Differential Elastic Scattering of Positrons from Argon Atoms at Low Energies

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We have measured relative cross sections in the angular range of 26° to 65° at 8.5 and 30 eV. Our 30-eV data show a monotonic increase with decreasing scattering angle, in disagreement with three theoretical calculations which predict a structure of the cross section in this range, but in qualitative agreement with a prediction of Joachain and Potvliege, derived from optical-potential calculations at and above 100 eV. At 8.5 eV, below all inelastic thresholds, our data agree very well with the theoretical results of McEachran and Stauffer as well as Nakanishi and Schrader but disagree with other calculations.

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Atomic-physics scattering experiments with positrons are performed in order to aid in the development of electron and positron scattering theory. Positron-atom scattering is an interesting test case for theory because of the absence of exchange with atomic electrons which complicates the theory of electron-atom scattering at low energies.

Low-energy beams of monoenergetic positrons are obtained by moderation of fast positrons (from β decay or pair creation) in a metal and reacceleration of the positrons which emerge from the moderator with nearly thermal energies. Despite considerable improvements in source and moderator technology, positron experiments are still much more difficult than corresponding electron experiments because the available intensities are orders of magnitude smaller. For many years only total-scattering cross sections could be measured in gas-cell transmission experiments. Recently, however, more sophisticated partial–cross-section measurements have become feasible.[1,2]

In a pioneering experiment, Coleman and McNutt[3] derived absolute differential elastic e^+-Ar cross sections for forward-scattering angles from time-of-flight spectra of a gas-target transmission experiment with longitudinal magnetic guiding field. This method is restricted to energies below the first inelastic threshold because above it the time-of-flight analysis cannot unambiguously distinguish between loss of axial velocity due to wide-angle scattering and due to energy loss. More versatile but also more difficult are positron-atom crossed-beam experiments on differential scattering as have been pursued by the experimental groups at Wayne State University and Universität Bielefeld for several years. The Wayne State group (Hyder *et al.*) published their first results on e^+-Ar elastic scattering form 100 to 300 eV in 1986,[4] and later Kauppila and Stein reported measurements at lower energies.[5] We present here our first results, of which a part was recently reported.[6]

Four theoretical groups have obtained results for low energies by means of different methods. McEachran and Stauffer[7] employed an adiabatic polarized-orbital approximation without the need to fit to experimental data. The other three groups performed model potential calculations: The polarization potentials of Nakanishi and Schrader[8] and Datta *et al.*[9] contain one effective radius and an experimental value for the polarizability of argon. In the cutoff function for the polarization potential, Nakanishi and Schrader use different effective radii for electrons and positrons. The polarization potential of Nahar and Wadehra[10] is determined by the polarizability and an energy-dependent cutoff parameter which is obtained from elastic electron-argon scattering cross sections.

All theories predict a minimum in $d\sigma(\theta)/d\Omega$ vs θ at small scattering angles, which becomes more pronounced with decreasing energy E. The results of Nakanishi and Schrader and of Datta *et al.* agree roughly with those of McEachran and Stauffer. The calculations of Nahar and Wadehra show the minimum at much smaller angles than those of the other authors; at energies larger than 75 eV it vanishes completely. None of those methods correctly accounts for the loss of flux due to inelastic channels (e.g., positronium formation), although the energy ranges covered are partially above inelastic thresholds. Joachain *et al.* and Khare *et al.* pointed out the importance of including absorption.[11] Joachain and Potvliege[12] used an *ab initio* optical potential for energies higher than 100 eV and found a monotonic increase of $d\sigma(\theta)/d\Omega$ with decreasing θ. They suggested that the monotonic behavior of $d\sigma(\theta)/d\Omega$ should also persist at energies below 100 eV.

The theoretical results differ not only in the shape of $d\sigma(\theta)/d\Omega$ but also in absolute cross-section values. Thus far, both crossed-beam differential-scattering experiments can only measure relative cross sections as functions of E or θ. The normalization of the experimental data to theory at some point reduces the comparison to an evaluation of curve shapes. Another difficulty arises from the fact that the pronounced shapes, maxima or minima, are predicted at very small scattering angles which for $E \geq 100$ eV are not yet experimentally accessible. But for decreasing energies, the structures move to larger angles; below 50 eV the minima lie above 20° and measurements are possible. Therefore, experimental results at low energies are decisive for the testing of theoretical approximations. Below the lowest inelastic threshold, which for argon is $E_{\mathrm{Ps}}=9.0$ eV, the absorption is zero and therefore the existing calculations, which do not yet account for absorption, should be more reliable.

Low-energy positron-atom scattering is a rapidly advancing field. Our results at 30 eV show that all the published theoretical results are wrong, presumably because absorption has not yet been taken into account. Our results at 8.5 eV, where absorption vanishes, show which theoretical approximations yield adequate angular dependence of the cross section.

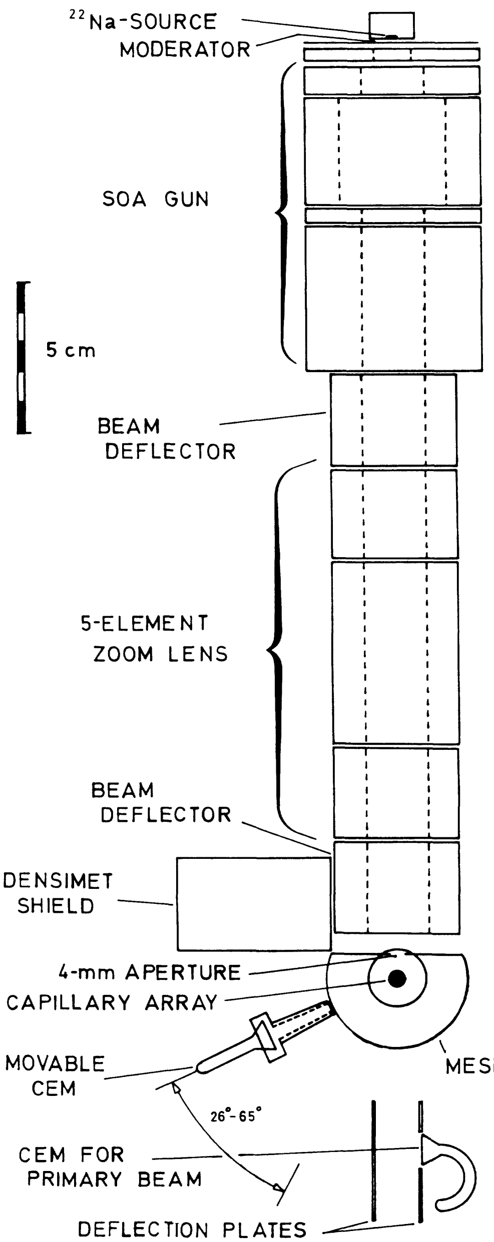

FIG. 1. Top view of the apparatus. (The dashed lines indicate the inner diameters of the optical elements.)

In our crossed-beam experiment (Fig. 1), the positron beam and the argon atomic beam intersect at right angles; the scattered positrons are detected by a channel electron multiplier (CEM) which can be pivoted around the atomic-beam axis, covering the angular range of $26° \leq \theta \leq 65°$. The detector is positively biased to discriminate against inelastically scattered positrons.

The atomic beam emerges from a glass-capillary array of 4 mm diameter (Galileo Inc.) onto which copper was evaporated in order to ensure a well-defined electric potential. The beam is dumped onto a liquid-helium cryopump with a surface temperature of about 15 K. Additional pumping is provided by a turbomolecular pump. The intersection with the positron beam is located about 8 mm away from the multichannel array. There the atomic beam has a diameter of about 7 mm (FWHM), as calculated according to Giordmaine and Wang.[13] The atomic density in the beam is monitored by measurement of the absorption of the primary beam. From the e^+-Ar total cross sections in the literature,[14] the density is estimated to be roughly 2×10^{14} cm^{-3} as compared with an argon background of 10^{13} cm^{-3} for the chamber pressure of 10^{-4} Torr.

The positrons emerge from an 8-mCi ^{22}Na radioactive source and are moderated by two annealed tungsten meshes. The beam is electrostatically guided to the scattering region. A Soa gun[15] and a five-element zoom lens[16] are employed for changing the scattering energy while retaining maximum beam intensity in the scattering region. Lens elements divided into four sectors are employed for beam steering. The primary-beam intensity is measured by a CEM beyond the scattering region. The positron-beam diameter is limited by a 4-mm aperture in front of the scattering region. At 30-eV scattering energy, the positron intensity is about 6000 e^+ s^{-1}.

Since it was clear from the outset that this experiment would be intensity limited, we decided not to use a 90° beam deflection for eliminating the unmoderated high-energy positrons and the γ rays. Instead we mounted the forward CEM off axis and employed internal γ-ray shielding by tungsten (Densimet, Metallwerke Plansee). The high-energy positrons scattered into the pivotable CEM do not cause a systematic error because they are a part of the background counting rate measured with a positively biased CEM. Because of the low positron-beam intensity, the signal is only about 0.1 to 0.4 s^{-1}, whereas γ rays from the source and from annihilating positrons cause a background of around 5 s^{-1}. Statistical errors are reduced by means of computer-controlled data collection over long periods.

Four different types of measurements are performed at

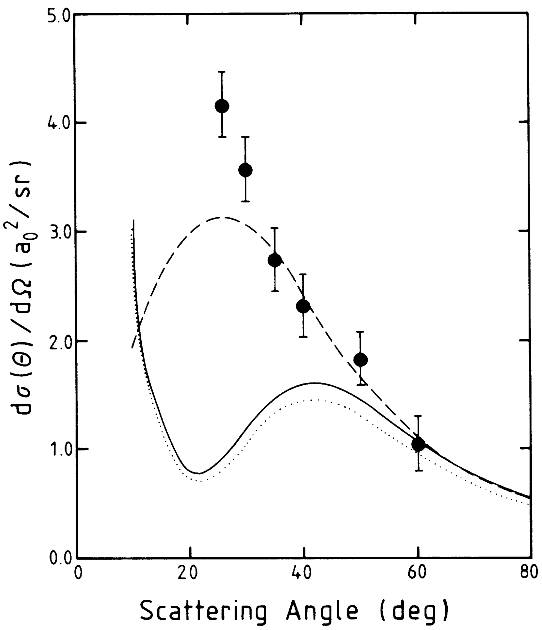

FIG. 2. Differential elastic cross sections at 30 eV: circles, present results, normalized to the average of theories of 60°, where the three curves are close to each other; solid line, McEachran and Stauffer; dotted line, Nakanishi and Schrader; dashed line, Nahar and Wadehra.

each angle: (a) gas beam on, CEM open for elastically scattered low-energy positrons; (b) gas beam on, CEM more positively biased, closed for all low-energy positrons; (c) gas beam off, CEM open for elastically scatterd low-energy positrons; (d) gas beam off, CEM more positively biased, closed for all low-energy positrons.

When the atomic beam is turned off, the same amount of gas is let into the vacuum system through a bypass. Relative cross sections are obtained from [(a)−(b)] −[(c)−(d)]. The second expression accounts for positrons scattered from residual gas outside the atomic beam. Terms (b) and (d) correct for background (positronium, fast e^+). The angular resolution of our measurements was estimated to be about ±6°.

Our data at 30 eV (Fig. 2) show a monotonic increase of $d\sigma(\theta)/d\Omega$ with decreasing θ, as was qualitatively predicted by Joachain and Potvliege.[12] The results of McEachran and Stauffer[7] and of Nakanishi and Schrader[8] differ from our data significantly; the prediction of Nahar and Wadehra[10] is lower for $\theta < 35°$. Thus

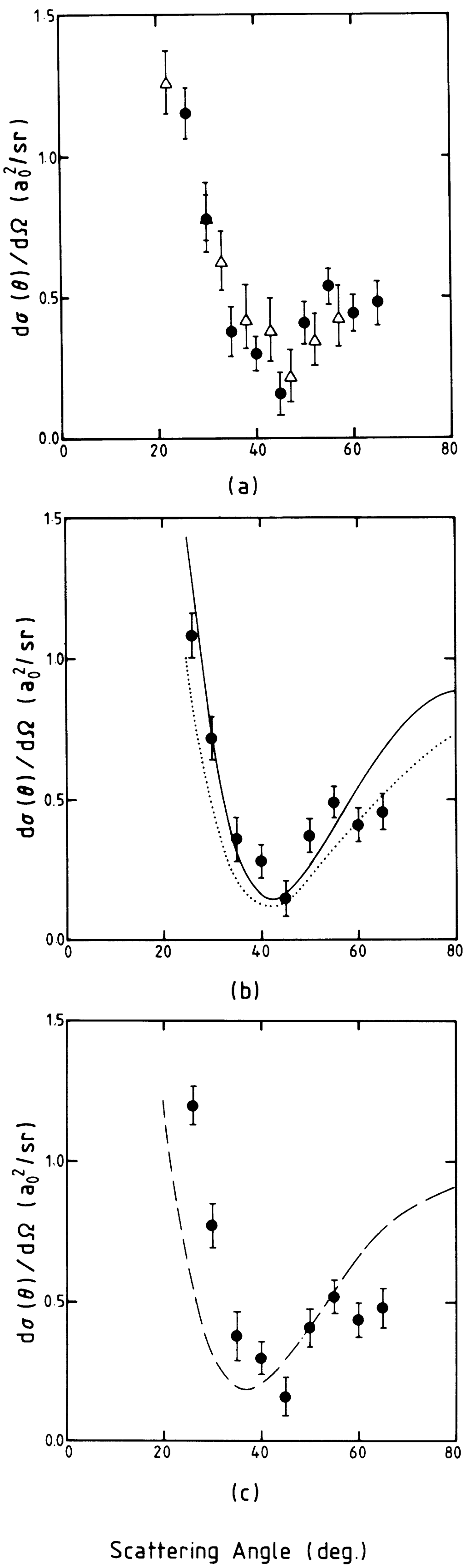

FIG. 3. Differential elastic cross sections at 8.5 eV. Circles , present results, normalized for a best fit of the comparison data. (a) Comparison with absolute experimental values of Coleman and McNutt obtained at 8.7 eV (triangles). (b) Comparison with McEachran and Stauffer (solid line). Also plotted are the 8.7-eV results of Nahanishi and Schrader (dotted line). (c) Comparison with the 8.0-eV results of Datta *et al.*, dash-dotted line.

all the published results are inadequate. New calculations with absorption taken into account are highly desirable.

At 8.5 eV our relative differential cross sections are consistent with the early time-of-flight experiment of Coleman and McNutt[3] at 8.7 eV [Fig. 3(a)], and agree well with the angular dependence predicted by McEachran and Stauffer [Fig. 3(b)] and also with the 8.7-eV calculation of Nakanishi and Schrader, but not so well with the 8.0-eV predictions of Datta *et al.*[9] The calculations of Nahar and Wadehra, published for 5 and 10 eV, are both significantly different from our 8.5-eV data.

The errors shown in Figs. 2 and 3 are statistical errors. Each datum point was determined as the weighted average of numerous measurements. The error of the average was derived from the variance of the set of measurements. Systematic errors were estimated to be much smaller than the statistical ones.

Our results show that polarized-orbital calculations describe the elastic cross sections satisfactorily below the threshold for positronium formation. Having shown the failure of most theoretical conceptions for elastic positron scattering above E_{Ps}, we hope to stimulate further theoretical work. Our comparison of experiment and theory also shows that absolute differential cross sections are urgently needed for a more crucial evaluation of competing theoretical approximations.

This experiment evolved from studies of differential electron scattering to which contributions were made by H. Rutz, R. Lienenbecker, and M. Kettler. This work has been supported by the Deutsch Forschungsgemeinschaft and the University of Bielefeld.

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