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Measurements of total scattering cross sections for low-energy positrons and electrons colliding with krypton and xenon

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Total scattering cross sections have been measured in the same apparatus for positrons and electrons of well-defined energies (0.35–100 eV) colliding with krypton and xenon using a beam-transmission technique. The positron total cross sections are largest at the lowest energies studied, and decrease in a manner very similar to the elastic scattering cross-section calculations by Schrader and by McEachran *et al.* The total cross sections for positron-krypton, xenon collisions experience abrupt changes in their slope at the respective positronium-formation thresholds indicating that positronium formation may be an important contributor to the total cross section above the formation threshold. The present electron measurements are in good agreement with the recent measurements of Wagenaar. Estimates of potential errors in the present measurements due to incomplete discrimination against small-angle forward elastic scattering are made.

Many interesting features can be observed when measuring total cross sections for low-energy electrons and positrons colliding with inert gas atoms. Early measurements by Ramsauer,[1] and Townsend and Bailey[2] revealed pronounced minima in the scattering cross sections for electrons colliding with argon, krypton, and xenon at energies of the order of 0.5 eV. These minima in the total cross-section curves are now referred to as Ramsauer-Townsend effects and are understood to arise from the quantum-mechanical nature of the elastic scattering of electrons by these atoms. No Ramsauer-Townsend effects have been observed for electrons scattering from helium and neon. Recent total cross-section measurements by Stein *et al.*[3] and Kauppila *et al.*[4] show that Ramsauer-Townsend effects are present for positrons scattering from helium, neon, and argon at energies in the vicinities of 2, 0.6, and 2 eV, respectively. The relatively high-resolution measurements (beam-energy width <0.1 eV) of Stein *et al.*[3] and Kauppila *et al.*[4] also reveal abrupt increases in the total cross-section curves above the thresholds for positronium formation with neon and argon as the target atoms, and a gradual increase above the positronium-formation threshold for helium. An extension of this work to study the scattering of low-energy positrons and electrons by krypton and xenon is reported in this paper. An initial survey of the present positron measurements over a smaller energy range has appeared elsewhere.[5]

The experimental apparatus and procedure used in the present total cross-section measurements have been discussed in detail elsewhere.[3,4,6] Basically, a transmission technique is used where the positron or electron beam is passed through a gas scattering region and the total cross section Q_T is deduced from the expression

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

where n (the target-gas number density), L (the beam-path length through the gas scattering region), I_0 (the detected beam current with no gas in the scattering region), and I (the transmitted and detected beam current with gas in the scattering region) are all measurable quantities. The absolute energies of the positron and electron beams were determined by using retarding potential measurements. A retarding potential method is also used to provide discrimination against detection of projectile particles which have experienced inelastic scattering and elastic scattering in the forward direction. In the case of inelastic scattering the discrimination is complete. For forward elastic scattering the discrimination is incomplete, particularly at the smallest angles. Discrimination against small-angle forward elastic scattering is also provided by the nature of the experimental system, where a small exit aperture from the gas scattering region effectively prevents many of the forward elastically scattered projectiles from reaching the detector. An analysis of the discrimination of the present experiment against small-angle forward elastic scattering, due to both the retarding potential method and the effect of the beam exit aperture, is given elsewhere[7] and this analysis will be used to obtain estimates of the angular discrimination for the present measurements.

The present positron-krypton total cross-section measurements are listed in Table I and shown in Fig. 1 along with the experimental results of Canter *et al.*[8] and the elastic scattering cross-section calculations by Massey *et al.*[9] (a semiempirical

TABLE I. Present total cross-section results for e^+-Kr.

E (eV)	Q_T (Å^2)
0.35	15.2
0.50	10.0
0.75	6.6
1.0	6.5
1.5	5.94
1.75	5.57
2.0	5.69
2.25	5.42
2.5	5.38
2.75	4.91
3.0	5.06
3.25	5.10
3.5	4.94
4.0	4.89
4.5	4.82
5.0	4.64
5.5	4.78
6.0	4.74
6.5	4.81
6.8	4.92
7.0	4.97
7.3	5.42
7.5	5.86
8.0	6.59
9.0	7.77
10.0	8.26
11.0	8.96
11.5	8.98
11.8	9.18
12.0	9.48
12.5	9.65
13.0	9.51
13.5	9.73
14.0	9.77
15.0	9.79
16.0	9.95
17.0	9.70
18.0	10.1
20.0	10.5
22.0	10.8
25.0	11.1
30.0	10.7
40.0	10.3
50.0	10.3

approach), Schrader[10] (a semiempirical model), and McEachran *et al.*[11] (polarized-orbital approximation). The present results indicate a large cross section at the lowest energies which decreases rapidly with increasing energy, becoming almost constant around 6 eV and then starting to increase abruptly at the threshold for positronium formation (7.2 eV). There is no evidence of a Ramsauer-Townsend effect as is predicted by the work of Massey *et al.*[9] The prior measurements of Canter *et al.*[8] differ significantly from the present results at the lowest energies of overlap, while above 4 eV there is some resemblance of the general shapes of the respective "curves" and their absolute values range from being somewhat higher (up to 50% between 5 and 20 eV) to somewhat lower (about 10% above 20 eV) than the present values. In the elastic scattering energy region (below the positronium-formation threshold) the present results are seen to be in quite good agreement with the shapes of the elastic scattering cross-section curves obtained by Schrader[10] and McEachran *et al.*[11]

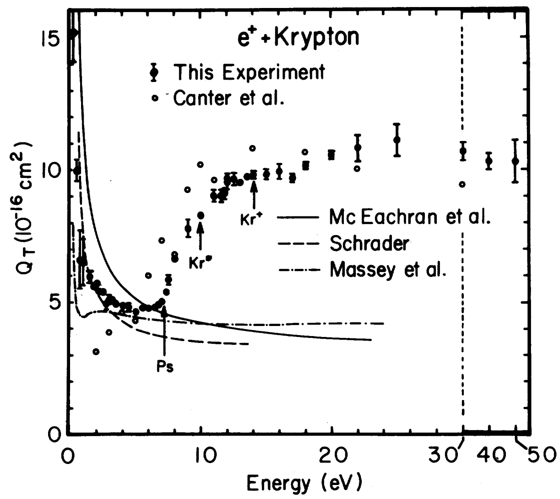

FIG. 1. Total positron-krypton scattering cross-section results. The threshold energies for positronium formation, excitation, and ionization are indicated by arrows. Statistical uncertainties of the present results are represented by error bars except where they are encompassed by the size of the dot. Note the change in the energy scale at 30 eV.

The present results for positron-xenon scattering displayed in Table II and Fig. 2 reveal a shape quite similar to the present positron-krypton results. The total cross section is large at the lowest energies after which it decreases rapidly with increasing energy, begins leveling out at about 5 eV, and then starts to increase abruptly at the positronium-formation threshold (5.3 eV). The earlier measurements of Canter *et al.*,[8] shown in Fig. 2, are generally lower than the present results, particularly at the lowest and highest energies of overlap. The present results are nicely "bracketed" by the calculations of Schrader[10] (semiempirical model) and McEachran *et al.*[11] (polarized-orbital approximation) in the energy region where only elastic scattering can occur.

Estimates of the positronium-formation cross sections for e^+-Kr and e^+-Xe scattering can be made, based on the present measurements, for energies between the respective positronium-for-

TABLE II. Present total cross-section results for e^{+}-Xe.

E (eV)	Q_T (Å^2)
0.35	30.4
0.50	31.2
0.75	25.6
1.0	20.1
1.25	18.1
1.5	15.2
1.75	15.1
2.0	14.1
2.25	12.7
2.5	12.1
2.75	11.4
3.0	10.9
3.5	10.4
3.75	10.0
4.0	9.97
4.25	9.38
4.5	9.83
4.75	9.97
5.0	10.5
5.25	11.0
5.5	11.9
5.75	12.2
6.0	12.7
6.5	13.4
7.0	13.7
7.5	14.3
8.0	15.9
8.5	16.0
9.0	16.4
9.5	17.1
10.0	16.4
10.5	16.5
11.0	16.8
11.25	15.9
11.5	16.1
12.0	16.1
13.0	16.0
14.0	16.5
14.5	16.3
14.7	16.9
15.0	16.7
15.5	16.4
16.0	16.5
17.0	16.4
18.0	16.6
19.0	16.4
20.0	16.6
22.0	16.7
25.0	16.4
30.0	15.6
35.0	15.1
40.0	14.3
45.0	14.1
50.0	14.4

mation thresholds and the lowest energies at which the target atoms can be excited (9.9 eV for Kr and 8.3 eV for Xe). If it is assumed that the elastic scattering portions of the measured total cross-section curves continue smoothly through the positronium-formation thresholds to the excitation thresholds, the difference between the measured total cross-section curves and the "extrapolated" elastic cross-section curves would give the positronium-formation cross-section curves. For positrons scattering from krypton the extrapolated formation cross section increases in a continuous manner from 0 (at the formation threshold) to about 3.5×10^{-16} cm^2 at the excitation threshold, while for scattering from xenon the increase is from 0 (at the formation threshold) to about 8×10^{-16} cm^2 at its excitation threshold. Charlton *et al.*[12] have deduced positronium-formation cross sections from their lifetime measurements of positrons in gas mixtures which are somewhat higher than the present estimates.

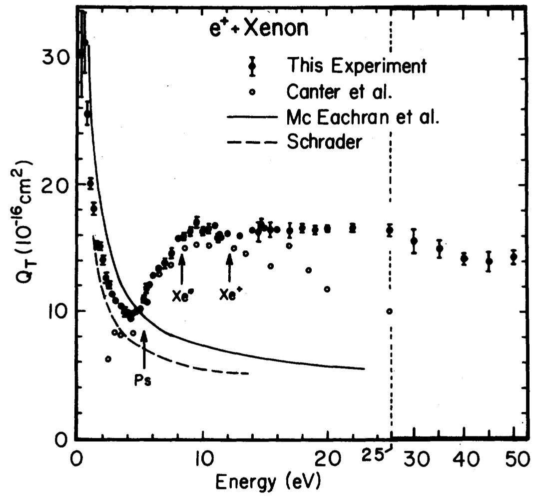

FIG. 2. Total positron-xenon scattering cross-section results. Other descriptive information is the same as for Fig. 1, except that the change in the energy scale is at 25 eV.

The present total cross-section results for the scattering of electrons by krypton and xenon are listed in Table III and shown in Figs. 3 and 4 along with the results of prior experiments and calculations. The present results are in best agreement with the recent measurements of Wagenaar[13] with the only difference being that the present results average 7 and 8% lower for krypton and xenon, respectively. At lower energies the historic measurements of Ramsauer[1] agree well with the present measurements in shape and magnitude of the respective cross-section curves. The present measurements could not be extended down to the region of the Ramsauer-Townsend minima for krypton and xenon (illustrated by the dotted curves in Figs. 3 and 4 representing the results of Ramsauer and Kollath[1]) due to a perturbing effect of the magnetic field from the electron-source cath-

TABLE III. Present total cross-section results for e^--Kr, Xe.

e^--Kr		e^--Xe	
E (eV)	Q_T (Å^2)	E (eV)	Q_T (Å^2)
1.9	3.14	2.8	16.24
2.9	6.96	3.7	25.9
3.6	10.23	4.7	34.1
4.7	14.05	5.7	39.2
6.6	21.64	6.7	40.8
9.7	26.4	7.7	41.4
11.6	28.6	8.7	40.6
12.9	27.3	9.7	39.0
14.5	26.6	11.7	37.7
15.9	24.1	14.7	35.6
17.5	24.3	17.7	34.6
19.5	23.0	19.6	33.8
21.9	21.4	22.1	31.7
24.5	20.3	24.7	27.4
27.0	19.24	27.1	23.3
29.4	18.86	29.5	20.5
34.4	17.24	34.6	16.89
39.4	16.65	39.6	15.04
44.4	15.14	44.6	14.29
49.3	14.79	49.6	13.19
99.4	10.41		

ode heater on lower-energy electrons. At energies above 20 eV the results of Ramsauer are consistently more than 10% lower than the present work. The semiempirical results deduced by de Heer *et al.*[14] are in good agreement with the present work for krypton but not in as good agreement for xenon. We have determined total cross-section values for the two-parameter "optical-model" calculations of McCarthy *et al.*[15] by integrating their differential elastic scattering cross sections at each energy and adding these resulting elastic cross sections to their total reaction (inelastic) cross sections. These optical-model results are consistently lower than the present results for all energies of overlap. It should be commented that the differential elastic cross-section results of McCarthy *et al.*[15] for krypton and xenon in this energy range are in quite good agreement (in shape and magnitude) with the available experimental results (see Ref. 14).

An important consideration pertaining to the present measurements is the realization that the measured total cross sections may be low due to incomplete discrimination against projectile particles elastically scattered at small forward angles. Using the procedures developed in Ref. 7 it is estimated, based on the relevant experimental information, that for electrons scattering from krypton and xenon, reasonable upper limits on the present angular discriminations are in the vicinity of 5° for all energies (ranging from 2–100 eV).

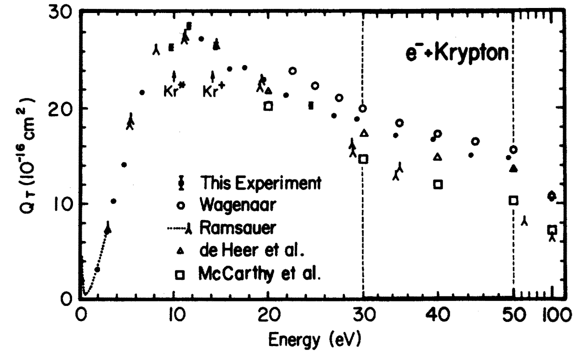

FIG. 3. Total electron-krypton scattering cross-section results. The threshold energies for excitation and ionization are indicated by arrows. Statistical uncertainties of the present results are represented by error bars except where they are encompassed by the size of the dot. Note the changes in the energy scale at 30 and 50 eV.

For positrons scattering from krypton and xenon the estimated upper limits on the angular discriminations are in the range of 15 to 20° for energies between 1 and 20 eV, which are the only energies for which all of the relevant experimental information is available. In general, the estimated angular discriminations are better (i.e., smaller) for the electron studies because it was found that the measured total cross sections for electron scattering were quite sensitive to tuning conditions, and it was possible with the more intense and constant (in time) electron beams to optimize the tuning of the beam for weaker axial magnetic fields in the gas scattering region than were readily attainable with positron beams. When this information on angular discriminations is used together with the differential elastic and total inelastic cross sections available from various theoretical

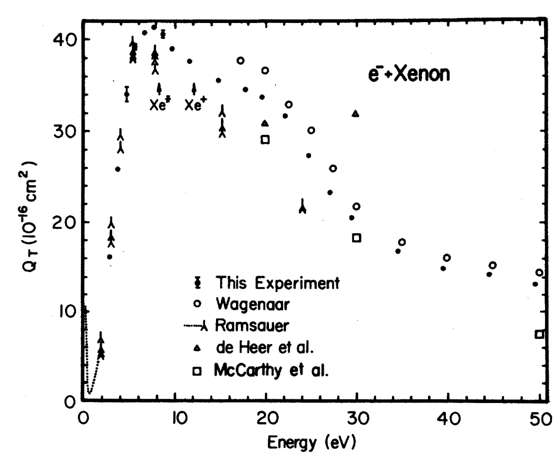

FIG. 4. Total electron-xenon scattering cross-section results. Other descriptive information is the same as for Fig. 3, except that the energy scale is constant.

calculations (and/or experiments), it is possible to estimate upper limits by which the present total cross-section measurements may be low due to incomplete discrimination against small-angle forward elastic scattering. For electron scattering the results of calculations by McCarthy *et al.*[15] have been used to estimate that the present total cross-section measurements for krypton may range from being 2% low at 20 eV to about 7% low at 100 eV, while for xenon they may range from about 3% low at 20 eV to about 5% low at 50 eV. It is interesting and relevant that the first electron measurements made in the present studies, taken with different tuning conditions (with the primary difference being higher axial magnetic fields in the gas scattering region), were up tp 25% lower than the results given in Figs. 3 and 4. Using the same procedures to determine the angular discriminations (generally 10 to 15°) and the amounts by which these initial measurements could be too low, we find a remarkable consistency with our reported results, when the angular corrections are considered, which supports our contention that our total cross-section measurements are low due to incomplete discrimination against small-angle forward elastic scattering. In the cases of positron scattering by krypton and xenon, sufficient information is available for energies where only elastic scattering can occur. Using the results of calculations by McEachran *et al.*[11] it is estimated that the present positron total scattering cross-section measurements for krypton may range from being about 16% low at 1 eV to about 21% low at the positronium-formation threshold, and for xenon they may range from being about 16% low at 1 eV to about 27% low at the positronium-formation threshold. If the positron elastic scattering cross sections are assumed to be changing in a continuous manner as the energy increases above the formation and other inelastic thresholds, some indirect estimates of errors due to incomplete discrimination against elastic scattering can also be made in this low-energy inelastic scattering region. From the present results shown in Figs. 1 and 2 it is deduced that immediately above 12 eV for krypton and 10 eV for xenon the total inelastic cross section is about equal to (or greater than) the elastic scattering cross section. Using the elastic differential cross-section data of McEachran *et al.*,[11] we estimate that we could miss up to 17% for krypton at 12 eV and up to 24% for xenon at 10 eV of the respective elastic scattering cross sections, which would translate into our measuring total cross sections that are too low by up to 9% for krypton at 12 eV and 12% for xenon at 10 eV. The important point to be made here is that when inelastic scattering becomes an appreciable part of the total cross section, the present experiment becomes less affected by the incomplete angular discrimination against elastic scattering. It should be emphasized that the estimated upper limits on the errors in the present measured total cross sections due to incomplete angular discrimination depend directly on the reliability of the theoretical information that is used, as well as the estimates of the upper limits on the angular discriminations. In any event, the preceding discussion provides an indication that the shapes of the present uncorrected total cross-section curves should not be significantly affected by a lack of complete discrimination against small-angle forward elastic scattering.

In view of the potential errors in the present total cross-section measurements due to incomplete angular discrimination, it is of interest to extend the comparison of some of the various experimental results. It is noteworthy that the electron scattering experiment of Wagenaar[13] has an estimated angular discrimination of less than 1°, which would result in his measured total cross sections being less than 0.5% low for energies below 100 eV for krypton and xenon. The present measurements, if adjusted for the errors estimated in the preceding discussion, would average less than 5% below the measurements of Wagenaar[13] for both krypton and xenon. This present comparison with Wagenaar for krypton and xenon is very consistent with a similar comparison made by Kauppila *et al.*[7] for helium, neon, and argon at intermediate energies. It appears that the principal source of the small differences between the electron measurements from these two laboratories is most likely a result of the differing angular discriminations. In the case of positron scattering measurements for krypton and xenon, there is no consistent explanation for the differences between the present results and those of Canter *et al.*[8] that could be based solely on the angular discrimination of the present experiment.

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