

## LETTER TO THE EDITOR

### A simple optical electron polarimeter

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Received 8 June 1983

**Abstract.** It is pointed out that heavy atoms (i.e. those which have spectroscopically resolvable fine structure) are not required for optical measurements of electron polarisation. A polarimeter which uses helium gas instead of heavy-metal vapour is proposed, and several experimental details are discussed.

Optical detection of electron polarisation was first proposed more than a decade ago by Farago and Wykes (1969). Their scheme involved the exchange excitation of Hg to the  $6^3P_1$  state by polarised electron impact. The resulting  $6^1S_0$ – $6^3P_1$  resonance radiation has circular polarisation (relative Stokes parameter  $S/I$ ) which can be related to the incident electron polarisation  $P$ . In a subsequent paper, Wykes (1971) suggested an alternative method in which the  $ns^2\ ^1S_0$  ground state of Hg, Cd or Zn is excited to the  $ns(n+1)s\ ^3S_1$  level and the resulting  $nsnp\ ^3P_J$ – $ns(n+1)s\ ^3S_1$  radiation is monitored. The  $^3P_J$ – $^3S_1$  multiplet must be resolved in order to observe circular polarisation; this dictates the use of relatively heavy atoms as targets. In the latter scheme,  $S/I$  and  $P$  have a simple relationship (ignoring hyperfine depolarisation) that holds at all incident electron energies for which cascade contributions to the relevant line radiation are negligible. In addition, the problem of radiation self-absorption by the target is significantly reduced. Eminyan and Lampel (1980) have described an experiment in which they measured the longitudinal polarisation of a beam of electrons in this manner, using a Zn-vapour target. More recently, Wolcke *et al* (1983) reported observations of circular polarisation in the Hg  $6^1S_0$ – $6^3P_1$  transition along the polarised electron beam axis. They found that a  $^4P\ Hg^-$  resonance 0.03 eV above the  $6^3P_1$  threshold caused significant deviation of  $S/I$  from the threshold value predicted by Farago and Wykes (1969).

Optical polarimeters have several advantages over devices based on Mott scattering. Their analysing power is generally higher;  $S/I$  for the  $4^3P_0$ – $5^3S_1$  transition in Zn equals  $0.974P$  (Wykes 1971) compared with typical Mott asymmetries of  $\sim 0.4P$ . Polarisation can be measured along any axis without first requiring a spin rotation. Experimental difficulties associated with the use of Au foils (acceleration of the electrons to high energy, the extrapolation of scattering asymmetries to zero foil thickness) in conventional Mott detectors are eliminated as well. The chief disadvantage of the optical method as it has been proposed and employed is the requirement that a heavy-metal vapour be used as the target.

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The purpose of this letter is to suggest that He gas be used in place of Zn, Cd or Hg vapours. We consider exchange excitation of the He  $3^3P_J$  manifold, and measurement of circular polarisation in the  $2^3S-3^3P$ , 388.9 nm multiplet. Immediately following production of the  $3^3P$  state, only the electron spin coordinate is oriented. (Another way to say this is that immediately following excitation, the multiplet must be resolved in order to observe circular polarisation.) At later times, however, the spin-orbit interaction transfers some of this vector polarisation to the atom's orbital coordinates. The time-averaged value of  $S/I$  is thus non-zero *even though the multiplet is unresolved*. The use of a He target results in the following simplifications.

(i) The gas is essentially mono-isotopic, and there is no hyperfine depolarisation of the excited state. In addition, He is sufficiently light that the Russell-Saunders coupling holds to an extremely good approximation. Thus a particularly simple relationship between  $P$  and  $S/I$  can be derived.

(ii) In contrast with the case of Hg (Wolcke *et al* 1983), spin flips resulting from spin-orbit coupling in resonant He<sup>-</sup> states are negligible, as we shall see. In addition, magnetic interactions between the incident electron and the target nucleus, which could also cause spin flips, are greatly reduced.

(iii) Investigations of systematic effects, such as the variation of light polarisation with target atom density, are considerably easier.

We now obtain an expression relating  $S/I$  of the unresolved 388.9 nm multiplet to  $P$ , using the formalism developed by Ellis (1973, 1977). Excitation of the target by a beam of electrons whose momenta are along the  $\hat{z}$  axis and whose polarisation is parallel to  $\hat{x}$  is considered. The excitation may be thought of as impulsive, because the collision time ( $\sim 10^{-16}$  s) is much shorter than the relevant spin-orbit periods ( $10^{-10}$  s <). Thus the initial density matrix is written most simply in the  $LS$  direct product space:

$$\rho(3^3P, t=0) = \rho_L \otimes \rho_S \quad (1)$$

where, in the  $m_z$  basis

$$\rho_L = \frac{1}{3} \begin{pmatrix} 1 + A_0^{\text{col}} & 0 & 0 \\ 0 & 1 - 2A_0^{\text{col}} & 0 \\ 0 & 0 & 1 + A_0^{\text{col}} \end{pmatrix} \quad (2)$$

and

$$\rho_S = \frac{1}{6} \begin{pmatrix} 2 & \sqrt{2}P & 0 \\ \sqrt{2}P & 2 & \sqrt{2}P \\ 0 & \sqrt{2}P & 2 \end{pmatrix}. \quad (3)$$

Equation (2) can be taken as the definition of the Fano-Macek alignment parameter  $A_0^{\text{col}}$ . The simple form of  $\rho_L$  is a result of the axially symmetric (ignoring electron spin) excitation process. The initial spin density matrix is diagonal in the  $m_x$  basis, with elements  $\rho_{jj} = (1 + jP)/3$ . Keeping the notation of Ellis (1973), the time-averaged circular polarisation fraction of light emitted by the He target along the  $\hat{x}$  axis is given by

$$\frac{S}{I} \equiv \frac{I^+ - I^-}{I^+ + I^-} = \frac{C^+ - C^-}{C^+ + C^-} \quad (4)$$

where  $I^+(I^-)$  is the intensity of RHC (LHC) polarised light,

$$C^\pm = \sum_{J,k,q} \langle J \| L^k \| J \rangle \rho_{-q}^k I_q^k(\pm) \quad (5)$$

$$\rho_{-q}^k = \sum_{MM'} (-1)^{M+J} \begin{pmatrix} J & k & J \\ -M & q & M' \end{pmatrix} \langle JM | \rho(t=0) | JM' \rangle \quad (6)$$

$$I_q^k(\pm) = \sum_{q_1 q_2} (-1)^{q_2} \varepsilon_{q_1}^*(\pm) \varepsilon_{q_2}(\pm) \begin{pmatrix} 1 & k & 1 \\ -q_2 & q & q_1 \end{pmatrix} \quad (7)$$

and

$$\hat{\varepsilon}(\pm) = \sqrt{\frac{T}{2}} (\hat{z} \pm i\hat{y}). \quad (8)$$

The sum in equation (5) is over the fine-structure states of the  $3^3P$  manifold,  $k = 2, 1$  and  $0$ , and  $-k \leq q \leq k$ . Finally, the reduced matrix element is given by

$$\langle J \| L^k \| J \rangle = K (-1)^{1+J} (2J+1)^2 (2k+1) \begin{Bmatrix} J & J & 0 \\ J & J & k \end{Bmatrix} \begin{Bmatrix} J & 1 & 1 \\ 1 & J & k \end{Bmatrix} \begin{Bmatrix} 1 & 1 & 0 \\ 1 & 1 & k \end{Bmatrix} \quad (9)$$

where  $K$  is a constant for the multiplet. In general, the expression for  $I^\pm$  contains interference terms proportional to  $\cos[(E_J - E_{J'})t/\hbar]$ , resulting from coherent excitation of the upper-state  $J$  sublevels. These terms have been averaged to zero here, because the  $3^3P$  lifetime is much longer (106 ns) than its fine-structure oscillation periods.

Transforming the initial density matrix to the  $|JM\rangle$  basis and evaluating equations (4)–(9), we find that

$$\frac{S}{I^-} = \frac{18P}{36 - 5A_0^{\text{col}}}. \quad (10)$$

The alignment parameter,  $A_0^{\text{col}}$ , is determined by measurement of the linear polarisation fraction

$$\frac{M}{I^-} \equiv \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} = \frac{-15A_0^{\text{col}}}{36 - 5A_0^{\text{col}}} \quad (11)$$

where we have now evaluated equation (7) using

$$\hat{\varepsilon}(\parallel) = \hat{z} \quad \hat{\varepsilon}(\perp) = \hat{y}. \quad (12)$$

In order to avoid cascades from the  $4^3S$  level, it is necessary to keep incident electron energies within 0.59 eV of the 23.0 eV threshold for  $3^3P$  production. Typical energy widths of GaAs polarised electron sources are such ( $\sim 300$  meV, Pierce *et al* 1980) that this condition can be met without energy selection of the beam. Heddle *et al* (1977) have measured an average  $M/I$  in this energy range of  $\sim 0.08$ , corresponding to  $A_0^{\text{col}} = -0.20$ . The analysing power of the He polarimeter can thus be expected to be 0.49.

Several conspicuous resonances in the 388.9 nm optical excitation function (and corresponding features in the linear polarisation) have been observed between the  $3^3P$  and  $4^3S$  thresholds (Kisker 1972, Heddle *et al* 1977). These resonances, due to short-lived  $\text{He}^-$  states, should not affect  $S/I$ . In contrast with the situation in Hg (Wolcke *et al* 1983), the natural widths of the  $\text{He}^-$  states ( $\sim 30$  meV) are much broader than any fine-structure splittings they are likely to have (Heddle *et al* 1977, Brunt *et*

al 1977, Manson 1971). Indeed, Heddle (1976) has tentatively identified the prominent features at  $\sim 23.04$  and  $\sim 23.36$  eV as  $^2\text{S}$  resonances; no spin flips can occur in such states. We conclude that  $P$  can be extracted directly from measurements of  $S/I$  and  $M/I$ , with no experimental calibration of the apparatus being required.

Finally, we determine the approximate efficiency of the proposed polarimeter. From the measurements of van Raan *et al* (1971) and McFarland (1964), the average  $^3\text{P}$  production cross section within 0.6 eV of threshold can be estimated to be  $8 \times 10^{-20} \text{ cm}^2$ . Heddle and Lucas (1963) have shown that below 5 mTorr, the linear polarisation of the 388.9 nm transition is independent of He target pressure, i.e. the effect of radiation trapping becomes negligible. Assuming, as does Wykes (1971), an optical train which images a 1 cm segment of the beam-target interaction region, has a photon acceptance solid angle of 0.1 sr, and has a detection efficiency of 6%, we calculate the polarimeter efficiency with a target pressure of 5 mTorr to be  $6.7 \times 10^{-9}$ , or  $4.2 \times 10^4$  counts/s  $\mu\text{A}$ . This rate is somewhat higher than that observed by Eminyan and Lampel (1980). If we consider nominal beam currents of 1  $\mu\text{A}$ ,  $P = 0.4$ , and an analysing power of 0.49,  $P$  can be measured to a statistical accuracy of 1% of itself in 6 s of photon counting time. In principle,  $M/I$  need only be measured once in order to determine the exact analysing power of the apparatus.

The author wishes to acknowledge several useful discussions with Dave Ellis. This work was supported by US DOE Grant No DE-AC02-76ER03075.

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