PHYSICAL REVIEW
LETTERS

VOLUME 33 21 OCTOBER 1974 NUMBER 17

Polarization and Collision-Induced Coherence in the Beam-Foil Light Source*

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(Received 15 July 1974)

Polarization up to 15% has been detected in the decay of electronic levels in many-electron monatomic systems which were excited by the beam-foil method, the foil being tilted with its plane at 65° to the particle velocity. Quantum beats were found even with an external magnetic field oriented parallel to the particle velocity, indicating that coherence is produced in the beam-foil interaction itself. Results are reported for various levels in He I, O II, and Ar II.

Berry *et al.*[1] showed that substantial anisotropy appears in the emitted light when a beam of He^+ ions is excited to the He I $3p\ {}^1P_1$ level by passage through a carbon foil whose normal makes a finite angle with the beam velocity. They interpreted their result to mean that a particular magnetic substate was preferentially populated. We have re-examined this possibility, using levels in O II, Ar II, and He I, and a simplified experimental geometry. We conclude that, with a tilted foil, (1) polarization up to ~15% may be achieved, (2) the polarization is due to the foil, (3) the foil induces coherence among the Zeeman substates, (4) the coherence previously reported[2] among Zeeman substates was almost entirely due to the externally applied magnetic field which was perpendicular to the beam direction, and (5) the angular momentum of the emitted photon is normal to the ion velocity, $\vec{v}$.

In a Zeeman quantum-beat experiment,[2] alignment ($I \propto$ number of $|m_J|$ states) associated with the magnetic-field–induced coherence gives a beat frequency of $2\omega_L$, but polarization ($I \propto$ number of m_J states) gives a beat frequency ω_L, where ω_L is the Larmor angular frequency and I is the intensity of the emitted light. Thus, a measurement of the beat frequency allows one to distinguish between the two situations. If the emitted light is sent through a circular polarizer, both ω_L and $2\omega_L$ are passed, whereas a linear polarizer transmits only $2\omega_L$. It is thus possible to detect the separate effects of alignment and polarization.

As shown in Fig. 1, a grating spectrometer se-

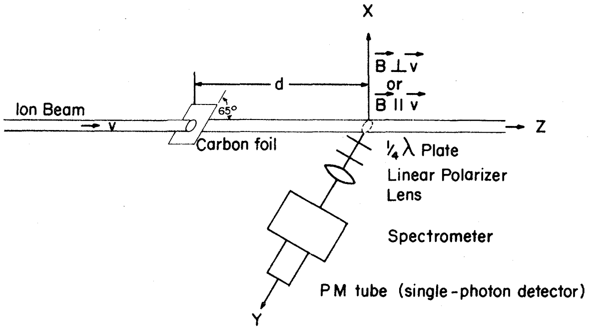

FIG. 1. Schematic arrangement of the experiment. Note that $\vec{B}$ was applied in two different directions relative to $\vec{v}$.

TABLE I. Alignment as measured in earlier work.[a]

Ion	Level	Wavelength (Å)	A (%)
O II	$3p'\,{}^2F_{7/2}{}^\circ$	4590.97	4.1
Ar II	$4p'\,{}^2F_{7/2}{}^\circ$	4609.56	6.5
	$4p\,{}^2P_{3/2}{}^\circ$	4764.86	3.2
He I	$3p\,{}^1P_1{}^\circ$	5015.68	

[a] See Ref. 3.

lected light from a slice of the beam, the slice being parallel to the foil. A magnetic field, $\vec{B}$, generated with Helmholtz coils, and varying linearly with time, was established perpendicular or parallel to $\vec{v}$. The observed beam slice was a distance d from the foil; d (1 or 2 cm) was chosen to be $\lesssim 1$ mean decay length from the foil for the levels studied. The angle, θ, was fixed at 65°, the largest through which the spectrometer could be rotated. Other features of the experiment are summarized in Tables I and II. One should note that the $\frac{1}{4}$-wave plate had a band pass of ±800 Å centered at 5600 Å, so that it was not particularly well suited to the present observations. Nonetheless it sufficed.

We define alignment, A, and polarization, P, by the usual relations,

$$A = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \text{ and } P = \frac{I_{\sigma^+} - I_{\sigma^-}}{I_{\sigma^+} + I_{\sigma^-}},$$

where I is an intensity [parallel or perpendicular to $\vec{v}$; the σ's refer to right- (+) and left- (−) circularly polarized light]. Earlier work[3] with the foil normal to $\vec{v}$ had shown that alignment was produced as listed in Table I. If $\vec{B} \perp \vec{v}$, any polarization is likely to be converted into alignment because of field-induced coherence. This is demonstrated by the patterns of Fig. 2; analysis shows that frequency components ω_L and $2\omega_L$ are both present. On the other hand, when $\vec{B} \parallel \vec{v}$, field-induced coherence cannot occur among Zeeman substates. For this case, we obtained the curves of Fig. 3, where only ω_L appears. Our results a are summarized in Table II.

The data in Table II show that substantial polarization occurs when the foil is tilted with respect to the ion beam. From previous results with $\theta = 90°$, the present experiment with $\theta = 65°$, and other work by Church *et al.*[4] on He I with $\theta \geqslant 30°$, it is found that the degree of polarization is a sharply decreasing function of θ, at least for He I. The situation for heavier elements is not yet known.

TABLE II. Summary of polarization and alignment data.

Ion	Ion energy (keV)	Level	$\vec{B} \perp \vec{v}$ P (%)	$\vec{B} \perp \vec{v}$ A[a] (%)	$\vec{B} \parallel \vec{v}$ P (%)	$\vec{B} \parallel \vec{v}$ A[a] (%)
O II	540	$3p'\,{}^2F_{7/2}{}^\circ$	5.5	0.7	9.6	$\lesssim 0.4$
	1080		2.3	0.8	7.2	
Ar II	675	$4p'\,{}^2F_{7/2}{}^\circ$	3.3	1.2	14.8	~0
	1350				12.2	
	675	$4p\,{}^2P_{3/2}{}^\circ$	3.0	0.3	7.5	~0
He I	260	$3p\,{}^1P_1$			16.0	~0

[a] Detected through a circular polarizer.

We have noted that $\vec{B} \parallel \vec{v}$ means that the external field cannot mix the Zeeman substates. The appearance of quantum beats under this condition proves that the magnetic substates are coherently

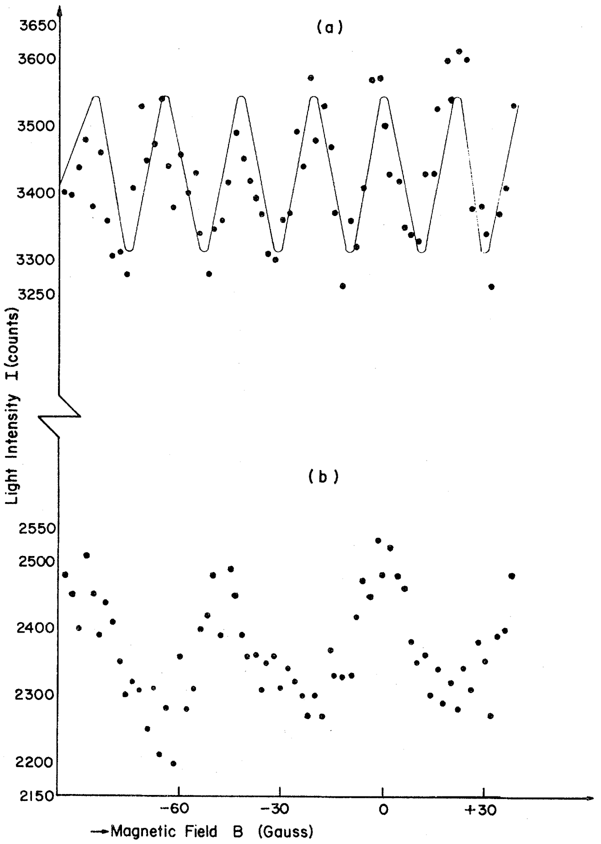

FIG. 2. With $\vec{B} \perp \vec{v}$, we show (a) quantum beats from the level O II $3p'\,{}^2F_{7/2}{}^\circ$, with a frequency $2\omega_L$, as detected through a linear polarizer; (b) as in (a), but with frequencies ω_L and $2\omega_L$, as detected through a circular polarizer.

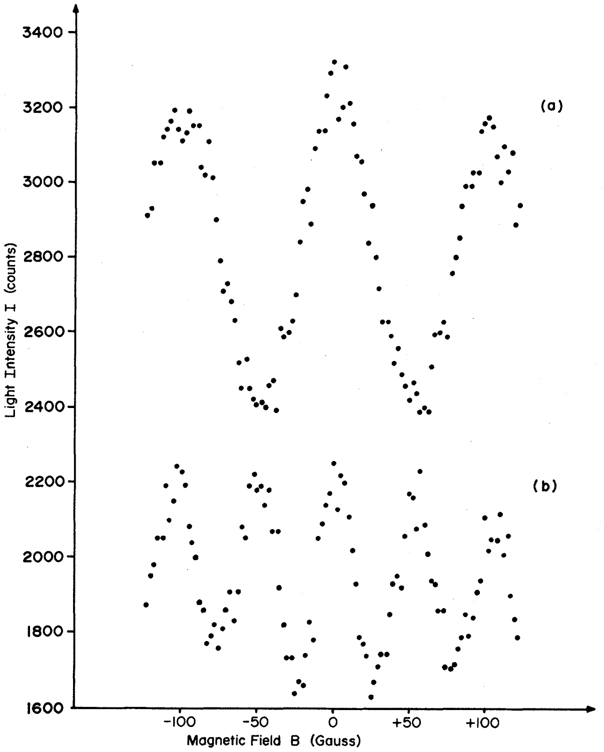

FIG. 3. With $\vec{B} \parallel \vec{v}$, quantum beats from the level Ar II $4p'\,{}^2F_{7/2}{}^{\circ}$, with frequency ω_L. In (a) we show the results for a distance $d \simeq 1$ cm, and in (b) for $d \simeq 2$ cm downstream from the exciter foil.

excited by the beam-foil interaction itself. Thus the beam-foil interaction populates the magnetic substates with a definite relative phase, giving rise to oscillations among the several m_J states on a time scale determined by the level separations.

Our owrk with $\vec{B} \perp \vec{v}$ shows that the polarization is much smaller than with $\vec{B} \parallel \vec{v}$, which means that the external field destroys the polarization through its coupling of m_J and $-m_J$ states. Therefore it appears that the alignment which is characteristic of $\vec{B} \perp \vec{v}$ arrangements derives from the foil-produced polarization and the field-produced coherence.

This experiment demonstrates that the angular momentum of the emitted photon is normal to $\vec{v}$. A determination of the clockwise or counterclockwise sense of the circularly polarized light would tell whether it is the m_J or $-m_J$ state which is preferentially selected in a given geometry. Since the v direction may be taken as the quantization axis, it is clear that nondiagonal elements are present in the state Hamiltonian, as, indeed, Berry *et al.* had reported.

Our limited variation of particle energy showed that the degree of polarization became smaller as the ion energy was raised.

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*Work supported in part by the National Aeronautics and Space Administration, the U. S. Office of Naval Research, and the National Science Foundation.

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Stark Effect of Metastable Hydrogen Molecules*

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(Received 21 August 1974)

The molecular-beam magnetic-resonance method has been used to measure the Stark effect of the metastable $c^3\Pi_u$ electronic state of H_2. The magnitude of the effect is found to be about 10^4 times greater than for the ground electronic state and to depend sensitively upon vibrational quantum number. A theoretical treatment of the effect has allowed us to identify at least three vibrational states of H_2 which are metastable, including $v = 0$ and 1.

Molecular-beam resonance methods have been little used to study the Stark effect of homonuclear diatomic molecules which lack a permanent electric dipole moment. One exception is a study[1] of the hydrogen molecule in its vibrational and electronic ground state. In this work the molecu-