Evidence for Absorption Effects in Positron Elastic Scattering by Argon

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Relative differential cross sections for elastic scattering of 5–50-eV positrons by argon atoms at angles from 30° to 134° are measured in a crossed-beam experiment. These measurements provide strong evidence that the positronium formation channel (threshold = 9.0 eV) is having a significant "absorption" effect on the elastic-scattering channel, as is observed by the "washing out" of clear structure (a maximum and minimum) present in the measured elastic differential cross section below 9.0 eV (where good agreement is found with theory) when the positron energy is increased to higher energies.

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In any collision process where two particles are interacting it is of interest to consider what effect two (or more) accessible scattering channels may have on each other, which has been the subject of prior investigations. In atomic physics, experimental studies by Eyb and Hofmann[1] of the differential elastic scattering of electrons by alkali-metal atoms in the vicinities of their lowest energy inelastic thresholds (for resonance excitation) have shown that the electron-K integrated elastic cross section exhibits a noticeable decrease after the resonance excitation threshold, which suggests that the resonance excitation channel may be "absorbing" some of the electrons that may otherwise have experienced only elastic scattering. Eyb and Hofmann[1] also found that the electron elastic differential cross sections (DCS's) for Na and K exhibit anomalies or cusps at the respective resonance excitation threshold energies. An example of a similar effect in nuclear physics is the observation by Malmberg[2] of anomalies in the elastic DCS's for proton scattering by ^{7}Li as the proton energy was increased through the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction threshold. Several decades ago, Wigner[3] commented that all scattering cross sections, which are possible below the threshold of a new scattering channel, will show a cusp at the threshold for the newly opened scattering channel. As a result, it is well known that one scattering channel can affect another.

In this Letter we report relative measurements of DCS's for positron elastic scattering by argon extending over the energy range from below the positronium (Ps) formation threshold to well above this threshold which provide evidence, when comparisons are made with available theoretical calculations, that Ps formation may have a significant effect on the elastic-scattering channel. It is relevant to the present work that total cross-section (Q_t) measurements[4] for positron-argon scattering revealed a dramatic increase in Q_t for positron energies immediately above the Ps formation threshold at 9.0 eV and it was then estimated[4] that the Ps formation cross section (Q_{Ps}) a few eV above this threshold may become as large as the elastic-scattering cross section (i.e., Q_t) just below the threshold, which is supported by the Q_{Ps} measurements for positron-argon scattering by Fornari, Diana, and Coleman.[5] In fact, these Q_{Ps} measurements account for more than half of Q_t in the vicinity of 15–20 eV (which is similar to the above situation for electron-alkali atom scattering where the resonance excitation cross section becomes larger than that for elastic scattering within several eV of the threshold energy[6]). There have been several predictions, based on either theoretical[7] or experimental[8,9] information, that the positron elastic-scattering cross section may show either a cusp and/or absorption effects as the positron energy is increased through the Ps formation thresholds for H,[7] He,[8] and other inert gases,[9] including Ar. At the present time direct observations of cusps are precluded in our experiment due to the relatively broad positron beam energy width (about 2 eV) and other experimental limitations.

The experimental setup and technique used for this work, a crossed positron and atom-beam experiment, is the same as that used by Hyder *et al.*,[10] except for modifications designed to improve the acquisition of scattered positrons. These modifications include (1) the addition of a second channeltron electron multiplier to detect positrons scattered at two angles (separated by 30°) simultaneously, (2) changing the shape of the collimators that limit the collection of scattered positrons by the secondary detectors, (3) upgrading the original sodium-22 positron source with a 150-mCi source, (4) adapting the experiment so that scattered positrons can be detected at any angle between 30° and 134°, and (5) adding some additional shields to reduce the likelihood that "stray" positrons will be detected at the more forward scattering angles (i.e., 30°–60°). The positron beam (obtained from an annealed tungsten backscattering moderator) has a full width at half maximum energy width close to 2 eV and the beam energy (obtained by an appropriate bias to the moderator) is determined by using stainless-steel grid retarding elements (preceding the scattered positron detectors) which are assumed to have the same average work function for positrons as the projectile-atom scattering that is predominantly surrounded by stainless-steel components. The angular acceptance of the scattered positron detectors is estimated to be $\pm 8°$. As with the measurements of Hyder *et al.*, relative electron elastic DCS measurements have been made[11] in the same apparatus at some of the corresponding energies as reported here for positrons in order to ensure that the basic experiment is performing reliably.

The present relative elastic DCS measurements are displayed in Figs. 1 and 2 where they have been arbitrarily normalized to theoretical calculations at 120° (and also 30° for the 30-eV results in Fig. 1). The present measurements are the first to ever clearly show a well-defined minimum and maximum in a positron DCS at any energy. Prior positron-argon elastic DCS measurements in the angular range of 20°–65° at 8.7 eV by Coleman and McNutt[12] (absolute values), and at 8.5 and 30 eV by Floeder *et al.*[13] (relative measurements normalized to theory) are also shown in Fig. 1, and are found to be consistent with the shape of the present results. Earlier results obtained by our group at 20 eV (Ref. 14) (not shown here) with the original setup of Hyder *et al.*[10] are superseded by the present results. Two calculations of the elastic DCS at 8.7 eV (that are quite close to the experimental DCS results) are the polarized orbital approximation results of McEachran, Ryman, and Stauffer[15] and of Montgomery and LaBahn.[16] By comparing the present results with the shapes of the calculated DCS curves it is seen that there is better agreement with McEachran, Ryman, and Stauffer with the only noticeable discrepancy being the depth of the minimum, which can partially (but not entirely) be explained by the finite angular acceptance of the scattered

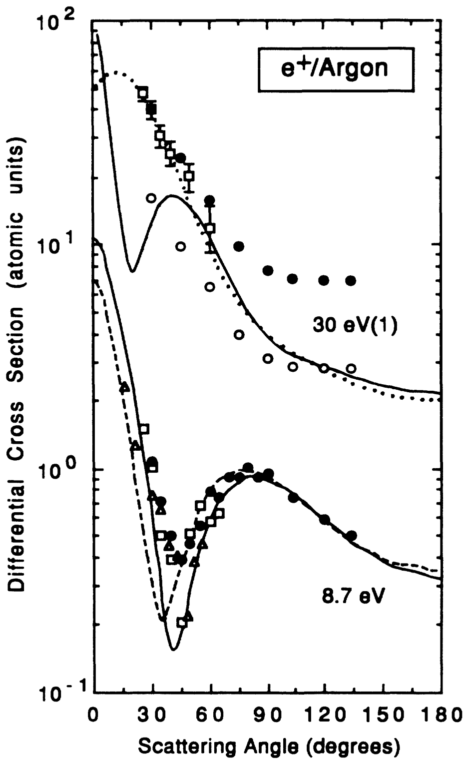

FIG. 1. Present elastic DCS measurements (●,○) compared with measurements of Ref. 12 (△) and Ref. 13 (□), and theoretical results of Ref. 15 (——), Ref. 16 (---), and Ref. 17 (···). The 8.5-eV results of Ref. 13 are compared with the other 8.7-eV results. The number in parentheses following an energy value indicates the power of ten by which the corresponding DCS values have been multiplied. The relative DCS measurements are normalized to theory at 30° and 120° for this work, and at 30° and 60° for Ref. 13. The statistical uncertainties for the present results are < 5% (smaller than the size of the data symbols), for Ref. 13 at 30 eV are shown, and for Ref. 12 at 8.7 eV and Ref. 13 at 8.5 eV are not shown in order to maintain clarity, but for both experiments range from about 10% to 50% for their largest to smallest DCS values, respectively.

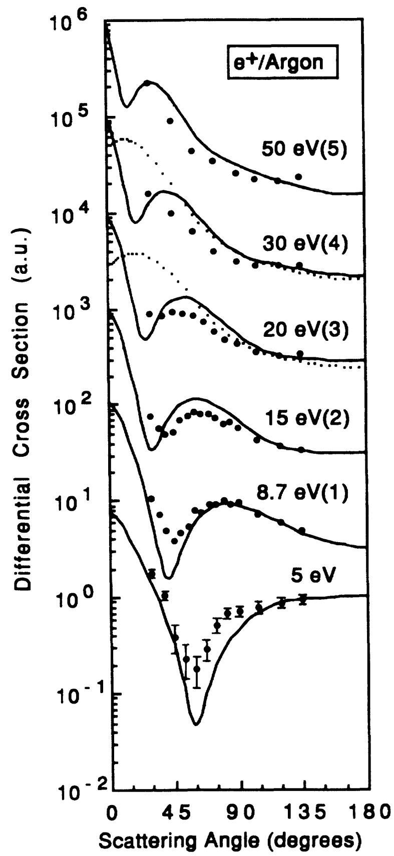

FIG. 2. Present elastic DCS measurements (●) compared with the theoretical results of Ref. 15 (——) and Ref. 17 (···). The number in parentheses following an energy value indicates the power of ten by which the corresponding DCS values have been multiplied. The present DCS results are normalized at 120° to Ref. 15. The statistical uncertainties for the present results are shown at 5 eV, and are < 5% at the other energies where they are smaller than the size of the data symbols.

positron detectors and the finite-energy width of the positron beam.

Based on the favorable comparison with McEachran, Ryman, and Stauffer[15] at 8.7 eV, the present results at the five other energies of investigation are compared with McEachran, Ryman, and Stauffer in Fig. 2. At 5 eV our measurements are also in reasonable agreement with McEachran, Ryman, and Stauffer. For energies increasing above 8.7 eV it is found that the observed structure in the DCS curve is rapidly disappearing with the minimum no longer being present at 20 eV and any remaining evidence of noticeable structure being gone at 30 eV. This observed behavior of the elastic DCS curves differs markedly from the calculation of McEachran, Ryman, and Stauffer where the minimum gradually decreases in depth (and shifts to smaller angles) as the positron energy is increased. It is to be noted that the calculation of McEachran, Ryman, and Stauffer does not include the possible effects on the elastic-scattering channel of any inelastic-scattering channels as the positron energy is increased above the Ps formation threshold energy of 9.0 eV.

An optical potential method calculation by Bartschat, McEachran, and Stauffer[17] for elastic scattering (which includes a local absorption potential to account for the loss of some incident positrons to the excitation of the ten lowest excited states of the argon atom) gives a DCS curve that exhibits no minimum at 20 or 30 eV, and is in this respect in better agreement with the present measurements than the polarized orbital calculation of McEachran, Ryman, and Stauffer[15] (where no allowance is made for any absorption effects due to inelastic scattering on the elastic cross section). There remains, however, a significant difference between our measurements and Bartschat, McEachran, and Stauffer in that our results at 30 eV show a (2-3)× smaller decrease of the relative DCS as the scattering angle increases from 30° to 134°.

The above comparisons raise several interesting points. It is noteworthy that the optical potential calculation of Bartschat, McEachran, and Stauffer[17] does not consider the effects of Ps formation and atomic ionization on the elastic-scattering cross section, while the evidence discussed earlier in regard to Ps formation suggests that it is the principal contributor to the total scattering cross section just a few eV above the Ps formation threshold. It would be very interesting to theoretically determine the effect that inclusion of Ps formation (and also atomic ionization) would have on the elastic-scattering channel at these energies to see if this would bring theory into better agreement with the present DCS measurements.

It is of interest to this discussion that in the case of electron elastic scattering by argon atoms, Bartschat, McEachran, and Stauffer[17] have shown that there is a difference in the magnitudes (at most about a factor of 2×) between the elastic DCS curves at 20 and 40 eV obtained by using a polarized orbital approximation calculation (where no absorption effects from inelastic channels are considered) and an optical potential method calculation (which includes the absorption effect due to the first ten excited states of the argon atom), while the general shapes of the DCS curves (which include two prominent minima) remain very similar. Since both of these calculations are in reasonably good agreement with available experimental electron DCS results (see Bartschat, McEachran, and Stauffer), absorption effects are apparently less important for electron scattering by argon than for positron scattering, which may result because inelastic scattering does not play as important of a role in the total scattering at lower energies for electrons by the inert gases as for positrons.[18]

A theoretical investigation by Joachain and Potvliege[19] of positron-argon elastic differential scattering at intermediate energies, using *ab initio* optical model potentials, has led them to predict that if proper account is made for the effects of absorption (due to inelastic channels) on the elastic-scattering channel then there should be no important structure (i.e., a well-defined minimum and an associated maximum) for small-angle positron elastic scattering by noble gases at intermediate and high energies. Our present measurements support this prediction in that we have observed the minimum-maximum structure to be gone for energies above 20 eV. Some preliminary DCS measurements that our group[20] has made for positron scattering by krypton and xenon are also consistent with the positron-argon results we report here for positron energies below and above the Ps formation thresholds.

Another theoretical prediction made by Joachain and Potviliege[19] in their work investigating the effect of absorption on the elastic-scattering channel is that DCS's calculated with proper account made for absorption should be reduced at medium and large angles when compared with DCS's calculated by using models which ignore absorption effects. For positron-argon scattering at 100 and 200 eV their calculations show a reduction by a factor of (2-4)× in the DCS's for scattering angles greater than 30° when they include absorption in their calculation. For reasons such as this, it would be of considerable interest to perform absolute DCS measurements. Although this is one of our goals for the future, we are not yet in a position to provide absolute DCS results.

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