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Anisotropy in the Beam-Foil Light Source

H. G. Berry
Department of Physics, University of Chicago, Chicago, Illinois 60637

and

L. J. Curtis, D. G. Ellis, and R. M. Schectman
Department of Physics and Astronomy, University of Toledo, Toledo, Ohio 43606
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We have measured the polarization state of the light emitted in the ^{4}He I, $2s\,^1S$-$3p\,^1P$ transition after excitation in a beam-foil experiment and find a partial elliptical polarization which depends upon the tilt angle of the carbon foil relative to the beam axis. This indicates that the emergent beam is oriented as well as aligned as a result of an interaction at the foil surface. The relative excitation cross sections and off-diagonal density-matrix elements have been deduced for the angular-momentum sublevels.

Beam-foil measurements are generally made with the foil perpendicular to the beam axis. With the use of this geometry, excited beam ions were first shown to be aligned in quantum-beat measurements[1] of the 3889-Å, $2s\,^3S$-$3p\,^3P$ transition in ^{4}He I. Such quantum beats only occur if the alignment is nonzero as shown by Macek[2] and more recently by other authors.[3-6] Cylindrical symmetry around the beam axis is generally assumed, although recently it has been shown that there is no reflection symmetry in the plane of the foil for the hydrogen $2s$, $2p$ excited states.[7-9]

However, since the excitation involves only one axis (that of the beam), no pseudovector can be formed and thus no circular polarization can be produced. Two recent theoretical papers[5,6] consider the beam-foil excitation not assuming cylindrical symmetry. If we tilt the foil axis relative to the beam axis *and* if the foil-surface direction affects the state of the excited beam, it should then be possible to observe a nonvanishing circular-polarization component as well as changes in the linear-polarization component of the emitted light as a function of this tilt angle. From these measurements the orientation and alignment of the emergent beam can be deduced. In a recent experiment, Eminyan *et al.*[10] have measured the relative excitation amplitudes (except for a sign of the phase) for the angular-momentum sublevels in the ^{4}He I $3p\,^1P$ state, but in a crossed-beam experiment of electrons and helium atoms.

Using a 400-kV Van de Graaff accelerator at the University of Toledo, we have accelerated ^{4}He$^+$ ions to 135 keV and, after magnetic analysis, directed them through thin carbon foils of about 6 μg cm^{-2} thickness. The beam energy after the foil was measured by time-of-flight analysis, which was checked by a measurement of the Doppler shift of the light emitted at 53° to the beam direction. Up to 20 foils were mounted so that they could be separately rotated into the beam, each foil set with the normal to its plane at an angle α to the beam axis, where $\alpha = 0°$, 20°, 30°, 45° to within ±1°. Figure 1 shows the geometrical arrangement and relevant angles used

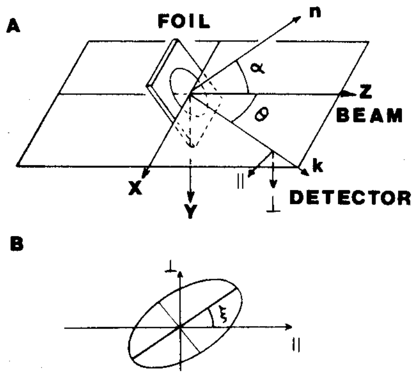

FIG. 1. (a) Beam and viewing geometry. The foil normal $\hat{n}$ is tilted at an angle α to the beam axis $\hat{z}$. The light vector $\hat{k}$ is in the $\hat{x}$-$\hat{z}$ plane, perpendicular to the $\hat{n}$-$\hat{y}$-$\hat{z}$ plane, at an angle θ to the z axis. (b) Polarization ellipse tilted at an angle ξ to the parallel direction.

for optical detection of the radiation emitted by the beam after foil excitation. We observed the $2s\ {}^1S$-$3p\ {}^1P$ transition in ^{4}He I at 5016 Å with a $\frac{1}{3}$-m Heath monochromator equipped with a Centronic 4283 photomultiplier. Photon counts were normalized to total beam charge collected in a Faraday cup. A single fused-silica lens focused light from the beam onto the monochromator entrance slit and was separated from the target chamber vacuum by viewing windows set perpendicular to the detected light. A quarter-wave plate could be inserted between the beam and the lens, and a rotatable polarizer was mounted between the lens and entrance slit.

The instrumental polarization was zero. This was achieved by introducing a "Hanle depolarizer" immediately after the polarizer.[11] Thus, light entering the entrance slit was polarization scrambled and the instrument became polarization insensitive. This was checked using a helium discharge tube illuminating a piece of frosted glass in place of the beam-foil light source; measurements at 5016 Å confirmed that the residual polarization was less than 0.2%. At this wavelength we also adjusted the axes of the quarter-wave plate relative to the polarizer axes, measured its transmission coefficients in the two polarization directions ∥ and ⊥, and determined its retardation (it was a quarter wave near 6000 Å).

The intensity and polarization condition of a beam of light can be specified completely by its four Stokes parameters,[12] which we denote as the vector $\underline{S} \equiv (I,M,C,S)$. Thus, for each foil tilt angle α and each observation direction angle θ we made sets of six measurements to determine $\underline{S}$: three without the quarter-wave plate with the polarizer axis at 0°, 45°, and 90° to the beam-detector plane, and three similar measurements with the quarter-wave plate in place. A number of these sets of six measurements were made for each foil tilt angle at each observation angle. Different foils with the same tilt angle were compared and the results were found to be the same to within experimental accuracy. We should note that previous experiments have shown the polarization to be independent of foil thickness in the range 5–15 μg cm^{-2}.[13] The polarization of the 5016-Å transition (with a perpendicular foil) has been measured as a function of time after excitation.[13] It is important to note here that cascade effects were found to be negligible and that the polarization fraction remains constant throughout the decay.

Table I shows the results of our measurements of the light emitted at two different angles to the beam axis. M/I is the standard linear-polarization fraction (positive if the component parallel

TABLE I. Stokes parameters for the 5016-Å, ^{4}He I, $2s^1S$-$3p^1P$ transition at 130 keV beam energy (see text for definition of symbols).

View angle θ	Foil angle (deg)	M/I	C/I	S/I	f_p	$\xi = -\frac{1}{2}\tan^{-1}(C/M)$
90	0	0.158(12)	−0.016(40)	0.007(58)	0.158(12)	0.0
	20	0.132(22)	−0.082(13)	0.042(22)	0.160(23)	16 ± 4
	30	0.123(29)	−0.042(25)	0.114(68)	0.171(78)	10 ± 6
	45	0.084(28)	−0.140(23)	0.105(10)	0.194(38)	30 ± 5
53	0	0.127(15)	···	···	0.127(15)	0.0
	20	0.106(10)	−0.045(18)	0.033(20)	0.120(29)	12 ± 5
	30	0.087(15)	−0.069(31)	0.093(29)	0.145(45)	22 ± 12
	45	0.059(18)	−0.077(07)	0.107(37)	0.144(42)	40 ± 15

to the beam-detector plane dominates), and its strong variation (a factor of 2) shows immediately that the *foil surface direction* relative to the beam direction affects the beam alignment along the beam axis. This is direct evidence that the final surface interaction is important in the beam-foil interaction mechanism. The polarization fraction for the untilted foil is in good agreement with previous measurements.[14]

The ratio C/M measures the tilt angle ξ of the polarization ellipse to the beam-detector plane. It must be zero for an untilted (normal) foil. Thus, ξ being positive (see Fig. 1), we find that the major axis of the ellipse always lies between the beam axis $\hat{z}$ and the foil surface normal $\hat{n}$.

The Stokes parameter S measures the amplitude of the circular polarization component. It also must be zero for an untilted foil, as we observe within our statistical error. The positive sign indicates that we observed right-handed polarization (negative photon helicity).

The polarization fraction $f_p = (M^2 + C^2 + S^2)^{1/2}/I$ appears to increase slightly with increasing tilt angles.

The Stokes parameters of the emitted light are related to the alignment and orientation of the excited atoms. In the spherical-tensor notation of Ref. 5, with the assumption of a spin-independent beam-foil interaction and reflection symmetry in the y-z plane, these relations are

$$\begin{aligned}
I &= I_0[2 + (\tfrac{3}{10})^{1/2}\rho_0^{\,2}(2 - 3\sin^2\theta) + (\tfrac{9}{5})^{1/2}\rho_2^{\,2}\sin^2\theta],\\
M &= I_0[-3(\tfrac{3}{10})^{1/2}\rho_0^{\,2}\sin^2\theta - (\tfrac{9}{5})^{1/2}\rho_2^{\,2}(1+\cos^2\theta)],\\
C &= I_0\tfrac{6}{5}\sqrt{5}\,\rho_1^{\,2}\sin\theta, \quad S = I_0 2\sqrt{3}\,\rho_1^{\,1}\sin\theta.
\end{aligned} \tag{1}$$

Here I_0 is a normalization constant, the second-rank tensor components $\rho_0^{\,2}$, $\rho_1^{\,2}$, $\rho_2^{\,2}$ define the alignment, and the first-rank component $\rho_1^{\,1}$ measures the orientation.[6]

For measurements at a single photon emission angle θ only the three ratios M/I, C/I, and S/I can be determined. Consequently we have made measurements at two angles: $\theta = 90^0$ and $\theta = 53^0$. The four density-matrix components are then overdetermined: The resulting values are listed in Table II.[15] Because of the dipole nature of the optical emission, the Stokes parameters are sensitive to tensor components $\rho_q^{\,k}$ with $k \leq 2$ only. These are sufficient to determine completely the density matrix ρ for the excited ^1P level studied here. This technique can be used to determine the alignment and orientation parameters in the general case, but ρ will have undetermined tensor components of rank $k > 2$.

In interpreting our results it is instructive to consider the measurements at $\theta = 90^0$, viewing photons emitted in the $+x$ direction. For that case the Stokes parameters are directly related to expectation values of the components of orbital angular momentum along the axes shown in Fig. 1:

$$\begin{aligned}
M/I &= \langle L_y^{\,2} - L_z^{\,2}\rangle / \langle L_x^{\,2}\rangle,\\
C/I &= 2\,\mathrm{Re}\langle L_y L_z\rangle / \langle L_x^{\,2}\rangle,\\
S/I &= -\hbar\langle L_x\rangle / \langle L_x^{\,2}\rangle,
\end{aligned} \tag{2}$$

where M/I is related to the alignment along the beam axis, while C/I measures the correlation of L_y and L_z. There can be no $\langle L_y L_x\rangle$ or $\langle L_z L_x\rangle$ correlation because of the reflection symmetry in the yz plane. The observation of a nonvanishing S indicates the presence of a net x component of angular momentum. Thus, classically, the atom has a preferred direction of orbital motion in the yz plane. Since we find S is positive in our geometry, this makes $\langle L_x\rangle$ negative which corresponds classically to the emitting electron pref-

TABLE II. Density-matrix components.

Foil tilt angle (deg)	$\rho_0^{\,2}/\sqrt{30}$ $\langle 1\vert\rho\vert 1\rangle - 1/3$	$\rho_2^{\,2}/\sqrt{5}$ $\langle 1\vert\rho\vert -1\rangle$	$i\rho_1^{\,2}/\sqrt{10}$ $\mathrm{Im}\langle 0\vert\rho\vert 1\rangle$	$+\rho_1^{\,1}/\sqrt{6}$ $-\mathrm{Re}\langle 0\vert\rho\vert 1\rangle$
0	−0.030(12)	−0.016(9)	⋯	⋯
20	−0.027	−0.012	−0.017(5)	0.009(8)
30	−0.024	−0.008	−0.015	0.027
45	−0.018	+0.0002	−0.028	0.029

erentially orbiting clockwise when viewed as in Fig. 1. We note that our measurements imply $\langle L_x^2\rangle \simeq \langle L_y^2\rangle$, an equality which is not a necessary consequence of the excitation geometry. If, on the other hand, a pure state of the form described by Eminyan *et al.*[10] were produced in the interaction, then necessarily $\langle L_x^2 - L_y^2\rangle$ would equal $\langle L_z^2\rangle$ which here is approximately $0.6\hbar^2$.

In conclusion, we note that this experiment has indicated a surprisingly large surface effect in beam-foil excitation. The asymmetric interaction at the surface has induced a relatively large orientation of the angular momentum of the atom. It should therefore be possible to observe quantum beats between states with F or $J=0$ and 1 using a tilted foil. These beats have zero amplitudes for untilted foils but will become observable when a circular-polarization component can be measured.[5]

Work is in progress to measure the dependence of the orientation and alignment on beam energy as part of a study of the beam-foil interaction in terms of the excitation amplitudes and their phases. Observation of $J=0$ and 1 quantum beats with circular polarization would provide a useful corroboration of these results.

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[15] We also give in Table II all the independent density-matrix elements in the more familiar representation $\langle M_L|\rho|M_L'\rangle$ with the beam direction as the quantization axis.