PHYSICAL REVIEW
LETTERS

VOLUME 27 25 OCTOBER 1971 NUMBER 17

Fine-Structure Measurements by the Beam-Foil Technique

H. G. Berry and J. L. Subtil
Laboratoire de Physique de l'Atmosphère, 69 Villeurbanne, France*
(Received 10 August 1971)

We have measured fine-structure separations in some ^3P states of He I ($n = 3, 4, 5$) and Li II ($n = 4, 5$) by observation of modulated light-intensity decay curves using the beam-foil technique.

Macek[1] has suggested that time-resolved light-intensity decays from closely spaced levels (e.g., within a multiplet) may have a modulated component in addition to the normal exponential decay. The theory is similar to that of quantum-beat and level-crossing experiments utilizing electronic excitation.[2] Assuming that the beam-foil interaction is a spin-independent, sudden interaction, we can attribute a cross section $\sigma(M_L)$ for excitation to each orbital angular momentum sublevel, relative to the beam axis. Each wave function of $(LS, M_L M_S)$ is then developed as a linear combination of states of total angular momentum (JM_J) as related by the Clebsch-Gordan coefficients. The electric dipole elements for the decay of such a state contain cross terms proportional to $\cos[\Delta E(J_1J_2)t/\hbar]$ where $\Delta E(J_1J_2)$ are the energy differences of the different J states. We can then write the decay of the light intensity behind the foil as a function of time in the form

$$I(t) = (a + \textstyle\sum_i b_i \cos\omega_i t)e^{-\gamma t}.$$

The summation is over all possible energy differences ω_i within the upper multiplet, and γ is the common decay constant. The coefficients b_i are zero if there is no alignment in the upper state, and the relative values of a and b_i depend on the initial coherence and populations of the angular momentum sublevels.

Thus, measurements of these modulation frequencies in lifetime decays can give direct measurements of atomic fine structures. Andrä has verified this in his observation of a modulation in the 3889-Å, $2s\,^3S$-$3p\,^3P$ transition in He I. Modulations have also been observed in hydrogen decays.[3,4]

We have used the normal side-on viewing system[5] to measure decay curves in He I and Li II. A rotatable polarizer enabled us to view the beam light polarized parallel and perpendicular to the beam axis, and quartz optics ensured a viewing length of the beam as small as 0.2 mm. No external electric or magnetic fields were applied, and it can easily be shown that the Earth's magnetic field gives rise to only a very low modulation frequency and amplitude, too small to be seen in these experiments. Figure 1 shows the decay curve observed for the 3188-Å, $2s\,^3S$-$4p\,^3P$ transition in He I. We note that there is only one modulation frequency observable. This frequency corresponds to the separation of the $4p\,^3P_1$ and $4p\,^3P_2$ levels. The light polarized perpendicular to the beam has modulations of half the amplitude, 180° out of phase. Thus, the total number of photons emitted at each point in the beam is unmodulated, as predicted by Macek.[1] Similar modulations were observed for the transitions in ^{4}He I from $3p\,^3P$ and $5p\,^3P$, and the results are compared in Table I with those of Descoubes,[6] as measured by level-crossing techniques. We find good agreement,

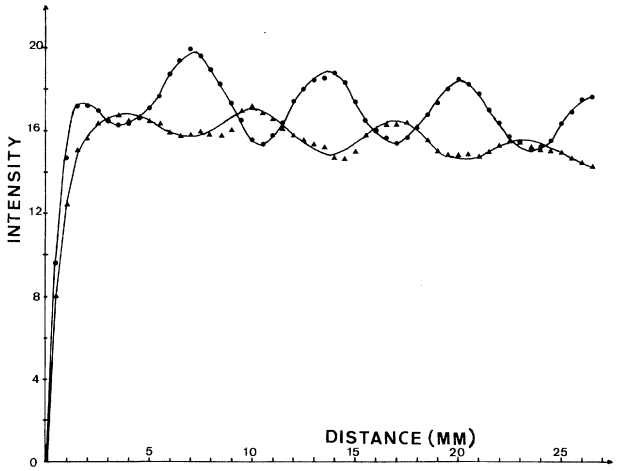

FIG. 1. Intensity decay of the $2s\,^3S$-$4p\,^3P$, 3188-Å, He I transition. The beam energy is 300 keV. The foil is located at the half-intensity point on the left-hand side. The circles and the triangles are the measurements in light polarized parallel and perpendicular to the beam, respectively. The residual instrumental polarization is (0 ± 1)%.

TABLE I. Fine structure in ^{4}He I and ^{6}Li II.

Level	Observed frequency This expt. (MHz)	 Ref. 6 (MHz)	Wavelength observed Å
^{4}He I $3p\,^3P$	658 ± 7	685.55	3889
$4p\,^3P$	275 ± 10	269.0	3188
$5p\,^3P$	135 ± 10	135.0	2945
^{6}Li II $4p\,^3P$	3470 ± 100	...	3684
$5p\,^3P$	2410 ± 100	...	2674

well within our estimated uncertainties.

The modulation amplitude for 3889 Å was measured at beam energies from 230 to 500 keV. The amplitude was a minimum around 400 keV, and increased at low and high energies. This is in general agreement with the degree of alignment measured in other He I transitions from 3^1P, 4^1D, and 4^3D, which showed similar energy variations.[7] Thus, we expect that the modulations arise from different relative cross sections of the M_L states rather than coherence in the excitation of these states.

The main interest in the beam-foil technique is in the application of this method to ions where the standard techniques of measuring fine structure cannot be used. We have studied these same ${}^3S$-${}^3P$ transitions in the isoelectronic spectrum of ^{6}Li II, where previously only the $2p\,^3P$ fine structure has been resolved.[8] A thermionic lithium source was mounted in a 2-MeV Van de Graaff, which gave beams of several microamperes of Li$^+$ in the target chamber. Decay times were measured at 1.5-MeV beam energy. At this energy the ^{6}Li II lines are quite strong, the alignment produced by the foil is a maximum, and the high velocity gives good spatial resolution. Preliminary measurements showed at least one frequency in each of the transitions from $4p\,^3P$ and $5p\,^3P$ as listed in Table I. These primary frequencies had varying modulation amplitudes of up to 10% indicating beating with other frequencies. The hyperfine structure for these levels is expected to affect their fine structure strongly, and we are making further calculations and experiments to ascertain the identity of the observed frequencies. The same transitions in ^{7}Li II were also measured but no modulations could be observed. In this ion the hyperfine structure is much larger,[8] and the increased mixing of the levels must be responsible for the disappearance of the modulations.

Our results show that zero-field modulation-frequency measurements can be used to measure both fine-structure and hyperfine-structure intervals in both neutrals and ions. Our recent measurements[7] indicate that the necessary requirement of alignment in the beam-foil excitation is in general satisfied for many ions. A primary limitation on the technique is the required spatial resolution, which gives an upper frequency limit of about 5 GHz.

---

*Equipe de recherche associée au Centre National de la Recherche Scientifique.

[1] J. Macek, Phys. Rev. A 1, 618 (1970).

[2] R. L. Kelly, Phys. Rev. 147, 376 (1966), and references quoted there.

[3] H. J. Andrä, Phys. Rev. Lett. 23, 325 (1970).

[4] D. J. Lynch, C. W. Drake, M. J. Alguard, and C. E. Fairchild, Phys. Rev. Lett. 26, 1211 (1971).

[5] M. Dufay, Nucl. Instrum. Methods 90, 15 (1970).

[6] J. P. Descoubes, thesis, Université de Paris, 1967 (unpublished).

[7] H. G. Berry, J. L. Subtil, W. S. Bickel, and M. Carré, to be published.

[8] G. Herzberg and H. R. Moore, Can. J. Phys. 37, 1293 (1959).