Alignment and orientation of the $3p\ ^3P$ He I term after tilted-foil excitation

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We have measured the optical-polarization parameters of the $2s\ ^3S$-$3p\ ^3P$ He I transition following tilted-foil excitation of fast-helium beams of 50- to 900-keV energy. From these measurements we have obtained the alignment and orientation parameters for the $3p\ ^3P$ state over foil-tilt angles of $0°-70°$ for this beam-energy range. We compare our results with those for the $3p\ ^1P$ state and note that one alignment parameter is independent of foil-tilt angle.

I. INTRODUCTION

The first observations[1] that a fast beam excited by a tilted thin foil produces atomic orientation proved conclusively that the final surface of the foil is important in producing the excited-state distributions of the ions. The degree of orientation and alignment produced in foil excitation is important for quantum-beat measurements of atomic structure.[2] Also, our understanding of the microscopic processes of the final-surface interaction with the fast ions is still far from complete. Several investigations have used measurements of alignment and orientation to probe this final-surface interaction, and they are reviewed by Schectman *et al.*[3] and Pinnington *et al.*[4]

The only systematic study of the variation of alignment and orientation over extended ranges of both foil-tilt angle (α) and ion-beam energy is that of Ref. 3 for the $3p\ ^1P$ and $4d\ ^1D$ states of He I. In this paper we have made similar measurements of the same parameters for the $3p\ ^3P$ state of He I over the same beam-energy and foil-tilt-angle ranges. Comparisons of these results show that although the alignment and orientation parameters for the $3p\ ^1P$ and $3p\ ^3P$ states are, in general, similar, there are some significant differences.

II. EXPERIMENT

We have measured the Stokes parameters of the transition $2s\ ^3S$-$3p\ ^3P$ of He I after excitation of He^+ beams of energy $E=50-900$ keV by thin carbon foils tilted at angles of $\alpha=0°-70°$ to the beam axis. To cover this large beam-energy range, the following three different He^+ accelerators were used: (1) the Argonne Dynamitron accelerator $E=500-900$ keV, (2) the Edmonton electrostatic accelerator $E=100-350$ keV, and (3) the Argonne electrostatic accelerator $E=50-100$ keV.

The technique used for measuring the Stokes parameters M/I, C/I, and S/I is similar to that described previously (e.g., Refs. 3–5). The light emitted at 90° to the beam axis passes through a rotating phase plate and a fixed linear polarizer into a spectrometer set for the wavelength 3889 Å of the $2s\ ^3S$-$3p\ ^3P$ transition and is detected by a cooled photomultiplier. The fine structure of the upper state ($J=0,1,2$) causes the polarizations M, C, and S to be modulated in time after the foil excitation. These quantum-beat frequencies are $\omega_{02}=8772$ MHz and $\omega_{12}=659$ MHz. The high frequency ω_{02} is unresolved spatially. One aspect, which differs from previous measurements,[4] is that we average our results over the frequency ω_{12} as well, making ten sets of Stokes parameter measurements over one beat length. From each such set we then obtain the time-averaged Stokes parameters $\langle I\rangle$, $\langle M\rangle$, $\langle C\rangle$, and $\langle S\rangle$. In order to obtain the three alignment parameters and one orientation parameter at each foil-tilt angle and beam energy, we measure the time-averaged Stokes parameter for light emitted in two directions, both at 90° to the beam axis: the two directions used are perpendicular to and in the plane containing the beam direction $\hat{v}$ and the foil surface normal $\hat{n}$. Figure 1 shows an example of such a set of data. Note the reduced spatial resolution of the overall quantum

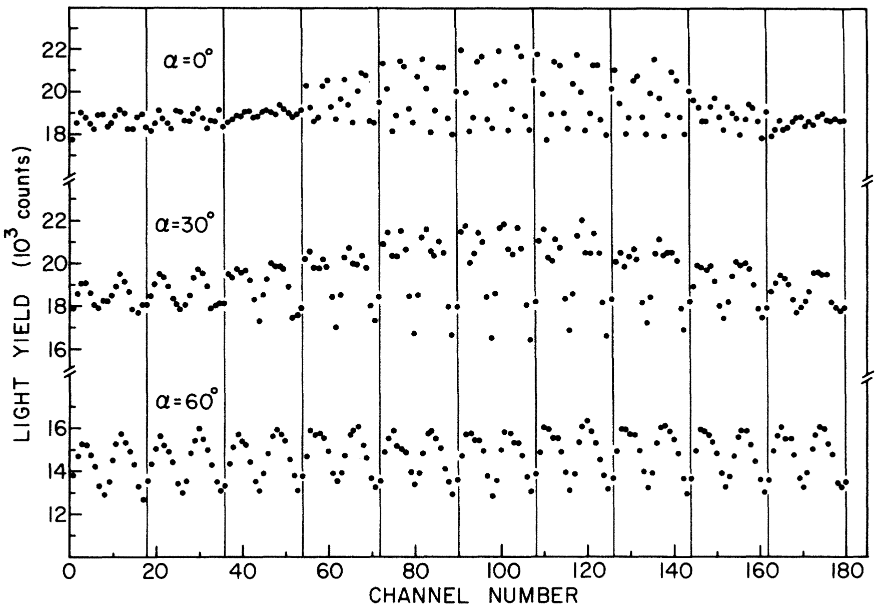

FIG. 1. Polarization data observed for a set of foil-tilt angles ($\alpha=0°$, 30°, 60°), each taken over one beat length of $J=1-2$ of the 3889-Å transition. The data consist of an 18-step rotation (20 deg/step) of the phase plate at ten equidistant positions along the beat. The beam energy is 300 keV. Statistical errors (square root of data) apply.

beat at the high tilt angles. For $\alpha=0°$, the linear polarization M/I is close to zero for the third and last sections. M/I is negative in the first two sections as shown by the opposite phase of the oscillations. The circular polarization component S/I, dominates the modulations of $\alpha=30°$ and 60°, and is of half the frequency of the linear polarization components.

Choosing a z axis parallel to the beam axis and a y axis perpendicular to both $\hat{v}$ and the foil normal $\hat{n}$ (see Fig. 9.2 of Ref. 6), one can write

$$\langle M\rangle/\langle I\rangle = -1.5(A_0^c \pm A_2^c)(1+F)^{-1}Q_2 , \quad (1)$$

$$\langle C\rangle/\langle I\rangle = -3A_1^c(1+F)^{-1}Q_2 , \quad (2)$$

$$\langle S\rangle/\langle I\rangle = 3O_1^c(1+F)^{-1}Q_1 , \quad (3)$$

where Q_i ($i=1,2$) are the fine-structure depolarization factors,[7] and

$$F=\tfrac{1}{2}(-A_0^c \pm 3A_2^c)Q_2 . \quad (4)$$

In Eqs. (1) and (4) the negative sign corresponds to observations perpendicular to $\hat{z}$ and $\hat{n}$ ($\theta=\phi=\pi/2$, y-axis observation). The positive sign corresponds to the observations in the plane of $\hat{z}$ and $\hat{n}$ ($\theta=\pi/2$, $\phi=0$, x-axis observation) when both C/I and S/I are zero. The alignment and orientation parameters are defined after Fano and Macek[8]

$$A_0^c = \langle 3L_z^2 - L^2\rangle/L(L+1) , \quad (5)$$

$$A_1^c = \langle L_xL_z + L_zL_x\rangle/L(L+1) , \quad (6)$$

$$A_2^c = \langle L_x^2 - L_y^2\rangle/L(L+1) , \quad (7)$$

$$O_1^c = \langle L_y\rangle/L(L+1) . \quad (8)$$

The four parameters A_0^c, A_1^c, A_2^c, and O_1^c can be derived algebraically at each value of (E,α) from the single measurements of $\langle C\rangle/\langle I\rangle$ and $\langle S\rangle/\langle I\rangle$, and the two measurements of $\langle M\rangle/\langle I\rangle$ ($\phi=0°$ and 90°). The parameters make up just one set of the magnetic-dipole and electric- quadrupole distributions of the electronic wave function of the excited $3p\,^3P$ state. Many other linear combinations are used in the literature[9] and we show in our analysis that other linear combinations may be more significant in this case.

III. RESULTS

We have made polarization measurements at 12 different beam energies for the helium ion exiting from the foils. The beam energies incident on the foils were adjusted approximately to take account of the small increase of energy loss in the more tilted foils. The 12 energies are 50, 80, and 100 keV at Argonne; 150, 200, 250, and 300 keV at

Edmonton; and 515, 620, 700, 800, and 900 keV at Argonne (on the dynamitron accelerator). In Figs. 2 and 3 we show the polarization results for eight of these energies.

Several features of the data are immediately apparent in these two figures: we note that the shapes of the dependence on tilt angle of the four measured Stokes parameters, $M/I(\phi=0°)$, $M/I(\phi=90°)$, S/I, and C/I, are the same for all beam energies. Furthermore, the values of these parameters change only slowly with beam energy. Also, the observed values of M/I $(\phi=0°)$ show no significant variation with foil-tilt angle for each beam energy.

IV. DISCUSSION

Since the interaction of the helium ions with the foil should be purely electrostatic, very little spin dependence of the excitation is expected. Hence, it is interesting to compare our measurements of the alignment and orientation of the $3p\,^3P$ state with those of the $3p\,^1P$ state.[3,10] Differences of the excitation of these two states may occur since the strong field interactions of the foil with the moving ion can cause mixing of these two states with other $n=3$ states and, in general, this mixing can be different for the singlet and triplet states.[11,12]

Although the alignment and orientation parameters have been measured as functions of two variables (beam energy and foil-tilt angle), the similarities of the curves shown in Figs. 2 and 3 for the different beam energies enable us to consider more simply their variations just for one or two specific foil-tilt angles. Thus, we have made straight-line fits to the data as a function of foil-tilt angle α for the Stokes parameters S/I, C/I, and M/I $(\phi=0°)$. The last is a constant independent of α. Note that at all measured energies S/I increases monotonically with tilt angle thereby confirming previous Edmonton results[4] obtained using a somewhat different technique.

In Fig. 4 we compare the orientations of the $3p\,^1P$ and $3p\,^3P$ states. Both sets of results show very little energy dependence, but the $3p\,^3P$ orientation is, in general, about 50% greater. Note that spin-orbit depolarization effects have been taken into account here and for the other alignment and orientation parameters.

The alignment parameter A_1^c is directly proportional to C/I, and Fig. 5 shows the similar results obtained by us for $3p\,^3P$ and by Schectman *et al.*[3] for $3p\,^1P$, for a foil-tilt angle of 60°. We note that A_1^c changes sign at high and low velocities.

The remaining two alignment parameters A_0^c and A_2^c can be obtained from measurements of M/I

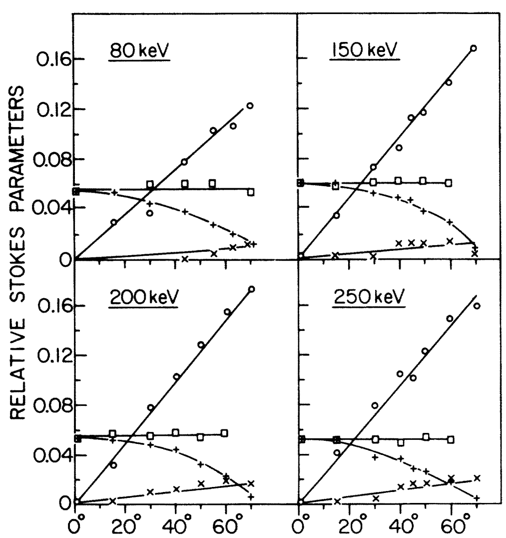

FIG. 2. The quantum-beat-averaged polarizations: $\langle S\rangle/\langle I\rangle$ (o), $\langle C\rangle/\langle I\rangle$ (×), $\langle M\rangle/\langle I\rangle$ $(\phi=\pi/2)$ (+), $\langle M\rangle/\langle I\rangle$ $(\phi=0)$ (□), as functions of foil-tilt angle for the 3889-Å, $2s\,^3S$-$3p\,^3P$ transition at beam energies of 80, 150, 200, and 250 keV. Errors are ±0.003 indicated by symbol size.

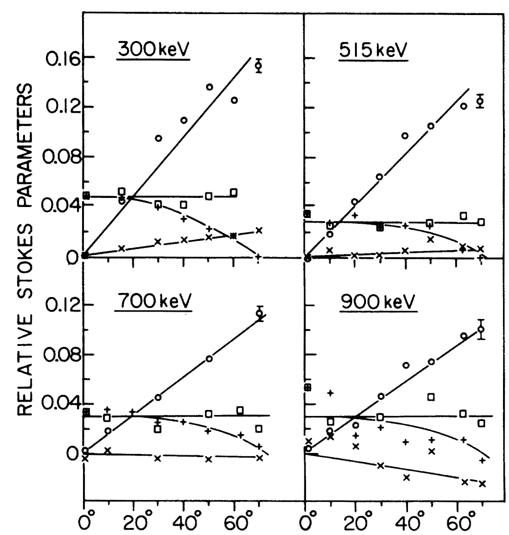

FIG. 3. The quantum-beat-averaged polarizations for the 3889-Å, $2s\,^3S$-$3p\,^3P$ transition at beam energies of 300, 515, 700, and 900 keV. The same labeling is used as in Fig. 2. Errors for all points indicated by symbol of S/I at 70°.

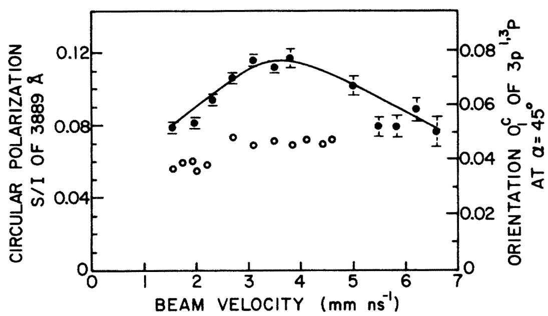

FIG. 4. Comparison of the orientation O_1^c for the $3p\,^1P$ (open circles, Ref. 3) and $3p\,^3P$ states (closed circles) at a foil-tilt angle of $\alpha=45°$. The left-hand scale gives the $\langle S\rangle/\langle I\rangle$ values of the transition from $3p\,^3P$ only (multiply left scale by $1/Q_1=2$ for S/I of the $3p\,^1P$ transition). Errors indicate one standard deviation of the measurements while the plotted points for the triplets come from the curves of Figs. 2 and 3. Singlet uncertainties are approximately ± 0.007 (measured polarization).

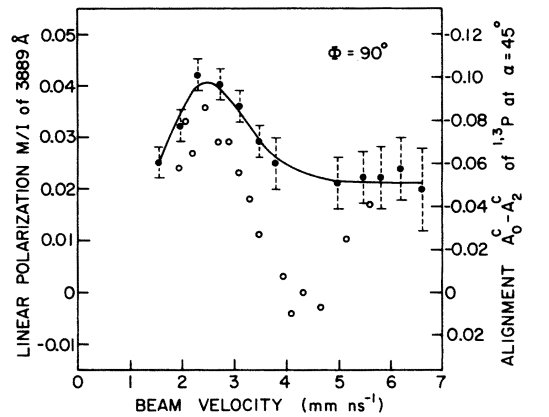

FIG. 6. Comparison of the alignment $A_0^c - A_2^c$ for the $3p\,^1P$ (open circles, Ref. 3) and the $3p\,^3P$ (closed circles) states at a foil-tilt angle of 45°. The left-hand scale gives $\langle M\rangle/\langle I\rangle$ values of the transition from $3p\,^3P$ only (multiply left scale by $1/Q_2=3.60$ for M/I of the $3p\,^1P$ transition). Comment of Fig. 4 regarding errors applies.

taken with $\phi=\pi/2$ and 0. Figures 6 and 7 display our results of $\langle M\rangle/\langle I\rangle$ for $3p\,^3P$ along with the results of Schectman *et al.*[3] for $3p\,^1P$ for a foil-tilt angle of 45°. The trends for this tilt angle are typical of other angles though the magnitudes do scale as discussed previously (see Figs. 2 and 3). Again the triplet values are larger than the corresponding singlets. More significantly, the general behavior for the triplets with increasing beam velocity appears different from the singlets. The pronounced minimum at a velocity of 4.3 mm/ns which appears for the singlets is absent on the triplet curve. We have remeasured four singlet values between 2.6 and 3.7 mm/ns and have reproduced both the sharp decline and the proper magnitude for a tilt angle of 50°.

Little additional information would be gained by plotting A_0^c and A_2^c separately. The former would look very much like the plots shown while the latter is a difference of nearly equal numbers causing a significant loss in precision. Granting that, A_2^c does appear to be nearly independent of beam

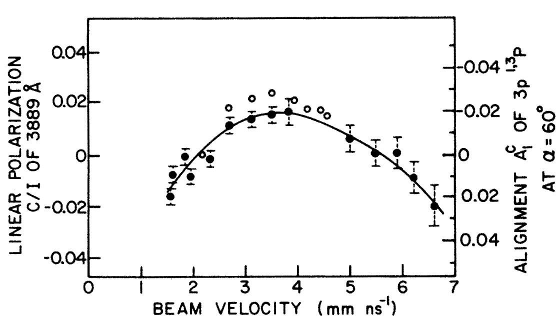

FIG. 5. Comparison of the alignment A_1^c for the $3p\,^1P$ (open circles) and $3p\,^3P$ states (closed circles at a foil-tilt angle of $\alpha=60°$). The left-hand scales give the $\langle C\rangle/\langle I\rangle$ values of the transition from $3p\,^3P$ only (multiply left scale by $1/Q_2=3.60$ for C/I of the $3p\,^1P$ transition). Comment of Fig. 4 regarding errors applies.

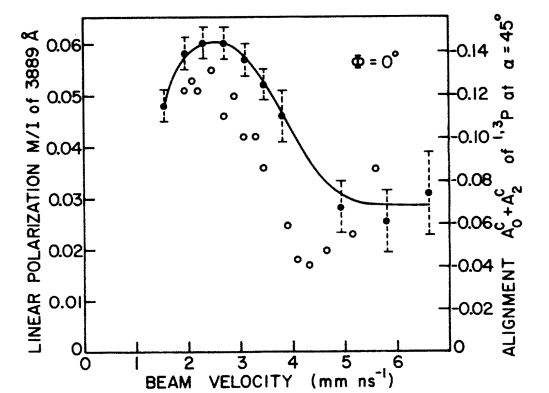

FIG. 7. Comparison of the alignment $A_0^c + A_2^c$ for the $3p\,^1P$ (open circles, Ref. 3) and the $3p\,^3P$ (closed circles) states at a foil-tilt angle of 45°. The left-hand scale gives the $\langle M\rangle/\langle I\rangle$ values of the transition from $3p\,^3P$ only (multiply left scale by $1/Q_2=3.60$ for M/I of the $3p\,^1P$ transition). Comment of Fig. 4 regarding errors applies.

velocity at least between 1.5 and 4.5 mm/ns.

An unexpected result from these measurements is the observation that, for each beam energy, the value of M/I ($\phi=0$) is independent of foil-tilt angle. This is the polarization fraction viewed in the x direction, in the plane of the beam and the foil normal. It should be noted that the other polarization fractions S/I and C/I are zero (by symmetry) along this direction. Thus, tilting the foil makes no changes in the light yield in this direction. To within the precision of these results we can replace $(1+F)$ by 1 and using Eqs. (5) – (8) we obtain

$$\langle M\rangle/\langle I\rangle(\phi=0)\approx-1.5\times0.278(A_0^c+A_2^c) \tag{9}$$

$$=0.834(\langle L_y^2-L_z^2\rangle)/L(L+1)\ . \tag{10}$$

There is no clear physical reason for this combination of alignment parameters to be invariant under foil rotation (a redefinition of axes can reduce it to a single alignment parameter). After reanalyzing the results obtained previously for the singlets and remeasuring some of them, we conclude that there is no evidence that this tilt-angle invariance fails to hold for the singlets as well. Without further measurements a more definitive statement regarding the singlets cannot be made.

V. CONCLUSIONS

We have measured the alignment and orientation parameters of the $3p\ ^3P$ state of He I when excited by a thin foil for a range of beam energies of 50–900 keV. The results, although similar in beam energy and foil-tilt-angle dependence to those for the $3p\ ^1P$ state, do show noticeable differences and, in general, are greater in magnitude. This spin dependence is surprising since the interaction is electrostatic and induced motional magnetic effects should be small. A possible interpretation of the singlet-triplet differences may be due to the different energy values of the final states. The $3p\ ^1P$ state is more closely degenerate to the $3d\ ^{1,3}D$ states than is the less degenerate $3p\ ^3P$ state. As suggested by several authors (see Ref. 11 for some analysis of the helium $n=3$ case), Stark mixing in the final surface electric field may be a strong influence on the shape of the outgoing atomic wave function. Gay *et al.*[11] also noted that excitation probabilities and alignments of the $3p\ ^1P$ and $3p\ ^3P$ states are significantly different in ion-atom collisions in helium.

Our observation that one alignment parameter appears invariant under foil rotation also needs further understanding. It may provide a test of the microscopic character of the final surface interaction. We know of no similar tests of this invariance in other atomic systems using tilted-foil excitation.

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