Alignment of Some Triplet and Singlet D States of Helium

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The alignment of some singlet and triplet D states of ^{4}He resulting from the beam-foil interaction process at 40 kV has been measured for principal quantum numbers $n = 3$, 4, 5, and 6. The measurements were based on zero-field level crossing.

The beam-foil interaction process is known to lead to an alignment of excited atomic states.[1] Alignment has been reported for a number of atomic as well as ionic[2] states; however, there appears to be as yet no systematic study of the dependence of alignment on principal quantum number, angular momentum state, and spin state. Such a study is of interest both for an understanding of the beam-foil interaction process and for the performance of experiments based on alignment,[3-6] e.g., level-crossing and radio-frequency spectroscopy. The present investigation was undertaken as part of a program to utilize the alignment induced by the beam-foil scattering process for the measurement of atomic constants.[5] We report here on the alignment of the $n^3D_{1,2,3}$ and n^1D_2 states of ^{4}He for principal quantum numbers $n = 3$, 4, 5, and 6. These measurements were done for incident energies of 40 kV. Carbon foils of 6.0 and 6.7 μg/cm^2 density were used.

The polarization fraction, which is related to the alignment,[7] is defined by

$$P = (I_\parallel - I_\perp)/(I_\perp + I_\parallel), \tag{1}$$

where $I_\perp$ is the intensity of light with polarization vector perpendicular to the beam axis and to the direction of observation and $I_\parallel$ is the intensity of light with polarization vector parallel to the beam axis. A direct measurement of the polarization fraction is susceptible to serious error resulting from reflection polarization in the detector optical system and it is for this reason that we chose to make the measurements by observing the integrated "quantum beat" in the limits where the observation time $\Delta t \ll \tau$, as well as when $\Delta t \sim \tau$, where τ is the lifetime of the state.

The intensity fluctuation or quantum beat for an aligned singlet D state is given by

$$I(\omega, t) \propto e^{-\gamma t}[1 + A\cos 2(\omega t - \theta)], \tag{2}$$

where $\omega = g_J \mu_0 H/\hbar$, θ is the angle which the linear polarizer makes with the beam axis, A is the alignment, and γ is the reciprocal lifetime in radians per second of the $^1D_2$ state. g_J is the gyromagnetic ratio ($=1$ for $^1D_2$), μ_0 is the Bohr magneton, and H is the magnetic field intensity. In Eq. (2) t is the time following excitation in the foil at which the observation is made and hence $t = l/v$, where l is the foil-detector separation and v the beam velocity. The detector is assumed to view a short region of the beam path Δl such that $\Delta l/v \ll 1/\gamma$. Thus by observing the intensity fluctuation the polarization fraction can be determined. If the detector integrates the light from a long segment of the beam defined by the end position $l_{\min} + l_{\max}$ or what is equivalent, if many small adjoining beam segments are viewed successively and summed, then the signal is

$$\begin{aligned} S(\omega) &= \int_{t_1}^{t_2} I(\omega, t)\, dt \\ &\propto -\gamma^{-1}[\exp(-\gamma t_2) - \exp(-\gamma t_1)] + \tfrac{1}{4}A[(\tfrac{1}{2}\gamma)^2 + \omega^2]^{-1}\{\exp(-\gamma t_2)[2\omega\gamma^{-1}\sin 2(\omega t_2 - \theta) - \cos 2(\omega t_2 - \theta)] \\ &\qquad - \exp(-\gamma t_1)[2\omega\gamma^{-1}\sin 2(\omega t_1 - \theta) - \cos 2(\omega t_1 - \theta)]\}, \end{aligned}$$

where $t_1 = l_{\min}/v$ and $t_2 = l_{\max}/v$. If the limits are carried from 0 to ∞ we have

$$S(\omega) \propto \frac{1}{\gamma} + \frac{A\gamma/4}{(\frac{1}{2}\gamma)^2 + \omega^2}\left(\frac{2\omega}{\gamma}\sin 2\theta + \cos 2\theta\right).$$

Thus, if observation is made of the polarization parallel to the beam axis ($\theta = 0$) or perpendicular to the beam axis ($\theta = 90°$) we see that $A = \pm[S(0) - S(\infty)]/S(\infty)$, respectively. In other words the relative amplitude of the Hanle or zero-field level-crossing signal gives the polarization fraction. This result is independent of the observation limits, t_1, t_2. For the $^3D_{1,2,3}$ state additional modulation terms occur corresponding to the fact that there are three g_J factors. In addition modulations due to mixing of fine-structure and Zeeman frequencies occur, but the latter do not contribute to the zero-field level-crossing signals. The interpretation of the ^3D signals is otherwise the same as for the ^1D states. In beam-foil experiments it is not usually practical to extend the limits of observation to many lifetimes. This is so because of the high velocity of the atoms. For example, a 40-kV $^4\mathrm{He}^+$ ion incident on a carbon foil of 6 μg/cm^2 emerges from the foil with an energy of 36 kV and a velocity of 1.3×10^8 cm/sec, so that 1 cm corresponds to 7.7 nsec. Considerations of magnetic field uniformity impose a severe limit on the maximum detector-foil separation which in the present experiment was 7 cm, corresponding to an upper limit of 59 nsec. When the limits of observation do not extend to infinity, modulations occur in the wings of the level-crossing signal. This is shown in Fig. 1 where we have plotted the zero-field level-crossing signal for a $^1D_2$ state for different values of t_2. It is seen that when $t_2=1$ lifetime the modulations are already considerably suppressed and we have essentially the Hanle signal. Curve fitting was used to determine the polarization fraction when inspection did not suffice. The measurements reported here also yield lifetime information for the states studied; however, we are presently concerned only with the alignment.

Details of the experimental technique have been described elsewhere,[5,6] and we review them here in brief. A 40-kV $^4\mathrm{He}^+$ ion beam from the Lawrence Berkeley Laboratory mass separator was incident on a thin carbon foil of 6.0 or 6.7 μg/cm^2 density and the light emitted downstream by neutral ^{4}He atoms observed through a linear polarizer by a cooled photomultiplier. Narrow-band (25 Å) interference filters were used to select the appropriate line. A magnetic field was applied perpendicular to the beam axis and along the direction of observation. The field intensity was stepped synchronously with the address advance of a multichannel scaler where the signal was stored. The magnetic field intensity covered a range of -6 to $+6$ G. This range was covered a predetermined number of times for each foil-detector separation starting with the extreme separation of 7 cm. In this way the "quantum beat" signal was obtained at each position. The foil position was then advanced downstream by a small increment and the measurement repeated for the same number of predetermined field sweeps, the photon counts being added to those taken at the previous foil position. This process was repeated until the foil position coincided with the detector. The direction of travel was then reversed. A sufficient number of position and magnetic field scans were taken to average out beam fluctuations and the effects of foil aging. The beam intensity was generally very stable and typically varied by $\lesssim 10\%$ during the course of a run. Beam currents of ~ 3.5 μA were used, and the foil lifetime was 20–30 min. Fresh foils of the same nominal thickness and from the same batch were introduced as needed by means of a circular foil holder on which ten foils were mounted. Generally one to three foils sufficed for a measurement. Counting rates varied from ~ 350 to 20 000 sec^{-1} depending on the transition and foil position. A schematic of the experiment is shown in Fig. 2. A cesium optical pumping magnetometer was used to monitor the magnetic field. The magnetometer was placed in a Helmholtz coil connected in series with the magnetic field coils of the beam-foil apparatus. The field in the beam-foil region was then cali-

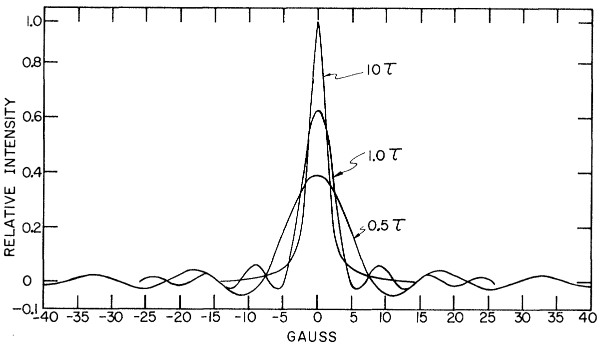

FIG. 1. Computed line shape for the zero-field level-crossing signal of the 5^1D_2 state of ^{4}He. The lifetime of the state was taken as $\tau=49$ nsec. The lower limit of integration is $t_1=0$ and the upper limit t_2 is shown in the figure.

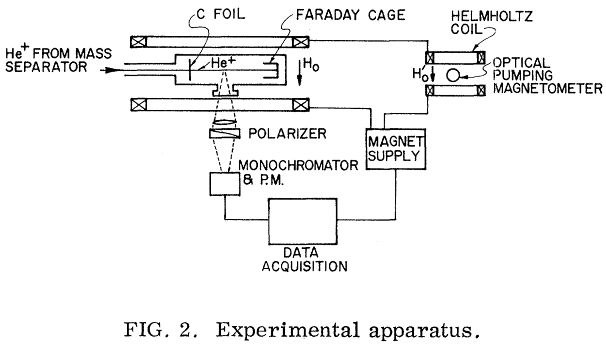

FIG. 2. Experimental apparatus.

TABLE I. Measured percentage polarization (P) and relative sublevel cross sections for the singlet and triplet D states of ^{4}He. λ is the wavelength of the observed transition, for transitions of the two types $n^3D_{1,2,3} \rightarrow 2^3P_{2,1,0}$ and $n^1D_2 \rightarrow 2^1P_1$.

n	P (%)	σ_2/σ_0	λ (Å)
^1D 4	12.0±1.8	$0.357(1+0.800\sigma_1/\sigma_0)$	4922
5	9.4±1.4	$0.385(1+0.852\sigma_1/\sigma_0)$	4388
6	4.3±1.9[a]	$0.445(1+0.938\sigma_1/\sigma_0)$	4144
^3D 3	3.6±1.5[a]	$0.406(1+0.888\sigma_1/\sigma_0)$	5876
4	2.9±1.6	$0.423(1+0.911\sigma_1/\sigma_0)$	4473
5	4.0±1.6	$0.398(1+0.871\sigma_1/\sigma_0)$	4026
6	5.0±1.8	$0.375(1+0.832\sigma_1/\sigma_0)$	3820

[a] These values based on quantum-beat signal only.

brated against the magnetometer.

Table I summarizes the polarization-fraction measurements and relative magnetic-substate cross sections which can be obtained from the mean data. The cross sections for magnetic sublevels 0, 1, and 2 are denoted, respectively, by σ_0, σ_1, and σ_2. The relative cross sections are calculated from data in Ref. 7. In Fig. 3 we show a typical quantum-beat and Hanle signal for the $3^3D_{1,2,3}$ state. Counting errors in all cases contribute an uncertainty of $<\frac{1}{2}\%$ to the percentage polarization fraction. The polarization fraction measurements varied by ~1% from foil to foil and from day to day and this is reflected in the errors. This variation we believe to be due to the condition of the foil. We have observed structural variations between some foil batches, and this plus contamination of the foil in preparation, in handling, or in the vacuum system of the apparatus may be responsible for some of the variations.

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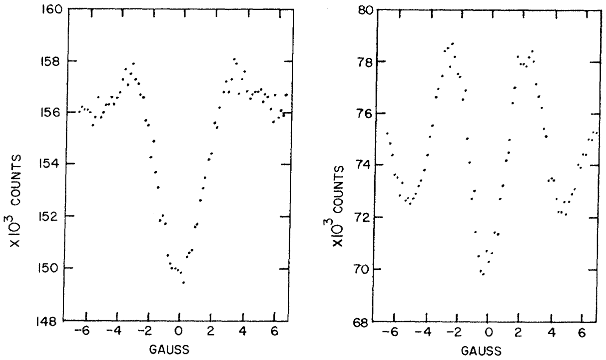

FIG. 3. Alignment signal for the $5^3D_{1,2,3}$ state of ^{4}He. (a) "Quantum beat" signal. The detector viewed a 7-mm portion of the beam 7 cm downstream from the foil. Thus this is not a pure beat signal but really a delayed Hanle signal with the observation time extending from 51.2 to 56.6 nsec. (b) Zero-field level-crossing (Hanle) signal. The observation extended from zero foil-detector separation to 7-cm foil-detector separation corresponding to about 1 lifetime of observation. Note the modulations in the wings. The polarizer axis was perpendicular to the beam axis, hence the inverted signal.

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[1] S. Bashkin, W. S. Bickel, D. Fink, and R. K. Wangsness, Phys. Rev. Lett. 15, 284 (1965); T. Hadeishi, Phys. Rev. Lett. 21, 957 (1968).

[2] W. S. Bickel and S. Bashkin, Phys. Rev. 162, 12 (1967); see also Nucl. Instrum. Methods 90 (1970) for additional references.

[3] C. H. Liu, S. Bashkin, W. S. Bickel, and T. Hadeishi, Phys. Rev. Lett. 26, 222 (1971).

[4] D. A. Church, M. Druetta, and C. H. Liu, Phys. Rev. Lett. 27, 1763 (1971).

[5] T. Hadeishi, M. C. Michel, J. Yellin, and E. Geneux, in Proceedings of the Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October, 1972 (to be published).

[6] J. Yellin, T. Hadeishi, and M. C. Michel, Lawrence Berkeley Laboratory Report No. LBL-1608, 1973 (unpublished), and Phys. Rev. Lett. 30, 417 (1973).

[7] I. C. Percival and M. T. Seaton, Phil. Trans. Roy. Soc. London 251, 113 (1958).