Measurements of positronium-formation cross sections for positrons scattered by Rb atoms

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Measurements of positronium (Ps) -formation cross sections (upper and lower limits) for positrons (1–17 eV) scattered by Rb atoms are reported. These measurements, along with recent measurements and calculations of total cross sections, provide evidence that coupling effects between Ps formation and other scattering channels may be very important for energies below 10 eV for Rb.

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We have been investigating the scattering of positrons by alkali-metal atoms, with a focus on measurements of total and positronium (Ps)-formation cross sections. An interesting feature of the alkali-metal atoms is that the Ps-formation scattering channel is open for all positron (e^+) impact energies because the binding energy (6.8 eV) of Ps in its ground state is larger than the ionization threshold energies of any of the alkali-metal atoms. Positron-alkali-metal atom collisions present an interesting challenge for theorists, in that there is a minimum of two open scattering channels (elastic scattering and Ps formation) for all positron impact energies.

Our group has previously measured total cross sections (Q_T's) for e^+'s scattered by Na [1,2], K [1,3], and Rb [3], and Ps-formation cross sections ($Q_{\rm Ps}$'s) for e^+'s scattered by Na and K [4]. These measurements have revealed an interesting pattern of differences and similarities between the three collision systems (e^+-Na, K, and Rb). For e^+-Na scattering, our Q_T's [1,2] and $Q_{\rm Ps}$'s [4] each rise steadily as the positron energy is decreased below 10 eV. In contrast to this, our Q_T's and $Q_{\rm Ps}$'s for K [1,3,4] and Q_T's for Rb [3] reveal a peak in the vicinity of about 6 eV, and decrease substantially as the e^+ energy is reduced below 6 eV. Our Q_T and $Q_{\rm Ps}$ measurements for Na and K [1–4] along with recent theoretical work by Hewitt, Noble, and Bransden [5] on these atoms suggest that coupling effects between Ps formation and elastic and excitation scattering channels are very important in e^+–alkali-metal atom scattering at low energies, and calculations which do not take such coupling effects into account can yield profoundly misleading results. Our measurements of $Q_{\rm Ps}$'s reported in this paper were performed in order to investigate the role of Ps formation in e^+-Rb collisions, and to try to shed additional light on the interesting pattern of differences and similarities which appears to be emerging in the observed Q_T's and $Q_{\rm Ps}$'s for the alkali-metal atoms.

In this paper we report $Q_{\rm Ps}$ measurements for 1–17-eV e^+'s scattered by Rb atoms. The apparatus and experimental approach are basically as described earlier [4], so only a brief description is provided below. Our experimental approach involves setting lower and upper limits on $Q_{\rm Ps}$. The lower limits (LL's) are obtained [4] by detecting (with photomultiplier tubes and attached NaI scintillators on opposite sides of the scattering cell) the 511-keV annihilation gamma rays in coincidence produced by the decay of para-Ps formed by e^+-Rb collisions in the scattering cell and by the interaction of ortho-Ps (also formed in the cell) with the walls of the cell. An axial magnetic field (90 G) prevents scattered e^+'s from reaching and annihilating on the cell walls and contributing to the lower limit signal. The contribution to the coincidence signal due to direct annihilation of e^+'s in the target vapor is known to be negligible [6] at the e^+ energies used in the present investigation. Since these coincidence measurements should account for all of the para-Ps formation and at least part of the ortho-Ps formation (through the interaction of ortho-Ps with the cell walls), they result in lower limits on $Q_{\rm Ps}$. The upper limits (UL's) are obtained by performing a beam transmission measurement similar to that used to determine Q_T's in our experiments [1], but with the angular discrimination of the apparatus deliberately made as poor as possible [4]. The idea here is that if the angular discrimination is made sufficiently poor that all scattered e^+'s pass through the exit aperture of the scattering cell and are detected except those which have formed Ps or have scattered into the backward hemisphere, then the resulting cross sections will include only contributions from Ps formation and from backward-scattered e^+'s, and thus will be upper limits on $Q_{\rm Ps}$. In the present measurements we have introduced a cylindrical reflector element into our system, located just before the scattering cell, and biased to reflect backward scattered e^+'s back through the cell. This reflector serves to produce a better (i.e., lower) upper limit (UL-R) on $Q_{\rm Ps}$ because some fraction of the e^+'s scattered into the backward hemisphere and reflected by this element will reach the detector, and in this way will not contribute to UL-R.

The present measured e^+-Rb $Q_{\rm Ps}$ upper and lower limits are shown in Fig. 1, along with distorted-wave (DWA) and first Born (FBA) approximation calculations of Guha and Mandal [7] and recent coupled-state calculations of Kernoghan, McAlinden, and Walters [8]. Our measured UL and LL values are within 20% of each other above 6 eV, which would indicate that if there are not serious systematic errors in our measurements, then the true value of $Q_{\rm Ps}$ would be rather closely bracketed by these limits above that energy. Such proximity of the UL and LL limits can occur if (1) there is not appreciable backward scattering (i.e., the smaller the amount of backward scattering, the closer the UL value will be to the true value of $Q_{\rm Ps}$), and (2) a major part of the ortho-Ps, which accounts for three-fourths of all the Ps formed in the cell, interacts with the cell walls, and gives rise to the emission of 511-keV annihilation gamma rays in coincidence i.e., the more ortho-Ps that gives rise to a two-gamma-ray coincidence signal, the closer the LL value will

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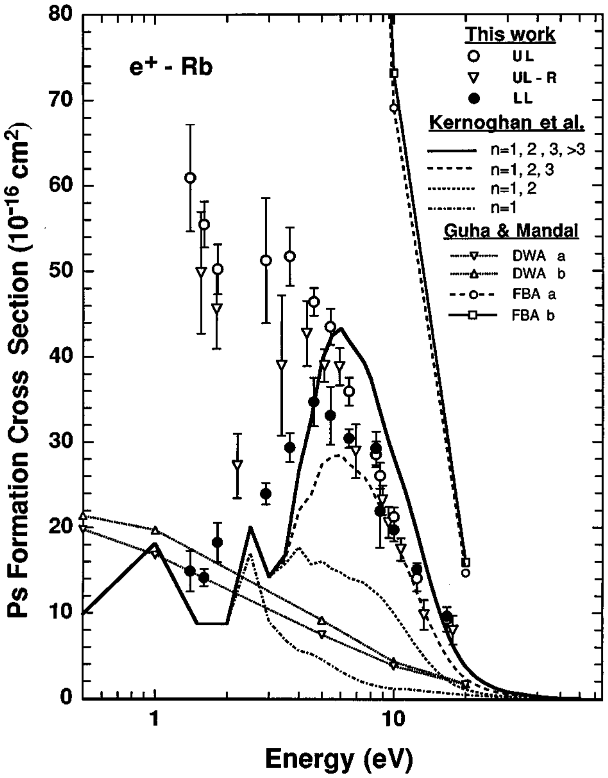

FIG. 1. Positronium formation cross sections for positrons scattered by Rb atoms. Statistical uncertainties are indicated by error bars except where they are encompassed by the size of the symbol.

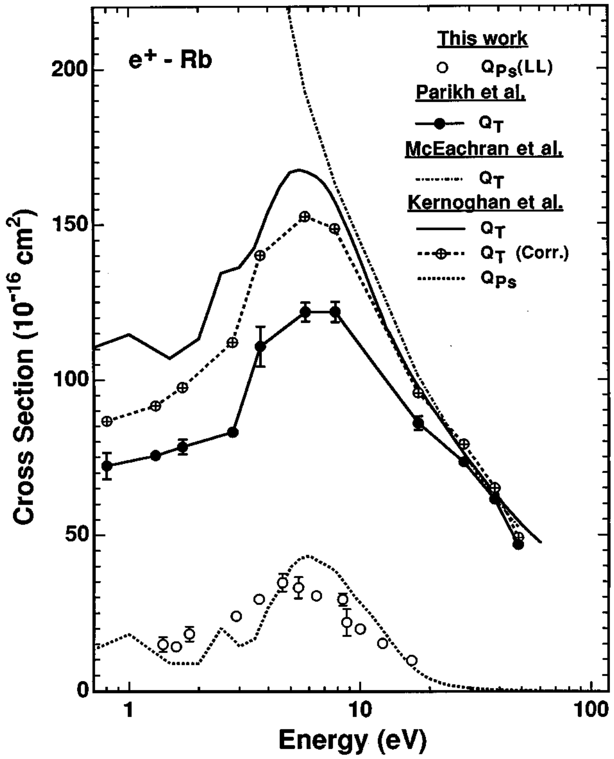

FIG. 2. Total and positronium formation cross sections for positrons scattered by Rb atoms.

be to the true value of Q_{Ps}. Below 6 eV our UL and LL values diverge significantly. In the case of Na, our group's measured Q_{Ps} UL and LL values [4] did not diverge appreciably down to the lowest energies, whereas, in the case of K, our measured UL and LL values [4] did diverge in a way which was very similar to the present corresponding measurements for Rb. The proximity of the UL and LL values down to about 1 eV (within about 35% of each other down to the lowest energy) in the case of Na would suggest that the ability of ortho-Ps to produce two-gamma coincidences is not appreciably diminished as the e^+ energy is reduced to that level. This would imply that the divergence of the UL and LL values in the cases of K and Rb is most likely mainly due to the UL value becoming significantly larger than the true Q_{Ps} value due to increased backward scattering of e^+'s. Our measured UL-*R* values shown in Fig. 1 are consistent with this idea since all of the UL-*R* values are lower than the corresponding UL values, and they diverge appreciably from the LL values only below 2 eV. Above 2 eV, the UL-*R* and LL values are within 30% of each other. All of these considerations taken together suggest that our LL values may be relatively close to the true Q_{Ps} values which in any case are closely bracketed by our LL values and our UL-*R* values above 2 eV.

Comparing our Q_{Ps} results with the FBA and DWA results [obtained using the "prior" (a) and "post" (b) forms of the interaction potential] of Guha and Mandal [7] in Fig. 1 reveals significant disagreement in shape and absolute values at all energies except for the lowest energies of overlap in the case of the DWA calculations. Realizing that the DWA calculation considers only formation of Ps in the $n=1$ state, it is at least somewhat encouraging to see that the very limited agreement of the DWA results and our measurements occurs where such agreement may be expected, namely below the threshold (2.48 eV) for formation of Ps in the $n=2$ state.

The coupled-state Q_{Ps} calculations of Kernoghan, McAlinden, and Walters [8] in Fig. 1 (which include the formation of Ps in the $n=1$, 2, and 3 states and estimate it for states with $n>3$ using n^3 scaling assumptions, and include the elastic scattering channel and $5s$-$5p$, $6s$, $6p$, and $4d$ atomic excitation channels) show reasonable agreement in shape and in absolute values with our measured LL and UL-*R* (above 2 eV) Q_{Ps} values. Both the Q_{Ps} results in Ref. [8] and our measured LL and UL-*R* Q_{Ps} values reveal a peak in the vicinity of 5–6 eV. The results of Ref. [8] indicate that more than 75% of the Ps is formed in excited states above 4 eV, and that more than 90% of the calculated Q_{Ps} at 6 eV (the peak) is associated with Ps formation in excited states.

In Fig. 2, our group's recently measured e^+-Rb Q_T's [3] and the present measured Q_{Ps} LL values are shown along with the Q_T's and Q_{Ps}'s calculated by Kernoghan, McAlinden, and Walters [8] and the Q_T's calculated by McEachran, Horbatsch, and Stauffer [9]. We have chosen to show only our Q_{Ps} LL values in Fig. 2 because, for reasons provided above, we believe that these LL values could be fairly close to the true Q_{Ps} values. The Q_T's of Ref. [9] were obtained using a five-state close-coupling approximation (CCA) which includes elastic scattering, and the $5s$-$5p$, $4d$, $6s$, and $6p$ atomic excitations, but does not include Ps formation (or ionization). It is particularly interesting that the Q_T's measured by our group [3] reveal a peak in the vicinity of 6 eV, and a significant decrease below that energy, in sharp contrast to the CCA calculation by McEachran, Horbatsch, and

Stauffer [9], which shows steadily increasing Q_T's as the positron energy is reduced below 10 eV. The profound disagreement between the Q_T's measured by our group below 10 eV [3] and those calculated by McEachran, Horbatsch, and Stauffer is especially intriguing when one considers that the CCA calculation [9] referred to above does not include the Ps formation channel, and agrees quite well with the measured values above 10 eV; yet the calculated Q_T's become much *larger* than our measured values as the positron energy is reduced below 10 eV. At first glance, it may seem surprising that the lack of inclusion of an open channel in the Q_T CCA calculation could produce a result which is significantly *larger* than the result obtained when the channel is included. Yet this was shown to be the case by Hewitt, Noble, and Brandsen [5] for e^+-K scattering where reductions in their calculated contributions to Q_T by the elastic and excitation channels due to coupling effects between those channels and the Ps formation channel more than offset the added contribution to Q_T by the Ps formation channel itself at low energies. The result of the strong coupling between Ps formation and other scattering channels was thus that the Q_T obtained by Hewitt, Noble, and Brandsen with Ps formation (in the $n=1$ and 2 states) included was significantly lower than the Q_T obtained without including Ps formation. Similar coupling effects appear to be playing an important role in the e^+-Rb case at low energies, since the Q_T's calculated by Kernoghan, McAlinden, and Walters [8] which include Ps formation agree very well with the Q_T's of McEachran, Horbatsch, and Stauffer and measurements of our group [3] above 10 eV, but show a peak near 5 eV and a significant decrease below that energy, similar to that observed by our group. Kernoghan, McAlinden, and Walters have also used our estimates of angular discrimination in our Q_T measurements [3] and their differential elastic cross-section results [8] to correct our measurements for incomplete discrimination against positrons elastically scattered through small angles. The results of this correction [Q_T(Corr)] are shown in Fig. 2, and are in quite good agreement (within about 15%) with the Q_T's calculated by Kernoghan, McAlinden, and Walters.

In Fig. 3, e^+-Na, K, and Rb Q_T's measured earlier by our group [1–3] are shown along with the present measured e^+-Rb Q_{Ps} LL's and the e^+-Na and K Q_{Ps} LL's measured earlier by our group [4] in order to compare the situations for the three alkali metals which we have investigated so far. Again, only the Q_{Ps} LL values are shown for the reasons mentioned above. We find it intriguing that there are such striking similarities between the behavior of the e^+-K and Rb Q_T's and Q_{Ps}'s and such differences between these and the corresponding cross sections for Na. The e^+-K and Rb Q_T's and Q_{Ps}'s have peaks in the vicinity of 5–6 eV, whereas the e^+-Na Q_T's and Q_{Ps}'s do not have such peaks, but rather, simply continue rising as the e^+ energy is reduced below 10 eV. The Q_{Ps} calculations of Hewitt, Noble, and Brandsen [5] and Kernoghan, McAlinden, and Walters [8] both indicate that Ps formation in the ground state is the main contribution to Q_{Ps} below 6 eV in the case of Na, whereas Ps formation in excited states plays a considerably more important role in K and Rb and accounts for 80% or more of their respective maximum Q_{Ps} values in the major peak that occurs for each of those elements in the vicinity of 5–6 eV.

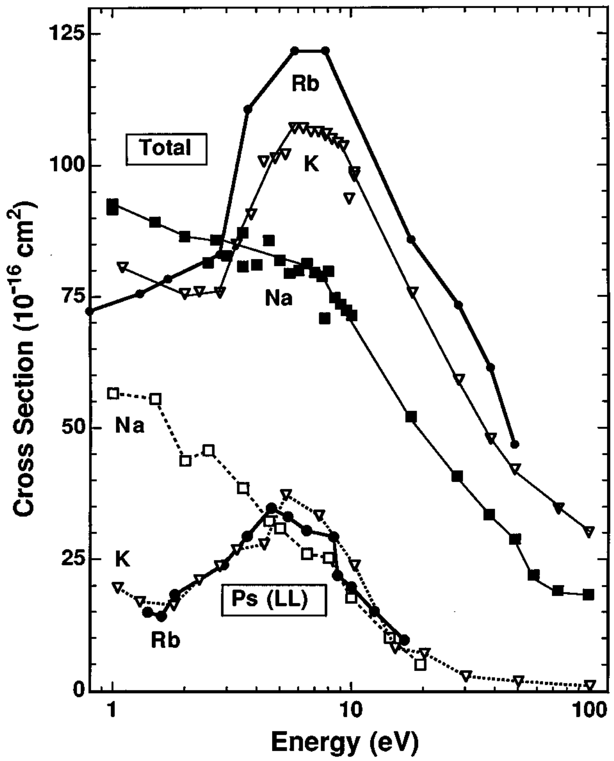

FIG. 3. Total and lower limit positronium formation cross sections for positrons scattered by Na, K, and Rb atoms.

In Table I we have listed the thresholds for Ps formation ($n=1$–4) and ionization for the alkali-metal atoms to see if these thresholds may provide any clues which could help explain the similarities and differences that appear to exist in the Q_{Ps}'s and Q_T's for Na, K, and Rb. The negative values for the $n=1$ "effective" Ps formation thresholds are the result of subtracting the binding energy of Ps in the $n=1$ state from the ionization threshold energies of the respective alkali-metal atoms. It is interesting to note that for K and Rb, the $n=1$ and 2 Ps formation thresholds are nearly "equidistant" from zero energy (i.e., nearly equally close to being "resonant"), whereas for Na, the $n=1$ Ps formation threshold is considerably "closer" (1.66 eV away) to zero energy than the $n=2$ threshold (3.44 eV away). This suggests that the relative proximities of the $n=1$ or 2 Ps formation thresholds to zero energy for the alkali-metal atoms, may be related to the relative importance of the roles of those states in the overall Ps formation process (although the number of available states for different n levels of Ps could also be playing a role in these considerations). This would be consistent with the findings of Hewitt, Noble, and Brandsen [5] and Kernoghan,

TABLE I. Thresholds (in eV) for Ps formation ($n=1$–4) and ionization for the alkali-metal atoms.

Atom	Ps ($n=1$)	Ps ($n=2$)	Ps ($n=3$)	Ps ($n=4$)	Ioniz.
Li	−1.41	3.69	4.64	4.97	5.39
Na	−1.66	3.44	4.38	4.71	5.14
K	−2.46	2.64	3.59	3.92	4.34
Rb	−2.63	2.48	3.42	3.75	4.18
Cs	−2.91	2.19	3.14	3.47	3.89

McAlinden, and Walters [8] that $n=1$ and 2 Ps formation play roughly equivalent roles in the total Ps formation process in the case of K and Rb, whereas $n=1$ Ps formation is dominant in the case of Na. If this basic idea is correct, then, from the information in Table I, one would expect that the behavior of Q_{Ps} for Li will be similar to that of Na but with perhaps an even greater dominance of formation of Ps in the $n=1$ state, while one would expect that the behavior of Q_{Ps} for Cs will be similar to that of K and Rb, but perhaps with an even more important role for the formation of Ps in excited states. Calculations of partial and total Q_{Ps} values by Kernoghan, McAlinden, and Walters [8,10–12] for the alkali-metal atoms have yielded results consistent with this pattern.

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