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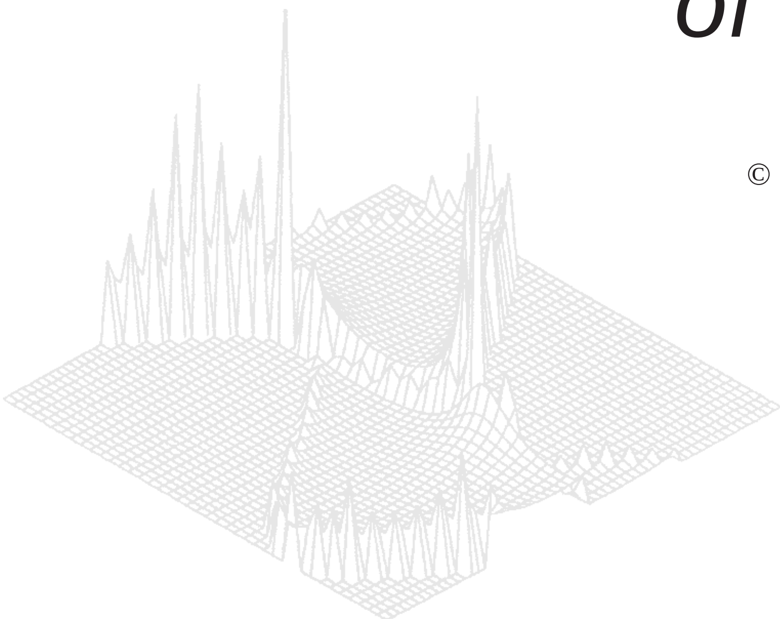

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Polarised Electron Study of Angular Momentum Coupling in the Neon 3p States*

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Abstract

The excitation of the $2p^5 3p[\frac{5}{2}]_3$ and $2p^5 3p'[\frac{1}{2}]_1$ states in the neon 3p manifold by transversally polarised electrons is studied in the electron energy region near threshold and beyond. The spin–orbit and exchange interactions during the excitation are explored by the measurement of integrated Stokes parameters P_2 and P_3 for the decay radiation from these states. Experimental evidence is given for the breakdown of LS coupling for the neon 3p ($J = 1$) state and the important role of spin–orbit and exchange interactions of the atomic electrons for the excitation of the state. Negative ion resonances strongly influence the polarisations of the decay radiations.

1. Introduction

The radiation emitted from electron impact excited atoms is usually polarised and measurement of the Stokes parameters P_i ($i = 1$–4) in coincidence with the scattered electrons leads to details of the collision dynamics (Andersen *et al.* 1988). However, when several processes are involved in the collisions they are usually difficult to separate from each other. Using incident polarised electrons it is possible to disentangle different spin-dependent processes through an analysis of the polarisations of the emitted radiation alone, that is, from measurements integrated over the unobserved electron scattering angles. For example, in some cases the integrated Stokes parameter P_2 (defined below) is an unambiguous signature of spin–orbit effects during the collision (Bartschat and Blum 1982). The close connection between the photon polarisations and the electron spin was given by Bartschat and Blum for such integrated measurements. This paper presents measurements of integrated Stokes parameters for the radiation from the neon $2p^5 3p[\frac{5}{2}]_3$ and $2p^5 3p'[\frac{1}{2}]_1$ states excited by transversally polarised electrons.

2. The Experiment

The emitted radiation is from the transitions $3p[\frac{5}{2}]_3 \rightarrow 3s[\frac{3}{2}]_2$ ($640 \cdot 2$ nm), $3p'[\frac{1}{2}]_1 \rightarrow 3s'[\frac{1}{2}]_0$ ($616 \cdot 4$ nm) and $3p'[\frac{1}{2}]_1 \rightarrow 3s[\frac{3}{2}]_1$ ($603 \cdot 0$ nm). The $2p^5 3p[\frac{5}{2}]_3$ state was studied to provide a benchmark of pure LS coupling. The $J = 1$ state was studied to explore spin-dependent effects during the excitation process because it offered two transitions from the same upper state with wavelengths

* Dedicated to Professor Robert W. Crompton on the occasion of his seventieth birthday.

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of 616·4 and 603·0 nm as well as ΔJ values of zero and 1. Since the photons originate from the same upper state, the information from the excited state should be identical and it should be modified only by the rearrangement of angular momenta in the decay process to lower states by transitions involving different ΔJ values. In this way we have a consistency check on the interpretation of the collision information transferred to the photon.

The incident electron beam direction determines the z axis and the electron spin polarisation direction is either parallel or antiparallel to the y direction along which observations are made of the polarisation of the emitted light. The Stokes parameters are defined in terms of the observed photon intensities by

$$P_1 = \frac{I(0°) - I(90°)}{I(0°) + I(90°)}\,, \qquad P_2 = \frac{I(45°) - I(135°)}{I(45°) + I(135°)}\,, \qquad P_3 = \frac{I(\sigma^-) - I(\sigma^+)}{I(\sigma^-) + I(\sigma^+)}\,, \qquad (1)$$

where $I(\theta)$ is the photon intensity with the transmission axis of the polariser at an angle θ with respect to the electron beam direction z and $I(\sigma^+)$ and $I(\sigma^-)$ are the intensities of the photons with positive and negative helicity respectively.

For collisions of unpolarised electrons with unpolarised atoms with axial symmetry defined for observation of integrated polarisations, the only non-zero Stokes parameter is P_1. However, when polarised electrons are used, the axial symmetry is broken and consequently non-zero values of P_2 and P_3 are possible. A non-zero value of P_3 is possible for radiation from a state excited via an exchange process, for example, radiation from a pure LS coupled triplet state excited from the singlet ground state. A non-zero P_2 is observable only when a spin–orbit interaction, either between the continuum electron and the target atom or within the atom, is effective during the excitation. Since the exchange process alone cannot produce a non-zero P_2, a non-zero P_2 value provides a distinct indication of the presence of spin–orbit interaction in the collision and, when it is confined to within the atom, causes the breakdown of LS coupling for the excited state.

Furst *et al.* (1993) measured zero values of P_2 for the decay radiation from the neon $2p^5 3p[\frac{5}{2}]_3\ ^3D_3$ state excited by polarised electrons. Since the excited state is pure LS coupled, the measured zero value of P_2 indicated that the spin–orbit interaction between the continuum electrons and the target (i.e. Mott scattering) can be neglected during the excitation. They also showed for a non LS-coupled state, the $5p^5 6p[\frac{5}{2}]_2(^3D_2)$ in krypton, that near threshold non-zero values of P_2 are a clear indication of the spin–orbit interaction becoming effective during the excitation process. A similar result was found by Uhrig *et al.* (1994) for the 6s state of xenon.

The apparatus has been described in detail elsewhere (Hayes *et al.* 1996); here we describe only the essential polarisation aspects of the production of spin polarised electrons and of the measurement of the polarised photons from the collision. We have found a description useful since ambiguities can arise from varying definitions of polarisation direction, especially the handedness of the photons. As shown schematically in Fig. 1, a laser illuminates a GaAs crystal with either left-hand (LHCP, σ^+) or right-hand circularly (RHCP, σ^-) polarised light from above. The direction of polarisation is computer controlled through a variable retarder. The GaAs preferentially emits electrons with their spin direction opposite to the angular momentum of the incoming photon. In our case

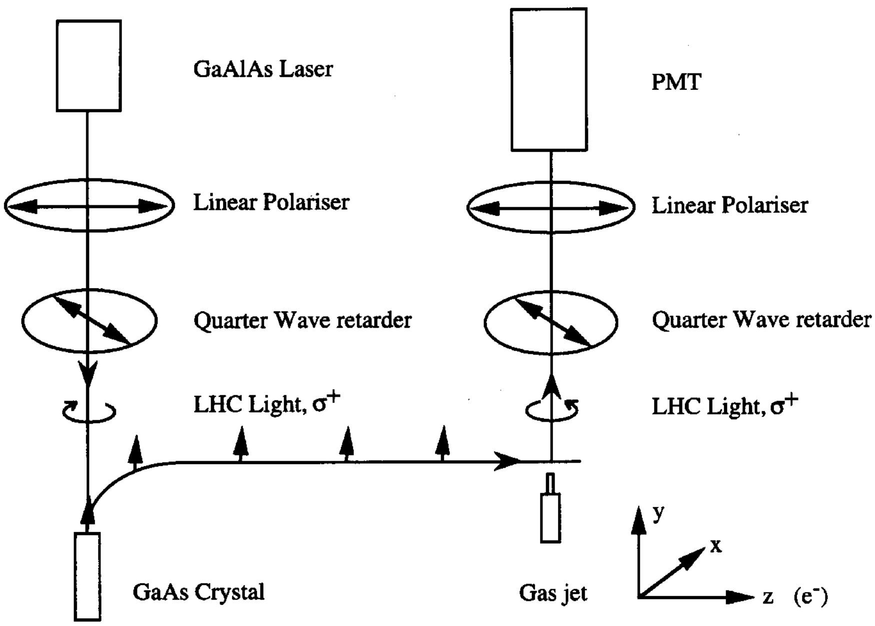

Fig. 1. Directions of the photon and electron polarisations. The downward laser beam is circularly polarised to produce polarised electrons which are transported to excite neon gas. The photons are collected by a photomultiplier tube (PMT), their polarisation being selected by the retarder and polariser.

σ^+ light, spin down photons, will produce a net polarisation up. The degree of electron polarisation is $28\cdot2\pm0\cdot5$% as measured by Ne optical polarimetry (Hayes *et al.* 1996). The polarised electrons are then transported electrostatically to the interaction region where they cross a jet of neon atoms formed from an effusive source. In a pure exchange process in a well LS coupled state, the orientation of the excited atom will be the same as the incoming electron. In this case, spin-up electrons will produce spin-up photons σ^+ from the decaying state and, consequently, a measurement for P_3 of this state would yield a negative value.

3. Results

The experimental values of P_2 and P_3 for the three transitions between the neon 3p and 3s manifolds are shown in Figs 2*a* and 2*b* respectively. The uncertainties in the data include only the statistical uncertainties since the contributions from other sources, for example the solid angle of the optical detector, the divergence of the electron beam and radiation trapping, are negligible.

Fig. 2*a* shows that the values of P_2, measured from below threshold at $18\cdot55$ to 300 eV for the $640\cdot2$ nm photons from the pure LS coupled $3p[\frac{5}{2}]_3\ {}^3D_3$ state, are clearly zero within small experimental uncertainties. These zero values are consistent with the requirements of the LS coupling mechanism discussed above. They agree with those of Furst *et al.* (1993) and confirm that the spin–orbit interactions, both between the continuum electron and the target atom and within the atom, are not significant for the pure LS coupled state. The high

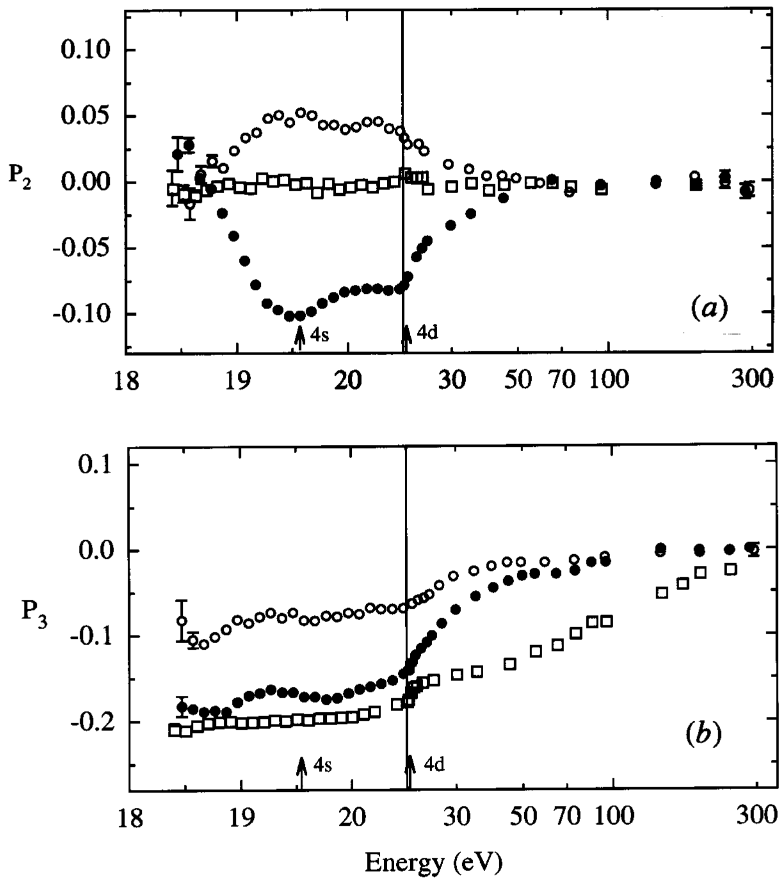

Fig. 2. Stokes parameters (*a*) P_2 and (*b*) P_3 for the 640·2 nm (squares), 616·4 nm (filled circles) and 603·0 nm (open circles) emission lines. Notice the energy scale is changed from linear to logarithmic above 20·5 eV, as indicated by the vertical line, and the threshold energies for 4s and 4d states are marked by the arrows.

P_3 polarisation for the 640·2 nm line shown in Fig. 2*b* also reflects the exchange nature of this collision from the singlet ground state to a triplet excited state. It should be noted that the data have not been scaled to the incident electron polarisation. The initial part of the curve is constant with increasing energy and this is consistent with an exchange process being the only method of excitation. Even resonances in this region are unable to affect P_3 to any significant extent, however they are readily seen in the intensity curves used to derive this plot. As the electron energy increases beyond the excitation threshold of the $n = 4$ states, cascade photons cause a marked drop in P_3 values. The general features of these polarisation curves are becoming well understood.

The P_2 and P_3 data for the 616·4 and 603·0 nm emission lines show unambiguously different behaviour to the 640·2 nm line. The data extend from below threshold at 18·72 to 300 eV. First, in each of Figs 2*a* and 2*b* for the 616·4 and 603·0 nm emission lines, the shapes of the polarisation curves are very similar within experimental uncertainty, the only difference being a multiplicative constant. This is consistent with the photons originating from the same excited upper state $3p'[\frac{1}{2}]_1$ and, as expected, the photons carry away the same information about the collision and hence the polarisation curves can be related directly by a constant of proportionality (Bartschat and Blum 1982). This constant can be calculated exactly through considering the change in angular momentum in the decay to two lower states of differing J. As far as we know, a comparison of two such processes has not been made previously.

Further, the lines from the $3p'[\frac{1}{2}]_1$ state show non-zero values of the P_2 parameter, ranging up to 8%. Again it should be noted that the polarisation measurements have not been normalised to the degree of polarisation of the incident electron beam. These non-zero values are in contrast to the zero P_2 values for the $3p[\frac{5}{2}]_3$ state photons and provide clear evidence of the role of internal spin–orbit interactions in the excitation process for the $J = 1$ state. This conclusion follows from the interpretation of the zero P_2 result for the $3p[\frac{5}{2}]_3$ state photons from the same 3p manifold, that only the spin–orbit coupling within the atom could cause non-zero P_2 values for other states within the 3p manifold.

These results give the first particle-impact collision evidence of the breakdown of LS coupling for the $J = 1$ states in the neon 3p manifold. The applicability of JL coupling for determining the energies of these states was shown definitively, for example, with multichannel quantum defect calculations reproducing highly accurate spectrometric energies (Lee and Lu 1973). The mixing coefficients for these $J = 1$ states were determined by Luke (1986) to be 1·8% $^3S_1$, 68·4% $^3P_1$ and 29·8% $^1P_1$. The large values of P_2 appear to be related to the P-like nature of this excited state whereas, for instance, an S-like state would cause a much lower value.

The two P_3 measurements for the excited $3p'[\frac{1}{2}]_1$ transitions as mentioned earlier show identical behaviour. The 616·4 nm line has characteristics in the circular polarisation equivalent to that of the 640·2 nm, which is also a $\Delta J = 1$ transition. Again P_3 is reasonably constant until the $n = 4$ single electron excited channels start to open and cascade processes begin to dominate. This excited state seems to be fed quite strongly by cascade channels, as evidenced by the rapid drop in circular polarisation as the incident electron energy is increased. In the region up to 2 eV above threshold, there is a slight decrease that we cannot attribute to experimental error. We believe this is due to a resonance or a number of resonances. The 0·4 eV energy resolution of the data does not permit the identification of the resonances.

4. Conclusions

In summary, the $J = 3$ and 1 excited states reveal the strength of the electron exchange process. The well LS coupled state $3p[\frac{5}{2}]_3$ shows a zero P_2 parameter, while the intermediate coupling of the $3p'[\frac{1}{2}]_1$ state is identified from the non-zero P_2. This is the first integrated polarisation measurement in neon to reveal this observation. The exchange process contributing to the non-LS coupled excited state may then allow the initial orientation of the electron to align the excited charge cloud. The large P_2 parameter for this excited state is probably related to the strong triplet and P-like nature of the $3p'[\frac{1}{2}]_1$ state when thought of in the intermediate coupling scheme. As yet, very little explicit theory exists for electron impact in neon. We are in the process of measuring the Stokes parameters for the entire $J = 1$ and 2 states to expand these conclusions.

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