Electron-Photon Coincidence Studies in Collisions of Polarized Electrons with Mercury Atoms

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Electron-photon coincidences with initially polarized electrons have been measured for the first time. Results for linear and circular polarization components of the 254-nm line (Hg 6^3P_1-6^1S_0 transition) are presented as a function of electron energy for electrons which are scattered inelastically (6^3P_1 excitation) in the forward direction. The analysis of these polarization components allows one to determine the role of spin-dependent interactions during collision as well as to determine the relative phase of the two scattering amplitudes involved.

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Electron-photon coincidences[1] and experiments with polarized electrons[2,3] are two successful methods to study inelastic electron-atom collisions in more detail. Up to now no experiments have been performed in which both methods were combined though the need for them has been frequently emphasized[3-7]: Whenever scattering is spin dependent, information is lost if only unpolarized electrons are used in electron-photon coincidence studies (of course, information is also lost if the initial atoms have nonzero angular momentum and are unpolarized).

In this Letter results are presented in which polarized electrons were used for the first time in an electron-photon coincidence experiment. Electrons which have excited the 6^3P_1 state of mercury were detected in coincidence with photons (6^3P_1-6^1S_0 transition, $\lambda = 254$ nm) transmitted by linear and circular polarization filters. The electron scattering angle was 0°, the present experiment being an extension of a previous one with unpolarized electrons.[8] As illustrated in Figure 1 light emitted along the y direction (which is the direction of electron polarization P_y) is characterized by polarization components (Stokes parameters)

$$\eta_1 = \frac{I(45°) - I(135°)}{I(45°) + I(135°)},$$
$$\eta_2 = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)}, \qquad (1)$$
$$\eta_3 = \frac{I(0°) - I(90°)}{I(0°) + I(90°)},$$

where $I(\alpha)$ denotes the intensity transmitted by a linear polarization filter oriented at one of the angles α in Fig. 1 and $I(\sigma^+)$ or $I(\sigma^-)$ is the intensity through filters for light with positive or negative helicity.

From a theoretical point of view the present investigation is of interest for several reasons. Firstly, we note that η_1 and η_2 vanish identically if the incident electrons are unpolarized. This follows easily by adaptation of the symmetry arguments of Bartschat and Blum[9] to the present case. Hence, it may be expected that η_1 and η_2 are sensitive tests of spin-dependent interactions.

The Stokes parameters (1) can be expressed in terms of the scattering amplitudes. By $f(Mm_1m_0)$ we denote the amplitude for a transition where an atomic $^3P_1$-state with $J_z = M$ has been excited by electrons with initial spin component m_0 and final spin m_1. Angular momentum conservation gives the condition $M + m_1 = m_0$ for forward-scattered

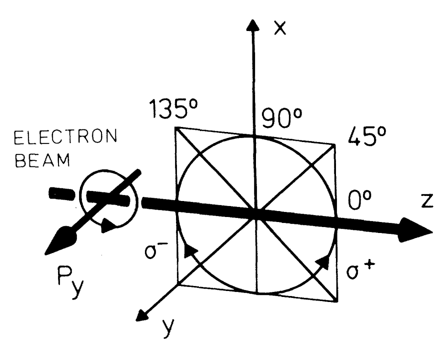

FIG. 1. Geometrical arrangement of the electron-photon coincidence measurement with polarized electrons.

electrons. When we take into account reflection invariance of the electron-atom interaction with respect to the x-z plane[6] it can be shown that two amplitudes are sufficient for a complete characterization of the scattering process. We choose $f_2 = f(M=1, m_1 = -\frac{1}{2}, m_0 = \frac{1}{2})$ and $f_5 = f(0, \frac{1}{2}, \frac{1}{2})$ using the notation of Ref. 6. Assuming that the Percival-Seaton hypothesis[10] is valid (that is, that the nuclear spin does not influence the collision but disturbs the excited atomic states after the excitation) and applying methods described in Ref. 6 we obtain

$$\eta_1 = -\frac{6\sqrt{2}\bar{G}_2 |f_2||f_5| \sin\chi}{(4-\bar{G}_2)|f_2|^2 + (4+2\bar{G}_2)|f_5|^2} P_y,$$

$$\eta_2 = +\frac{6\sqrt{2}\,\bar{G}_1 |f_2||f_5| \cos\chi}{(4-\bar{G}_2)|f_2|^2 + (4+2\bar{G}_2)|f_5|^2} P_y, \tag{2}$$

$$\eta_3 = -\frac{3\bar{G}_2(|f_2|^2 - 2|f_5|^2)}{(4-\bar{G}_2)|f_2|^2 + (4+2\bar{G}_2)|f_5|^2}.$$

Here χ is the relative phase between the two scattering amplitudes and $\bar{G}_1$ and $\bar{G}_2$ are coefficients describing the perturbation of the atomic states by the hyperfine-structure interaction. For the natural isotope mixture of mercury we have $\bar{G}_1 = 0.887$ and $\bar{G}_2 = 0.789$.[11] As shown by Eqs. (2) a measurement of the Stokes parameters allows a complete determination of the two amplitudes (that is, of the two moduli and their relative phase) if the total excitation cross section $Q = |f_2|^2 + |f_5|^2$ is known.

The Bonham-Ochkur approximation predicts a vanishing phase between f_2 and f_5.[12] From Eqs. (2) it follows then that $\eta_1 = 0$. A measurement of η_1 allows one therefore to draw some immediate conclusions on the validity of these approximations for forward-scattered electrons. This point is of interest in view of recent discussions.[12]

Finally we note that from Eqs. (2) the following inequality can be derived:

$$0.55 < \bar{\eta}^2 < 0.80, \tag{3}$$

with $\bar{\eta}^2 = (\eta_1/P_y)^2 + (\eta_2/P_y)^2 + \eta_3^2$. Equations (2) and (3) have been derived under the assumption that the Percival-Seaton hypothesis is valid. Any measured deviation from the inequality (3) indicates therefore that the influcence of the nuclear spin on the collision cannot be neglected. If hyperfine structure can be completely neglected ($\bar{G}_1 = \bar{G}_2 = 1$) then $\bar{\eta}^2 = 1$ (this case would be perfectly realized by use of $I = 0$ isotopes only).

A scheme of the experimental apparatus is shown in Fig. 2. Longitudinally polarized electrons are emitted from a GaAs photocathode which is placed in ultrahigh vacuum and irradiated with circularly polarized light from a krypton-ion laser. After deflection of the electrons by 90° their polarization is rotated by two magnetic coils through 90° to be transverse and parallel to the axis of the light analyzer (cf. Fig. 2). The electrons then pass through a differential pumping stage where they are again deflected by 90°. A lens system focuses the polarized electron beam onto the mercury target. Some of the mercury atoms are excited by electron impact to the 6^3P_1 state (4.9 eV energy loss). Electrons which are scattered in the forward direction and have passed an energy analyzer are detected in coincidence with photons (6^3P_1-6^1S_0 transition, 254 nm) which are transmitted by the photon-analyzer system. The photon analyzer detects photons which are emitted in the direction of the electron-spin polarization vector. It consists of a collimating lens system, a $\lambda/4$ plate, and a pile-of-quartz-plates analyzer to measure either linear or circular polarization components. A wavelength filter is placed in front of the photomultiplier.

The electron polarization was between 0.25 and 0.35, depending on the state of the GaAs photocathode. It was monitored by a spin-up–spin-down asymmetry measurement where electrons scattered elastically by mercury atoms are detected by an electron analyzer placed at a scattering angle of 90°. We used an asymmetry function of 0.82 at 12 eV collision energy.[13] Additionally the circular light polarization of the 254-nm line was measured without observing the scattered electrons. An extension of previous measurements[11] served as a calibration curve. The accuracy of these calibrations was ±10%.

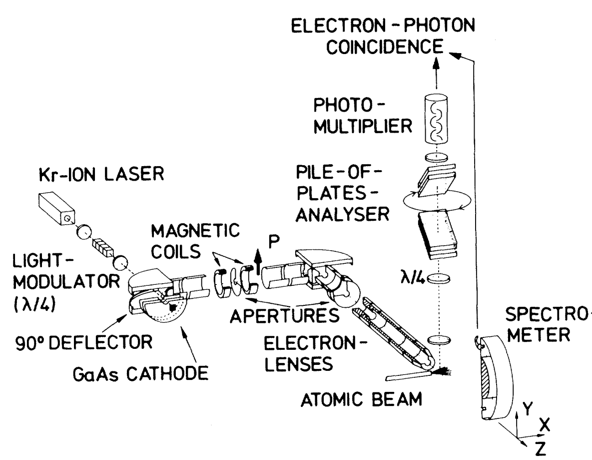

FIG. 2. Scheme of the apparatus.

At a fixed electron energy, spectra of delayed coincidences were accumulated for two orthogonal positions of the light polarization analyzer and for positive and negative directions of the electron polarization (P_y and $-P_y$, cf. Fig. 1). From these two pairs of spectra the background of chance coincidences was subtracted and the total number of true coincidences of each spectrum was calculated. The geometrical means of each pair of measurements were proportional to the two intensities required for evaluation of a Stokes parameter from Eqs. (1). A typical accumulation time for a measured point of η_1/P_y or η_2/P_y shown in Fig. 3 was 12 h. The error bars were calculated from the statistical error of the numbers of accumulated counts. The error of the absolute electron polarization calibration was not included.

Figure 3 shows the energy dependence of the measured polarization components η_1 and η_2, normalized to the initial electron polarization P_y by which they are caused. For comparison the previous data of η_3 (Ref. 8) which does not depend on P_y are also shown. Around 10.5 eV new measured points with smaller energy steps are included in this curve showing a structure which has been missed in the older data.

Above 11 eV a nearly constant value of $\eta_2/P_y \approx 0.3$ is observed, whereas η_1/P_y is close to zero. Below 11 eV the measured polarization values vary strongly with energy. This can be explained by resonances which have also been found in measurements of electron scattering cross sections[14] and in spin polarization measurements.[15] The long-term stability of our apparatus was not sufficient for resolving these structures in more detail.

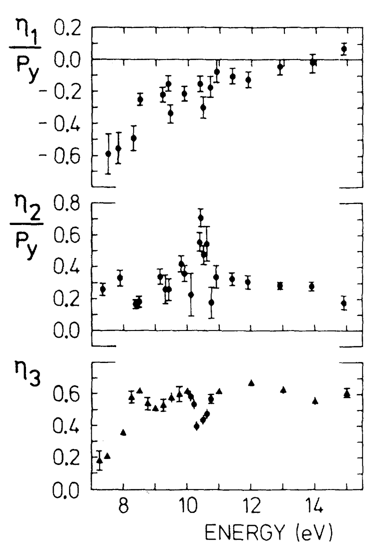

FIG. 3. Light polarization components η_1/P_y, η_2/P_y, and η_3 for Hg 6^3P_1-6^1S_0 transition (254 nm) vs collision energy. The photons are detected in coincidence with electrons scattered inelastically in the forward direction (4.9 eV energy loss).

The fact that significant values of η_1 and η_2 have been found confirms that spin-dependent interactions play a dominant role in the excitation process studied. As has been shown in earlier work[3,8] these spin effects are mainly caused by the breakdown of *LS* coupling for the excited state of the target (intermediate coupling) in conjunction with electron exchange. This also explains the findings of Zaidi, McGregor, and Kleinpoppen[16] in their angular polarization correlation experiment.

The measurements enable the relative phase χ of the amplitudes f_2 and f_5 to be calculated according to $\chi = \arctan(-\overline{G}_1\eta_1/\overline{G}_2\eta_2)$. This results in values of χ between 1.2 at low energies and -0.4 at 15 eV, where, as a general trend, χ decreases slowly with increasing energy. In contrast, the Bonham-Ochkur approximation predicts $\chi = 0$ implying $\eta_1 = 0$. Although such calculations are not expected to be valid for such low energies the general shape of η_3 is fairly well described by the Bonham-Ochkur approximation.[12] Our results for χ show, however, that this approximation clearly fails to predict the results for η_1 and η_2. A detailed analysis of parameters like λ, χ, and Δ[17] will be published when our measurements are completed.

Because of the low rate of true coincidences the measurements could not be extended below 7 eV though in the energy range from 6 to 8 eV the polarization components presumably have an interesting behavior: As measured earlier, η_3 has positive values of about 0.6 above 8 eV, passes through zero around 7 eV, and reaches negative values down to -0.5 at 6 eV. Because of the limits for the magnitude of the total polarization given by Eq. (3), $(\eta_1/P_y)^2$ and/or $(\eta_2/P_y)^2$ are expected to reach larger values around 7 eV, thus compensating the small η_3 near this energy. From the present measurements one may anticipate that $(\eta_1/P_y)^2$ becomes large, while η_2/P_y keeps a nearly constant value of ≈ 0.3. With an improved apparatus we are trying to measure this in more detail.

From our results we calculated $\overline{\eta}^2$ and checked inequality (3). We found that for some values a breakdown of the Percival-Seaton hypothesis seems likely in accordance with the recent findings of McLucas *et al.*[18]. Because of some experimental uncertainties like the absolute values of electron polarization, electron scattering angle, and angular acceptance of the photon detector we will, however, not emphasize this point too much. Further investigations will be performed to clarify the influence of hyperfine interaction.

Theoretical results with which the measurements can be compared are not yet existent. First attempts to calculate numerical data have been made recently in collaboration with Scott and coworkers.[19,20]

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