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Polarization measurements for the $3p\ ^3P^o$ and $4d\ ^3D$ terms of neutral helium excited by the beam-tilted-foil interaction

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Polarization measurements have been made as a function of foil-tilt angle for the He I transitions $2s\ ^3S$-$3p\ ^3P^o$ (3889 Å) and $2p\ ^3P^o$-$4d\ ^3D$ (4471 Å). Particular attention was paid to the systematic effects that can enter into the analysis of such data from the decreasing time resolution as the foil-tilt angle is increased. It is shown that particle scattering at the foil is the main source of systematic error, but that this error can be eliminated by appropriate analytic techniques. The forms of the variation of the relative Stokes parameters with tilt angle are found to be very similar to those previously found for the corresponding singlet transitions, although the magnitudes of the alignment and orientation parameters are generally different for the singlets from the values we find for the triplets. The present results for $3p\ ^3P^o$ are shown to be reasonably consistent with those recently published by Burns *et al.*, *provided* that the necessary correction for decreasing time resolution at high tilt angles is included.

I. INTRODUCTION

Previous experimental studies in this laboratory of the polarization of radiation excited by the beam-tilted-foil interaction have been conducted for the He I singlet transitions at 5016 Å ($2s\,^1S$-$3p\,^1P^o$), 3965 Å ($2s\,^1S$-$4p\,^1P^o$), 6678 Å ($2p\,^1P^o$-$3d\,^1D$), and 4922 Å ($2p\,^1P^o$-$4d\,^1D$)(Refs. 1 and 2) and the He I doubly excited triplet transitions at 2578 Å ($2s2p\,^3P^o$-$2p3p\,^3D$) and 3013 Å ($2p^2\,^3P$-$2p3d\,^3D^o$),[3] both these studies being conducted using an incident energy of 160 keV. Qualitatively, the relative linear polarization, M/I of all four singlet transitions shows the same type of dependence on the angle of tilt of the foil—a positive value at 0° tilt, decreasing with increasing tilt angle, reaching zero at ~60° tilt for ^1S-$^1P^o$ transitions and at ~45° tilt for $^1P^o$-^1D transitions, and thereafter becoming increasingly negative with further increase in the tilt angle. This behavior contrasts strongly with that observed for the doubly excited triplet transitions, where M/I is observed to be essentially independent of the tilt angle. The variation with tilt angle of the relative circular polarization S/I is much more similar for the singlet and doubly excited transitions—zero at 0° tilt, becoming increasingly negative as the tilt is increased—although here some qualitative difference is observed between the ^1S-$^1P^o$ transitions and the doubly excited triplet transitions on the one hand, all of which show an almost linear dependence on tilt angle, and the two $^1P^o$-^1D transitions on the other, these show S/I remaining at zero until the tilt angle reaches about 35° and then becoming increasingly negative with further increases in the tilt angle.

Most theoretical models of this process assume spin independence,[4,5] although it has been shown that this is not an obligatory assumption.[6] In order to investigate the spin dependence of the beam-tilted-foil excitation mechanism for He I, we have conducted measurements of the polarization of the radiation emitted by two He I singly excited triplet transitions, viz., 3889 Å ($2s\,^3S$-$3p\,^3P^o$) and 4471 Å ($2p\,^3P^o$-$4d\,^3D$). Since similar measurements have recently been reported for the 3889 Å transition using an incident energy of 200 keV,[7] we have also made our studies of these two lines at 200 keV. (Although this to some extent invalidates the comparison of the present data obtained at 200 keV with that obtained for the singlet transitions using 160 keV, in practice, the variation of M/I and S/I from 160 to 200 keV is not too large. Studies in this laboratory of the $2p\,^1P^o$-$4d\,^1D$ transition show that the dependence of S/I upon foil-tilt angle is essentially the same at 160 and 200 keV while the effect on M/I is an almost uniform reduction of 0.01—roughly the experimental uncertainty of each datum—as the energy is increased from 160 to 200 keV, again giving a very similar dependence on tilt angle at the two energies.) The Burns *et al.* results suggest a marked difference in S/I as a function of tilt angle between the $2s\,^1S$-$3p\,^1P^o$ and $2s\,^3S$-$3p\,^3P^o$ transitions,[7] which they suggest may arise from stronger mixing of $3p$ and $3d$ by surface electric fields for the singlet levels than for the triplet levels. The results of our investigation suggest, however, that the difference may just be an instrumental effect that can be corrected in the data analysis. Before presenting the results, we first describe briefly how the measurements were made.

II. EXPERIMENTAL AND ANALYTIC PROCEDURES

Our previous reports[1-3] contain full details of the accelerator and computer facilities used to collect and analyze the data to be discussed here. In the present experiment a beam of He^+ ions of energy 206 ± 2 keV were made incident on self-supporting carbon foils of areal density 5 ± 2 $\mu g/cm^2$. The beam current was 6 ± 1 μA over an area of 0.20 cm^2 (0.5 cm diameter) perpendicular to the beam direction. As was reported previously,[3] by using elongated foil holders all the beam was transmitted through the foil aperture at all tilt angles in this experiment (viz., 0° to 70° in 10° increments).

One of the consequences of tilting the foil used to excite the helium atoms is that the effective thickness of the foil along the beam direction increases as sec α, α being the tilt angle. At 200 keV, the energy lost by He^+ ions passing through carbon foils is approximately 1.4 keV per $\mu g/cm^2$, thus amounting in this experiment to an energy loss of 7 keV for 0° tilt angle, and rising to about 21 keV at 70° tilt angle. The energies of the helium atoms emerging from the foil in this experiment were therefore 199 ± 4 keV at 0° tilt angle and 185 ± 8 keV at 70° tilt angle, where the error limits include an allowance for the uncertainty in the areal density of the foils.

This variation in the energy of the emerging atoms with tilt angle has two consequences for this work. Firstly, as was discussed briefly in the introductory section of this report, the polarization parameters derived from beam-tilted-foil measurements do vary with beam energy. However, the variation to be expected for a maximum change of beam energy from 199 to 185 keV is small and well within the statistical error limits that we derive from our computer analyses of the polarization data. The second consequence is that the variation in the beam velocity could introduce errors into the analyses of the data used to derive the quantum amplitudes. However, this problem does not occur in our analyses as the appropriate beam velocity is used at each tilt angle and, in any case, our fitting routines include the quantum beat frequency as one of the fitted parameters and also make provision for the possibility that the measurements are not made over exactly an integral number of beats. We conclude that variation of the energy of the emerging atoms as a function of foil-tilt angle does not contribute any significant errors in the measurements to be reported here.

Polarization measurements for the He I triplet transitions at 3889 and 4471 Å are necessarily more difficult than for the corresponding singlet transitions because of the presence of quantum beats. The expressions for the Stokes parameters using the standard side-one viewing configuration[1] may be written as follows. For a ^3S-^3P transition in which only ω_{12} falls in the observable range for detection (as is the case for the 3889-Å transition for detector slitwidths as used in this experiment):

$$
\begin{aligned}
I &= Ce^{-\Gamma t}\{1 - \tfrac{5}{12}[A_{2+}^{col}(0) + A_0^{col}(0)/3] \\
&\qquad \times (1 + \tfrac{9}{5}\cos\omega_{12}t)\}, \\
M &= Ce^{-\Gamma t}\tfrac{5}{12}[A_{2+}^{col}(0) - A_0^{col}(0)](1 + \tfrac{9}{5}\cos\omega_{12}t), \qquad (1) \\
S &= Ce^{-\Gamma t}\tfrac{3}{2}O_{1-}^{col}(0)(1 + \tfrac{5}{9}\cos\omega_{12}t),
\end{aligned}
$$

where C, Γ, and ω_{12} are constants for the given ^3P state, and $A_0^{col}(0)$, $A_{2+}^{col}(0)$, and $O_{1-}^{col}(0)$ are the Fano-Macek parameters[8] at $t = 0$. The corresponding relations for the ^3P-^3D transition are more complex since, in general, all three beat frequencies can be detected. However, for the 4471-Å transition, $\omega_{12} = 555$ MHz, $\omega_{23} = 36$ MHz, and $\omega_{13} = 591$ MHz. Thus three oscillations of the 555 MHz beat only correspond to one-fifth of an oscillation of the 36 MHz beat, which will therefore be largely absorbed by the background decay term $e^{-\Gamma t}$. Furthermore, the 591 MHz beat contributes only ~11% of that from the 555 MHz beat to the total beat pattern in I and M light, and is totally absent in S light. Hence, to a good approximation, we may write for the $2p\,^3P^o$-$4d\,^3D$ transition

$$
\begin{aligned}
I &= Ce^{-\Gamma t}\{1 - \tfrac{111}{200}[A_{2+}^{col}(0) + A_0^{col}(0)/3] \\
&\qquad \times (1 + \tfrac{39}{111}\cos\omega_{12}t)\}, \\
M &= Ce^{-\Gamma t}\tfrac{111}{200}[A_{2+}^{col}(0) - A_0^{col}(0)] \\
&\qquad \times (1 + \tfrac{39}{111}\cos\omega_{12}t), \qquad (2) \\
S &= Ce^{-\Gamma t}\tfrac{81}{20}O_{1-}^{col}(0)(1 + \tfrac{1}{9}\cos\omega_{12}t),
\end{aligned}
$$

where now C, Γ, ω_{12}, $A_0^{col}(0)$, $A_{2+}^{col}(0)$, and $O_1^{col}(0)$ relate to the ^3D state. (Naturally, if all these three fine-structure frequencies are detectable in a particular experimental situation, then the full expression for I, M, and S must be used).

In order to avoid problems associated with imprecise knowledge of the phase of the quantum beats, it is necessary to measure the polarization around at least one complete beat and to fit the data to expressions such as Eq. (1) or (2), depending on the transition being studied. This must be repeated at each tilt angle. We have therefore modified our experimental procedure from that described in our earlier reports.[1,2] Using the detection system reported previously, for a given angle of tilt and at a given distance downstream from the foil, we measure the transmitted intensity for settings of the retarder plate increasing in steps of 45°. This was repeated for each tilt angle at a series of distances from the foil equally spaced around three complete beats. The relations between the intensity transmitted through the polarimeter and the angle θ between the fast axis of the retarder plate (phase Δ) and the beam axis, and for the plane polarizer axis set parallel to the beam axis, are as follows:

$$\begin{aligned} I_1(\theta=45°,\Delta) &= \tfrac{1}{2}(I+M\cos\Delta - S\sin\Delta)\,, \\ I_2(\theta=90°,\Delta) &= \tfrac{1}{2}(I+M)\,, \\ I_3(\theta=135°,\Delta) &= \tfrac{1}{2}(I+M\cos\Delta + S\sin\Delta)\,. \end{aligned} \tag{3}$$

Similar relations hold for other values of θ (in multiples of 45°) and for the plane polarizer axis set perpendicular to the beam. The Stokes parameters can be evaluated from a set of values (I_1, I_2, I_3), although a little care is needed in treatment of the errors to give rigorous uncertainties in the derived values for I, M, and S. (The fourth Stokes parameter C could be included in the measurement procedure, but requires the intensity to be measured at an angle not a multiple of 45°. Since in all cases that we have studied previously, C remains relatively small for all tilt angles compared with M and S, we decided that the additional complications for the measurement and analysis techniques that would be required to include a measurement of C were not justified. The recent work of Burns *et al.*[7] for the 3889 Å transition has shown that C remains within a few standard deviations of zero from 0° to 75° tilt, thus supporting our decision to omit its measurement.)

One possible way to analyze the polarization data recorded around one or several oscillations of a quantum beat at a particular tilt angle is to use the beat amplitude directly. For ^3S-^3P transitions in which only ω_{12} falls in the experimental range for detection Eq. (1) leads to

$$\begin{aligned} (I+M) &= Ce^{-\Gamma t}[1-\tfrac{5}{9}A_0^{\mathrm{col}}(0)] \\ &\quad\times\{1-A_0^{\mathrm{col}}(0)[1-\tfrac{5}{9}A_0^{\mathrm{col}}(0)]^{-1}\cos\omega_{12}t\}\,, \\ (I-\tfrac{M}{3}) &= Ce^{-\Gamma t}[1-\tfrac{5}{9}A_{2+}^{\mathrm{col}}(0)] \\ &\quad\times\{1-A_{2+}^{\mathrm{col}}(0)[1-\tfrac{5}{9}A_{2+}^{\mathrm{col}}(0)]^{-1}\cos\omega_{12}t\}\,, \end{aligned} \tag{4}$$

with a similar pair of relations for ^3P-^3D transitions, using Eq. (2). The measured beat amplitudes in $(I+M)$ and $(I-M/3)$ can thus yield the alignment parameters $A_0^{\mathrm{col}}(0)$ and $A_{2+}^{\mathrm{col}}(0)$. These values in turn can be used to obtain the constant C and hence $O_{1-}^{\mathrm{col}}(0)$ from the observed value of S. The hazard associated with this technique is that the observed beat amplitude is affected by several factors. Obviously, the foil and detector slits must be tilted together, and the slit widths reduced as $\cos\alpha$, α being the tilt angle, to maintain a constant time resolution as the foil is tilted. However, even if this is done, the time resolution will change with tilt angle because of the increased scatter and straggling at the foil due to the increase in the foil thickness along the beam direction. The effective length of the observation region varies as $\tan\alpha/\cos\alpha$ (scattering) and $1/\cos\alpha$ (straggling). In addition, any slight misalignment of the foil and the detector slits will give an additional source of beam observation length varying roughly as $(1+\tan^2\alpha)$. Fortunately the combined effect of all these factors on reducing the measured beat amplitude can be directly measured during the experiment by measuring the beat amplitudes in M and S, and comparing the results with those forecast by Eqs. (1) and (2). The values thus obtained for the beat amplitude degradation factors can then be used to correct the beat amplitudes observed in $(I+M)$ and $(I-M/3)$ to yield values for $A_0^{\mathrm{col}}(0)$ and $A_{2+}^{\mathrm{col}}(0)$, which are independent of errors caused by the beat amplitude damping factors just discussed. These results may be checked by other means of analysis. For example, the value obtained for the constant C from the fits to Eq. (4) may be used in (1) to solve directly for $A_0^{\mathrm{col}}(0)$ and $A_{2+}^{\mathrm{col}}(0)$. Alternatively, fits to M/I and S/I may be used to remove the $Ce^{-\Gamma t}$ factor. In this case, a fit to M/I around a beat will yield $A_0^{\mathrm{col}}(0)$ and $A_{2+}^{\mathrm{col}}(0)$, and these values may be used in an analysis of S/I to derive $O_{1-}^{\mathrm{col}}(0)$. A final consistency check is possible by calculating the effective observation window length from the observed beat damping factors for the 3889 Å data and comparing this with the lengths found from the 4471 Å data. In all cases, these consistency checks were satisfied for our data to within the calculated uncertainties.

III. RESULTS

The results of the analyses described in the preceding section are shown in Table I and in Figs. 1 and 2. Clearly the sign of the observed circular polarization depends on the side from which the beam is viewed, or, which is equivalent, in which direction the foil is rotated. In this work we have used the same geometry as in our previous work,[1] resulting in negative values for (S/I) and hence for $O_{1-}^{\mathrm{col}}(0)$. In their work

TABLE I. Alignment and orientation parameters as a function of foil-tilt angle.

Foil-tilt angle[a]	1s3p $^3P^o$ $A_0^{col}(0)$	1s3p $^3P^o$ $A_{2+}^{col}(0)$	1s3p $^3P^o$ $O_{1-}^{col}(0)$ [b]	1s4d ^3D $A_0^{col}(0)$	1s4d ^3D $A_{2+}^{col}(0)$	1s4d ^3D $O_{1-}^{col}(0)$ [b]
0°	−0.129 ± 0.003	−0.004 ± 0.002	0.000 ± 0.001	−0.074 ± 0.004	−0.008 ± 0.004	0.001 ± 0.001
10°	−0.129 ± 0.004	−0.005 ± 0.002	0.021 ± 0.001	−0.074 ± 0.004	−0.012 ± 0.004	0.004 ± 0.001
20°	−0.132 ± 0.004	−0.014 ± 0.002	0.039 ± 0.002	−0.058 ± 0.004	−0.011 ± 0.004	0.004 ± 0.003
30°	−0.129 ± 0.006	−0.022 ± 0.002	0.057 ± 0.005	−0.044 ± 0.004	−0.022 ± 0.004	0.007 ± 0.005
40°	−0.130 ± 0.006	−0.032 ± 0.002	0.081 ± 0.004	−0.019 ± 0.004	−0.031 ± 0.004	0.017 ± 0.003
50°	−0.119 ± 0.006	−0.044 ± 0.002	0.099 ± 0.004	+0.017 ± 0.008	−0.053 ± 0.004	0.029 ± 0.005
60°	−0.106 ± 0.007	−0.053 ± 0.004	0.117 ± 0.004	+0.023 ± 0.010	−0.089 ± 0.004	0.043 ± 0.004
70°	−0.072 ± 0.007	−0.074 ± 0.006	0.133 ± 0.006	+0.030 ± 0.017	−0.157 ± 0.014	0.059 ± 0.007

[a] Angles defined with respect to the vertical (i.e., 90° is parallel to the beam) using the geometry of Ref. 1.

[b] Only the magnitude of $O_{1-}^{col}(0)$ is given as the sign depends on the convention used to define a positive angle of tilt. (See text.)

Burns *et al.* rotate the foil in the opposite direction and hence observe positive values for $O_{1-}^{col}(0)$. For this reason we have shown only the magnitude of $O_{1-}^{col}(0)$ in Table I and in Fig. 3. For easy comparison with our earlier work[1] we have retained the sign of (S/I) as observed using our geometry, where a positive rotation of the foil is clockwise when viewed from a direction looking into the detection system, in Figs. 1 and 2. Figure 1 plots the behavior of M/I for the $2s\,^3S$-$3p\,^3P^o$ (3889 Å) transition, and of the $2p\,^3P^o$-$4d\,^3D$ (4471 Å) transition in He I, from 0° to 70° tilt

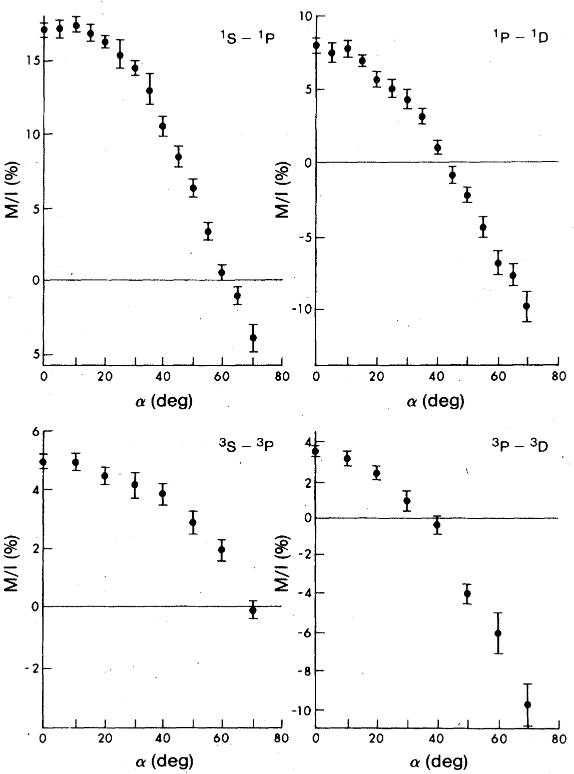

FIG. 1. Linear polarization observed for singlet and triplet transitions in neutral helium as a function of the foil-tilt angle (α). The curves on the left are for the 1s2s-1s3p transitions and those on the right are for the 1s2p-1s4d transitions. The results for the singlet transitions are taken from Ref. 1.

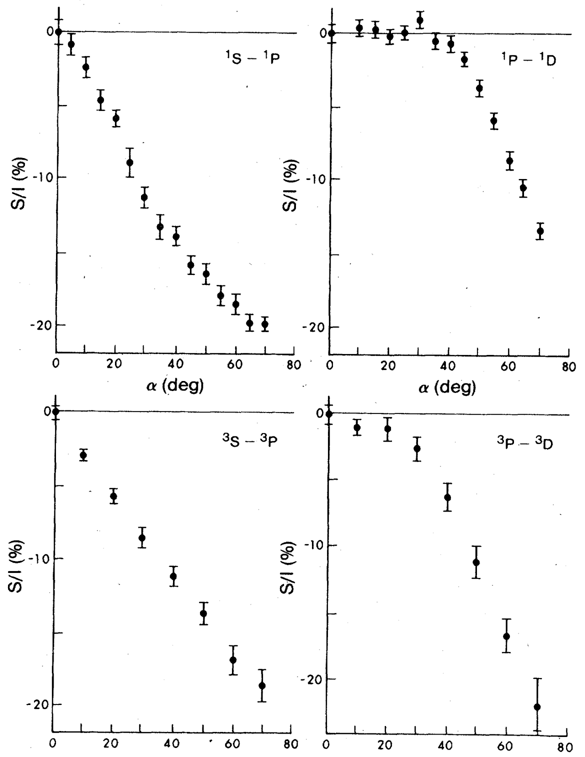

FIG. 2. Circular polarization observed for singlet and triplet transitions in neutral helium as a function of the foil-tilt angle (α). The curves on the left are for the 1s2s-1s3p transitions and those on the right are for the 1s2p-1s4d transitions. The results for the singlet transitions are taken from Ref. 1.

angle. Comparison with our published data for the corresponding singlet transitions (at 5016 and 4922 Å, respectively)[1,2] show the same general trend in both cases, namely that M/I falls with increasing tilt angle, from an initial positive value at 0° tilt, reaching zero at a rather higher angle for ^1S-$^1P^o$ than for $^1P^o$-^1D. Figure 2 shows the corresponding trends for S/I. Again, the ^3S-$^3P^o$ and $^3P^o$-^3D trends closely follow their singlet counterparts, with ^3S-$^3P^o$ showing a decrease from zero which is almost linear with tilt angle, while $^3P^o$-^3D shows S/I to remain close to zero until a tilt angle of ~30° is reached, and only then to decrease rapidly with further increase in the tilt angle. The conclusion must therefore be drawn from these measurements that the differences in the behavior of M/I and S/I that have been observed between ^1S-$^1P^o$ transitions on the one hand, and $^1P^o$-^1D transitions on the other, are closely followed by the corresponding triplet transitions. Thus, to a first approximation at least, the *variation* in the linear and circular polarization with tilt angle shows very similar trends for corresponding singlet and triplet terms. The natural question to ask is whether the *magnitudes* of the parameters are the same in both cases. Unfortunately, it is not possible to analyze our previous (M/I) data for the helium singlet transitions to obtain the $A_0^{\mathrm{col}}(0)$ and $A_{2+}^{\mathrm{col}}(0)$ parameters. However, it is relatively straightforward to show that, if these parameters are the same for singlet and triplet terms of the same L, the singlet-to-triplet ratio for (M/I) should be ~3.6 for P states and ~1.4 for D states, and that the corresponding ratios for (S/I) should be ~2.0 and ~1.1, respectively. Our observations do not agree with these predictions except for the (M/I) values of the P states at low tilt angles. We conclude that, in general, the alignment and orientation parameters show some dependence on the spin of the state involved, while the form of the *variation* of the polarization of the emitted radiation as a function of foil-tilt angle is approximately spin independent.

IV. COMPARISON WITH OTHER DATA

The results presented here for the 3889 Å $2s\,^3S$-$3p\,^3P^o$ transition differ significantly from these recently published by Burns *et al.*,[7] and it is obviously necessary to explain the cause of this apparent discrepancy. It was stressed earlier in this report that various effects combine to decrease the experimental time resolution, and hence the observed quantum beat amplitude, as the foil-tilt angle is increased, and that these effects become rapidly more serious at high angles. In Fig. 3 we compare the results we have obtained for $O_{1-}^{\mathrm{col}}(0)$ as a function of tilt angle for the $2s^3S-3p^3P^o$ transition at 3889 Å with those reported by Burns *et al.*[7] [As was explained previously in this report, we expect to obtain negative values of $O_{1-}^{\mathrm{col}}(0)$, while Burns *et al.* observed positive values, because the foil is rotated in opposite directions in the two experiments, and hence we plot the magnitude of $O_{1-}^{\mathrm{col}}(0)$ in Fig. 3.] We also include the results obtained from the analysis of our data using only the *observed* beat amplitude without compensating for the beat amplitude damping factors arising from scattering, straggling, etc. It is apparent that this correction is of the right magnitude to explain the difference between the results from the two experiments. In fact, Burns *et al.* did use the beat amplitudes to derive their values for the alignment and orientation parameters, but make no mention of correcting for the effects of the factors we have discussed. They do report a consistency check made by comparing the observed and theoretical beat amplitudes in M and S light at 40° but, as can be seen from Fig. 3, the errors only become serious at higher tilt angles. In order to confirm that these effects are sufficiently large to explain the discrepancy between the two experiments, we will now calculate the magnitude of the error corresponding to the experimental conditions of the Burns *et al.* experiment.

The dominant cause of decreased time resolu-

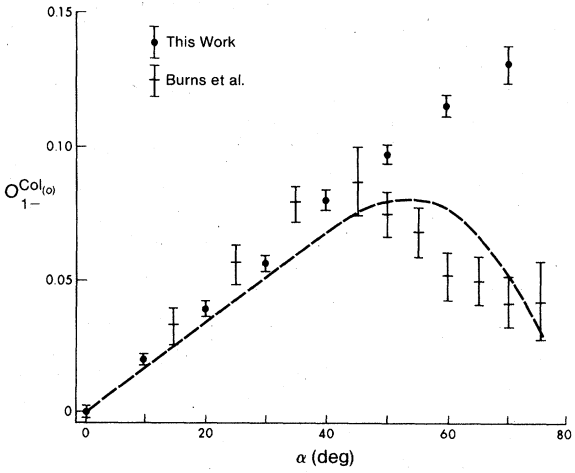

FIG. 3. The magnitude of $O_{1-}^{\mathrm{col}}(0)$ for the $1s3p\,^3P^o$ term of neutral helium as a function of foil-tilt angle (α). The comparison data of Burns *et al.* are taken from Ref. 7. The dotted curve shows the results obtained in the present experiment using only the observed beat amplitude without correcting for the effects of decreasing time resolution at higher tilt angles.

tion, and hence of the observed beat amplitude, is scattering of the ions during their passage through the foil. It is easy to show that the effective length of the observation region is given by $\theta D \tan\alpha$, where θ is the total angular half-width, D the distance of the observation region from the foil, and α is the foil-tilt angle. Extrapolation of the data presented by Högberg *et al.*[9] suggests that, for 200 keV He^+ ions incident on 10 $\mu g/cm^2$ carbon foil, $\theta \sim 3.4°$. (The tabluations of Biersack *et al.*[10] suggest a somewhat higher value of about 4°.) Since the effective foil thickness increases as $(\cos\alpha)^{-1}$, the effective length of the observation region is given by $\theta_0 D \tan\alpha/\cos\alpha$, where θ_0 is the total angular halfwidth at 0° tilt. In their article, Burns *et al.* report that observations were made over 3–7 quantum beat oscillations, corresponding to an average length of about 24 mm from the foil. We will use 12 mm as an effective value for D. The averaging length of the observation region due to scattering at the foils is then found to be 1.3 mm at a tilt angle of 50°, 2.5 mm at 60°, and 5.7 mm at 70°. Smaller contributions arise from energy straggling at the foil and from the finite width of the detector slit. Straggling may be shown to contribute an amount $D\Delta E/(2E\cos\alpha)$ to the averaging length, where ΔE is straggling at 0° tilt for an incident energy E. For fixed slit widths, the effective slit width varies as $1/\cos\alpha$. From the tabulations of Biersack *et al.*[10] and the details given by Burns *et al.* in their report we obtain additional contributions to the averaging length given by 0.15 mm (at 50°), 0.18 mm (at 60°), and 0.27 mm (at 70°). The beat degradation factor is $(\sin\Delta)/\Delta$ for the case where the lifetime of the upper state is much longer than the beat period, as in the case for the 3889 Å transition in helium, and where Δ is averaging length multiplied by π/b, b being the length of one complete beat in mm. This factor has the values 0.82 (50°), 0.51 (60°), and 0.21 (70°) for the cases considered here, assuming a beat length of 4.7 mm, appropriate for 200-keV He^+ beam and a beat frequency of 658 MHz. Allowing for this effect, the corrected values for the Burns *et al*, $O_{1-}^{col}(0)$ parameters become 0.96 ±0.007 (50°), 0.104 ± 0.020 (60°), and 0.21 ± 0.03 (70°). These values are reasonably consistent with the results of the present work, thus supporting the contention that the effect of decreasing time resolution with increased angle of foil tilt is sufficient to explain the apparent discrepancy between the two sets of results for $O_{1-}^{col}(0)$.

V. CONCLUSION

We have presented data for the alignment parameters $A_0^{col}(0)$ and $A_{2+}^{col}(0)$, and the orientation parameter $O_{1-}^{col}(0)$, as a function of foil-tilt angle for the helium transitions at 3889 Å ($2s\,^3S$-$3p\,^3P^o$) and 4471 Å ($2p\,^3P^o$-$4d\,^3D$) measured with an incident 200 keV beam of helium ions. We have shown that the form of the variation of the relative Stokes parameters (M/I) and (S/I) with tilt angle is, to a first approximation, the same as that exhibited by the corresponding singlet transitions, although the magnitudes of the alignment and orientation parameters are different for the singlets from the values found here for the triplets. An apparent discrepancy with the recent work of Burns *et al.* has been explained in terms of the decrease in time resolution as the tilt angle is increased. As a final remark it is worth noting that the (S/I) results presented here are reasonably consistent with the recent model calculations of Burgdörfer *et al.*,[5] who show that capture into a hydrogenic $2p$ state of the projectile ion should produce a circular polarization proportional to the sine of the tilt angle. It will be interesting to see if such calculations can be extended to include capture into a d state.

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[1] R. L. Brooks and E. H. Pinnington, Phys. Rev. A 18, 1454 (1978).

[2] R. L. Brooks and E. H. Pinnington, J. Phys. (Paris) Colloq. C1 40, 295 (1979).

[3] R. L. Brooks and E. H. Pinnington, Phys. Rev. A 22, 529 (1980).

[4] Y. B. Band, Phys. Rev. A 13, 2061 (1976).

[5] J. Burgdörfer, H. Gabriel, and H. Schröder, Z. Phys. A295, 7 (1980).

[6] D. G. Ellis, J. Phys. B 10, 2301 (1977).

[7] D. J. Burns, R. D. Hight, and C. H. Greene, Phys. Rev. A 20, 404 (1979).

[8] U. Fano and J. H. Macek, Rev. Mod. Phys. 45, 553 (1973).

[9] G. Högberg, H. Nordén, and H. G. Berry, Nucl. Instrum. Methods 90, 283 (1970).

[10] J. P. Biersack, E. Ernst, A. Monge, and S. Roth, Hahn-Meitner-Institut, Berlin, Report No. HML-B175 (unpublished).