ALIGNMENT EFFECTS IN HEAVY IONIZED BEAM FOIL EXCITED ATOMS

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We have measured the polarization of light emitted in optical transitions in P V, O VII and O VIII, produced by beam foil excitation, using a 400 keV phosphorus beam from a heavy ion accelerator and a 36 MeV oxygen beam from a Tandem Van de Graaff generator.

Since the discovery [1] that the beam foil interaction can provide a source of anisotropically excited atoms, this property has been widely exploited in measurements utilizing quantum beat, field quenching, rf resonance and level crossing techniques [2], and it can sometimes be utilized to obtain cascade-free mean-life measurements [3]. Since nearly any ionization state of any atom is accessible to beam foil excitation, such measurements could greatly extend our knowledge of fine and hyperfine structure, Lamb shifts, g-factors, etc., which is now generally limited to neutral or few times ionized atoms. However, until now, there has been little or no evidence for the persistence of these beam foil excitation asymmetries in highly ionized systems. Although there is presently no satisfactory model for describing the beam foil interaction process, the recent discovery [4] that tilting the foil relative to the beam axis can produce orientation (dipolar excitation anisotropies) indicates that an important portion of the dynamical excitation arises at the foil surface. This gives an added parameter for producing excitation asymmetries, which has also not been tested until now at very high energies.

It has been found that the beam foil source exhibits substantial alignment (quadrapolar excitation anisotropies) for low energies (50 keV–2 MeV) and low ionization states (I–III) which manifests itself in the linear polarization and angular distribution of the emitted radiation. Linear polarization fractions M/I, defines as

$$M/I = (I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp}) , \quad (1)$$

of as high as 20% have been observed for some members of the He I and Li I isoelectronic sequences [5] but more typical are the 6% polarization fractions which have been observed for neutral, singly and doubly ionized oxygen, neon and argon [6]. Polarization fractions of a few percent have also been seen in N IV [7]. However, as has been pointed out by Andrä [8], the trand of measurements in this energy region is such that the alignment seems to decrease with increasing mass of the beam and with increasing charge of the excited atoms. For this reason we have sought to extend the range of energies, masses and charge states for which such polarization measurements have been made. It is well known [9] that transitions along the "Yrast Line" [10] of states of highest angular momentum can totally transfer their alignment in cascade processes, so special attention was given to these transitions.

Polarization measurements were performed using an analyzer consisting of a rotatable linear polarizer and a demountable achromatic quarter wave plate. The linear polarization analyzer consisted of a polaroid transmission filter followed by and mounted coaxially with a Hanle scrambler depolarizer, which eliminated virtually all instrumental polarization effects. In preparation for these measurements the optical axes of the polarizer and depolarizer were precisely adjusted on an optical bench so that light polarized by the filter was

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Table 1
Measured linear polarization in 350 keV phosphorus and 36 MeV oxygen beam foil excited ions, compared with theoretical predictions for electron impact excitation.

Ion	Wavelength (Å)	Transition ($n-n'$)	M/I (%)		
				Electron impact theory	
			Expt.	High energy	Low energy
P V	4943	6h–7i	+ 6±1	−23.6	+38.2
O VII	3880	7–8	− 7±2	−23.3	+37.7
O VIII	4345	8–9	− 7±1	−23.4	+37.9
O VIII	6075	9–10	−10±3	−23.1	+37.5
O VIII	4665	10–12	− 6±3	−22.6	+36.8

pseudo depolarized by the scrambler to within the fluctuations in a bench mounted regulated discharge lamp source, which were ~1/10%. Stokes parameter measurements were made with the linear polarizer axis set at angles of 0, 45, 90 and 135 degrees to the beam, with and without the quarter wave plate (fast axis along the beam). The phosphorus measurements were performed using the 400 keV heavy ion accelerator at Forskningsinstitutet för Atomfysik in Stockholm and the oxygen measurements were made at the 6 MeV tandem Van de Graaff Laboratory at the University of Uppsala. The foil chambers and monochromators at the two accelerators were essentially equivalent and the same polarization analyzer system was used at both laboratories. The entire system was tested in place at the 400 keV accelerator by observation of beam foil light from several He I transitions of known polarization. The He I 2p $^1P^0$ – 4s ^1S transition at 5047 Å was determined to have $M/I = 0 \pm 1\%$ in agreement with the spherical symmetry of the wave function. The He I 2s ^1S – 3p $^1P^0$ transition was determined to have $M/I = 17 \pm 2\%$ at 200 keV, in excellent agreement with previous measurements [4]. The circular polarization measurement capabilities of the system were qualitatively tested in place using grazing scattering of a beam by a solid target [11]. Thus the system was considered to be capable of reliable determination of the Stokes parameters of beam foil emitted light.

The results are presented in table 1. The polarization was found to be positive in phosphorus and negative in all of the oxygen levels studied, suggesting that a different excitation mechanism is acting at 36 MeV than at 350 keV. The similarity of the magnitude of the various polarizations in the oxygen transitions is quite striking, and indicates a similarity among these highly excited levels. The hydrogenic or nearly hydrogenic L-degeneracy of this type of transition prevented the yrast portion from being resolved for the high lying $\Delta n = 1$ transition in oxygen, but it was possible to resolve the yrast portion for P V, 6–7. However, the similarity of the polarization of $\Delta n = 1$ and $\Delta n = 2$ transitions in O VIII implies that non-yrast transitions also possess alignment. Stokes parameter measurements were made for all of these transitions using foils tilted at 30° to the beam. No appreciable circular polarization was observed for any of the levels studied, but the linear polarization diminished by more than a factor of two with tilted foils.

It is possible to compare these results with theoretical predictions for electron impact excitation, using a mathematical formalism presented by Fano and Macek [12]. For a foil excited beam for which the foil surface and the viewed photons are both perpendicular to the beam direction the linear polarization of radiation emitted in a transition between initial and final states of orbital angular momenta L and L' with unresolved fine and hyperfine structure arising from electronic and nuclear spins S and I is given by

$$M/I = 3h^{(2)}QA_0^{\mathrm{col}}/[4 + h^{(2)}QA_0^{\mathrm{col}}] \,, \qquad (1)$$

where

$$h^{(2)} = (-)^{L-L'} \begin{Bmatrix} L & L & 2 \\ 1 & 1 & L' \end{Bmatrix} \Big/ \begin{Bmatrix} L & L & 2 \\ 1 & 1 & L \end{Bmatrix} \,, \qquad (2)$$

and

$$Q = \sum_{JF} \frac{(2F+1)^2(2J+1)^2}{(2I+1)(2S+1)} \begin{Bmatrix} F & F & 2 \\ J & J & I \end{Bmatrix}^2 \begin{Bmatrix} J & J & 2 \\ L & L & S \end{Bmatrix}^2 \,, \qquad (3)$$

and A_0^{col} is the only non-vanishing component of the collision frame alignment tensor. For $L' = L - 1$, eq. (2) reduces to

$$h^{(2)} = -(L+1)/(2L-1) .$$

For $S = I = 0$, $Q = 1$, and for non zero S and I it approaches unity for large L, e.g. for $I = 0$, $S = \frac{1}{2}$

$$Q = [4L(L+1) - 5]/(2L+1)^2 . \quad (5)$$

Thus if a A_0^{col} can be predicted by some model eq. (1) infers M/I. For the case of excitation by electron impact, Fano and Macek [11] have used the Born approximation and angular momentum considerations to show that A_0^{col} has the asymptotic limits ‡

$$A_0^{col} \to -1 \text{ (low energy electron impact)}$$
$$\to +\tfrac{1}{2} \text{ (high energy electron impact)} . \quad (6)$$

Table 1 also includes the limits of possible polarizations implied by eqs. (1), (4) and (5) together with the limits of eq. (6). Although the electron impact model probably bears little resemblence to the beam foil excitation mechanism, it nevertheless provides a useful comparison with our results in the absence of any better model.

‡ The rigorous limits are $-1 \leqslant A_0^{col} \leqslant (2J-1)/(J+1)$. Notice also that, due to the negative sign inherent in $h^{(2)}$, the signs of A_0^{col} and the M/I it implies are opposite.

Clearly the sign of the polarization is consistent for the high and low energy limits.

The results indicate alignment is a very general property of the beam foil excitation, and can occur over a very wide range of beam energies, particularly for transitions of the yrast type.

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