, but their results are substantially lower than ours above 6 eV in neon. The results of Canter *et al.* also do not clearly indicate the onset of positronium formation as the present measurements do. This may be due, at least partially, to the considerably broader energy width of the positron beam used by Canter *et al.* (of the order of 1 eV).

The polarized orbital calculation of Ryman *et al.*[28] gives values in reasonable agreement with the present measured cross sections below 1 eV, but their results remain significantly lower than the present results above 1 eV. Ryman *et al.* have suggested[28] that the discrepancy at higher energies may be related to their not having taken virtual positronium formation into account. The present results are bracketed by two polarized orbital calculations of Montgomery and LaBahn,[27] in which the specific perturbed orbitals $2s$-p and $2p$-d, normalized to give the correct polarizability, and $2p$-d, unnormalized, respectively, have been considered. The exchange adiabatic calculation of Massey *et al.*[23] predicts much higher cross-section values than the present results, and does not exhibit a minimum, contrary to the present experimental observations.

C. Checks for possible systematic errors in the present measurements

We have performed numerous different checks for possible systematic errors in our measurements, some of which are discussed below.

To determine whether thermal transpiration is being adequately taken into account by Eq. (3), cross sections have been measured at a given energy for scattering-region temperatures which differ by as much as 65 °C. The cross sections measured at these different scattering-region temperatures are the same within the statistical uncertainties of the individual measurements.

To check for the possibility that we are detecting particles which have been scattered through small angles in the forward direction, the detector retarding element voltage has been changed from the usual 80% value discussed above to values ranging from zero to a value which reduces the transmitted beam current by 50%. A very interesting result of these tests is that for positron-helium and -neon collisions in the regions of the minima, the cross sections which are obtained are independent of the voltage applied to the retarding element. This indicates in particular that in the region of the minimum in helium, where the discrepancy between the present results and the calculation of Campeanu and Humberston[9] (and the measurements of Canter *et al.*[5]) is the largest, either the angular discrimination of the present experiment is much better than the estimate of the upper limit (13° at 2 eV) made in Ref. 12, which was obtained by just considering discrimination by the detector retarding element, or there is little scattering at angles less than 13°. As pointed out by Campeanu and Humberston[9] the latter possibility seems unlikely. The primary means of discriminating against small-angle forward scattered projectiles at low energies is evidently related to changes in the trajectories of scattered projectiles which are subsequently unable to pass through the small exit gas-confining aperture.

A necessary test of the present cross-section measurements is provided by frequent checks of the dependence of the ratio I/I_0 on the target-gas number density n which should be exponential according to Eq. (1). Several such number-density-dependence checks are shown in Fig. 4 where I/I_0 is plotted versus n on a semilogarithmic graph for positrons and electrons colliding with helium and neon. (The electron measurements are discussed later.) The data shown in Fig. 4 indicate that the exponential dependence is followed for the largest attenuations which were tested in both gases. In general, values of I/I_0 greater than 0.7 were used to determine cross sections to be sure that we were operating well within the attenuation region where the dependence of I/I_0 on gas number density is exponential. The largest target-gas number densities (17×10^{13}/cm^3) shown in Fig. 4 were determined by the maximum safe pressure [(a few) $\times 10^{-5}$ Torr] at which the CEM detector can be operated.

For our positron-atom cross-section measurements, we have checked for the possibility that the target gas could directly affect the number of slow positrons emitted per second by the source and thus introduce an error into our cross-section

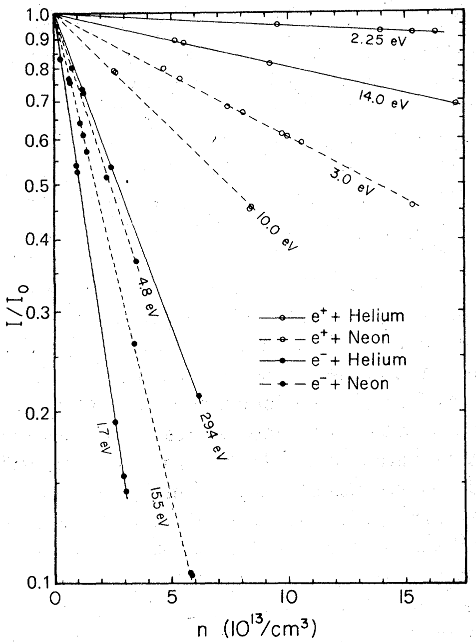

FIG. 4. Semilogarithmic plot of I/I_0 (where I is the transmitted beam current with target gas present and I_0 is the beam current with no gas present) vs target-gas number density.

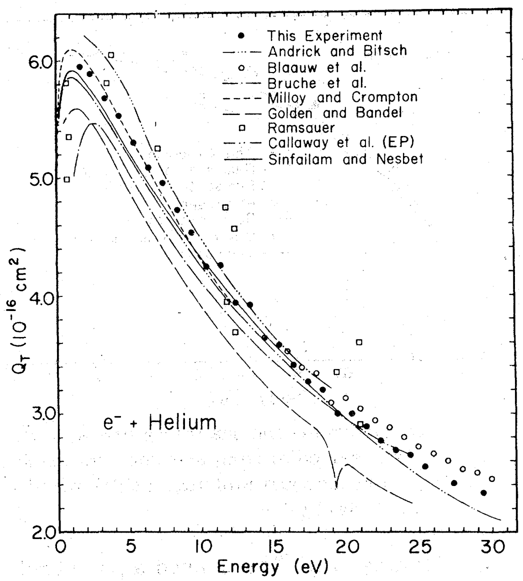

FIG. 5. Total electron-helium scattering cross-section results. (The results labeled "this experiment" were presented initially in Ref. 12.) Curves are used to represent the data points of Andrick and Bitsch, Bruche *et al.*, and Golden and Bandel, to enhance clarity.

determinations. These checks were conducted by admitting the target gases directly into the source chamber at pressures comparable to those present in the source chamber when the actual cross-section measurements are made. We did not observe any measurable direct effect of helium or neon on the emission of low-energy positrons from the source. This type of check is made possible by the small gas-confining apertures in our system.

1. Measurements of electron-helium total cross sections

An overall test of the present approach to measuring total scattering cross sections has been obtained by measuring cross sections for electrons colliding with the same gas atoms in the identical apparatus, and using the same technique as used for positrons. The positron beam apparatus has been designed so that it is convenient to replace the positron source by an electron source (type-B Philips cathode) having the same geometry as the positron source. The polarities of the voltages applied to the lens elements, the projectile source, and the detector retarding element are then reversed, and total scattering cross sections for electrons are measured. It should be noted that the lowest electron beam energy that could be used in the present system was 1.7 eV due to a perturbing effect of the magnetic field from the cathode heater on lower-energy electrons.

Figure 5 shows total cross sections for electrons colliding with helium obtained using the present system,[12] and includes the results of several other experiments[16,29-33] and theoretical calculations.[19,34] The results of this experiment are in excellent agreement (within 3% at all energies of overlap) with the recent results of Milloy and Crompton,[32] who have measured momentum-transfer cross sections in a swarm experiment and converted these to total cross sections using phase shifts calculated by Sinfailam and Nesbet.[34] The total cross sections of Andrick and Bitsch[29] have been obtained by fitting the partial-wave formula to their measured angular distributions of electrons elastically scattered by helium atoms, and in this way determining scattering phase shifts from which total cross sections are computed. Their total cross sections are within 4% of the present results above 5 eV and agree with the present results to well within their stated uncertainties below 5 eV. (The uncertainties of their individual points are larger than ±15% for energies below 5 eV, but are less than ±5% for energies above 5 eV.) The beam measurements of Golden and Bandel,[16] using a Ramsauer method, are an average of about 12% lower than our results. The recent beam experiment of Blaauw *et al.*[30] gives results which are within 2% of ours at 16 eV and remain slightly higher than our values as the energy increases, becoming about 6% higher than our values near 30 eV. The present measurements agree to better than 5% with the theoretical calcu-

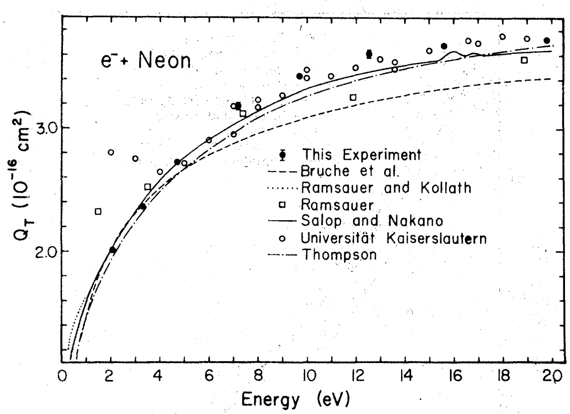

FIG. 6. Total electron-neon scattering cross-section results. Curves are used to represent the data points of Bruche *et al.*, Ramsauer and Kollath, and Salop and Nakano to enhance clarity.

lation of Callaway *et al.*[19] (who used a polarized orbital method with an extended polarization potential) and of Sinfailam and Nesbet[34] (who used a variational calculation).

The good agreement between the present results and those of prior experiments (including those considered to be the most reliable in a critical review of measurements of total cross sections in electron-atom collisions by Bederson and Kieffer[35]) and theoretical calculations provides support for the present approach for measuring total cross sections.

2. *Measurements of electron-neon total cross sections*

Our recent measurements of total cross sections for electrons colliding with neon are shown in Fig. 6 which also contains the results of prior experiments[31,33,36-38] (including those considered to be the most reliable in the Bederson and Kieffer review article mentioned above), and of a theoretical calculation by Thompson[39] (using an exchange approximation and a polarized orbital method to estimate the polarization contribution).

The present measurements are in good agreement with the results of Salop and Nakano,[37] which were obtained using basically the same apparatus as used by Golden and Bandel[16] in their work on e^--He collisions. The present measurements yield cross sections which are an average of about 3% higher than those of Salop and Nakano above 7 eV. The preliminary results of the group at Universität Kaiserslautern[38] are also shown in Fig. 6. There is very good agreement between the Kaiserslautern data and the present measurements above 4 eV. At lower energies the uncertainties of the Kaiserslautern data become large as was mentioned for the e^--He results of Andrick and Bitsch.[29] The results of the theoretical calculation by Thompson[39] are within 6% of the present measurements over the entire energy range of overlap.

It is interesting to note that there is appreciable small-angle forward scattering in e^--Ne collisions.[40,41] In view of this, the agreement of our e^--Ne measurements with prior experiments considered[35] to be most reliable provides a good test of our ability to discriminate against small-angle forward-scattered projectiles.

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[1]H. S. W. Massey, Phys. Today 29, 42 (1976).

[2]C. Ramsauer, Ann. Phys. 64, 513 (1921); 66, 546 (1921); 72, 345 (1923); C. Ramsauer and R. Kollath, *ibid.* 3, 536 (1929).

[3]J. S. Townsend and V. A. Bailey, Philos. Mag. 43, 593 (1922).

[4]W. E. Kauppila, T. S. Stein, and G. Jesion, Phys. Rev. Lett. 36, 580 (1976).

[5]K. F. Canter, P. G. Coleman, T. C. Griffith, and G. R. Heyland, J. Phys. B 6, L201 (1973); Appl. Phys. 3, 249 (1974).

[6]B. Jaduszliwer and D. A. L. Paul, Can. J. Phys. 51, 1565 (1973); 52, 1047 (1974).

[7]D. G. Costello, D. E. Groce, D. F. Herring, and J. Wm. McGowan, Can. J. Phys. 50, 23 (1972).

[8]B. Jaduszliwer and D. A. L. Paul, Can. J. Phys. 52, 272 (1974). Note: These total cross-section measurements are subject to a substantial uncertainty in the effective length of the scattering chamber (standard error of about 10%) as mentioned in J-S. Tsai, L. Lebow, and D. A. L. Paul, Can. J. Phys. 54, 1741 (1976).

[9]R. I. Campeanu and J. W. Humberston, J. Phys. B 10, L153 (1977).

[10]R. I. Campeanu and J. W. Humberston, J. Phys. B 8, L244 (1975).

[11]W. E. Kauppila, T. S. Stein, V. Pol, and G. Jesion, in Proceedings of the Fourth International Conference on Positron Annihilation, Helsingor, Denmark, 1976 (unpublished), p. A25.

[12]W. E. Kauppila, T. S. Stein, G. Jesion, M. S. Dababneh, and V. Pol, Rev. Sci. Instrum. 48, 822 (1977).
[13]T. S. Stein, W. E. Kauppila, and L. O. Roellig, Rev. Sci. Instrum. 45, 951 (1974).
[14]T. S. Stein, W. E. Kauppila, and L. O. Roellig, Phys. Lett. 51A, 327 (1975).
[15]MKS Instruments type 145AH-1 (1 Torr) differential head with 170-series electronics.
[16]D. E. Golden and H. W. Bandel, Phys. Rev. 138, A14 (1965).
[17]D. E. Golden, Phys. Rev. Lett. 17, 847 (1966).
[18]H. Aulenkamp, P. Heiss, and E. Wichmann, Z. Phys. 268, 213 (1974).
[19]J. Callaway, R. W. LaBahn, R. T. Pu, and W. M. Duxler, Phys. Rev. 168, 12 (1968).
[20]R. J. Drachman, Phys. Rev. 144, 25 (1966).
[21]Y. K. Ho, Ph.D. thesis (University of Western Ontario, 1975) (unpublished); Y. K. Ho and P. A. Fraser, J. Phys. B 9, 3213 (1976).
[22]R. P. McEachran, D. L. Morgan, A. G. Ryman, and A. D. Stauffer, J. Phys. B 10, 663 (1977).
[23]H. S. W. Massey, J. Lawson, and D. G. Thompson, *Quantum Theory of Atoms, Molecules, Solid State* (Academic, New York, 1966), p. 203.
[24]H. S. W. Massey and A. H. Moussa, Proc. Phys. Soc. Lond. 77, 811 (1961).
[25]M. F. Fels and M. H. Mittleman, Phys. Rev. 182, 77 (1969).
[26]P. G. Coleman, T. C. Griffith, G. R. Heyland, and T. L. Killeen, J. Phys. B 8, L185 (1975).
[27]R. E. Montgomery and R. W. LaBahn, Can. J. Phys. 48, 1288 (1970). Total cross-section values provided by R. E. Montgomery and R. W. LaBahn (private communication).
[28]A. G. Ryman, R. P. McEachran, and A. D. Stauffer, *Abstracts of the Tenth International Conference on the Physics of Electronic and Atomic Collisions* (Commissariat a L'Energie Atomique, Paris, 1977), p. 820.
[29]D. Andrick and A. Bitsch, J. Phys. B 8, 393 (1975).
[30]H. J. Blaauw, F. J. de Heer, R. W. Wagenaar, and D. H. Barends, J. Phys. B 10, L299 (1977).
[31]E. Bruche, D. Lilienthal, and K. Schrodter, Ann. Phys. (Leipz.) 84, 279 (1927).
[32]H. B. Milloy and R. W. Crompton, Phys. Rev. A 15, 1847 (1977).
[33]C. Ramsauer, Ann. Phys. 66, 546 (1921).
[34]A. L. Sinfailam and R. K. Nesbet, Phys. Rev. A 6, 2118 (1972).
[35]B. Bederson and L. J. Kieffer, Rev. Mod. Phys. 43, 601 (1971).
[36]C. Ramsauer and R. Kollath, Ann. Phys. 3, 536 (1929).
[37]A. Salop and H. H. Nakano, Phys. Rev. A 2, 127 (1970).
[38]D. Andrick, Universität Kaiserslautern (private communication). The method used to obtain the e^--Ne results is similar to that described in Ref. 29.
[39]D. G. Thompson, J. Phys. B 4, 468 (1971).
[40]C. Ramsauer and R. Kollath, Ann. Phys. 12, 529 (1932).
[41]E. C. Bullard and H. S. W. Massey, Proc. R. Soc. A 133, 637 (1931).