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Alignment, Orientation, and the Beam–Foil Interaction

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We present the results of a number of recent measurements of alignment and orientation for a variety of atomic systems. The significance of these results in understanding the ion–foil interaction process is discussed.

1. Introduction

The general aim of our study of the ion–foil interaction is twofold: (1) to provide as complete as possible a description of the state of the outgoing beam produced when ions are transmitted through thin foils and (2) to construct a physical model of the interaction process that can explain these results. In constructing such a model it is instructive to consider three distinct classes of interaction, one or all of which may contribute to the phenomena observed: (1) excitation by the bulk, (2) electron capture—both at or near the surface and of secondary electrons traveling with the emerging beam, and (3) interaction with the surface and with surface electric fields. In terms of these processes, one can attempt to assess the relative importance of bulk and surface interactions in determining the properties of the observed outgoing beam, as well as try to determine the relative importance of collision processes vis à vis electron capture. It is also of great importance to discover whether there are significant effects of surface electric fields and—if so—what the strength, range, and

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time-dependent characteristics of these fields are. The results to be presented here furnish much descriptive information concerning the nature of the interaction, but not a complete model of the interaction process. They do, however, suggest an important role for surface effects, and are strongly suggestive of an important role in these processes for electron capture.

2. Phenomenology

The most complete description of the beam that emerges from the foil is contained in the specification of the density matrix of this system, and the experiments described here are designed to measure part of this density matrix. While recent work has shown that present experiments do not *require* the interaction process to be spin-independent,(1) all experiments are, in fact, compatible with such an assumption and —since theoretical arguments generally also lead to this assumption—it has been adopted in the analysis of our results, where the portion to the density matrix studied is presented in the $|LM_L\rangle$ representation. For states of $L \leq 1$, the optical measurements carried out determine the entire density-matrix block as, e.g., was presented in our earliest work describing the orientation produced by transmission of ions through tilted foils.(2) For larger L, field free measurements determine only combinations of density-matrix elements and it is convenient to carry out a spherical tensor expansion of ϱ, in terms of which the expansion coefficients $\varrho_q{}^k$ with $k \leq 2$ are then uniquely determined by our experiments.(3) An equivalent parametrization of the outgoing beam which can provide a direct physical interpretation has been given by Fano and Macek,(4) who introduce the alignment (A) and orientation (O) parameters. There is a one-to-one correspondence between the alignment/orientation parameters and the $\varrho_q{}^k$'s introduced earlier, so that measuring the alignment and orientation is equivalent to specifying the accessible part of the density matrix. A generalization of the approach of Fano and Macek to the case of mixed parity coherences and radiation emitted in the presence of electromagnetic field has been carried out by Gabrielse,(5) and is particularly useful in describing hydrogenic systems.

3. Experiments

All experiments to be described here involve detection of radiation emitted by the beam subsequent to traversing the foil. In some cases, quantum beats were measured; in other cases, the detailed polarization state of the emitted light (specified by the three relative Stokes parameters M/I, C/I, and S/I) was determined—sometimes as a function of the azimuthal angle of observation, ϕ. In all cases, determination of the density matrix describing the emergent beam was the aim of the measurements.

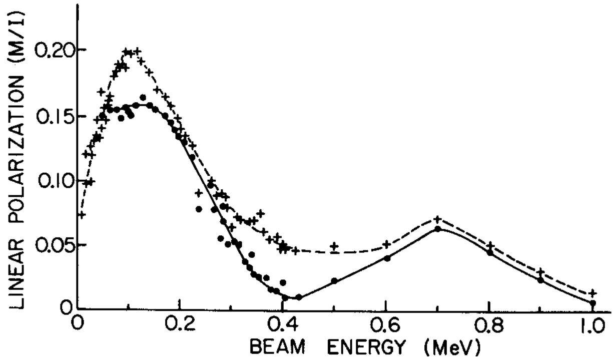

Figure 1. The linear polarization fraction M/I for the $3p\,{}^1P$ level of He I as a function of energy. +, current density 30 μA/cm²; ●, zero current density extrapolation. For this case, $A_0^c = -\frac{3}{2}M/I$.

4. *Results for the $3p\,{}^1P$ and $4d\,{}^1D$ Levels of He I*

4.1. *Foils Perpendicular to the Incident and Outgoing Beams*

In this case, only a single ϱ_q^k, ϱ_0^2 (proportional to a single relative Stokes parameter, M/I) is nonvanishing, and Figures 1 and 2 show the variation of this parameter with energy for the two states studied. Note that ϱ_0^2 is always positive and that, in both cases, it oscillates with energy. A noteworthy aspect of Figures 1 and 2 is the beam current density dependence of the alignment,(6) which occurs in both cases, and itself oscillates with energy as shown in Figure 3.

4.2. *Tilted Foils*

Here, field free measurements can determine the four ϱ_q^k's with $k \leq 2$ (i.e., the four Fano–Macek parameters). Measurements at one detection position (θ, ϕ)

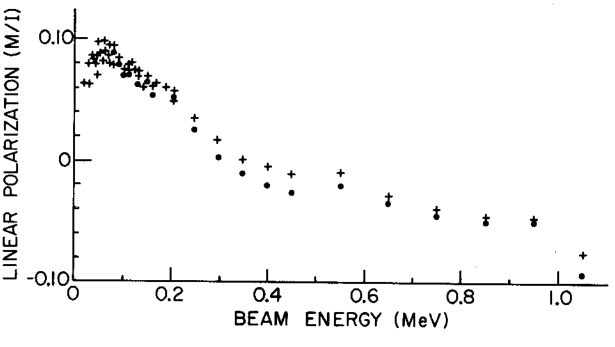

Figure 2. The linear polarization fraction M/I for the $4d\,{}^1D$ level of He I as a function of energy. + and ● as in Figure 1.

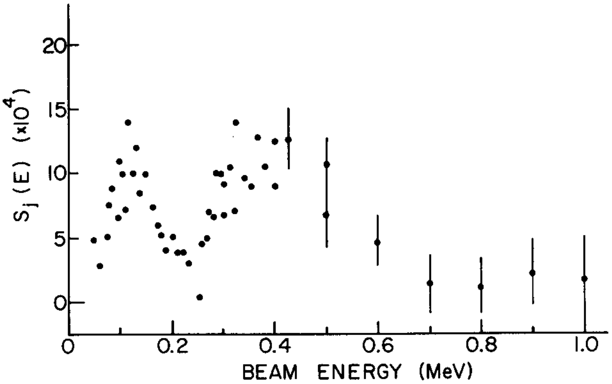

Figure 3. The rate of current density dependence of the linear polarization $S_j = \Delta(M/I)/\Delta(j)$ for the $3p\,^1P$ level of He I as a function of energy.

provide three relative Stokes parameters. For $\theta = \pi/2$, $\phi = 0$, these have been measured between 0° and 60° in 5° increments over the entire energy range 30–1000 keV for both the $2s\,^1S$–$3p\,^1P$ transition at 4016 Å and the $3p\,^1P$–$4d\,^1D$ transition at 4922 Å. The results for the latter transition for a tilt angle $\alpha = 45°$ are shown in Figure 4. From these measurements, the alignment and orientation parameters

$$A_1^c \sim C/I$$

and

$$O_1^c \sim S/I \tag{1}$$

are directly determined; however, only the combination

$$(A_0^c + A_2^c \cos\phi) \sim M/I$$

is obtained. We have therefore carried out a number of measurements of M/I vs. ϕ

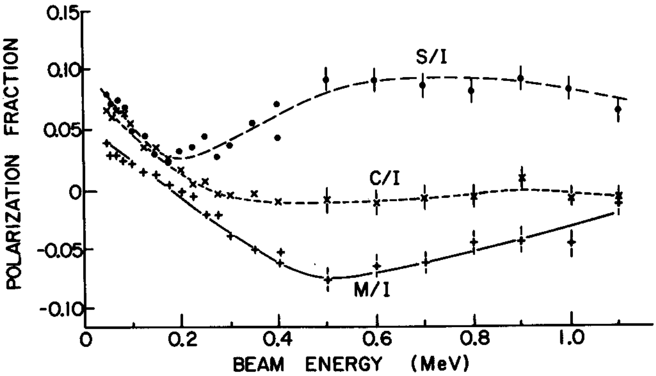

Figure 4. Relative Stokes parameters M/I (+), C/I (×), and S/I (●) for the $4d\,^1D$ level as a function of energy.

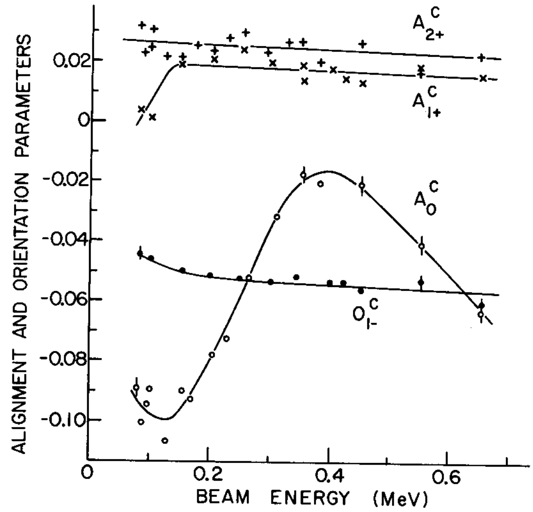

Figure 5. Alignment and orientation parameters for the $3p\,^1P$ level of He I vs. energy: A_2^c (+), A_1^c (×), A_0^c (○), and O_1^c (●).

for the 5016-Å transition, with the results for $\alpha = 45°$ shown in Figure 5. Similar measurements for the 4922-Å transition are in progress.

Comparison of Figures 1 and 5 shows that $\varrho_0{}^2$ is essentially unchanged by rotating the foil through 45°; other measurements suggest that the angular dependence of the other $\varrho_q{}^k$'s is also energy independent. It thus seems likely that, to a good approximation, one can write

$$\varrho_q{}^k(E, \alpha) = g_q{}^k(E) f_q{}^k(\alpha) \tag{2}$$

This is well illustrated, for example, in Figure 6, where all of the measured values of $\varrho_1{}^2$ for the $3d\,^1D$ level, measured between 100 and 425 keV, are plotted as a function of the foil tilt angle after factoring out the energy dependence measured for a tilt angle of $\alpha = 45°$ (data for $3p\,^1P$ corresponding to Figure 4). These results agree very well with a single universal—here linear—curve representing the observed

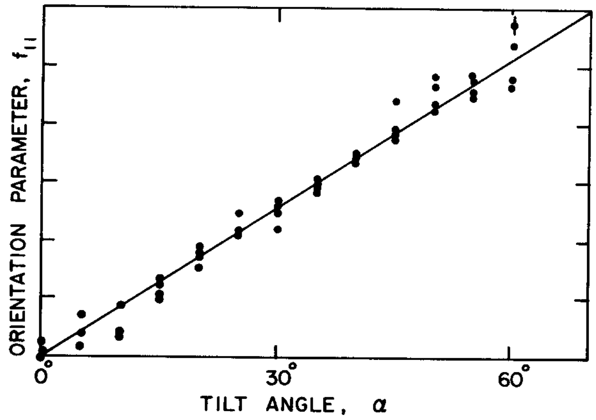

Figure 6. Angular dependence of the orientation, $f_1{}^1(\alpha)$ for the $3p\,^1P$ level of He I.

angular variation. For all cases measured to date, such an approximation seems valid and the resulting $f_q^k(\alpha)$ are as follows: f_0^2: constant for $3p\,^1P$; f_1^2: linear for both $3p\,^1P$ and $4d\,^1D$; f_2^2: quadratic for $3p\,^1P$; f_1^1: linear for $3p\,^1P$, quadratic for $4d\,^1D$.

5. *Interpretation*

One feature of the excitation by foils normal to the beam displayed in Figures 1 and 2 is that M/I is everywhere positive (A_0^c everywhere negative). It should be noted that this is, indeed, the sign expected from electron pickup in the simple model that the ion emerges from the foil and captures an electron whose velocity relative to the foil is small compared with that of the ion itself.(7) If one next turns one's attention to the observed oscillations in A_0^c with outgoing ion velocity (energy), it is tempting to try to relate them to the oscillatory electron wake which is set up by the ion's traversal through the foil.(8)† for a plasma frequency $\omega_p \sim 10^{15}$ sec^{-1}, the assumption of electron pickup from an oscillating charge density extending some few angstroms beyond the foil can give a reasonable fit to the experimental data. Scattering from an oscillatory potential of similar characteristics also would give rise to such oscillation in A_0^c.

The observation for the $3p\,^1P$ that A_0^c does not change significantly when the foil is tilted is also consistent with the simple electron pickup model described earlier(7) where the direction of the principal axis for the alignment is determined by the beam velocity. It is also expected if the alignment is produced in the bulk. The variation of the three alignment parameters with foil tilt angle is *not* what would result from alignment produced parallel to the tilted foil normal. Since capture of secondary electrons has been suggested above as a significant contributor to our observations, it is interesting to observe that measurements of the dependences of the yield of such electrons upon foil tilt angle(10) is proportional to $1/\cos\alpha$, due to an increase with tilt angle in the number of electrons that can reach the final surface without absorption. This same mechanism requires that the secondary electron density is asymmetric about the incident beam in exactly the way required to produce orientation of the sense observed in all measurements carried out to date.

Finally, we note that the lack of oscillations with energy in measurements of the orientation suggest that the mechanism for producing it may be different from that producing the alignment.

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† See also Reference 9 for an experimental verification of the effects of this potential in a beam–foil experiment.

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