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SCATTERING OF POSITRONS AND ELECTRONS BY ALKALI ATOMS

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ABSTRACT

Absolute total scattering cross sections (Q_T's) have been measured for positrons and electrons colliding with sodium, potassium, and rubidium in the 1-102 eV range, using the same apparatus and experimental approach (a beam transmission technique) for both projectiles. The present results for positron-sodium and -rubidium collisions represent the first Q_T measurements reported for these collision systems. Features which distinguish the present comparisons between positron- and electron-alkali atom Q_T's from those for other atoms and molecules (room-temperature gases) which have been used as targets for positrons and electrons are (1) the proximity of the corresponding positron- and electron-alkali atom Q_T's over the entire energy range of overlap, with an indication of a merging or near-merging of the corresponding positron and electron Q_T's near (and above) the relatively low energy of about 40 eV, and (2) a general tendency for the positron-alkali atom Q_T's to be higher than the corresponding electron values as the projectile energy is decreased below about 40 eV.

INTRODUCTION

One of the incentives for making direct comparison measurements between positron- and electron-scattering from the same target gases is the potential that such comparisons have for providing deeper insight into atomic scattering phenomena than may be acquired by studying the scattering of only one type of projectile from various gases. Since positrons, being the antiparticles of electrons, have the same magnitudes for the mass, charge, and spin as the electron, but have the opposite sign of charge, comparison measurements of the scattering of positrons and electrons by atoms and molecules can reveal interesting differences and similarities that arise from the basic interactions which contribute to scattering. The exchange interaction contributes to electron scattering but does not play a role in positron scattering. The static interaction (associated with the interaction of the projectile with the Coulomb field of the undistorted atom) is attractive for the electron and repulsive for the positron, while the polarization interaction (resulting from the distortion of the atom by the charged projectile) is attractive for both projectiles. The net effect of the static and polarization interactions is that they add to each other in electron scattering whereas they tend to cancel each other in positron scattering. Thus, if one considers just the contributions from the static and polarization interactions, in general, Q_T's for positrons would be expected to be smaller than those for electrons at low energies. As the projectile energy is increased, the polarization and exchange interactions eventually become negligible compared with the static interaction, and the expected result is a merging of the corresponding positron and electron Q_T's at sufficiently high projectile energies. Two scattering channels that are open only to positrons are (1) annihilation, which is negligible for the positron energies (>0.2 eV) that have been used in positron-beam scattering experiments, and (2) positronium (Ps) formation, which has a threshold energy 6.8 eV below the ionization threshold energy of the target atom.

The general trends observed in comparisons of the total scattering of positrons and electrons by the room-temperature gases that have been investigated appear to be consistent with predictions based on the simple interaction model described above. As illustrations of these general trends, comparison measurements[1-4] for the inert gases (Ne, Ar, and Kr) which correspond to the alkali metal atoms (Na, K, and Rb) discussed in this article, are shown in Figs. 1, 2, and 3 respectively. In these Figures, one can see (1) the tendency for the measured positron-inert gas Q_T's to be significantly lower than the corresponding electron Q_T's at low energies (except in the immediate vicinities of the deep Ramsauer-Townsend

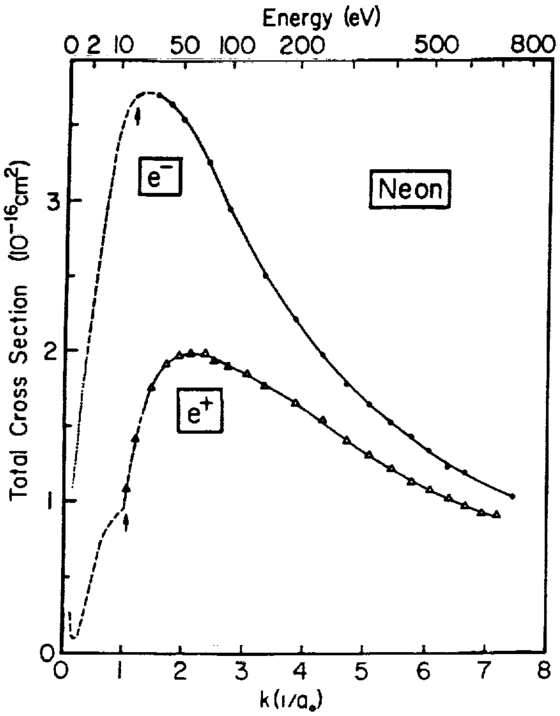

Fig. 1. Comparison of positron- and electron-Ne total cross sections. The lowest inelastic thresholds for each projectile are indicated by arrows. (From Kauppila et al., Ref. 1).

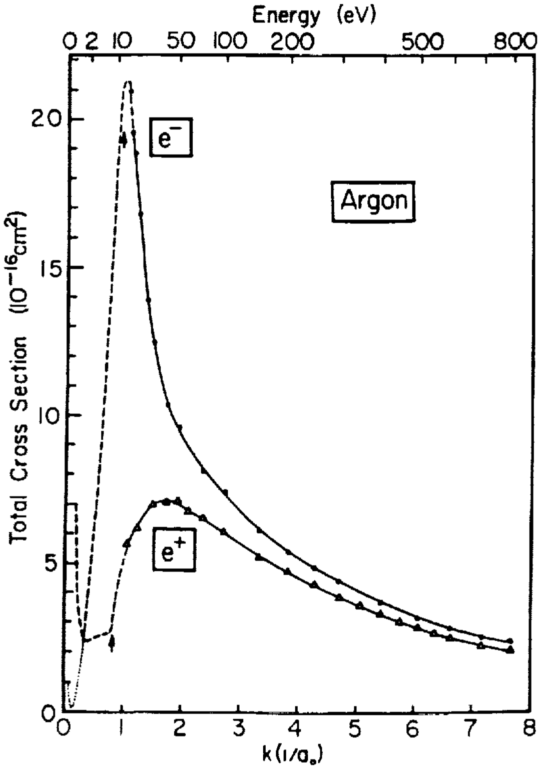

Fig. 2. Comparison of positron- and electron-Ar total cross sections. (From Kauppila et al., Ref. 1).

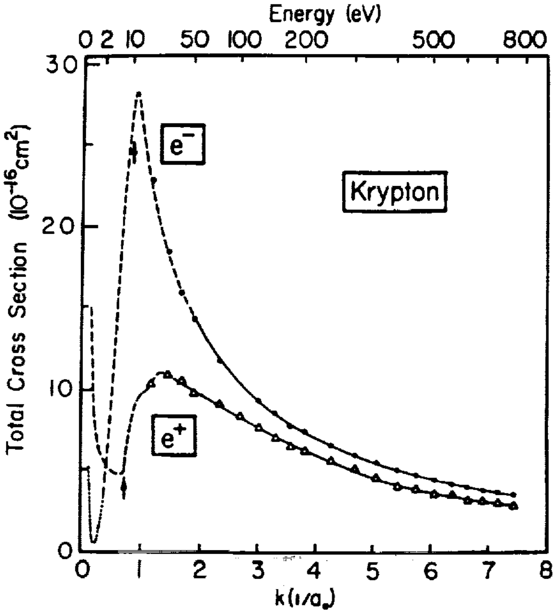

Fig. 3. Comparison of positron- and electron-Kr total cross sections. (From Dababneh et al., Ref. 3).

minima for the electron cases as shown in Figs. 2 and 3), (2) clear indications in the positron Q_T curves of the onset of Ps formation near the predicted Ps formation thresholds, and (3) the tendency for the positron and electron Q_T's to approach each other as the projectile energy is increased to sufficiently high energies. Mergings of positron and electron Q_T's have actually been observed for helium,[1] molecular hydrogen,[5] and water vapor[6] in the vicinity of about 200 eV.

It is of interest to consider whether all atoms and molecules would be expected to exhibit the same general tendencies for positron and electron scattering comparisons as those described above (and illustrated in Figs. 1-3). In order to investigate this matter further, we have been focusing our attention recently on positron-electron scattering comparisons for the alkali atoms. The alkali atoms have a relatively simple electronic structure with a single loosely bound valence electron moving outside a core of closed shells. Although there is some similarity between the single valence electron alkali atoms and atomic hydrogen, it has been pointed out[7] that the ground states of the alkali atoms have different characteristics than that of the H atom and that approximation schemes developed for the hydrogen atom will not necessarily be equally successful for the alkali atoms. One difference is associated with the atomic energy level separations. The energy separation between the ground state and first excited states of H is 10.2 eV whereas the largest corresponding separation for all of the alkali atoms is only 2.1 eV (which is for the case of sodium). The large coupling between the ground state and the first excited state of the alkali atoms influences significantly the behavior of both elastic and inelastic scattering.[7] Another feature of the alkali metal atoms is their very large polarizabilities relative to room-temperature gases. As examples, Na, K, and Rb have polarizabilities[8] of approximately 159, 293, and 319 a_o^3 (where a_o = Bohr radius), respectively, in comparison with the corresponding inert gas atoms, Ne, Ar, and Kr, with polarizabilities of 2.67, 11.1, and 16.7 a_o^3, respectively. Another unique feature of the alkali atoms is that since they all have ionization threshold energies less than the binding energy (6.8 eV) of Ps in its ground state, Ps can be formed by positrons of arbitrarily small incident energy, and thus the Ps formation channel is always open for these atoms. In contrast to this, the room temperature gases which have been used as targets for positrons and electrons all have Ps formation thresholds of at least several eV.

Our first report on the measurement of positron and electron-alkali atom Q_T's was on potassium[9], where we found that the corresponding positron and electron Q_T's were much closer to each other over the entire energy range studied (5 - 49 eV) than had been observed for any other target atoms and molecules investigated previously. In this paper, we report our present[10] positron- and electron-Na, K, and Rb results from 1 - 102 eV. The positron-Na and -Rb results represent the first reported Q_T measurements for these collision systems.

EXPERIMENTAL TECHNIQUE

We use a beam transmission technique to make absolute Q_T measurements for positrons and electrons colliding with alkali atoms in the same apparatus. Details of the apparatus and technique are provided elsewhere,[9,10] so only a brief description of our experimental approach is provided below. The positron source is ^{11}C produced on site by the $^{11}B(p,n)^{11}C$ reaction, generated by bombarding a boron target with protons from a Van de Graaff accelerator. The electron source is a thermionic cathode. A weak, curved axial magnetic field (produced by a curved solenoid) is used to guide the projectile beam from the source region to the scattering region, and to discriminate against high energy positrons coming from the source. The measured full-width at half-maximum of the energy distribution of the detected positron beam is less than 0.10 eV, while that of the electron beam is between 0.15 and 0.20 eV.

A schematic diagram of the alkali-atom scattering system is shown in Fig. 4. The main component in this system is the scattering cell consisting of the main oven body, and a detachable cylinder which contains the alkali metal. The weak guiding axial magnetic field produced by the curved solenoid is extended into the scattering region by means of two coils located concentrically with the entrance and exit apertures of the scattering cell. A Channeltron electron multiplier (CEM) on the input side of the oven serves (when its front end is biased appproriately) as a detector for positrons or electrons about to enter the oven. When the cone (front end) of that detector is placed at ground potential, the projectile 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 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 (beyond geometrical considerations) against projectiles scattered through small angles in forward directions.

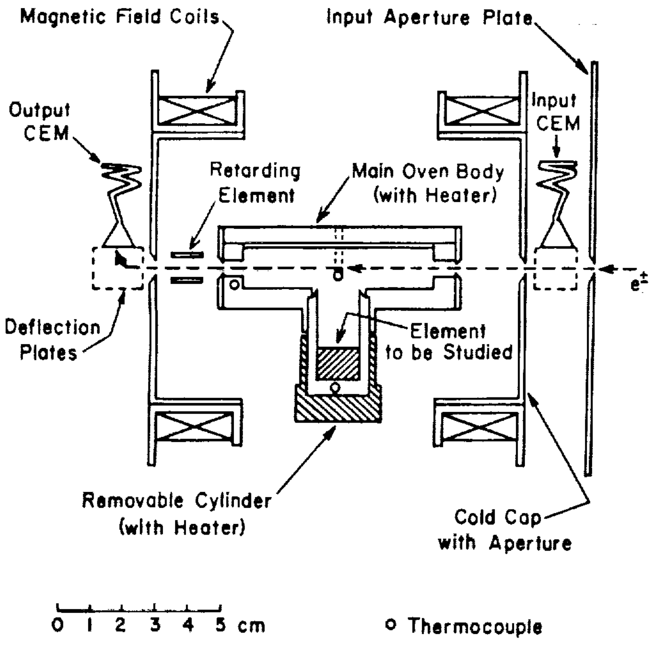

Fig. 4. Experimental setup for measuring total cross sections for alkali atoms. (From Stein et al., Ref. 9).

Our Q_T's are determined by measuring (1) the ratio, R_{cold}, of the output CEM to the input CEM counts per second when the oven is relatively cool so that there is a negligible vapor-pressure in the oven, and (2) the ratio, R_{hot} of the output CEM to the input CEM counts per second with the oven at an elevated temperature so that there is a high enough vapor-pressure in the oven to attenuate the projectile beam appreciably. The purpose of using the ratio of the output CEM to the input CEM counts per second is to normalize the transmitted beam intensity with respect to the incident beam intensity. Determinations of (1) the beam transmission ratio, R_{hot}/R_{cold}, (2) the number density, n, of the alkali atoms, which is determined by measuring the temperature of the oven and by using published vapor pressure data,[11] and (3) the beam path length, L of the projectiles thorough the oven, can be used with the relationship,

$$R_{hot} = R_{cold} \exp(-nLQ_T)$$

to obtain absolute positron- and electron-alkali atom Q_T's. It should be recognized that a major potential source of error in our Q_T measurements is related to the accuracy of the determination of n which is limited by the accuracy of our measurements of the scattering cell temperature, and by the accuracy of the vapor pressure data that we use. As a result of our continuing efforts to improve our determination of n (by improving the accuracy of our measurements of the scattering cell temperature and by trying to identify the most reliable vapor pressure data in the literature), we feel that the present positron- and electron-K and electron-Na Q_T measurements[10] should be regarded as superseding our corresponding earlier measurements.[9,12]

RESULTS AND DISCUSSION

Electrons

Our present electron-Na, and -K, Q_T measurements (Kwan et al.[10]) are shown in Figs. 5 and 6 respectively along with prior measurements[13-19] and theoretical[20-22] results. The present electron results were obtained using the same apparatus and technique as was used for our positron measurements. Walters[20] has obtained Q_T's for electron-Na and -K collisions by adding the partial cross sections that he selected from existing theoretical and experimental results for the elastic (Q_E), resonance excitation (Q_R, which represents the 3s-3p transition for Na, and the 4s-4p transition for K), the sum of other discrete excitations (Q_D), and the ionization (Q_I) cross sections. Since Walters reported these Q_T values, Q_R and cross sections for numerous other discrete excitations have been measured by Phelps and Lin[16] for Na and by Phelps et al.[18] for K, and we have added these more recent excitation cross section results (rather than the Q_R and Q_D values used by Walters) to the values of Q_E and Q_I selected by Walters, to obtain the Q_T curves shown in Figs. 5 and 6 for Na and K, which we refer to as "Walters-Phelps curves". Our measured electron-Na Q_T values are in reasonable agreement with the shape and absolute values of the Walters-Phelps curves and in good agreement (averaging about 10% lower) with the theoretical values of Msezane[22] who added the elastic, resonance excitation, 3s-3d, 3s-4s, 3s-4p, and 3s-4d cross sections obtained from his 6 state close-coupling calculation to existing direct ionization cross sections obtained by others. Our measured electron-K Q_T

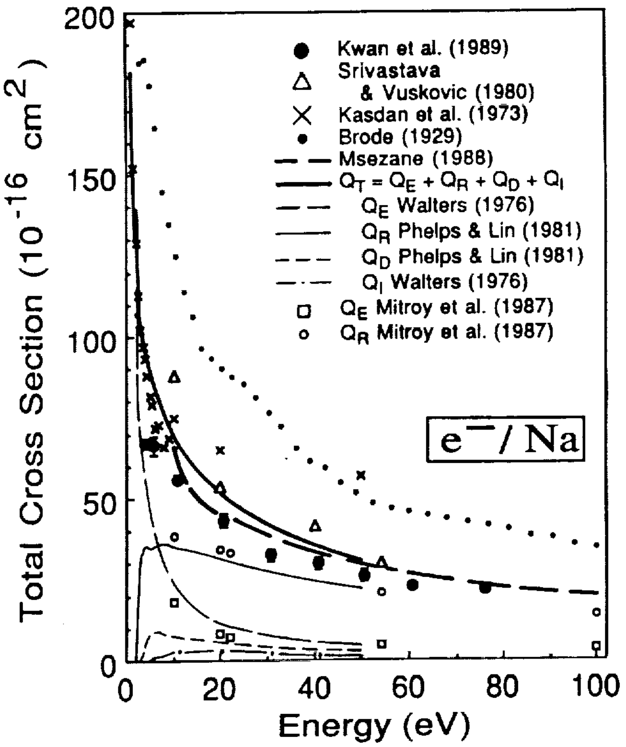

Fig. 5. Electron-Na cross sections.

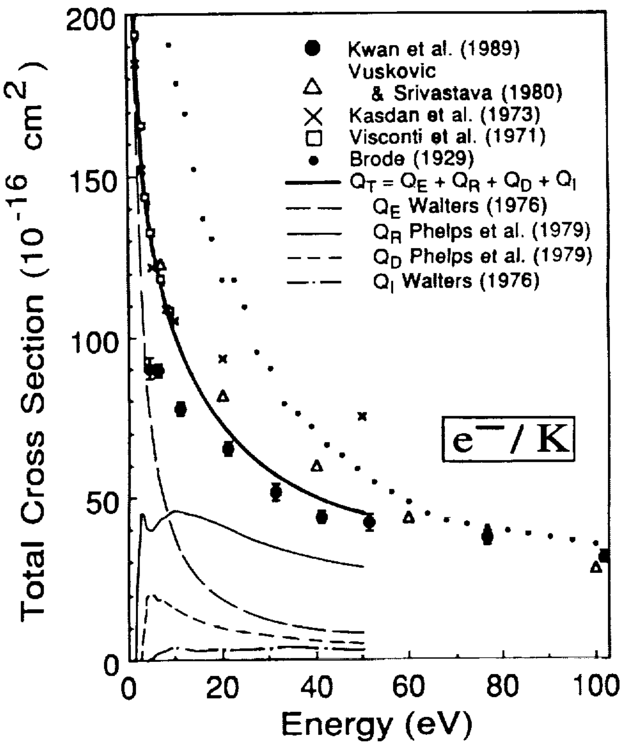

Fig. 6. Electron-K cross sections.

values are also in quite good agreement with the corresponding Walters-Phelps Q_T curve, averaging only about 10% lower from 20 to 50 eV. Of the prior measurements, the indirect determinations of Srivastava and Vuskovic[15] for Na, and of Vuskovic and Srivastava[19] for K, (who used their own crossed-beam measurements of differential cross sections for elastic scattering and for a number of different transitions from the ground state, and ionization cross sections measured by others) are in the closest overall agreement with the present corresponding measurements. As the energy is reduced below 10 to 20 eV, there is a tendency for our measured electron-Na and -K Q_T's to fall somewhat further below the corresponding curve of Msezane (for Na) and the Walters-Phelps curves. We feel that the explanation for this trend in Na and K may be as follows. The bias on the retarding element shown in Fig. 4 is always set within 1.25 V of the "cut-off" retarding voltage for the projectiles, and since the Na and K excitation thresholds are 2.10 eV and 1.61 eV respectively, there should be 100% discrimination against all inelastically scattered projectiles. In the vicinity of 20 eV for Na and K, the Walters-Phelps results in Figs. 5 and 6 show that the elastic scattering cross section (Q_E) is about 20% of Q_T for Na and about 25% of Q_T for K, and becomes an even smaller fraction of Q_T as the electron energy increases toward 50 eV. As the electron energy is reduced below 10 eV on the other hand, Q_E rapidly becomes a progressively larger fraction of Q_T, and at 5 eV, Q_E accounts for more than 50% of Q_T for both Na and K. In addition, the angular discrimination of our apparatus[9,10] against elastically scattered projectiles becomes poorer as the projectile energy decreases. For instance, the angular discrimination for electrons is estimated to be about 13° near 5 eV, 9° near 10 eV, 7° near 20 eV, and is about 5° or less from 30 eV to 100 eV. (The angular discrimination for elastically scattered positrons is somewhat poorer than that for electrons, but behaves in a similar way, being about 13° near 10 eV, 11° near 20 eV, 9° near 30 eV, and continuing to improve with increasing energy, reaching about 5° from 75 to 100 eV.) Our estimates of errors introduced into the electron-Na and -K Q_T's due to an inability to discriminate against projectiles elastically scattered through small angles in the forward direction suggest that as the electron energy is reduced below 10 to 20 eV, the increasing ratio of Q_E to Q_T, and the poorer angular discrimination may account for our measured Q_T's falling further below Msezane's results[22] and the Walters-Phelps curves. At 20 eV and above on the other hand, we estimate that the amount by which our measured Q_T's would be low due to our inability to discriminate against projectiles elastically scattered through small angles in the forward direction, should be of the order of 10% or less for electron-Na and -K collisions. Taking into consideration the uncertainty in our determination of the number density of atoms in our oven (±20%), and the potential errors in our measured Q_T's associated with the angular discrimination of our measurements, the closeness (and the consistency) of the close-coupling electron-Na Q_T results of Msezane[22] and the Walters-Phelps electron-Na and -K Q_T curves to our own corresponding measured values gives us some confidence that our experimental technique and apparatus for measuring electron-alkali atom Q_T's is basically sound. Since the same apparatus and technique is used for the positron measurements, we feel that they should not be greatly in error.

Positrons

The present measured positron-Na, -K (Kwan et al.[10]) and -Rb (preliminary) Q_T's are shown in Figs. 7-10 along with prior theoretical results.[23-33] Two separate Figures (Figs. 7 and 8) have been used for Na because of the abundance of theoretical results for this system. Ward et al.[25,32] have performed five-state close-coupling calculations of Q_T for positron-Na and

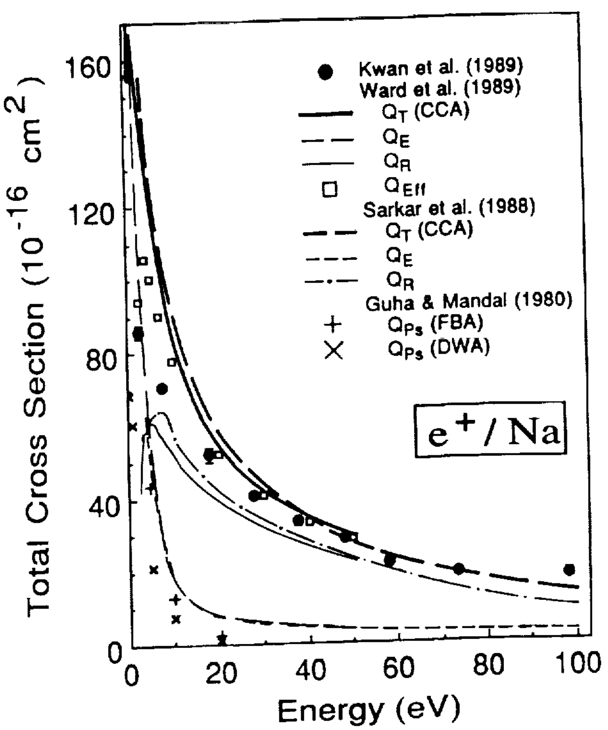

Fig. 7. Positron-Na cross sections.

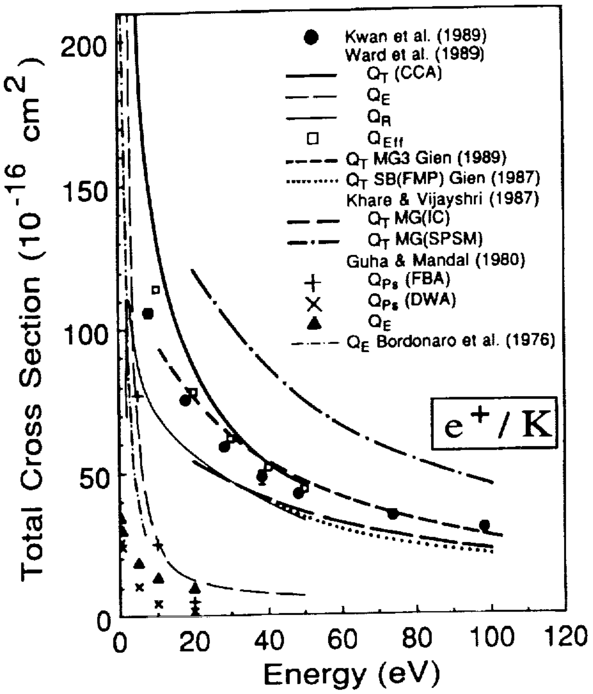

Fig. 9. Positron-K cross sections.

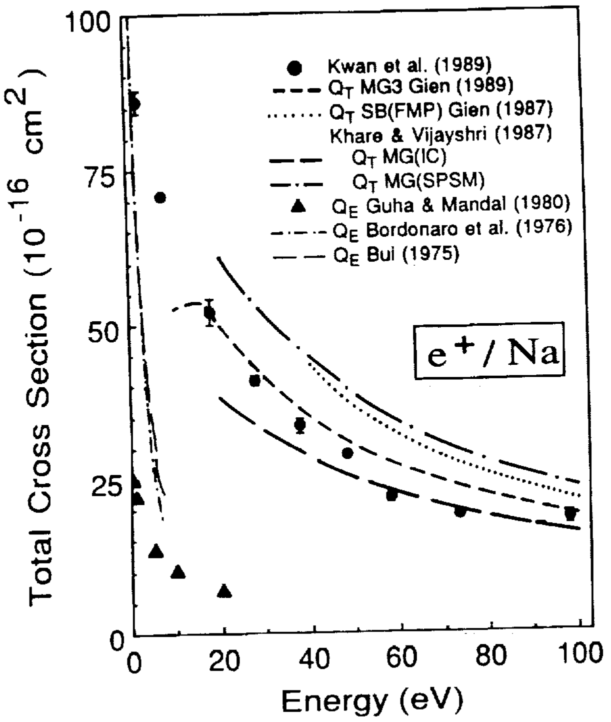

Fig. 8. Positron-Na cross sections.

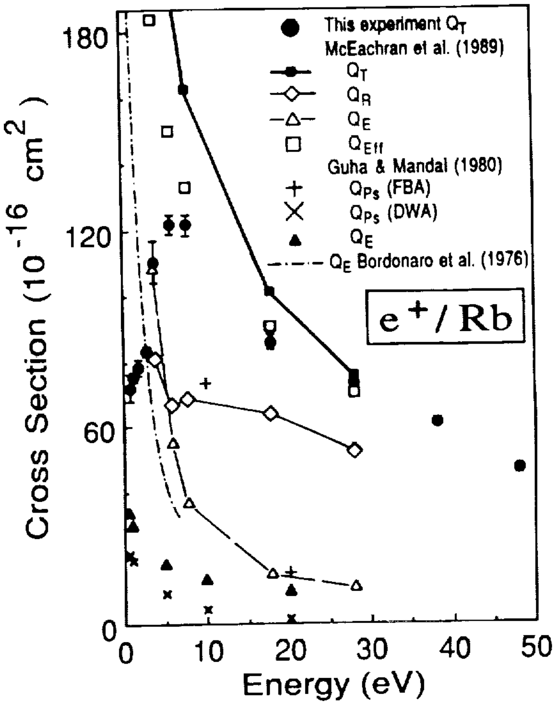

Fig. 10. Positron-Rb cross sections. The present Q_T measurements are preliminary values.

-K collisions that include the cross sections for elastic scattering, resonance excitation, and a few other discrete excitations (3s-4s, 3d, 4p for Na and 4s-5s, 3d, 5p for K) but do not include the cross sections for Ps formation and for ionization which are both expected to be relatively small[20,23] above 10 eV. McEachran et al.[33] have extended such Q_T calculations to Rb where they include the cross sections for elastic scattering, resonance excitation (5s-5p), and other discrete excitations (5s-4d, 6s, 6p) and do not include the cross sections for Ps formation and for ionization. In addition, Ward et al.[25,32] (for Na and K) and McEachran et al.[33] (for Rb) have used our estimates of our angular discrimination along with their differential elastic cross section results to calculate effective cross sections, Q_{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 our inability to discriminate against projectiles elastically scattered through small angles in the forward direction. Our measured Q_T's are in reasonable agreement with their corresponding Q_T calculations for Na (Fig. 7) and K (Fig. 9) and are even closer to their Q_{Eff} values (within 10% over most of the energy range of overlap). For Rb (Fig. 10), our measured Q_T's are in good agreement with the theoretical Q_{Eff} values of McEachran et al.[33] for all energies of overlap above about 6 eV. However, as the positron energy is reduced below 4 eV, our measured Q_T values decrease sharply, whereas the theoretical Q_{Eff} values of McEachran et al. continue rising, and this gives rise to a significant discrepancy at the lowest energies of overlap. Aside from this puzzling discrepancy at the lowest energies in the positron-Rb case, there is good overall agreement between the close-coupling approximation Q_{Eff} results of Ward et al.[25,32] for positron-Na, -K and of McEachran et al.[33] for positron-Rb for most of the energy range of overlap. The positron-Na Q_T results of Ward et al.[25] are also quite close to the earlier four-state close-coupling approximation Q_T results of Sarkar et al.[24] (Fig. 7) which include their cross sections for elastic scattering, resonance excitation, 3s-3d and -4p excitations, and the Ps formation cross sections calculated by Guha and Mandal,[23] and first Born approximation values of ionization cross sections obtained by Walters[20]. The positron-Na and -K modified Glauber approximation ("MG3") Q_T results (Figs. 8 and 9) of Gien[30,31] are in reasonable agreement with the present results.

Positron and Electron Comparisons

In Figs. 11-13 our direct comparison measurements between positron- and electron-Na, -K, and -Rb Q_T's are shown along with selected experimental[13,16-18] and theoretical[20,25,32] results. It should be noted that even though, as mentioned earlier, a major potential source of error in our absolute Q_T determinations is associated with the determination of the number density of atoms in the scattering cell, our direct positron-electron comparison measurements should still be meaningful because essentially the same oven temperatures are used for each projectile for a given alkali atom. We find that Na, K, and Rb each exhibit remarkably similar Q_T's for positron and electron collisions over the entire energy range that has been studied. (The only indication of a substantial difference between the positron and electron Q_T's for these atoms so far is at the lowest energies studied for Rb, where the measured positron Q_T decreases abruptly as the positron energy is reduced below 4 eV.) We also find that our corresponding positron and electron Q_T's for Na, K, and Rb merge within the uncertainties of the measurements in the vicinity of 40 eV and remain essentially merged up to the highest energies studied thus far. In sharp contrast to the case for positron- and electron-room temperature gas Q_T's, the positron-Na,

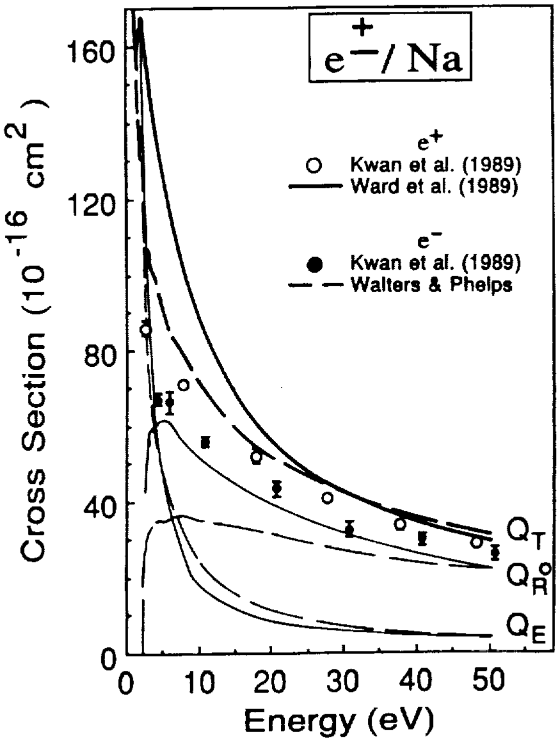

Fig. 11. Comparisons of positron- and electron-Na cross sections.

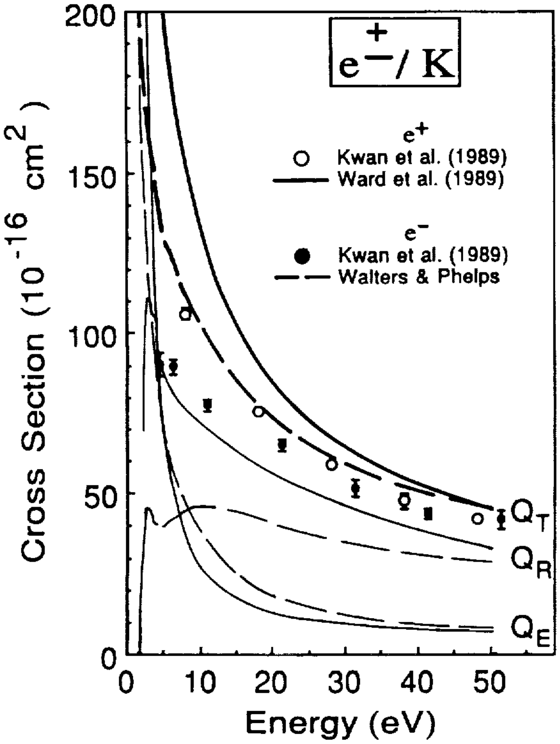

Fig. 12. Comparisons of positron- and electron-K cross sections.

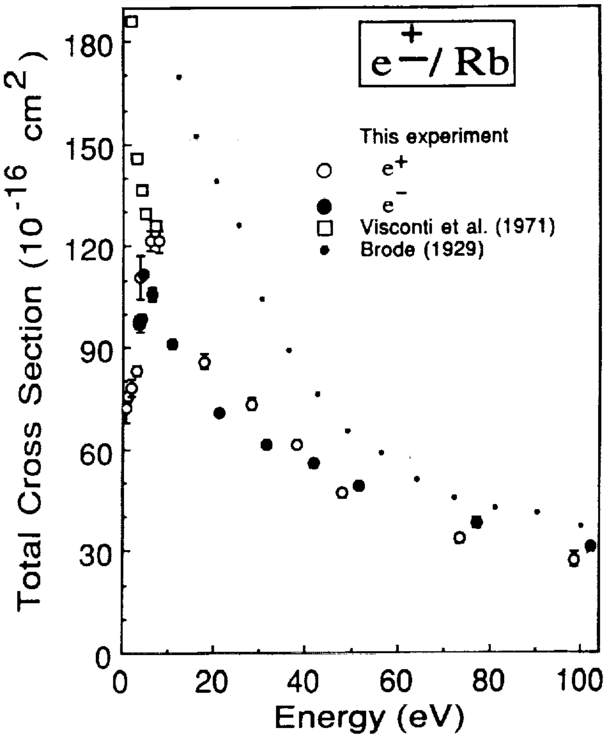

Fig. 13. Comparison of positron- and electron-Rb total cross sections. The present measurements are preliminary values.

-K, and -Rb Q_T's become increasingly higher than the corresponding Q_T's for electrons as the projectile energy is reduced from 40 eV down to the lowest energies studied in each case with the exception of the lowest energies for Rb shown in Fig. 13 (preliminary results).

It is interesting that when the Walters-Phelps electron-Na and -K Q_T curves are compared with the corresponding positron-Na and -K Q_T results obtained by Ward et al.[25,32] as shown in Figs. 11 and 12 respectively, mergings, or at least near-mergings of the positron and electron Q_T's are observed to occur in the vicinity of 30 to 50 eV, and as the projectile energy is reduced below this energy range, the positron Q_T's are observed to become increasingly larger than the corresponding electron values for each of these atoms. The close-coupling electron-Na Q_T results of Msezane[22] are consistent with this picture since they are in good agreement with the Walters-Phelps curves shown in Fig. 11. Thus, the comparisons between the Walters-Phelps electron-Na, and -K Q_T curves (and the Msezane[22] curve for Na) and the close-coupling results of Ward et al.[25,32] for positrons colliding with Na and K tend to support our observations of a merging (or near-merging) of the positron and electron Q_T's near the relatively low energy of 40 to 50 eV, and also support our observations that the positron Q_T's are higher than the corresponding electron values below 40 eV (at least down to the lowest energies studied thus far). If these observations are correct, it is of interest to consider why the comparisons between positron and electron scattering from the alkali atoms indicate a dominance of the positron- over the electron-Q_T's at low energies whereas for the room-temperature gases, the situation is for the most part, reversed. Why do the room-temperature gases (illustrated by Figs. 1-3) all seem to fit, in general, the simple interaction model referred to in the Introduction which implies that the positron cross sections at low energies would be expected to be lower than the corresponding electron cross sections? That prediction was based upon the tendency toward cancellation of the static and polarization interactions in positron scattering, in contrast to the addition of these interactions in the electron case. Why do the alkali atoms appear to be showing the opposite behavior?

Perhaps the simple argument referred to in the Introduction concerning the relative roles of the static and polarization interactions is applicable to the total scattering cross section if the dominant contribution to it is elastic scattering for both positrons and electrons. However, perhaps when inelastic processes become dominant for either positrons or electrons (or both), this argument in its simple form no longer applies to a comparison of their total scattering cross sections. Theoretical investigations by Walters[20,34] of electron-alkali atom scattering indicate that with increasing energy beyond the first excitation thresholds (which are 2.10 eV or less for the alkali atoms) there is a change-over from a situation where polarization effects are dominant to one in which flux loss[34] becomes dominant. Figs. 11 and 12 indicate that the resonance excitation becomes the dominant contribution to positron and to electron scattering from Na and K near the relatively low energy of 10 eV. It can also be seen from Figs. 11 and 12 that while the elastic cross section (Q_E) is predicted to be somewhat larger for electrons than for positrons above 10 eV, it makes a relatively small contribution to Q_T as the projectile energy is increased above this energy. On the other hand, Figs. 11 and 12 indicate that the resonance excitation cross section (Q_R) is significantly larger for the positron than for the electron at low energies and is the main contribution to Q_T above 10 eV. We have chosen not to show a comparison of the sum of the other discrete excitations (Q_D) for positrons and electrons in Figs. 11 and 12 because Ward et al.[25,32] have only included cross sections for three such excitations for Na(3s-4s, 3d, 4p) and K(4s-5s, 3d, 5p) whereas the Q_D's used for the Walters-Phelps Q_T electron curves in Figs. 11 and 12 include 14 such excitations. However it is interesting to note that for the 3 corresponding excitation processes in Na and K which have been calculated for positrons[25,32] and measured for electrons,[16,18] the positron cross sections tend to be significantly larger than the corresponding electron cross sections at low energies, similar to the situation shown for the resonance excitation in Figs. 11 and 12. The positron- and electron-Na and -K ionization cross sections are expected to be small, and if the positron- and electron-He ionization cross section comparisons[35] can serve as a guide, one might expect Q_I for the positron-Na and K collisions to be larger than the corresponding electron values. In addition to this, although the theoretical predictions of Q_{Ps} by Guha and Mandal[23] shown in Figs. 7 and 9 indicate that Q_{Ps} makes a relatively small contribution to Q_T for energies above 10 eV, this is still an additional inelastic contribution to Q_T which does not have a counterpart in electron-alkali atom collisions, and it appears (as seen in Figs. 7 and 9) to be playing an increasingly important role in Q_T as the positron energy decreases below 10 eV. The above information suggests that the positron-alkali atom Q_T's may rise above the corresponding electron values as the projectile energy is reduced below 40 eV mainly due to the relatively large contributions to Q_T by inelastic processes (especially excitation) which are predicted to have larger cross sections for positrons than for electrons at these low energies. Although the elastic cross section for alkali atoms is predicted to be slightly larger for electrons than for positrons at low energies (between 5 and 50 eV), it appears that Q_E contributes too little to Q_T to make Q_T larger for electrons than it is for positrons, as is the case for the room-temperature gases in this energy range.

It should be noted that although our observations indicate a merging of the positron- and electron-Na and -K Q_T's at the relatively low energy of about 40 eV, and a dominance of the positron Q_T's over the corresponding electron Q_T's at lower energies, and although this picture is supported by the comparisons of the Walters-Phelps Q_T curves (and the Msezane[22] curve) for electrons with the Ward et al.[25,32] close-coupling approximation results for positrons, modified Glauber (MG3) calculations by Gien[30,31] for positron- and electron-Na and -K collisions, shown in Figs. 14 and 15 predict a different behavior for the positron-electron comparisons. According to Gien's calculations,[30,31] the positron- and electron-Na and K Q_T's do not merge even up to energies as high as 1000 eV, and furthermore, the electron Q_T's are larger than the positron Q_T's over

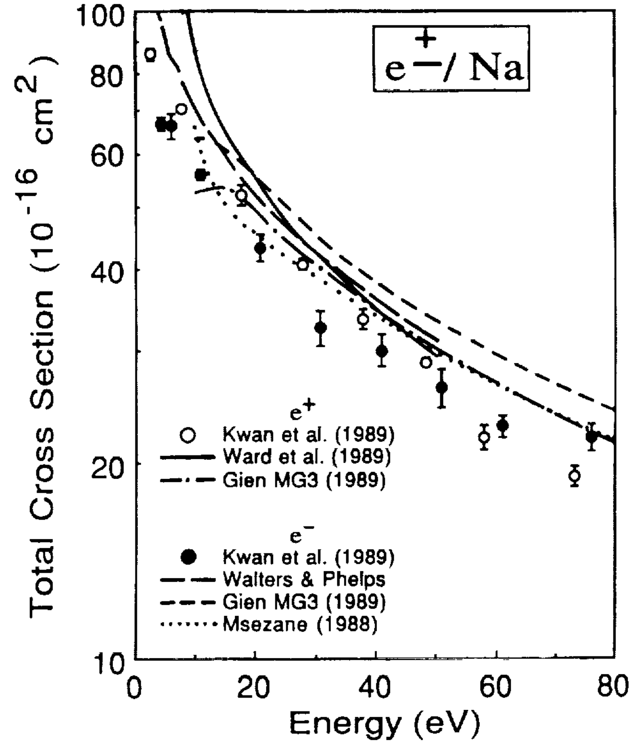

Fig. 14. Comparisons of positron- and electron-Na total cross sections.

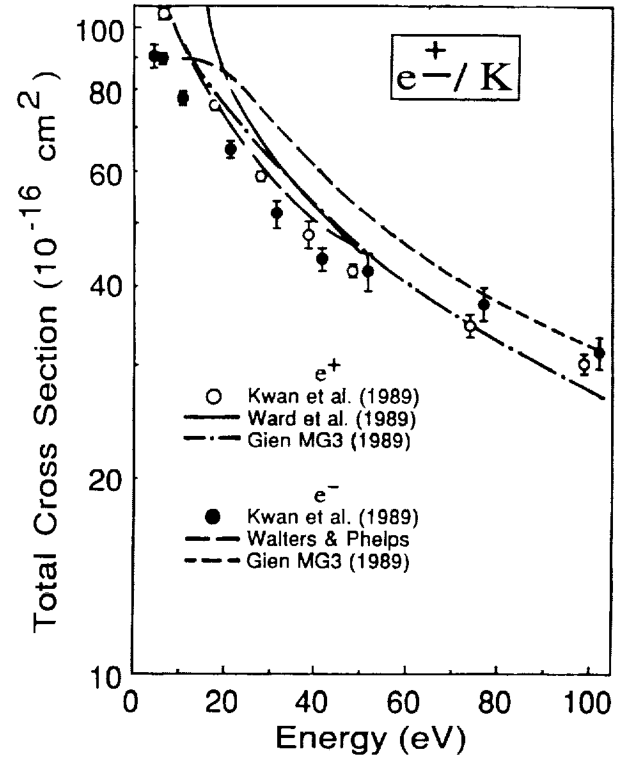

Fig. 15. Comparisons of positron- and electron-K total cross sections.

essentially his entire energy range. It should be noted however, that whereas Gien's positron-Na and -K Q_T's are in quite good agreement with those of Ward et al.[25,32] (and Sarkar et al.[24] for Na), his electron Q_T's are somewhat higher than those associated with the Walters-Phelps curves for Na and K and the results of Msezane[22] for Na. It is also of possible interest that Gien has not included the effects of exchange in his electron calculations.

FUTURE DIRECTIONS

Based upon our direct comparison measurements of Q_T's for positron- and electron-alkali atom collisions up to the present time, we feel that it would be of interest to address the following points in future research. (1) Is there actually a merging (or near-merging) of Q_T's for positron- and electron-Na, K, and Rb collisions in the vicinity of 40 eV, and are the positron Q_T's larger than the corresponding electron values below that energy as our observations (preliminary for Rb) indicate? As mentioned above, our observations tend to be supported by a comparison (Figs. 11 and 12) of the Walters-Phelps electron-Na and -K Q_T curves (and electron-Na Q_T's obtained by Msezane[22] using a close-coupling approximation) with the corresponding positron values obtained by Ward et al.[25,32] using a close-coupling approximation. However the modified Glauber approximation (MG3) results of Gien[22] for Na and K suggest a significantly different behavior for the positron and electron comparisons (Figs. 14 and 15). Up to the present time, theorists who have done close-coupling approximation calculations of Q_T for positron-alkali atom collisions have not done them for electron-alkali atom collisions and vice versa. In order to conduct a more stringent theoretical test of the validity of our observed low energy mergings and the reversal of the "normal" arrangement of positron and electron Q_T's at low energies, it could be helpful if theorists who have done a close-coupling approximation calculation for one of these projectiles colliding with an alkali atom would do a comparable close-coupling approximation calculation for the other projectile. In a certain sense, this could be considered to be the theoretical counterpart to our having measured Q_T's for the two projectiles in the identical apparatus using the same experimental technique as opposed to comparing our measured positron-alkali atom Q_T's to another experimental group's measured electron-alkali atom Q_T's. (2) Although the positron and electron elastic scattering cross sections predicted by Ward et al.[25,32] and Walters,[20] respectively, for Na and K collisions are in the usual order from about 5 to 50 eV (the electron Q_E's being higher than the corresponding positron values), it is curious that the the positron and electron Q_E's appear to cross each other (Figs. 11 and 12) in the vicinity of 5 eV, so that as the projectile energy is reduced below 5 eV, it appears that the positron Q_E's are larger than the corresponding electron values. Is this representative of the actual situation, or is it possible that the Ward et al. calculation of Q_E at these low energies is too large due to the neglect of Ps formation, which may be playing a more important role as the positron energy decreases. (3) If our observed low-energy mergings of positron- and electron-alkali atom Q_T's are valid, this may provide additional evidence that mergings of positron- and electron-atom Q_T's can occur at unexpectedly low energies. In this connection it should be noted that the first observation[1] of such a low energy merging was for He where the positron and electron Q_T's were found to merge (to within 2%) near 200 eV. The distorted wave second Born approximation (DWA) calculations of Dewangan and Walters[36] predict that a merging of the positron and electron-He Q_T's (to within 2%) does not occur until 2000 eV. These calculations also indicate that at 200 eV, where Kauppila et al.[1] have observed the merging of positron and electron Q_T's, the electron total elastic cross section is about 2.4 times as large as the corresponding positron cross section. Thus at the energy (about 200 eV) where the positron and electron Q_T's have been observed[1] to merge, the partial contributions (such as Q_E) to Q_T are apparently behaving much differently for positrons than for electrons. A comparison[37] of a calculation of Q_T for 54.4-300 eV positron-atomic hydrogen collisions by Walters[37] (using a pseudostate close-coupling approximation that is supplemented by the second Born approximation) with similar calculations for electrons by Van Wyngaarden and Walters[38] indicates a situation similar to that just described for helium in the sense that the Q_T's for these projectiles remain very nearly merged down to the lowest energies studied (54.4 eV) whereas the cross section for elastic scattering is about 3 times as large for electrons as for positrons at 54.4 eV, while the cross sections for the 1s-2s and 1s-2p excitations are larger for positrons than for electrons. Our present observations[10] indicate that the alkali atom Q_T's may be merging at energies considerably lower than the asymptotic energies at which the first Born approximation is valid,[39] but based upon the information in Figs. 11 and 12, the partial elastic and inelastic contributions to Q_T may be at least close to separately merged where the Q_T's appear to be merging, in possible contrast to the He and atomic hydrogen situations. In relation to the question of mergings of positron and electron cross sections at unexpectedly low energies, it is of interest that a theoretical analysis by Dewangan[40] related to higher order Born amplitudes calculated in the closure approximation has been shown to imply[34,41] that if electron exchange can be ignored in the electron-scattering case, and if the closure approximation is valid, then a merging (or near-merging) of positron- and electron-atom Q_T's can occur at energies considerably lower than the asymptotic energies at which the first Born approximation is valid. <u>(4)</u> In light of the information (theoretical and experimental) that we have on positron and electron scattering comparisons up to the present time, it is interesting to consider the possibility that at low energies, in general, elastic scattering cross sections for electron-atom collisions may tend to be larger than those for positron-atom collisions (aside from complications like Ramsauer-Townsend effects), whereas inelastic scattering cross sections for positron-atom collisions may tend to be larger for positrons than they are for electrons. Perhaps the simple explanation given in the Introduction for why the electron Q_T's are larger than the corresponding positron values at low energy applies only to elastic scattering. Could there be a correspondingly simple explanation for why inelastic scattering cross sections may tend to be larger for positrons than for electrons in general (if this is indeed the case)? <u>(5)</u> In relation to item (4), it would be useful to have direct positron-electron comparison measurements (using the same apparatus and experimental technique) of resonance excitation cross sections for the alkali atoms to see if it is the case (as indicated by the comparisons shown in Figs. 11 and 12) that the resonance excitation cross section is so much larger for positrons than it is for electrons at low energies. This would be of particular interest in view of the indications shown in Figs. 11 and 12 that the resonance excitation becomes the main contribution to Q_T at energies above 10 eV or so. <u>(6)</u> What is the contribution of Ps formation to Q_T in positron-alkali atom scattering? The theoretical calculations of Q_{Ps} shown in Figs. 7,9, and 10 suggest that it plays a relatively unimportant role above 10 eV, but is increasing as the positron energy is reduced toward zero. As was mentioned above, it is possible to form Ps in collisions with alkali atoms at arbitrarily small positron energies. Does Q_{Ps} increase without limit as the positron energy approaches zero? It would be useful to have direct measurements of Q_{Ps} for positron-alkali atom collisions at low energies to investigate questions such as this.

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REFERENCES

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1. W.E. Kauppila, T.S. Stein, J.H. Smart, M.S. Dababneh, Y.K. Ho, J.P. Downing, and V. Pol, Phys. Rev. A 24, 725 (1981).
2. T.S. Stein, W.E. Kauppila, V. Pol, J.H. Smart, and G. Jesion, Phys. Rev. A 17, 1600 (1978).
3. M.S. Dababneh, Y.-F. Hsieh, W.E. Kauppila, V. Pol, and T.S. Stein, Phys. Rev. A 26, 1252 (1982).
4. M.S. Dababneh, W.E. Kauppila, J.P. Downing, F. Laperriere, V. Pol., J.H. Smart, and T.S. Stein, Phys. Rev. A 22, 1872 (1980).
5. K.R. Hoffman, M.S. Dababneh, Y.-F. Hsieh, W.E. Kauppila, V. Pol, J.H. Smart, and T.S. Stein, Phys. Rev. A 25, 1393 (1982).
6. O. Sueoka, S. Mori, and Y. Katayama, J. Phys. B 19, L373 (1986).
7. B.H. Bransden and M.R.C. McDowell, Phys. Rep. 46, 249 (1978).
8. T.M. Miller and B. Bederson, Adv. At. Mol. Phys. 13, 1 (1977).
9. T.S. Stein, R.D. Gomez, Y.-F. Hsieh, W.E. Kauppila, C.K. Kwan, and Y.J. Wan, Phys. Rev. Lett. 55, 488 (1985).
10. C.K. Kwan, W.E. Kauppila, R.A. Lukaszew, S.P. Parikh, T.S. Stein, Y.J. Wan, S. Zhou, and M.S. Dababneh, to be published.
11. R.E. Honig and D.A. Kramer, RCA Rev. 30, 285 (1969).
12. T.S. Stein, M.S. Dababneh, W.E. Kauppila, C.K. Kwan, and Y.J. Wan, in "Atomic Physics with Positrons", edited by J.W. Humberston and E.A.G. Armour, NATO ASI Series B, Vol. 169, pp. 251-263 (Plenum, 1987).
13. R.B. Brode, Phys. Rev. 34, 673 (1929).
14. A. Kasdan, T.M. Miller, and B. Bederson, Phys. Rev. A 8, 1562 (1973).
15. S.K. Srivastava and L. Vuskovic, J. Phys. B 13, 2633 (1980).
16. J.O. Phelps and C.C. Lin, Phys. Rev. A 24, 1299 (1981).
17. P.J. Visconti, J.A. Slevin, and K. Rubin, Phys. Rev. A 3, 1310 (1971).
18. J.O. Phelps, J.E. Solomon, D.F. Korff, C.C. Lin, and E.T.P. Lee, Phys. Rev. A 20, 1418 (1979).
19. L. Vuskovic and S.K. Srivastava, J. Phys. B 13, 4849 (1980).
20. H.R.J. Walters, J. Phys. B 9, 227 (1976).
21. J. Mitroy, I.E. McCarthy, and A.T. Stelbovics, J. Phys. B 20, 4827 (1987).
22. A.Z. Msezane, Phys. Rev. A 37, 1787 (1988).
23. S. Guha and P. Mandal, J. Phys. B 13, 1919 (1980).
24. K.P. Sarkar, M. Basu, and A.S. Ghosh, J. Phys. B 21, 1649 (1988).
25. S.J. Ward, M. Horbatsch, R.P. McEachran, and A.D. Stauffer, J. Phys. B 22, 1845 (1989).
26. T.D. Bui, J. Phys. B 8, L153 (1975).
27. G. Bordonaro, G. Ferrante, M. Zarcone, and P. Cavaliere, Nuovo Cimento Soc. Ital. Fis. 35 B, 349 (1976).
28. S.P. Khare and Vijayshri, Indian J. Phys. 61B, 404 (1987).
29. T.T. Gien, Phys. Rev. A 35, 2026 (1987).
30. T.T. Gien, J. Phys. B 22, L463 (1989).
31. T.T. Gien, J. Phys. B 22, L129 (1989).
32. S.J. Ward, M. Horbatsch, R.P. McEachran, and A.D. Stauffer, J. Phys. B 21, L611 (1988).
33. R.P. McEachran, M. Horbatsch, A.D. Stauffer, and S.J. Ward, to appear in Proceedings of the "Workshop on

Annihilation in Gases and Galaxies", to be published as a NASA Conference Publication (NASA Goddard Space Flight Center, July, 1989).

34. H.R.J. Walters, Physics Reports 116, 1 (1984).
35. D. Fromme, G. Kruse, W. Raith, and G. Sinapius, Phys. Rev. Lett. 57, 3031 (1986).
36. D.P. Dewangan and H.R.J. Walters, J. Phys. B 10, 637 (1977).
37. H.R.J. Walters, J. Phys. B 21, 1893 (1988).
38. W.L. van Wyngaarden and H.R.J. Walters, J. Phys. B 19, 929 (1986).
39. H.R.J. Walters, private communication.
40. D. P. Dewangan, J. Phys. B 13, L595 (1980).
41. F.W. Byron, Jr, C.J. Joachain, and R.M. Potvliege, J. Phys. B 15, 3915 (1982).