Toward measurements of total cross sections for positrons and electrons scattered by potassium and rubidium atoms

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We have attempted to measure total cross sections (Q_T's) for positrons and electrons scattered by potassium and rubidium atoms in the energy range 1–102 eV using a beam-transmission technique. The measurements are subject to increasing errors as the projectile energy is reduced below 20 eV due to the incomplete discrimination of our apparatus against projectiles scattered through small angles. Our measured positron-K and -Rb Q_T's each show a peak in the vicinity of 6 eV and decrease substantially as the positron energy is reduced below 6 eV. The observed peaks may be artifacts due to the incomplete-discrimination problems referred to above, but careful consideration of those problems does not resolve the marked discrepancies between our low-energy positron-Rb results and those obtained in recent five-state close-coupling-approximation calculations.

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Initial attempts [1] by our group to measure total cross sections (Q_T's) for positron-Rb scattering revealed a peak in the vicinity of 6 eV, and a significant decrease below that energy, in sharp contrast to a recent five-state close-coupling-approximation (CCA) calculation [2] which shows steadily increasing Q_T's as the positron energy is reduced below 10 eV. Although it was recognized [1] that our Q_T measurements were subject to increasing errors as the projectile energy was reduced below 20 eV due to the incomplete discrimination of our experiment against projectiles scattered through small angles, the five-state CCA calculation [2] did not show any peak, even after taking our angular-discrimination values into account. This discrepancy is of particular interest in view of the good agreement [1] of those same experimental and theoretical results above 10 eV. The present investigations were undertaken to check our initial measurements on Rb and to attempt to measure Q_T's at low energies for K to see if those values also show a peak below 10 eV.

We use a beam-transmission technique [3] to measure Q_T's for positrons (e^+'s) and electrons (e^-'s) colliding with alkali-metal atoms in the same apparatus. A brief description of the apparatus and technique is provided below; Ref. [3] provides additional details.

Two different e^+ sources have been used for the present measurements. Our original e^+ source [3] was ^{11}C. More recently we have taken additional data using a 6-mCi ^{22}Na source along with an annealed tungsten (W) thin-film transmission moderator. The e^- source is a thermionic cathode.

We have modified our original scattering apparatus [3] by electrically isolating the scattering cell (oven) and we apply an appropriate potential to it to set the desired projectile energy. By careful adjustment of our beam controlling parameters and by grounding the W moderator used with our ^{22}Na source, we can obtain a relatively narrow energy width (0.2 eV) e^+ beam (while the energy width that can be derived from our ^{11}C source is 0.1 eV). We can obtain higher transmission efficiencies for our lowest-energy e^- measurements by transporting the beam at higher energies and then decelerating it at the scattering cell. The energy width of our e^- beam is about 0.2 eV.

A Channeltron electron multiplier (CEM) on the input side of the oven with its cone (front end) biased at an attractive potential is used to measure the incident-beam intensity. When the cone of that detector is placed at ground potential, the beam is permitted to pass through the oven and the transmitted beam is detected by another CEM at the output end of the oven. A cylindrical retarding element located between the oven and the output CEM is used to measure the projectile energy as well as to provide additional discrimination beyond geometrical considerations [3], against projectiles scattered through small angles. The estimated angular discrimination of our apparatus for elastically scattered e^-'s is about 20° near 2 eV, 11° near 10 eV, 8° near 20 eV, and 5° or less near and above 30 eV. The corresponding values for e^+'s are 23° near 2 eV, 15° near 10 eV, 11° near 20 eV, and 9° or less near and above 30 eV. We have essentially 100% discrimination against inelastically scattered projectiles [3].

Our Q_T's are determined by measuring the ratio R_{cold} of the projectile current at the output CEM to that at the input CEM when the oven is relatively cool (i.e., when the alkali-metal vapor pressure is negligible), and then measuring the corresponding ratio R_{hot} when the oven is at a sufficiently high temperature to give alkali-metal vapor pressures of the order of 10^{-4} Torr. The number density n of alkali-metal atoms is determined by measuring the oven temperature and using published vapor pressure data [4]. We estimate that dimers constitute less than 0.1% of the total number of target particles in the scattering cell at the temperatures used in this experiment. R_{hot}, R_{cold}, n, and the beam path length L through the oven are used with the relationship

$$R_{\text{hot}}=(R_{\text{cold}})e^{-nLQ_T} \tag{1}$$

to obtain Q_T's. Since the Q_T's obtained in this way can be lower than the actual Q_T's due to incomplete discrimination against projectiles scattered elastically through small angles, we use the symbol Q_{TM} to represent our measured Q_T's in all the figures in this paper. Other potential systematic errors in our measured Q_T's are discussed in detail in Ref. [3], where we estimate a "total" experimental uncertainty of 21% (excluding angular-discrimination considerations).

Our e^+-*K* (present and prior [3]) and -Rb (present) Q_T's are shown in Figs. 1 and 2, respectively, along with prior theoretical results for total [2,5–7], positronium (Ps) [8], and elastic (El) cross sections [8]. Three sets of e^+-K Q_T measurements made by our group are shown in Fig. 1. The measurements of Kwan *et al.* [3] (closed circles) are earlier measurements made with the scattering cell grounded and an ^{11}C e^+ source. The large closed squares ["This Expt: Direct (Q_{TM})"] represent our present measurements made with a "floating" scattering cell and a ^{22}Na e^+ source. The small closed squares ["This Expt: Relative (Q_{TM})"] represent our present relative Q_T values obtained with a ^{22}Na e^+ source and a floating scattering cell. These results are normalized to provide the best fit to the corresponding present direct Q_T measurements. For the relative measurements, we take data with the same tuning conditions for the projectile beam for several different energies (varied by changing the potential applied to our "floating" scattering cell) with the oven cold; then repeat this with the oven hot, and then with the oven cold again. For our direct measurements, we take data for just one energy value for each cold-hot-cold oven cycle. Since one cold-hot-cold oven cycle requires a few hours by itself, the direct measurements require much more time than the relative measurements.

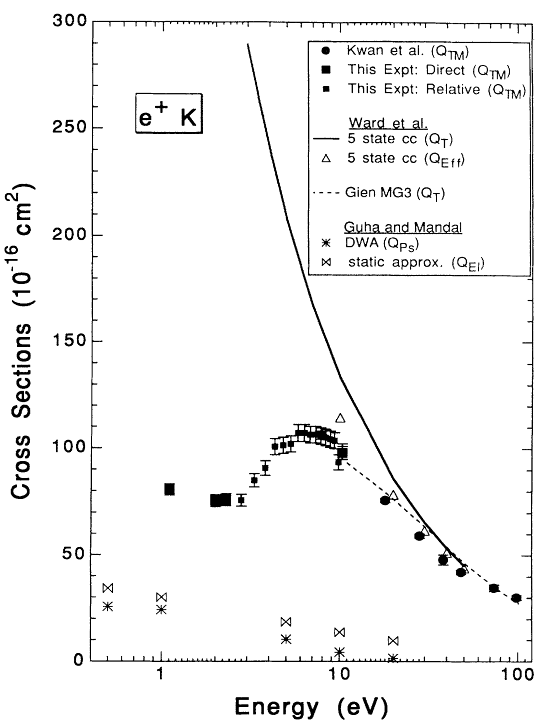

FIG. 1. Positron-K total, "effective," positronium-formation [distorted-wave-approximation (DWA)], and integrated elastic cross sections. The error bars represent statistical uncertainties. The theoretical curves in this and in the following figures are generated by drawing straight line segments between points obtained from the indicated references.

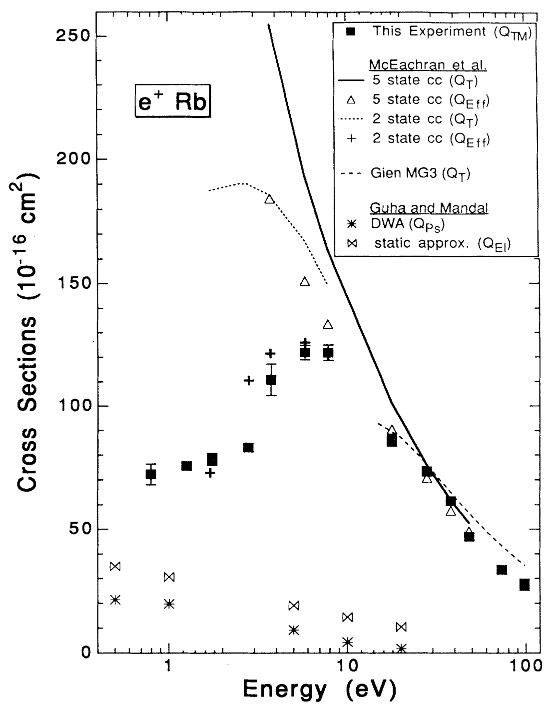

FIG. 2. Positron-Rb total, "effective," positronium-formation, and integrated elastic cross sections.

Ward *et al.* [5] and McEachran, Horbatsch, and Stauffer [2] have performed five-state CCA calculations of Q_T for e^+-K and -Rb collisions, respectively, that include the cross sections for elastic scattering, resonance excitation, and a few other discrete excitations (4*s*-5*s*, 3*d*, and 5*p* for K and 5*s*-4*d*, 6*s*, and 6*p* for Rb), but do not include the cross sections for Ps formation or ionization. In addition, Ward *et al.* [5] and McEachran, Horbatsch, and Stauffer [2] have used our estimates of our angular discrimination [1,3] along with their elastic differential-cross-section (DCS) results to calculate effective cross sections $Q_{\rm eff}$, which represent their theoretical estimates of the Q_T's that we would be expected to obtain if the only error in our measurements were that associated with the incomplete discrimination of our apparatus against projectiles elastically scattered through small angles. Our measured Q_T's are slightly lower than their corresponding Q_T calculations for K (Fig. 1) and Rb (Fig. 2) above 10 eV and are even closer to their $Q_{\rm eff}$ values above that energy. The e^+-K and -Rb modified Glauber approximation (MG3) Q_T calculations of Gien [6,7] are also in reasonable agreement with the present results.

A major discrepancy between our Q_T measurements and the five-state CCA calculations [5,2] appears below 10 eV for K and Rb, where the measurements indicate a maximum (near 6 eV) and a significant decrease as the e^+ energy is decreased below 6 eV, while the theoretical results just continue increasing as the e^+ energy is decreased. The maximum which we observe could be an artifact due to angular-discrimination problems in our experiment, since we expect [3] to miss an increasing fraction of the actual Q_T as the projectile energy is lowered due to a worsening of our angular discrimination and also to the increasing relative contribution of elastic scattering to Q_T as the energy is reduced. However, these considerations themselves do not explain the discrepancy between experiment and theory since even the $Q_{\rm eff}$ values for Rb based upon the five-state CCA calculations of McEachran, Horbatsch, and Stauffer [2], which take these considerations into account, do not show a maximum in the e^+-Rb Q_T curve (Fig. 2), but rather keep rising as the e^+ energy is lowered. In fact, at 3.7 eV our measured Q_T is about 25% *lower* than the sum of all the inelastic integrated cross sections of McEachran, Horbatsch, and Stauffer [2], which represents the Q_T we would be expected to measure in the extreme case where our experiment fails completely to discriminate against elastic scattering. The e^+-Rb $Q_{\rm eff}$ values based upon two-state CCA results of McEachran, Horbatsch, and Stauffer [2] agree quite well with our measurements, but this is puzzling because, normally, the five-state CCA results would be expected to be more reliable than the two-state results.

Our present and prior [3] e^--K and -Rb Q_T's are shown in Figs. 3 and 4 along with prior measurements by other groups [9–11] and theoretical results [6,7,12,13]. The Walters-Phelps curve in Fig. 3 is derived [3] from elastic and ionization cross sections selected by Walters [12] and excitation cross sections measured by Phelps *et al.* [14]. The symbols used to represent our e^--K Q_T measurements in Fig. 3 have the same meaning as the corresponding symbols used for our e^+-K measurements in Fig. 1. Above 20 eV, our measured Q_T's for e^-'s are quite close to the Walters-Phelps curve for K (Fig. 3) and to the modified Glauber approximation (MG3) results of Gien [7] for Rb (Fig. 4). Below 20 eV, our e^--K Q_T's become appreciably lower than prior measurements

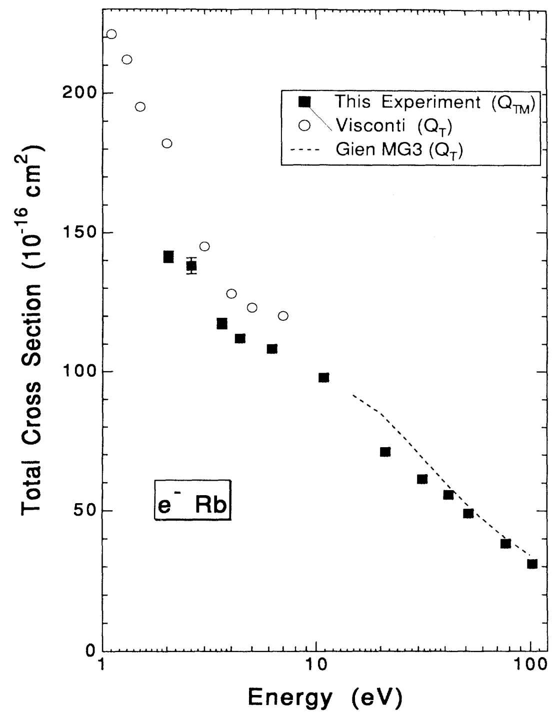

FIG. 4. Electron-Rb total cross sections.

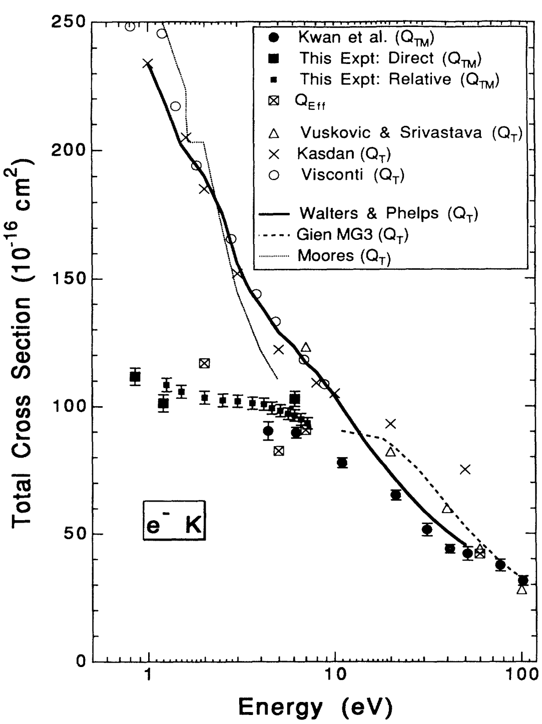

FIG. 3. Electron-K total and "effective" cross sections.

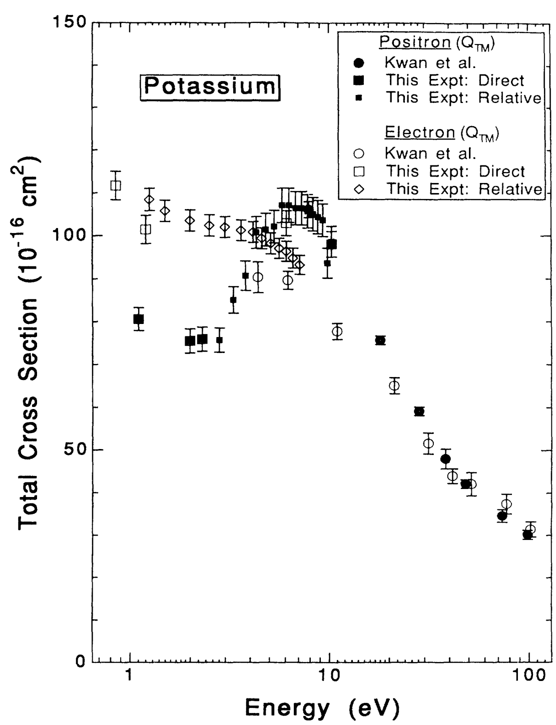

FIG. 5. Comparisons of positron- and electron-K total cross sections.

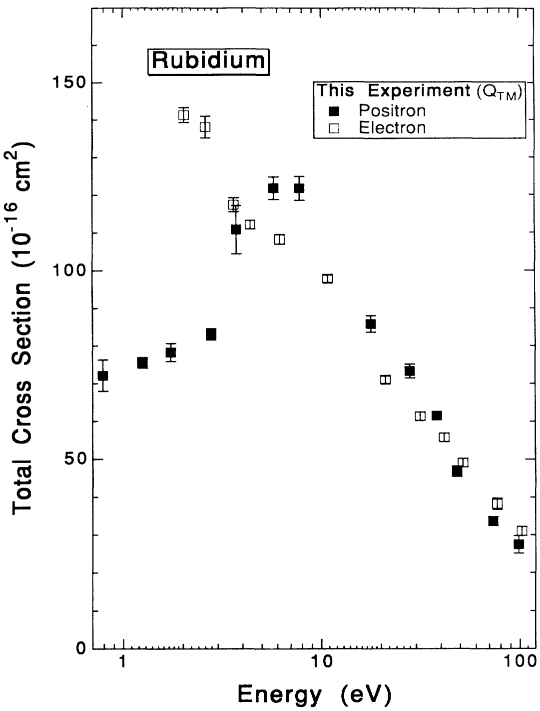

FIG. 6. Comparisons of positron- and electron-Rb total cross sections.

[9–11] and the Walters-Phelps curve. Using estimates of our angular discrimination [1,3] along with available elastic DCS's [9,13] for e^--K scattering, we have calculated effective cross sections, $Q_{\rm eff}$ (shown in Fig. 3), which represent the Q_T's that we would expect to measure if the only error in our measurements were due to incomplete discrimination against small-angle elastic scattering. At 7 and 60 eV, using the measurements of Vuskovic and Srivastava [9] as well as their analysis of the DCS results provided by Walters (also cited in Ref. [9]) the $Q_{\rm eff}$'s agree very well with our measured Q_T's. At 5 eV, using the CCA elastic DCS calculations of Moores [13], $Q_{\rm eff}$ is lower than our measured Q_T by about 16%, but the Q_T of Moores includes only the elastic and resonance excitation cross sections and is lower than the Walters-Phelps curve by about 15% at this energy. At 2.0 eV, also using the calculations of Moores, $Q_{\rm eff}$ again agrees quite well with our measured Q_T (to within 2° of our estimated discrimination angle). The $Q_{\rm eff}$ calculations indicate that the discrepancy between our measured Q_T's and the Walters-Phelps curve (as well as prior experimental results) below 20 eV is due mainly to angular-discrimination effects in our experiment, in contrast to the situation described above for e^+'s.

Comparisons of our measured e^+- and e^--K and -Rb Q_T's are shown in Figs. 5 and 6, respectively. It is interesting that for both K and Rb, our measured e^+-Q_T's are very close to being merged with our corresponding e^- values above 30 eV, but rise above those values as the projectile energy is reduced below 30 eV and then plunge below the e^- values, falling by more than 25% as the e^+ energy is reduced from about 6 to 3 eV. The drop in our measured e^+-Q_T's below 6 eV could be due to incomplete discrimination against small-angle elastic scattering, but since (as discussed above) it is not consistent with the five-state CCA calculations of McEachran, Horbatsch, and Stauffer [2], other possibilities should be considered. Perhaps coupling effects between the Ps formation channel (which is open at all e^+ energies for the alkali-metal atoms) and the elastic and excitation channels are important below 10 eV, where our preliminary Ps formation cross section ($Q_{\rm Ps}$) measurements [15] for K indicate that $Q_{\rm Ps}$ is much larger than the distorted-wave-approximation calculations of Guha and Mandal [8] (Fig. 1) would suggest. Large $Q_{\rm Ps}$ values below 10 eV could possibly result in the integrated elastic cross sections ($Q_{\rm El}$) and/or the resonance and other excitation cross sections being considerably different from those calculated by Ward *et al.* [5] for K and McEachran, Horbatsch, and Stauffer [2] for Rb due to their neglect of Ps formation. It is interesting to note that the $Q_{\rm El}$ values (shown in Figs. 1 and 2) calculated by Guha and Mandal [8], who have taken Ps formation into account, are much lower (more than a factor of 4 below 5 eV) than those obtained in the CCA calculations [2,5] where Ps formation is neglected.

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