measured values obtained from circular polarization measurements. Since P_3 is negative over the measured range of positive scattering angles, χ is also negative in agreement with the prediction of a multichannel eikonal approximation.[19]

In conclusion, we wish to point out that vector-polarization and coherence-parameter measurements, besides providing a more complete analysis of coincidence experiments, allow consistency checks to be made for those experiments where coherent excitation is expected ($|\vec{P}|$ and $|\mu|$ should be constant independent of electron energy or angle) and offer a means of investigating the nature of the excitation mechanism where coherent excitation may not apply (e.g., resonances and near-threshold excitations).

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Direct Observation of a Ramsauer-Townsend Effect in Positron-Argon Collisions*

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Transmission measurements of the total scattering cross section for positrons of well-defined energy colliding with argon atoms in the energy range extending from 0.4 to 18 eV reveal a shallow minimum in the vicinity of 2 eV. The measured total cross section at the minimum is 2.4×10^{-16} cm^2. These measurements also reveal an abrupt increase in the total cross section above the threshold for positronium formation (9.0 eV).

The Ramsauer-Townsend effect derives from the pioneering work of Ramsauer[1] and Townsend and Bailey,[2] who independently (and by different techniques) observed pronounced minima in the total scattering cross sections for electrons colliding with Ar, Kr, and Xe for energies of about 1 eV. Ramsauer's measurements were made using the direct technique of studying single scattering of low-energy electrons in a beam with a gas target, while Townsend and Bailey employed a swarm technique in which the multiple scattering of electrons in a dense gas was observed. Calculations by Thompson[3] show that a Ramsauer-Townsend effect appears for electron-argon collisions only when the long-range polarization of the atom by the slow incident electron is included, along with the static interaction (arising from the unperturbed mean static electric field of the atom) and the effect of electron exchange.

It is of particular interest to consider the collisions of positrons with inert gas atoms to see whether similar total-cross-section minima exist because only the polarization interaction will be the same (attractive) as for electron collisions: The static interaction for positrons is repulsive (attractive for electrons) and the nonlocal interaction of electron exchange is replaced by the possibility of virtual or real positronium formation.[4]

There have been several theoretical predictions[4-7] of a Ramsauer-Townsend effect for positrons colliding with He, Ne, Ar, and Kr, and recent indirect experimental evidence obtained by Canter and Heyland[8] (studying the annihilation lifetime spectra of positrons in argon) suggests the existence of a pronounced minimum in the positron-argon momentum-transfer cross section below 3 eV.

In this Letter we report the first direct observation of a Ramsauer-Townsend effect for positrons colliding with an inert gas—in this case, argon. We also observe a sizable cross section for the formation of positronium above the formation threshold.

The total scattering cross section, Q_T, was measured by observing the transmission of a beam of positrons of well-defined energy through a gas scattering region. The transmitted beam intensity is given by

$$N = N_0 \exp(-nQ_T L), \qquad (1)$$

where N_0 is the number of positrons detected per second with the scattering region evacuated, N is the number of positrons detected per second with a number density n of argon atoms in the scattering region, and L is the path length of the positrons through the gas.

The experimental setup is shown in Fig. 1. A Van de Graaff accelerator is used to produce an ^{11}C positron source by the reaction ^{11}B$(p,n)^{11}$C. The production of our positron beam, having an intrinsic energy width less than 0.1 eV, has previously been reported.[9,10] In the present measurements the target gas is admitted into a 1-m-long curved solenoid that is differentially pumped at both ends. A capacitance manometer (MKS Baratron) is used to monitor the target-gas pressure at each end of the solenoid and it is found that there is a 10% pressure difference. The number density used in Eq. (1) was determined from the average of the pressures measured at each end of the solenoid and the measured temperature of the solenoid. The path length used in Eq. (1) was 109 cm, which does not include any allowance for possible spiralling of the positrons in the weak magnetic field of the solenoid.

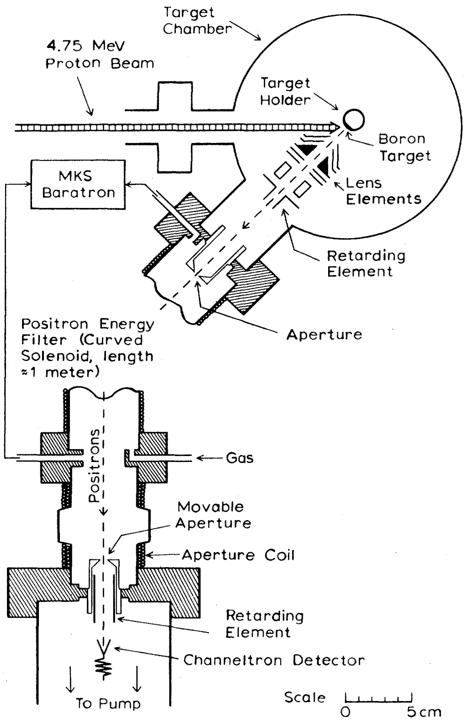

FIG. 1. Schematic diagram of the experimental setup.

To optimize the transmission of slow positrons through our system, the effect of Earth's magnetic field was reduced by a double layer of magnetic shielding surrounding the solenoidal gas-scattering region, and by Helmholtz coils at the source and detector ends of the solenoid. In addition, the gas-confining aperture at the detector end of the solenoid was movable so that an allowance could be made for the drift of the positrons in the curved magnetic field, and a small coil was used to produce an additional guiding axial magnetic field (0–30 G) at this aperture.

In experiments of the transmission type where total cross sections are being measured, it is important that proper discrimination be made against projectile particles scattered in the forward direction; otherwise the measured cross sections would be too small. We employed several procedures to try to minimize the effect of forward scattering on our measurements. In tuning up our positron beam (by varying all the beam-controlling parameters) to obtain an optimum number of positrons per second with no gas present, we used the lowest reasonable axial magnetic fields in the solenoid (which ranged from less than 4 G at 0.5 eV to 20 G at 18 eV) and at the detector aperture. To provide additional discrimination against forward scattering, a cylindrical retarding-potential element was placed immediately after the detector aperture and before the Channeltron detector. As the final step before the gas-scattering measurements were made, the potential applied to this element was adjusted to decrease the detected beam intensity by 20–25%. This retarding element served as a filter that preferentially transmitted the positrons with energies predominantly in the forward direction and thereby helped to discriminate against positrons that had undergone small-angle forward scattering. We found that using larger solenoidal (or detector-aperture) magnetic fields at a particular energy, while not using the retarding element near the detector, resulted in our measuring smaller cross sections due to our detecting more of the forward-scattered positrons. Using the detector retarding element, however, had a pronounced effect, because we no longer observed solenoidal (or detector-aperture) magnetic field dependence of our measured cross sections, suggesting to us that we were no longer detecting positrons scattered in the forward direction. Similarly, after installing the detector retarding element, we found that changing any of the other beam-controlling parameters did not alter our measured cross sections, as long as these parameters were adjusted for maximum beam transmission.

An important test of our experiment was the demonstration of exponential attenuation of our positron beam as a function of the target-gas density, which would justify our using Eq. (1) to determine our measured cross sections. We found agreement with Eq. (1) for pressures which produced attenuations ranging from 15 to 90% of the primary beam. For the data reported in this Letter we generally used attenuations of 15–30%.

We also conducted tests to investigate the possibility that argon, when admitted to the scattering region, might affect the emission of slow positrons from our source, thereby introducing an attenuation (or enhancement) of the detected beam that is unrelated to the total scattering cross section. We checked for this possibility by admitting argon only into the source vacuum chamber at pressures typically present during the gas scattering measurements (up to 2×10^{-6} Torr) and we found no measurable effect.

In order to provide an independent and overall test of our experimental apparatus and technique we measured the total scattering cross section for electrons on argon by replacing the positron source with an electron source (a Phillips cathode). The electron beam currents that we used ranged from 1×10^{-10} A at the lowest energies to 1×10^{-8} A at the highest energies. Our electron measurements, which were obtained in the same apparatus and with the same technique as we used in the positron measurements, are compared in Fig. 2 with the total-cross-section measurements compiled by Kieffer,[11] and made by Ramsauer,[1] Bruche, Lilienthal, and Schrodter,[12] and Golden and Bandel.[13] It is seen that the shape and absolute values of our measurements are in good agreement with the most reliable prior measurements.

It should be noted that if spiralling were a problem in our experimental approach to measuring total scattering cross sections, it would produce a longer effective path length, which, if unaccounted for, would result in measured cross sections which are too large. Our electron measurements provide a good indication that spiralling is not a serious problem in our experiment.

Our measured total scattering cross sections for positrons on argon with statistical uncertainties are shown in Fig. 3 with the most striking features being (1) the dramatic increase in the total cross section as the positron energy is decreased below 1 eV, (2) the existence of a shallow minimum in the vicinity of 2 eV with only a slowly increasing cross section to 8.5 eV, and

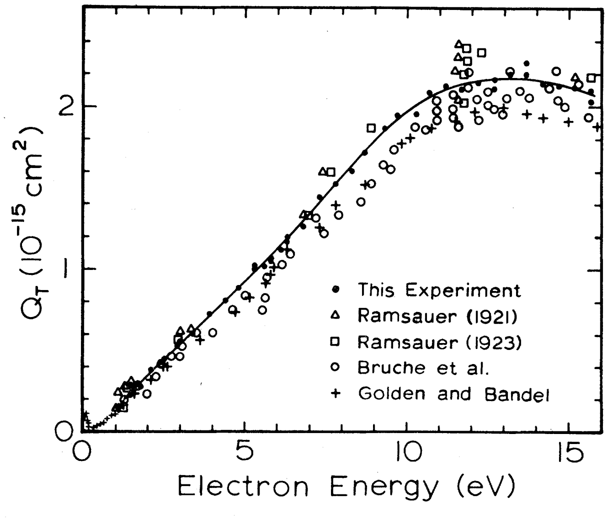

FIG. 2. A comparison of the present e^-+Ar total scattering cross section measurements with prior measurements. For clarity, only the measurements of Golden and Bandel are shown below 1 eV. The solid line is drawn to guide the eye through the results of the present experiment.

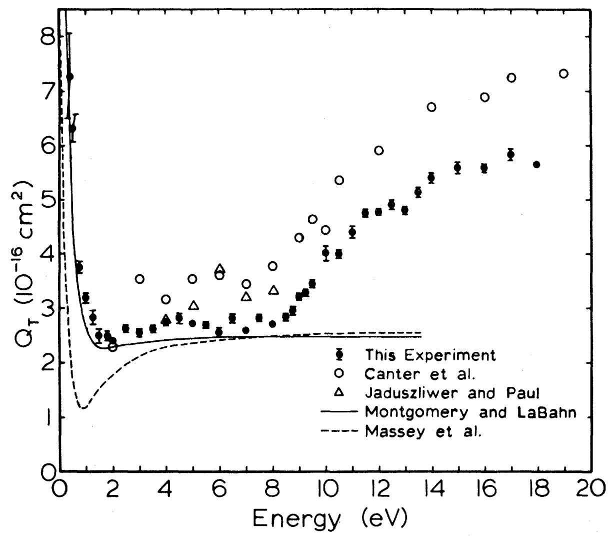

FIG. 3. A comparison of the present $e^+ + \mathrm{Ar}$ total scattering cross section measurements with prior measurements and theoretical calculations. The bars on the present data indicate statistical uncertainties. The points having no bars have their errors encompassed by the circles.

(3) an abrupt increase in the total cross section above the positronium-formation threshold (9.0 eV). A comparison of our results with the total-cross-section measurements of Jaduszliwer and Paul[14] and Canter *et al.*[15] shows that their absolute values are somewhat higher than the present results, while the shapes are in reasonable agreement.

The experimental energy calibration was obtained by making retarding-potential measurements (as described in Refs. 9 and 10) with a stainless-steel retarding element that preceded the solenoidal gas-scattering region, which also was stainless steel. The retarding-potential technique indicated a mean positron energy that was always within 0.2 eV of the voltage applied to the source. It is the applied voltage that is plotted in Fig. 3. The measured threshold for positronium formation also serves as a good indication that our energy scale is accurate to within a few tenths of an eV. (For the electron measurements we relied on retarding-potential measurements to assign the appropriate energy.) All the positron measurements reported in this Letter were made while the boron target was not being bombarded by the accelerator beam. Under these conditions, signal-to-noise ratios generally varied from 10:1 at the lower energies to more than 500:1 at the higher energies.

It is particularly interesting to compare our results with the polarized orbital calculations of Montgomery and LaBahn.[6] This comparison shows remarkable agreement in the shape, and near agreement with the absolute values of the total scattering cross sections for energies less than 8.5 eV. Also shown in Fig. 3 is the calculation by Massey, Lawson, and Thompson,[4] who used a semiempirical approach similar to that used by Holtsmark[16] for obtaining a good approximation for the scattering of slow electrons by atoms.

If the elastic scattering cross section remains a slowly varying function of energy beyond the positronium-formation threshold, as the above calculations predict and as an extrapolation of our measured total cross sections below 9 eV suggests, then we can obtain a reasonable estimate of the positronium-formation cross section from threshold (9.0 eV) up to the lowest possible energy for excitation of the argon atom at 11.5 eV. The measured positronium cross section increases almost linearly from 0 to 2×10^{-16} cm^2 in this energy range. It should be pointed out that any positrons that form positronium will be completely removed from our beam, and as a result will not be affected by any angular scattering considerations.

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Polarization Rotation Induced by Resonant Two-Photon Dispersion

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A polarization-rotation effect is demonstrated which utilizes the dispersion associated with 3S-5S two-photon transitions in sodium vapor. A linearly polarized beam at ν_1 is rotated by a circularly polarized beam at ν_2 when $\nu_1+\nu_2$ is near the two-photon transition frequency. When combined with a polarizer a rapid optical shutter is obtained.

Recently there has been considerable interest in two-photon processes in atomic and molecular vapors.[1] Until now, however, most experiments have dealt only with the absorptive process, i.e., the imaginary part of the two-photon susceptibility. The dispersive part of the two-photon susceptibility can also produce strong effects and many new and important phenomena based on two-photon dispersion can be expected. We report here on one such phenomenon. We have made measurements of the polarization rotation which is produced by the dispersion associated with an S-to-S two-photon transition in an atomic vapor. This rotation effect is unique to the two-photon process and, unlike other effects of two-photon dispersion such as self-defocusing,[2] it has no single-photon analog.

A rotation of the polarization of a linearly polarized dye-laser beam of wavelength λ_1 (signal laser) is produced with a circularly polarized, control-laser beam of wavelength λ_2. The wavelengths are chosen such that the sum frequency of the two lasers is near but not equal to the 3S → 5S two-photon transition in atomic sodium. The magnitude and resonant behavior of the effect is found to be in good agreement with theory. When combined with a polarizer, a fast, optically controlled shutter or modulator is obtained.

Many phenomena which utilize the dispersion associated with single-photon transitions in atomic or molecular vapors have been previously studied. Transient and cw self-focusing effects have been investigated by Grischkowsky[3] and by Bjorkholm and Ashkin.[4] Gibbs, Churchill, and Salamo[5] have reported Faraday-rotation angles in excess of 180° which were produced in sodium vapor in a magnetic field of 1 kG, and resonant birefringence due to optically induced level shifts has been reported by Bonch-Bruevich, Kostin, and Khodovoi.[6] In addition the large dispersion available with near-resonant atomic and molecular transitions has recently been used to produce pulse compression and the conversion of cw light into pulses by Grischkowsky,[7] by Loy,[8] and by Bjorkholm, Turner, and Pearson.[9]

A major limitation of phenomena arising from single-photon dispersion is the requirement of a near-resonant atomic or molecular transition. This restriction is considerably relaxed when one uses two-photon transitions. In a two-photon transition we can picture the control-laser beam at frequency ν_2 as inducing the atom to exhibit an absorption resonance at $\Omega-\nu_2$, where Ω is the two-photon transition frequency. From the Kramers-Kronig relationships one finds a dispersion associated with this induced absorption resonance. The resonance frequency of this induced absorption can be adjusted by adjusting the control-laser frequency, ν_2, and hence the need for a chance coincidence with atomic transition frequencies is removed.

The polarization-rotation effect reported here is a result of the selection rules for two-photon absorption. In particular, the selection rules[10] for S-to-S transitions in atomic vapors are such that if circularly polarized photons are used, the