Photon Vector Polarization and Coherence Parameters in an Electron-Photon Coincidence Experiment on Helium

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We present linear and circular polarization measurements of 3^1P-2^1S (501.6 nm) photons detected in delayed coincidence with electrons inelastically scattered from the 3^1P level of helium. Vector polarization and coherence parameters of the coincident radiation provide direct experimental evidence of the coherent nature of the excitation process. Atomic orientation is obtained directly from the circular polarization measurements. Analysis of the data also yields λ and χ parameters for 3^1P excitations, which are compared with previous data and theory.

The recent introduction of coincidence techniques, in which photons are detected in coincidence with electrons (ions) inelastically scattered from atoms, has yielded more detailed information on collision parameters and on coherence effects occurring in collisional excitation of atoms. Two methods have been used to analyze the photon radiation in these coincidence experiments. One method is to measure the polarization of coincident photons detected in a fixed direction with respect to a symmetry axis or plane for the experiment.[1-3] The other method used is to measure the angular distribution of coincident photons by rotating the photon detector in the scattering plane.[2,4-7,8]

In this Letter we report on linear and circular polarization measurements of photons emitted from the electron-impact–excited 3^1P-2^1S (501.6 nm) transition of helium which are detected in delayed coincidence with electrons inelastically scattered from the 3^1P level. Such measurements provide a further test of the theory of coincidence measurements[9-12] including, as we shall demonstrate, a direct experimental test of the coherent nature of the electron-impact excitation of atomic states. The apparatus (see Fig. 1), described in detail in Eminyan *et al.*,[5] has been modified so that the photons are detected perpendicular to the scattering plane. A photon detector has been mounted outside the vacuum chamber, the interaction region being viewed through a quartz window. A lens with a large collection solid angle (0.45 sr) focuses radiation from the interaction region onto the photon detector. The effect of the collection solid angle on the polarization is small (< 1%) for the experimental geometry used here. The photon detector consisted of a rotatable polarizer followed by a 501.6-nm interference filter (10 nm bandwidth) and a photomultiplier tube. A Polacoat (type PL 40) Polaroid was used for linear analysis and a $\lambda/4$ ($\lambda = 501.6$ nm) low-order quartz plate was inserted to provide circular analysis. The handedness of the circular analyzer was determined with a Babinet-Soleil compensator. To minimize instrumental polarization, a Hanle-type depolarizer[13] was placed immediately after the polarizer. The overall instrumental polarization was small (< 1%). Since the real coincidence rate is normalized to the total scattered-electron count, the effect of variations in the target gas pressure and the incident electron beam current are eliminated. The absence of pressure-dependent effects such as radiation trapping was confirmed by carrying out runs at different target pressures.

In order to determine completely the polarization state of the coincident photons it is neces-

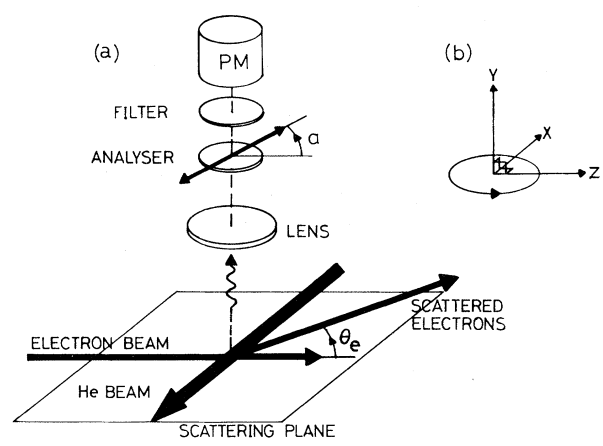

FIG. 1. Schematic diagram of experiment. The x-z plane is the scattering plane; the photons are detected along the y axis. Scattering angle θ_e and linear polarizer angle α are measured in the x-z plane. Positive scattering angle is shown.

sary to introduce quantities such as the elements of the photon density matrix, or equivalently, the Stokes parameters which completely characterize their quantum mechanical state. These parameters (I, P_1, P_2, P_3) have been extensively discussed in the literature.[14,15] Normalized to the total intensity I, the remaining three Stokes parameters are associated with linear and circular polarization measurements as follows: $P_1=I(0°)-I(90°)$, $P_2=I(45°)-I(135°)$, and $P_3=I(\mathrm{RHC})-I(\mathrm{LHC})$, where RHC and LHC denote right- and left-hand circular polarizations, respectively. For photons observed perpendicular to the scattering plane, $I(\alpha)$ is the linearly polarized intensity component measured at an angle α to the incident electron beam direction. P_1 and P_2 are, respectively, linear polarizations measured with reference to the incident electron beam direction and at 45° against this direction, whereas P_3 is the circular polarization. The polarizations P_1, P_2, and P_3 can be regarded as components of a three-dimensional vector polarization $\vec{P}=(P_1, P_2, P_3)$ which has magnitude $|\vec{P}|=(P_1^2+P_2^2+P_3^2)^{1/2}$, where $0\leq|\vec{P}|\leq 1$.[14] $|\vec{P}|$ is often referred to as the degree of polarization. Following Born and Wolf,[14] a further quantity which characterizes the polarization state of the coincidence radiation is obtained by defining a correlation factor

$$\mu=|\mu|e^{i\beta}=(P_2-iP_3)/(1-P_1^2)^{1/2}. \quad (1)$$

μ is a measure of the correlation between the two orthogonal linearly polarized components of the radiation, parallel and perpendicular to the incident electron beam. $|\mu|$ is the "degree of coherence" between the orthogonal components, and β is their effective phase. It can be readily shown that $|\mu|\leq|\vec{P}|\leq 1$.[14] The significance of a degree of coherence and a degree of polarization equal to unity is that this can occur if and only if every detected photon is in the same polarization state.

For the electron-impact excitation of the 3^1P state the connection between the atomic target parameters and the photon polarization is particularly straightforward. Based upon the assumption of coherent excitation of the degenerate magnetic sublevels, the excited state is assumed to be a linear superposition of magnetic sublevels such that

$$|\psi(t=0)\rangle=a_1|11\rangle+a_0|10\rangle+a_{-1}|1-1\rangle, \quad (2)$$

where the amplitude a_M describes the excitation to the $|M\rangle$ sublevel.[16] These amplitudes are functions of the incident electron energy E_0 and scattering angle θ_e. The components of the vector polarization $\vec{P}$ can be expressed in terms of the parameters λ and χ,[12] where $\lambda=\sigma_0/\sigma$, the ratio of the $M=0$ partial differential cross section to the total differential cross section, and χ is the quantum-mechanical phase difference between the excitation amplitudes a_1 and a_0. When photons emitted from excited helium atoms are detected in a direction perpendicular to the scattering plane, P_1, P_2, and P_3 reduce to

$$P_1=2\lambda-1, \quad P_2=-2[\lambda(1-\lambda)]^{1/2}\cos\chi, \quad P_3=2[\lambda(1-\lambda)]^{1/2}\sin\chi. \quad (3)$$

Several conclusions can be drawn from Eq. (3). In the coherent-excitation model the complex correlation factor becomes a pure phase factor with $|\mu|=1$ and $\beta=\chi$. Thus the quantum-mechanical phase difference between the excited-state sublevels is obtained directly from the effective phase difference associated with the coincident photon radiation. In addition, the degree of polarization and degree of coherence are predicted to be unity independent of electron impact energy and scattering angle. These results only hold true provided the assumption of coherent excitation is valid. In the absence of coherent excitation the phase difference χ can be regarded as random, P_2 and P_3 are zero, β is undetermined, $|\mu|$ is zero (for $P_1\neq 0$), while $|P|$ is no longer independent of electron impact energy and scattering angle.

The connection between the vector polarization and the alignment and orientation parameters of Fano and Macek[11] is as follows: $A_0^{\mathrm{col}}=-(1+3P_1)/4$, $A_{1+}^{\mathrm{col}}=-P_2/2$, $A_{2+}^{\mathrm{col}}=(P_1-1)/4$, and $O_{1-}^{\mathrm{col}}=-P_3/2=\frac{1}{2}\langle L_y\rangle$. Accordingly, the linear polarization measurements determine the components of the alignment tensor, whereas the circular polarization measurements determine only the orientation. We note here that $O_{1-}^{\mathrm{col}}=\frac{1}{2}\langle L_y\rangle$, where $\langle L_y\rangle$ is the only nonzero component of orbital angular momentum transferred to the atom during the collision. Figure 2 shows linear- and circular-polarization data for the helium 3^1P-2^1S (501.6 nm) transition at an incident electron energy of 80 eV. Note the striking behavior of P_3; unlike the linear polarizations P_1 and P_2, the circular polarization changes sign as the electron scattering angle is changed from positive to negative [Fig. 1(a) shows positive scattering angle]. This result is a direct consequence of the parity invariance of the scattering process.[18] Also shown are the predictions of the Born approximation and a recent multichannel eikonal calcula-

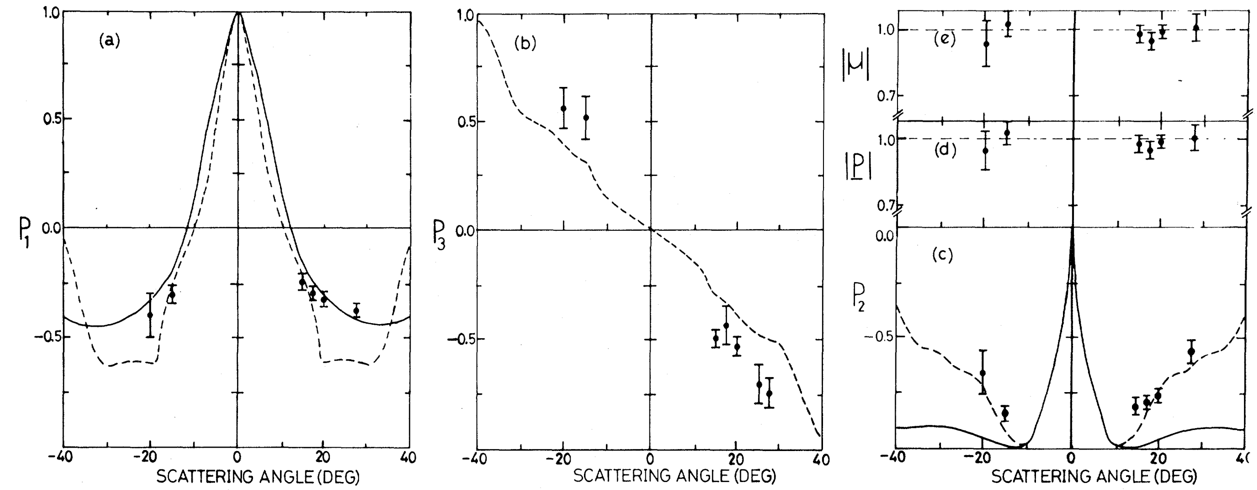

FIG. 2. (a)-(c) Experimental data for the vector polarization components P_1, P_3, and P_2, respectively, of He 3^1P-2^1S (501.6 nm) coincident photons at 80 eV incident electron energy versus electron scattering angle. Solid line, first Born approximation; dashed line, multichannel eikonal approximation (Ref. 19). (d) Degree of polarization. (e) Degree of coherence.

tion.[19]

The complex correlation factor and the degree of polarization have been determined from the experimental polarization data (see Fig. 2 and Table I). Within experimental uncertainty the degree of coherence and the degree of polarization are unity independent of scattering angle, confirming the predictions of the coherent-excitation model. Comparison with previous 3^1P ($E = 80$ eV) angular correlation measurements of Eminyan *et al.*[6] (see Table I) shows that over all there is good agreement with the values for λ and $|\chi|$ obtained from the linear polarization data. Furthermore, there is good agreement between the $|\beta|$ and $|\chi|$ data. It should be emphasized that the extraction of λ and $|\chi|$ parameters from angular-correlation or linear-polarization data is based upon the assumption of coherent excitation, whereas data for the correlation factor and the vector polarization are obtained from the linear- and circular-polarization measurements independently of any model for the atomic excitation process. Also included in Table I are atomic orientation data. Since the circular polarization observed in a direction perpendicular to the scattering plane is directly proportional to the atomic orientation, the observation of nonzero circular polarization provides direct evidence of the transfer of a net y component of angular momentum to the atom during the collision. Note that there is good agreement between values for the atomic orientation computed from λ and $|\chi|$ data and directly

TABLE I. Data for He 3^1P excitations at an incident electron energy of 80 eV. Data in parentheses are from 3^1P-1^1S (537 nm) angular correlation measurements (Ref. 6). Quoted experimental uncertainties are one standard deviation. $|O_{1-}^{\mathrm{col}}|$ is computed from λ and $|\chi|$ data.

θ_e (deg)	λ	$\lvert\chi\rvert$ (rad)	β (rad)	$\lvert O_{1-}^{\mathrm{col}}\rvert$	$P_3/2(=-O_{1-}^{\mathrm{col}})$
−20	0.30 ± 0.05	0.76 ± 0.14	0.69 ± 0.13	0.31 ± 0.05	0.28 ± 0.05
−15	0.35 ± 0.02	0.49 ± 0.07	0.55 ± 0.09	0.23 ± 0.03	0.26 ± 0.05
15	0.38 ± 0.02	0.58 ± 0.07	−0.55 ± 0.04	0.27 ± 0.03	−0.25 ± 0.04
	(0.38 ± 0.01)	(0.55 ± 0.02)		(0.25 ± 0.01)	
17.5	0.36 ± 0.02	0.62 ± 0.06	−0.51 ± 0.09	0.28 ± 0.02	−0.22 ± 0.05
20	0.34 ± 0.02	0.63 ± 0.05	−0.62 ± 0.04	0.28 ± 0.02	−0.27 ± 0.02
	(0.36 ± 0.02)	(0.64 ± 0.05)		(0.29 ± 0.02)	
27.5	0.36 ± 0.02	0.98 ± 0.07	−0.93 ± 0.06	0.40 ± 0.03	−0.38 ± 0.04

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 ex-