Total-Cross-Section Measurements for Positrons and Electrons Colliding with Potassium

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The first measurements of total cross sections for positrons (5–49 eV) colliding with a non-room-temperature gas (namely potassium) are reported. Comparisons of these measurements with the corresponding electron measurements using the same apparatus and technique (a beam-transmission method) indicate an overall degree of similarity that has not been observed for any other target atoms or molecules, which could be related to the large polarizability of potassium atoms.

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Partly because of their relatively simple atomic structure, the alkali-metal atoms, with their single, weakly bound valence electron (e^-) moving outside of a core of closed shells, have provided important tests of various approximation schemes used by atomic theorists to describe e^--atom collisions. Their low ionization potentials (3.9–5.4 eV) and their resonance lines in the visible or quartz ultraviolet part of the electromagnetic spectrum make the alkali metals interesting as components of stellar atmospheres and other plasmas (such as exist in alkali-metal vapor lamps). With consideration of the positron (e^+) as a complementary probe, the combination of intriguing differences (opposite sign of the projectile charge, and absence of the exchange interaction in the case of the e^+) and similarities (same magnitudes for the mass, charge, and spin) of the e^+ and the e^- has stimulated several theoretical investigations of e^+-alkali-metal collisions in recent years. However, up to the present time, total-cross-section (Q_T) measurements have been reported for positrons colliding only with room-temperature gases (inert gas atoms and a variety of molecules). A unique feature of e^+–alkali-metal collisions is that since the alkali metals all have ionization potentials less than the binding energy (6.8 eV) of positronium (Ps) in its ground state, an e^+ with arbitrarily small kinetic energy can form Ps. Another distinguishing feature of the alkali metals is that their polarizabilities are considerably larger than those of any of the gases which have been studied for positrons (e.g., the polarizability of K is about 26 times as large as that of Ar). In this paper, we present the first Q_T measurements for positrons colliding with a non-room-temperature gas (namely K) and the corresponding e^- measurements using the same apparatus and technique. Prior direct-comparison (e^+,e^-) Q_T measurements have revealed interesting similarities and differences in the scattering of these projectiles.[1–3] For example, it has been found that the e^--He Q_T values are 2 orders of magnitude larger than the corresponding e^+ values near 2 eV, but merge with the e^+ values near the relatively low energy of 200 eV.[1]

The experimental approach used in the present experiments for producing the e^+ and e^- beams (which have energy widths of less than 0.1 and 0.2 eV, respectively) has been described elsewhere.[1,3] For the present measurements, instead of a 109-cm-long scattering cell (as was used in our Q_T measurements on room-temperature gases[3]), a thermally isolated stainless-steel (type 304) oven (shown in Fig. 1) is used as the scattering cell. A weak, axial magnetic field is used to guide the positrons and electrons from their respective sources to the oven via a curved region (> 1 m in length) containing ten knife-edge collimators which provide very effective isolation of the e^+ and e^- sources from the alkali-metal vapor. The axial field is extended into the alkal-metal scattering region by means of two coils concentric with the oven apertures. A Channeltron electron multiplier (CEM) on the input side of the oven serves (when its front

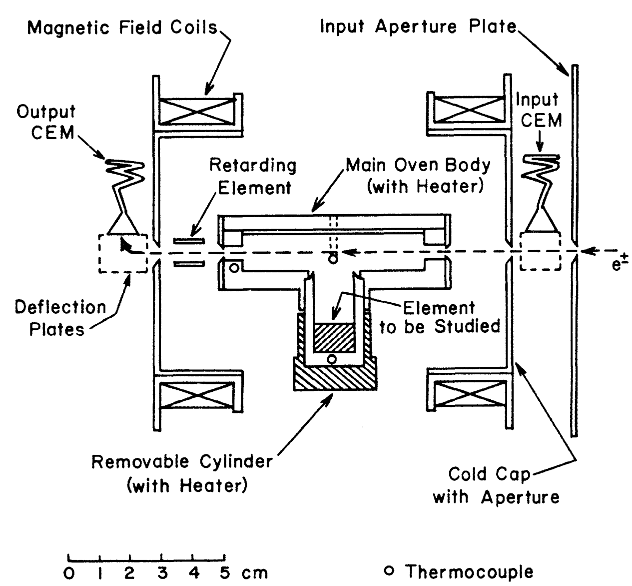

FIG. 1. Schematic diagram of the (e^+,e^-)–alkali-metal scattering apparatus.

end is biased appropriately) as a detector for projectiles about to enter the oven. When the cone (front end) of that detector is grounded, the projectiles are permitted to enter the oven and the transmitted beam is detected by a second CEM located beyond the output end of the oven. A stainless-steel retarding element (which becomes coated with the alkali metal effusing from the oven) located between the oven and the output CEM is used to measure the projectile energy as well as to provide additional discrimination[1] (beyond geometrical considerations) against projectiles scattered through small angles in forward directions. A pair of biased vertical metal plates near each CEM produce a transverse electric field so that the axial magnetic field and the resultant electric field in the vicinity of the biased cone of either CEM produce an $\mathbf{E}\times\mathbf{B}$ drift into the cone of that CEM.

In our Q_T determinations, measurements are made of (1) the ratio, R_{cold}, of the output CEM to the input CEM counts with negligible K vapor in the oven (oven at room temperature) and (2) the ratio, R_{hot}, of the output CEM to the input CEM counts with sufficient vapor (oven at elevated temperature) to attenuate appreciably the projectile beam. The purpose of using the ratio of the output CEM to the input CEM counts is to normalize the transmitted beam intensity with respect to the incident beam intensity. Determinations of (1) the beam-transmission ratio, $R_{\text{hot}}/R_{\text{cold}}$, (2) the number density, n, of K atoms in the oven, which is obtained by measurement of the oven temperature at three different locations in the oven walls (indicated by circles in Fig. 1) and in the oven's interior with Chromel-Alumel thermocouples and by use of published vapor pressure data,[4] and (3) the path length, L, of the projectiles through the oven can be used with the relationship

$$R_{\text{hot}} = R_{\text{cold}} e^{-nLQ_T}$$

to obtain absolute Q_T values.

The magnitudes of several potential sources of systematic errors have been analyzed by use of methods similar to those outlined by Kauppila *et al.*[1] A brief summary is provided here and details of this analysis and of various experimental checks for potential systematic errors will be presented elsewhere[5] along with a more detailed description of the experimental technique and apparatus. Upper limits to the increase in the path length due to spiraling in the axial magnetic field of the oven have been estimated to be less than 2% over the entire energy range except for e^+ below 10 eV where the maximum increase in path length is estimated to be less than 4%. The uncertainty in the path length due to effusion from the oven apertures[6] is estimated to be less than 10%. In the present measurements we have used the actual distance between the entrance and exit apertures of the oven (6.99 cm) as the effective path length of the projectiles through the scattering cell. Discrimination against projectiles which have undergone small-angle elastic scattering is provided by the size of the oven's exit aperture (3.6 mm diam) and by the voltage applied to the retarding element located between the oven's exit aperture and the output CEM.[1] Estimates of the angular discrimination for elastically scattered projectiles give a range from 15° for e^+ (10° for e^-) near 5 eV down to less than 6° near 50 eV (and above) for both projectiles. As a result of the bias on the retarding element always being set within 1.25 V of the "cutoff" retarding voltage of the projectiles, and since the K excitation threshold is 1.61 eV, there should be 100% discrimination against all inelastically scattered projectiles. A major potential source of uncertainty in the present measurements is related to the uncertainty in the determination of the vapor pressure in the oven which is very sensitive to the oven temperature. Since practical considerations[5] make it difficult to measure directly the temperature in the oven's interior when a projectile beam is passing through the oven's entrance and exit apertures, the average of the three wall thermocouple temperatures is compared with the temperature measured in the interior of the oven when there is no projectile beam passing through the oven. These comparison temperature measurements have been made both with and without the presence of potassium vapor. During the actual beam-transmission measurements, only the three wall thermocouple temperatures are measured, and the average of these is used with the comparison temperature measurements made in the absence of the projectile beam to determine the oven's interior temperature when the projectile beam is present. For all the data used in this report, the maximum deviation of each of the three wall thermocouple temperatures from the average of those temperatures was less than 1.5 °C over the duration of any given run. The thermocouples used to monitor the oven temperature were checked periodically at ice and boiling water temperature and were always found to be within 0.5 °C of the correct values. Interior oven temperatures were varied in the range from 142 to 164 °C (corresponding to a number density change of more than a factor of 3) at various projectile energies to check for any dependence of the measured Q_T values on number density. The resulting Q_T values were consistent within their statistical uncertainties. If we take ± 3 °C as the uncertainty in the oven temperature, the corresponding uncertainty in measured Q_T values due to temperature uncertainties would be less than 20%. The dimer (K_2) number density is estimated to be less than 0.1% of the K number density and should thus play a negligible role in the present measurements.

Using the approach outlined above, we have measured e^+-K Q_T values from 5.2 to 48.6 eV and e^--K Q_T values from 6.25 to 102.5 eV. The present e^+ Q_T

results are shown in Fig. 2 along with theoretical estimates of the elastic cross sections[7,8] (Q_E) and Ps-formation cross sections[8] (Q_{Ps}), and, for comparison, the present corresponding e^- Q_T results. The present direct comparisons of e^+-K and e^--K Q_T values indicate that the e^+ Q_T values are lower than the e^- values from 5 to 50 eV, but it is intriguing that they are closer to the corresponding e^- values (within 25%) over this energy range than has been the case for any other gases for which such comparisons have been made.[1-3] It should also be noted that the present e^+ and e^- comparison measurements should be more meaningful because of their being equally affected by several of the potential errors in these measurements.

Our measured e^+ Q_T values are more than twice as large as the theoretical estimate of Q_E by Bordonaro *et al.*[7] (who used a JWKB-approximated polarized orbital method) at the only energy of overlap (5 eV) and are more than five times as large as the theoretical estimates of Q_E by Guha and Mandal[8] (who used a pseudopotential formalism) at all energies of overlap. The first-Born-approximation and distorted-wave-approximation calculations of Q_{Ps} by Guha and Mandal[8] suggest that Ps formation accounts for a relatively small fraction of the present Q_T values above 10 eV. Although the theoretical estimates of Q_E and Q_{Ps} for positrons referred to above are not very elaborate compared with some calculations of elastic and inelastic cross sections for electrons, the discussion above suggests the possibility that for positrons between 10 and 50 eV, excitation or perhaps ionization (for both of which no measurements or calculations of cross sections yet exist for K) may make the major contribution to Q_T (as is the case for e^--K collisions discussed below).

The present e^--K results are shown in Fig. 3 along with other experimental[9-12] and theoretical[13] results. The pioneering measurements of Brode[9] (who used a modified Ramsauer technique), and the relatively recent results of Visconti, Slevin, and Rubin[10] and Kasdan, Miller, and Bederson[11] (where both groups used atom-beam recoil techniques), have somewhat different energy dependences than the present results. The indirect total-cross-section determinations of Vuskovic and Srivastava[12] (who used their own crossed-beam measurements of differential cross sec-

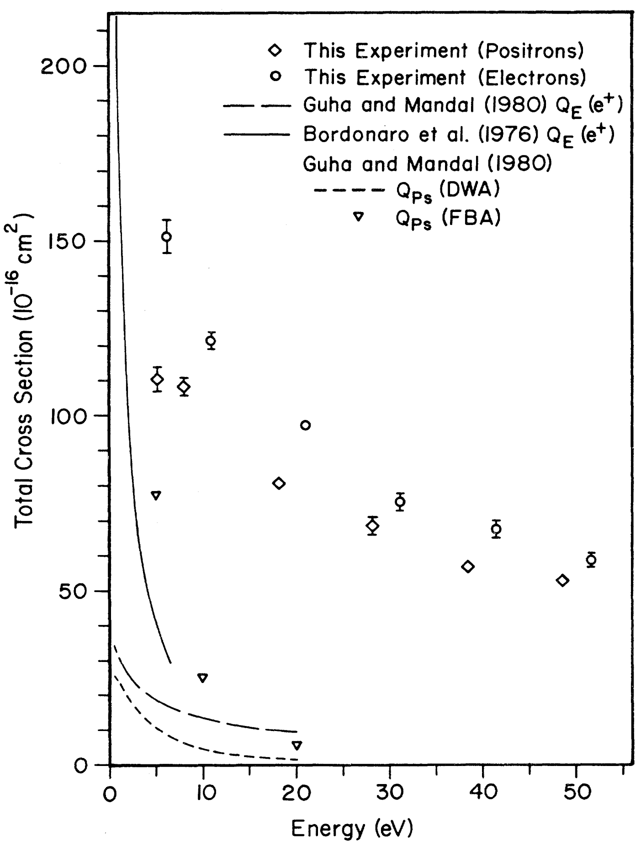

FIG. 2. (e^+,e^-)-K Q_T values. Statistical uncertainties for the present measurements are indicated by the error bars where the uncertainty is encompassed by the size of the symbol. The values shown for Q_{Ps} are the largest of the distorted-wave-approximation and first-Born-approximation values obtained by Guha and Mandal, Ref. 8.

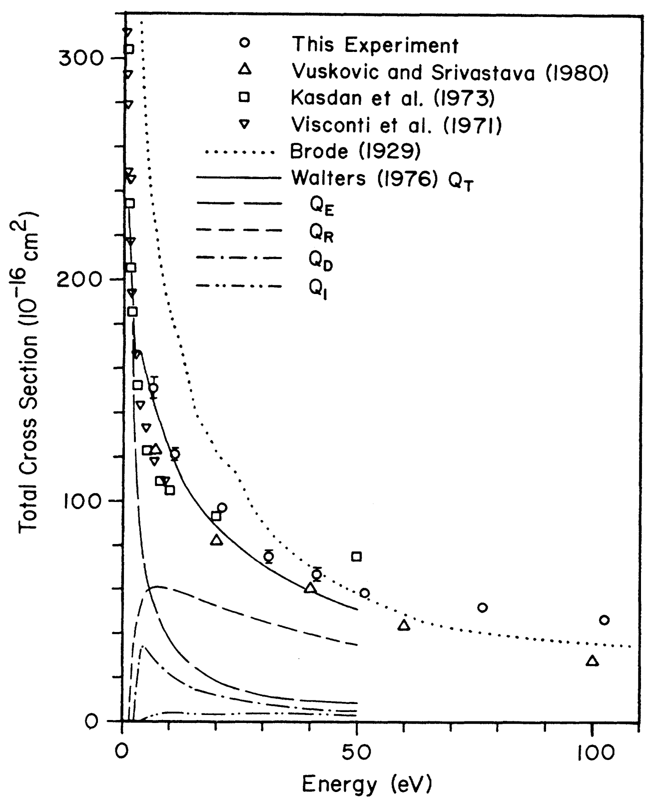

FIG. 3. e^--K Q_T values.

tions for elastic scattering and for a number of different transitions from the ground state, and ionization cross sections measured by other groups) are somewhat lower than the present results over the entire energy range of overlap but have a similar energy dependence up to 50 eV. The present results are in good agreement (within 20%) with the total-cross-section estimates made by Walters[13] [obtained by adding the cross sections which he selected from existing theoretical results for elastic (Q_E), resonance excitation (Q_R), and the sum of all the other discrete excitations (Q_D), and from existing experimental results for the ionization (Q_I) cross sections].

It is also pertinent to this Letter that our initial measurements of e^--Na Q_T values (work in progress) from 4 to 77 eV suggest that a consistent pattern exists for the relationship between the present e^--K and e^--Na results and those of Kasdan, Miller, and Bederson[11] in that the present results are larger than those of Kasdan, Miller, and Bederson by roughly the same factor in K and Na at the lowest energies of overlap (near 5 eV), and smaller than those of Kasdan, Miller, and Bederson by roughly the same factor in K and Na at the highest energies of overlap (near 50 eV).

In conclusion, one possible interpretation of the proximity of the e^+ and e^- results at low energies is that the polarizability of K is so large that it could be overwhelming the static interaction at the low energies used in these experiments, even when dynamical (nonadiabatic) effects[13] are taken into account. As a result, the tedenency of the static and polarization interactions to cancel each other in the case of e^+ scattering and to add in the case of e^- scattering may not differentiate between these projectiles to the same degree for K as it does in scattering from targets of much lower polarizability. By extension of this train of thought, there could be a diverging of the e^+ and e^- Q_T values at intermediate energies due to a more complete cancellation of polarization and static interactions in the positron case (in contrast to an addition of these interactions in the electron case) where the polarization interaction diminishes to become more comparable in magnitude to the static interaction. Finally, at sufficiently high energies, where the polarization interaction has become relatively insignificant, the total cross sections would be expected to merge for positrons and electrons, and would be given by the first Born approximation.

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