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ALIGNMENT, ORIENTATION AND THE BEAM FOIL INTERACTION*

R. M. Schectman and L. J. Curtis

The University of Toledo, Toledo, Ohio 43606

and

H. G. Berry

The University of Chicago and Argonne National Laboratory

Résumé - Nous présentons les résultats d'un certain nombre de mesures récentes de battements quantiques, d'alignements et d'orientations pour une varieté de systemes atomiques. On en discute la signification dans le but de comprendre le processus d'interaction entre les ions et la lame.

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

I. INTRODUCTION

The nature of the beam-foil interaction has long been a subject of much interest. For the past several years we have been carrying out an extensive program of experiments aimed at probing this interaction, and we will describe here some recent results which shed some light on the nature of the processes concerned.

The general aim of any study of the ion-foil interaction is two-fold: (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 which 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 travelling 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 a 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 time dependent characteristics of these fields are. The results to be presented here furnish much descriptive information concerning the nature of the interaction, but do not uniquely determine the details of 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.

II. PHENOMENOLOGY

The most complete description of the beam which 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 parts of this density matrix. Since these experiments have been carried out utilizing radiation which has been wavelength selected either by use of a monochromator or an interference filter, a single measurement provides no information on the distribution of charge states, nor upon the distribution of, and possible coherence between states of different principal quantum number; in addition information upon states varying in orbital quantum number ℓ are obtained here only for the hydrogenic atoms described in Section IV. While recent work has shown that present experiments do not require the interaction process to be

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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 $|L\ M_L>$ 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 $\rho^k{}_q$ with $k \leq 2$ are then uniquely determined by our experiments.[3] An equivalent parameterization 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 (0) parameters:

$$A_o^c = <3L_z{}^2 - L^2>/\ell(\ell+1) = 3/10\ \rho_o^2$$

$$A_1^c = <L_y L_z + L_z L_y>/\ell(\ell+1) = -i/5\ \rho_1^2$$

$$A_2^c = <L_y - L_z{}^2>/\ell(\ell+1) = -1/5\ \rho_2^2$$

$$0_1^c = <L_x>/\ell(\ell+1) = 1/3\ \rho_1^1\ . \qquad (1)$$

(Here the z axis lies along the beam.) It is clear that there is a one-to-one correspondence between the alignment/orientation parameters and the $\rho^k{}_q$'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.

III. 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) were 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.

IV. RESULTS FOR HYDROGEN

A) n = 2

In this case, ρ is specified by five parameters. The ratio ρ_{p1}/ρ_{p0} has been carefully measured over a wide energy range by Winter et al [6] and we have carried out measurements in parallel and antiparallel electric fields, as originally suggested by Eck,[7] to determine the other four elements of ρ over the energy range 30 KeV - 1 MeV. [8] Particular care has been paid to effects of hyperfine interaction, experimental efficiency and location of the foil position, revising and extending the preliminary work of Gaupp et al [9] and Sellin et al.[10] The detailed results will be described elsewhere in these proceedings by Gabrielse.[11]

A very slow variation of the parameter with energy is observed and ρ_s is observed to exceed both ρ_{p1} and ρ_{p0} over the entire energy range studied.

B) n = 3

Field free measurements probing the density matrix for this system have been carried out by Wells,[12] extending the 250 KeV measurements of Denis et al [13] to a variety of other energies down to 94 KeV. Again, here, only a very slow variation of density matrix elements with energy was observed, and again s-states are grossly over-populated compared with their statistical weights.

V. RESULTS FOR THE 3p ^{1}P and 4d ^{1}D LEVELS OF HE I

A) Foils Perpendicular to the Incident and Outgoing Beams

In this case, only a single $\rho^k{}_q$, ρ_0^2 (proportional to a single relative Stokes parameter, M/I) is non-vanishing, 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,[14] which occurs in both cases, and itself oscillates with energy as shown in Figure 3.

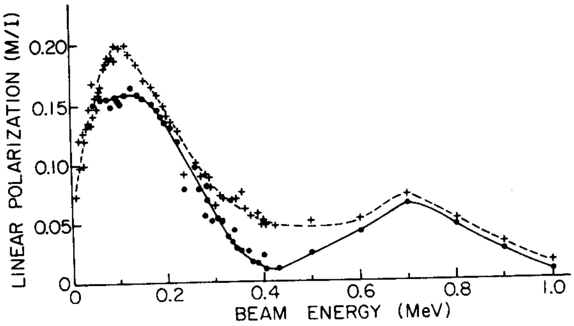

Figure 1 - The linear polarization fraction M/I for the 3p ^1P level of He I as a function of energy.
+ current density 30 $\mu a/cm^2$
● zero current density extrapolation
For this case, $A_0^c = -2/3$ M/I.

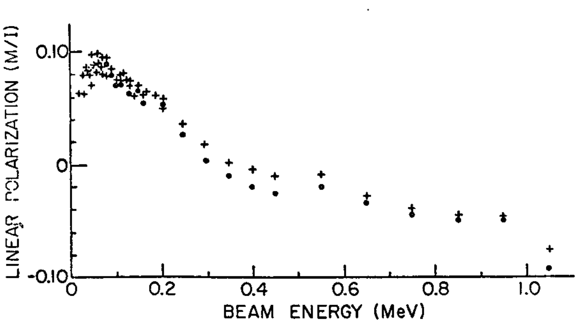

Figure 2 - The linear polarization fraction M/I for the 4d ^1D level of He I as a function of energy.

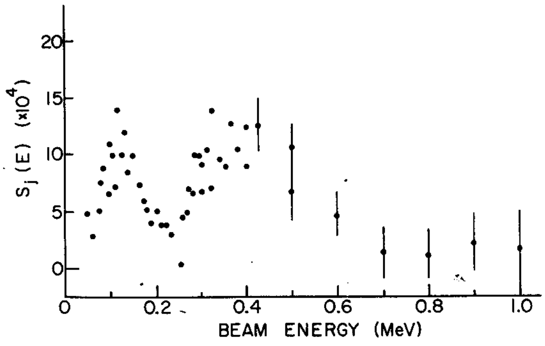

Figure 3 - The rate of current density dependence of the linear polarization $S_j = \Delta(M/I)/\Delta(j)$ for the 3p ^1P level of He I as a function of energy.

B) Tilted Foils

Here, field free measurements can determine the 4 ρ^k_q's with $k \leq 4$ (i.e., the four Fano-Macek parameters). Measurements at one detection position (θ, ϕ) provide three relative Stokes parameters and 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 2p ^1P - 4d ^1D transition at 4922 Å. The results for the latter transition for a tip angle $\alpha = 45°$ are shown in Figure 4. From these measurements, the alignment and orientation parameters

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

and

$$O_1^c \sim S/I \qquad (2)$$

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 versus ϕ 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.

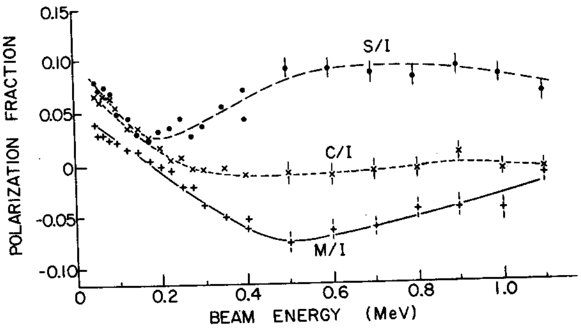

Figure 4 - Relative Stokes parameters M/I (+), C/I (×) and S/I (●) for the 4d ^1D level as a function of energy.

Comparison of Figure 1 and 5 shows that ρ_0^2 is essentially unchanged by rotating the foil through 45°; other measurements suggest that the angular dependence of the other ρ^k_q's is also energy independent. It thus seems likely that, a good approximation, one can write

$$\rho^k_q\,(E,\alpha) = g^k_q\,(E)\,f^k_q\,(\alpha) \quad . \qquad (3)$$

This is well illustrated, for example in Figure 6 where all of the measured values of ρ_1^2 for the

3d ^1D level, measured between 100 KeV and 425 KeV are plotted as a function of the foil tip angle after factoring out the energy dependence measured for a tip 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 angular variation. For all cases measured to date, such an approximation seems valid and the resulting f^kq (α) are

f^2_0 - constant for 3p ^1P
f^2_1 - 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

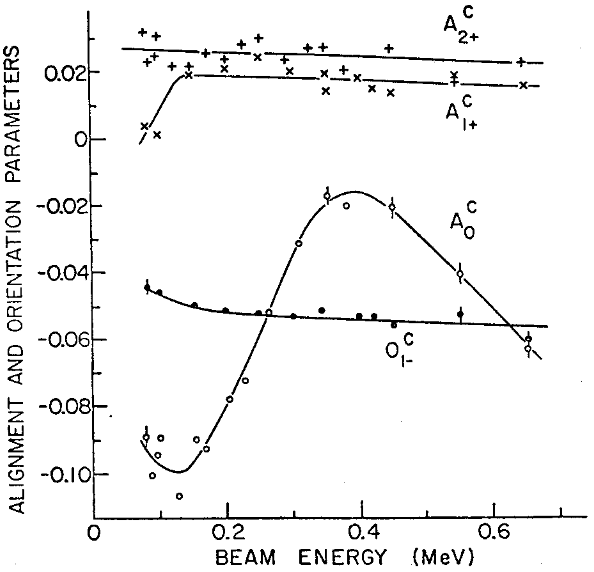

Figure 5 - Alignment and orientation parameters for the 3p ^1P level of He I vs energy: A^c_2 (+), A^c_{10}(✖), A^c (◉), O^c_1 (●) .

We have also explored the question of a possible current density dependence of the relative Stokes parameters for tilted foils. Our results show a current density dependence for M/I measurement with $\alpha = 45°$ which again oscillates in magnitude with energy--closely following the results obtained for $\alpha = 0°$ in phase, though not in absolute value. The observed current density dependence for S/I, on the other hand, shows oscillations which are approximately out of phase with those in M/I; i.e., variations in S/I with beam current density are large when those in M/I are small and vice versa.

VI. INTERPRETATION

While much progress has clearly been made in improving our knowledge of the nature of the outgoing beam produced by the ion-foil interaction, less progress has been made in realizing a physical model of the interaction process. Nevertheless, the results presented here do provide a number of hints at the direction in which a successful model must proceed and we wish to here discuss the implications of the results so far obtained.

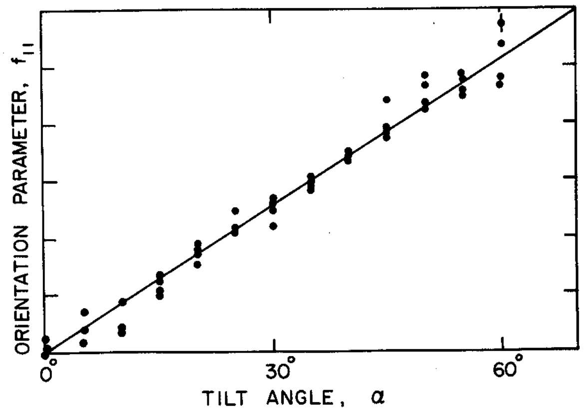

Figure 6 - Angular dependence of the orientation, f^1_1 (α) for the 3p ^1P level of He I.

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^c_0 everywhere negative). It should be noted that this is, indeed, the sign expected from electron pick-up 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.[15] If one next turns one's attention to the observed oscillations in A^c_0 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.[16] For a plasma frequency $\omega_p \sim 10^{15}$ sec^{-1}, the assumption of electron pick up from an oscillating charge density extending some few Å 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 oscillations in A^c_0. The current dependence observed remains somewhat mysterious. However, our recent measurements provide strong evidence that these changes in A^c_0 are correlated with changes in foil temperature. In this work [17] it was observed that A^c_0 increased with foil temperature for fixed beam current density and the rate of increase varies with beam energy in exactly the same fashion as the data shown in Figure 3. Since foil temperature is known to change the secondary electron flux, these results can be interpreted as additional circumstantial evidence for the importance of electron pick-up.

The observation for the 3p ^{1}P that A_0^c does not change significantly when the foil is tilted is also consistent with the simple electron pick-up model described earlier [15] where the direction of the principal axis for the alignment is determined by the beam velocity. It is also, of course, what would be expected if the alignment were 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 [18] is proportional to $1/\cos\alpha$, due to an increase with tip angle in the number of electrons which 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.

Various theoretical attempts have been made to explain the observed variation of the alignment and orientation with foil tilt angle as due to the effects of surface electric fields, following the initial suggestion of Eck.[19] All have been successful in predicting some properties of the measurements, but no model is in agreement with all of the available data. The most general of these models in terms of the processes included is that of Band.[20] This work makes the prediction that ρ_1^2 and ρ_1^1 should be directly proportional to each other. As described earlier, this is indeed the case in He I for the 3p ^{1}P level, but is not so for the 4d ^{1}D level. While this model employs several approximations (sudden approximation, power expansion in terms of $V_0a/\cos\alpha$) it may well be that its neglect of possible orientation production by electron capture causes its failure in this case.

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. This may also be responsible for the differing current density dependences observed for these two quantities.

VII. CONCLUSIONS

It is clear that much progess has been made in learning about the nature of the states produced when ions traverse foils. Somewhat less progress has been made in constructing a comprehensive model which can explain all of these results, although many qualitative features can be explained by a simple electron pick-up model. Additional work--both theoretical and experimental--aimed at further elucidating this problem is underway.

VIII. ACKNOWLEDGEMENTS

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