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Tests of the Final Surface Electrostatic Interaction in Beam—Tilted-Foil Experiments

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We present a series of new measurements of orientation and alignment in the beam—tilted-foil source designed to test the final surface electrostatic-interaction theory proposed by Eck. We find that the predictions of the model in its simplest form are not borne out by the data.

The establishment of anisotropic distributions of atomic excited states makes possible a variety of important quantum-beat, level-crossing, and resonance measurements. The alignment of atomic states—that is, the production of a quadrupolar distribution of angular momentum states—in the beam-foil excitation process has resulted in such measurements for heavy ions. The recent discovery[1] that the final surface interaction in a beam–tilted-foil geometry can produce strong orientation—that is, can produce a dipolar distribution of angular momentum states—provides yet an additional important advance in studies of heavy-ion atomic structure. In addition, this production of excited atoms with net angular momenta with respect to a given spatial axis is a striking property of such a source which may become a useful probe of the interactions of heavy ions with solids. Ellis[2] and Fano and Macek[3] have pointed out the connection between the symmetry properties of the source and the possible production of atomic orientation. More recently, Eck[4] has addressed the problem of the dynamical interaction which could cause such an effect. We present here new experimental data designed to test these models.

Eck has presented a simple theoretical model[4] for the production of alignment and orientation of atoms excited in a beam-foil experiment when the foil is tilted at an angle α to the beam direction. The model gave reasonable agreement with major features of the first observations[1] of elliptically polarized light emitted from the $3p\,{}^1P$ state of He I. The polarization state of any light beam is completely specified by the three relative Stokes parameters M/I, C/I, S/I.[5] Eck derives expressions for these Stokes parameters as a function of the foil tilt angle α. He suggests that the alignment produced by excitation in a perpendicular foil experiment is transferred into a coherence between states of different m_L when the cylindrical excitation symmetry is destroyed by a strong electric field along the surface normal of the tilted foil. The Stark effect removes the degeneracy of different $|m_L|$ states, introducing definite phase differences between different m_L states beyond the foil. Similarly, Lombardi[6] has demonstrated that external electric fields skewed to an already aligned excited state can produce orientation. In either case, the original alignment is redistributed as orientation and alignment by an applied electric field. We present here new experimental tests of further predictions of the electrostatic interaction model.

Our experimental geometry is essentially the same as described in Ref. 1, in which we have measured the Stokes parameters M/I, S/I, and C/I for the light emitted in the $2s\,{}^1S$-$3p\,{}^1P$ transition at 5016 Å in ^{4}He I at 90° and 54° to the beam direction. We report further measurements of this transition at varying foil tilt angle α and beam energies from 50 to 400 keV, as well as the Stokes parameters of two neon transitions: Ne III, 2866 Å, $3s'\,{}^1D$-$3p'\,{}^1F$, and Ne II, 3230 Å, $3s'\,{}^2D$-$3p'\,{}^2D$, at beam energies of 1 to 4 MeV. All three transitions show appreciable elliptical polarizations; together with the observations of Church *et al.*[7] and Liu, Bashkin, and Church[8] in He, O, and Ar, they confirm that atomic orientation induced by the final surface of the beam-foil interaction is quite a general phenomenon.

Eck derives expressions for the angular variation of the Stokes parameters M/I, C/I, and S/I which are tested by the detailed measurements of this experiment. In all cases it appears as though the predicted angular dependence is too rapid, and better agreement can be obtained by the phenomenological substitution of $\alpha/2$ for α in all three of Eck's equations.[9] For example, the predicted $\sin 4\alpha$ dependence of C/I requires its vanishing at $\alpha = 45°$ where the experimental data show a maximum for the (^1S-^1P) transition in He I observed at 130 keV. Similarly the results for S/I for the same transition, displayed in Fig. 1, show far better agreement with a $\sin\alpha$ variation than with the predicted $\sin 2\alpha$. The same conclusions are supported by data for the 2866-Å Ne III transition shown in Table I. The prediction that M/I will change sign at an angle θ_c which varies smoothly with energy has been verified; the dependence of θ_c upon energy, however, cannot be obtained from Eck's equation for M/I without modifying the angular dependence as described above.

Although Eck's model is explicitly applied to p states, one general consequence for all excited states is that the total polarization fraction, defined as $f_p = (M^2 + C^2 + S^2)^{1/2}/I$, is independent of α. For the perpendicular foil ($\alpha = 0$), $f_p = M/I$ with $C = S = 0$. As α increases, the polarization fraction is redistributed among the linear- and circular-polarization components, corresponding to a rotation within the Poincaré polarization sphere of radius f_p. While this prediction is in reasonable agreement with the low-energy data of Ref. 1, Fig. 2 shows three examples measured here

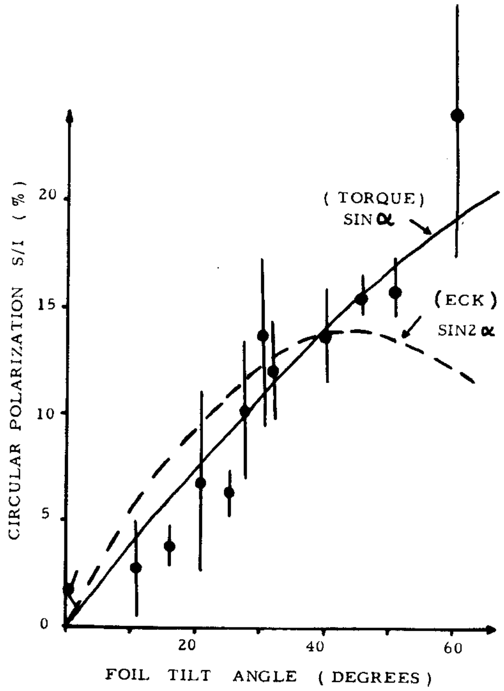

FIG. 1. The circular polarization S/I of $2s\,{}^1S$-$3p\,{}^1P$ of ^{4}He I at 5016 Å as a function of foil tilt angle α. The errors are rms deviations from the mean, and the data are compared with Eck's theory (long dashes) and the torque model (solid line). The beam energy is 130 keV.

TABLE I. Stokes parameters (in percent) for Ne III, 2866 Å, $3s'\,{}^1D$-$3p'\,{}^1F$.

Tilt angle α (deg)	M/I	C/I	S/I	f_p
0	5.5 ± 0.9	−1.2 ± 1.6	−0.9 ± 1.1	5.5 ± 0.9
6	5.2 ± 0.5	−0.3 ± 2.1	+2.1 ± 2.0	5.7 ± 0.9
11	5.0 ± 0.3	−1.3 ± 1.6	+1.8 ± 1.2	5.5 ± 0.6
19	5.3 ± 0.7	−4.1 ± 4.0	+4.5 ± 2.1	8.1 ± 2.4
30	5.3 ± 1.0	−0.3 ± 3.9	+4.9 ± 1.3	7.2 ± 1.2
36	5.5 ± 0.8	−2.7 ± 3.0	+6.6 ± 0.7	9.0 ± 1.1
45	6.0 ± 0.7	−4.1 ± 0.5	+9.9 ± 0.9	12.3 ± 0.8
50	5.0 ± 0.7	−4.8 ± 0.9	+11.4 ± 0.9	13.3 ± 1.0
58	5.9 ± 0.5	−5.8 ± 1.4	+14.8 ± 0.8	17.0 ± 0.9

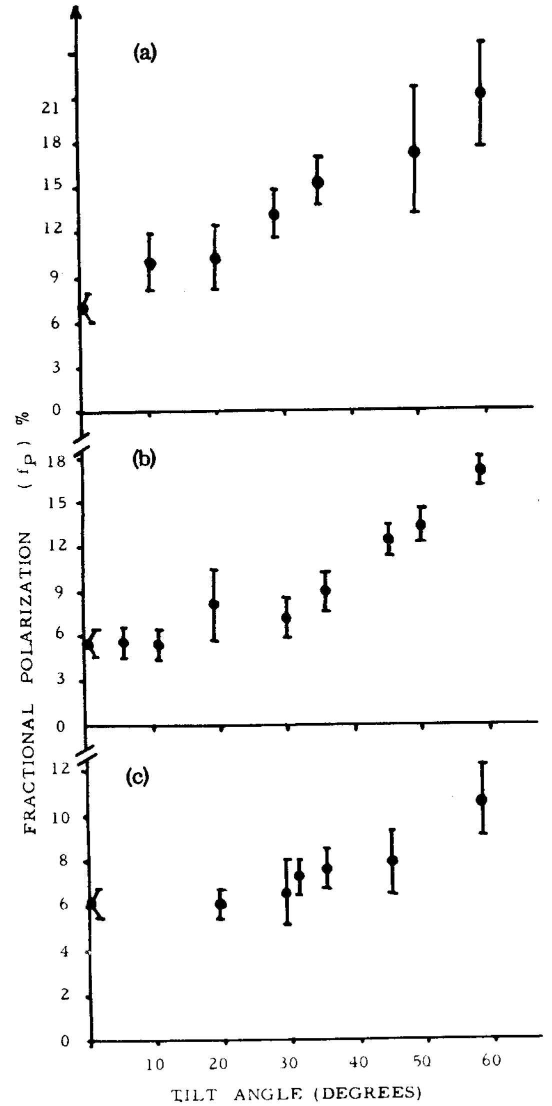

FIG. 2. The total fractional polarization f_p for three transitions as functions of the foil tilt angle α: (a) ^{4}He I, $2s\,^1S$-$3p\,^1P$, 5016 Å, 130 keV; (b) ^{20}Ne III, $3s'\,^1D$-$3p'\,^1F$, 2866 Å, 1.0 MeV; and (c) ^{20}Ne II, $3s'\,^2D$-$3p'\,^2D$, 3230 Å, 1.0 MeV.

where the fractional polarization increases dramatically with the foil tilt angle α. These results directly contradict the predictions of the model of Eck and is the point upon which the Eck model seriously disagrees with experiments. It can be seen in Figs. 1 and 2, as well as in Table I, that states with very little alignment for a straight foil can give rise to much larger orientations when the foil is tilted.

The increase in total polarization suggests that the large orientation observed at large tilt angles cannot correspond solely to a redistribution of the initial alignment. In fact, the marked difference between the energy dependence of M/I and S/I observed previously[10,11] suggests that these are largely independent quantities.

In Fig. 1 we also show that the circular polarization is consistent with a $\sin\alpha$ dependence. Such a $\sin\alpha$ dependence could be produced by a simple classical model[10] in which the atoms leaving the surface are subjected to a torque proportional to $\hat{n}\times\vec{v}$, $\hat{n}$ being the surface direction and $\vec{v}$ the beam velocity.

We conclude that although the Eck model showed reasonably good agreement with our early work,[1] it does not agree with the much more extensive present results. The clearest discrepancy is the variation with α of the total fractional polarization f_p. This suggests that Eck's postulate that the excitation cross sections come from the ion interaction with the bulk of the solid should be adjusted to include surface excitation.

It is clear that these results cannot be explained by a model in which all excitation originates in the bulk. In addition to the transfer of alignment into orientation which is provided by the surface electrostatic field, dynamical surface interactions which create orientation directly must also be significant. Further experiments and calculations to elucidate this interaction are in progress.

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[5] See, for example, D. Clarke and J. F. Grainger, *Polarized Light and Optical Measurement* (Pergamon, New York, 1971), Sect. 1.3.3. The Stokes parameters are defined in terms of the electric vectors in two arbitrary perpendicular transverse directions: $I=|E_\parallel|^2+|E_\perp|^2$, $M=|E_\parallel|^2-|E_\perp|^2$, $C=2\mathrm{Re}(E_\parallel E_\perp^*)$, and $S=2\times\mathrm{Im}(E_\parallel E_\perp^*)$.

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