Circular Polarization of Impact Radiation Produced by Polarized Electrons in Mercury

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Polarization measurements of nonresonant radiation produced by impact excitation of mercury atoms by polarized electrons are reported. In particular, the circular polarization of the transition $7^3S_1 \rightarrow 6^3P_0$ (404.7 nm) is presented as a function of electron energy. At excitation threshold, the polarization predicted by theory has been confirmed while above threshold the polarization is strongly affected by resonances. Connections with the role of the atomic interactions in the excitation process and with electron polarimetry are discussed.

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Lately, there has been much interest in the polarization of the light emitted after impact excitation of atoms by polarized electrons. The light contains polarization components which do not appear if the incident electrons are unpolarized and which enable one to draw direct conclusions as to the role played during the excitation process by the various atomic interactions.

As illustrated in Fig. 1, a radiation field observed along the y direction (which is our quantization axis as well as the direction of electron polarization P_y) can be characterized by the polarization components (Stokes parameters)

$$\eta_1 = \frac{I(45°) - I(135°)}{I(45°) + I(135°)}, \quad \eta_2 = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)},$$

$$\eta_3 = \frac{I(0°) - I(90°)}{I(0°) + I(90°)},$$

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. It can easily be seen from symmetry arguments[1] that only η_3 may differ from zero while η_1 and η_2 must disappear if the incident electrons are unpolarized. If, however, the radiation is excited by polarized electrons one has, in general, also $\eta_1 \neq 0$ and $\eta_2 \neq 0$. That is why studies of the polarization η_3 of impact radiation have been made for quite some time, whereas measurements of η_1 and η_2 could be made only in recent years.

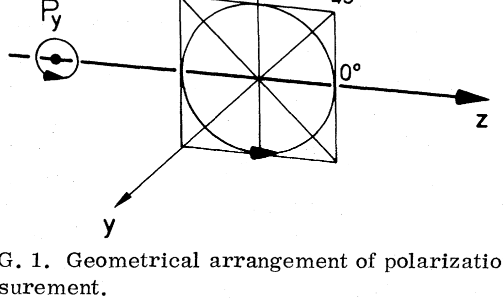

FIG. 1. Geometrical arrangement of polarization measurement.

The interest in such measurements has several reasons. A theoretical analysis[1] has shown that nonvanishing values of η_1 reflect the role of spin-orbit interaction in the process studied whereas the circular polarization η_2 reflects the influence of exchange interaction. Besides giving such specific information on atomic interactions, measurements of the light polarization were proposed to be a suitable means for determining electron polarization.[2] As appropriate candidates for that purpose the following processes have been suggested[3]: excitation of the $ns(n+1)s\ ^3S_1$ states from the $ns^2\ ^1S_0$ ground states of two-electron atoms followed by radiative decay to $nsnp\ ^3P_0$. These processes have the following advantages. (i) The light observed is not resonance radiation so that problems of self absorption do not occur. (ii) The states of interest are Russell-Saunders states so that the connection between the light polarization and the electron polarization could be calculated without difficulty. It was concluded that, as a consequence, this method of electron-polarization analysis needs no experimental calibration.

In a pioneer experiment a few years ago, the circular light polarization produced by polarized electrons has been detected[4] for the transitions $5s\ ^3S_1 \rightarrow 4p\ ^3P_J$ in zinc atoms (ground state $4s^2\ ^1S_0$). Meanwhile the accuracy of such experiments has been considerably improved so that now curves with low statistical error, like that shown in Fig. 2, can be measured. Briefly, mercury atoms in their ground state $6s^2\ ^1S_0$ were excited by an elec-

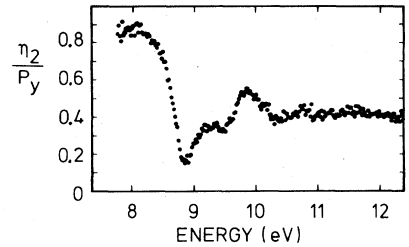

FIG. 2. Circular light polarization η_2 normalized to the transverse electron polarization P_y by which it is caused. Transition Hg $7^3S_1 \rightarrow 6^3P_0$ (404.7 nm).

tron beam having a transverse polarization P_y along the y direction (see Fig. 1). The polarization of the light emitted along the y direction in the transition $7s\,^3S_1 \rightarrow 6p\,^3P_0$ (404.7 nm) was analyzed. The circular polarization on which we are focusing attention here is caused by exchange collisions of the polarized electrons with the Hg atoms, resulting in a preferential orientation of the excited 7^3S_1 state. In other words, the magnetic sublevels $M_y = +1$ and -1 are unequally populated. Accordingly, there is a disparity in the number of transitions obeying the selection rules $\Delta M = +1$ and $\Delta M = -1$ that govern the emission of right and left circularly polarized light. Thus the close connection between exchange collisions and the circular light polarization η_2 is clearly seen.[5]

A detailed description of the apparatus has been given in an earlier paper.[6] Here we mention a few details which are of particular import for the present results. The data of Fig. 2 were obtained with an electron polarization $P_y = 0.24 \pm 0.02$. It has been determined by measuring the asymmetry of elastic electron scattering at the Hg beam for 90° and an energy of 12 eV (Sherman function $S = 0.82$). The energy width of the polarized-electron beam from a GaAs cathode was $\Delta E = 150$ meV; the current at the target 2×10^{-8} A. For energy calibration the resonances[7] in the excitation function of the 404.7-nm line at 8.8 and 9.56 eV have been used. An additional check with the 4.9- and 5.5-eV resonances of the 253.7-nm line has been made. For separation of the 404.7-nm line an interference filter (Schott MA 3-0.3, $\lambda = 405.5$ nm, $\Delta\lambda = 3.8$ nm full width at half maximum) has been used. The neighboring wavelength 407.7 nm ($7^1S_0 \rightarrow 6^3P_1$) could not be completely suppressed. Since the 7^1S_0 state is spherically symmetric this line is unpolarized and thus has a depolarizing influence. Because of the small excitation cross section of the 7^1S_0 state[8] its influence is clearly less than 5% at collision energies below 12 eV. This estimate is also confirmed by a measurement of the linear polarization η_3: We reproduced the shape of the η_3 curve obtained by Fedorov and Mezentsev[9] and though these authors used a light monochromator and thus had a much better spectral resolution, our values are even about 10% larger. This allows us to conclude that below 12 eV the 407.7-nm line does not appreciably disturb the measurements of η_2 shown in Fig. 2. Above 12 eV an increasing depolarization by the 407.7-nm line with increasing energy is expected, due to a relatively increasing cross section of the 7^1S_0 state. Registration of Fig. 2 took 4 h.

We will start the discussion with the remark that, near threshold (7.73 eV), Wykes's theoretical result has been confirmed, who predicted for the line observed a circular polarization η_2 of 88.7% if the incident electron beam is totally polarized. The accuracy of the comparison is limited by the absolute calibration of our electron polarization having an uncertainty of ±10%. As the electron energy is increased, η_2 decreases showing a pronounced structure which we attribute to the resonances above 8 eV that have earlier been found by other authors.[7,9] Another mechanism to affect the light polarization occurs if the electrons have enough energy to excite energy levels above the 7^3S_1 state so that this state becomes populated also by decay of the higher levels ("cascading").

Both resonances and cascading processes tend to lower the orientation of the Hg (7^3S_1) atoms produced by exchange excitation as discussed above. Together with the influence of the 407.7-nm line this explains, qualitatively, the decrease of η_2 with increasing electron energy. Resonances in the excitation function of the $7^3S_1 \rightarrow 6^3P_0$ transition have been found[7,9] at 8.18, 8.80, 9.02, 9.56, 10.51, 10.90, and 11.50 eV. Some of them are clearly seen in Fig. 2 to have a strong influence on the circular light polarization. The 8.8-eV resonance, for instance, reduces the polarization from 88% to 15% within an energy range of 1 eV above threshold! At this energy, the influence of cascading on η_2 has already set in (excitation of 7^3P states); but the measurements show that it is not as strong as the influence of the resonances: Between 11 and 21 eV, the energy up to which the measurements have been extended, the light polarization drops monotonically from 40% to 25%. Taking into account that at these energies one has a great number of cascading processes one finds that the effect of a cascading transition on the circular light polarization is less dramatic than that of a resonance. Incidentally, we expect that a more accurate measurement of the zinc line mentioned above will also yield resonances in the circular polarization since such resonances are clearly seen in the excitation curve.[10]

Without giving the details here, we will mention the following results that have also been obtained in our experiment. The circular polarizations of the 435.8-nm ($7^3S_1 \rightarrow 6^3P_1$) and 546.1-nm ($7^3S_1 \rightarrow 6^3P_2$) lines have been found to be given by curves which are obtained by scaling down Fig. 2 by factors $\frac{1}{2}$ and $-\frac{1}{2}$, respectively. This is what is anticipated from theory.[11] As mentioned before the measurements of the linear polarization η_3 by Fedorov and Mezentsev[9] for $7^3S_1 \rightarrow 6^3P_J$ have been confirmed. Preliminary measurements of the polarization η_1 yielded, within the resonance range, strongly fluctuating curves with values below 10%. Recalling the remark on η_1 at the beginning we conclude that, though exchange interaction is the dominant excitation mechanism, the influence of spin-orbit interaction is visible in the resonance range.

The results show also that it is certainly possible to utilize the circular polarization of nonresonant impact radiation for electron-polarization measurements. Because of the complicated dependence of η_2 on the electron energy, the original proposal[3] to use this method without calibration cannot be recommended except for a narrow region above threshold (cf. Fig. 2). Compared to certain resonance lines, the intensity of the present line is fairly low so that the time needed for the measurements was more than 10 times larger than for the 253.7-nm line.[6]

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