Laser-Induced $M1$ Resonance Spectroscopy of the $1s2p\ ^3P_1$-$^3P_2$ Fine Structure of $^{19}F^{7+}$

E. G. Myers
University of Oxford, Clarendon and Nuclear Physics Laboratories, Oxford OX1 3RH, England

and

P. Kuske and H. J. Andrä[a]
Institut für Atom- und Festkörperphysik, Freie Universität Berlin, Berlin, West Germany

and

I. A. Armour,[b] N. A. Jelley, H. A. Klein, J. D. Silver, and E. Träbert[c]
University of Oxford, Clarendon and Nuclear Physics Laboratories, Oxford OX1 3RH, England
(Received 6 April 1981)

We report the first observation of a laser-induced $M1$ transition in a fast beam. This new method has been applied to a measurement of the $F=\frac{1}{2}-\frac{3}{2}$ and $F=\frac{3}{2}-\frac{5}{2}$ hyperfine components of the $1s2p\ ^3P_1-{}^3P_2$ fine-structure interval in heliumlike fluorine. The results are 953.60(3) and 961.77(3) cm^{-1}, respectively. From these we extract the fine-structure splitting $\Delta_{12}=957.88(3)$ cm^{-1}.

PACS numbers: 35.10.Fk, 32.30.Bv

Because the relative simplicity of the two-electron system enables precise *ab initio* calculation, the fine structures of helium and heliumlike ions have remained of fundamental interest in atomic physics. For the 2^3P_1-2^3P_0 interval in helium both theory and experiment are now at the level of 1 ppm.[1] In heliumlike ions, fine structures are more sensitive to highly Z-dependent higher-order relativistic effects. Precise measurements of the $2^3S_{1,F}$-$2^3P_{J,F}$ transition energies in $^{6,7}Li^+$ have been performed using laser resonance techniques on low-energy ion beams,[2,3] while for higher Z there have been several measurements of the 2^3S_1-2^3P_J wavelengths using grating spectroscopy.[4] However, in the region $3<Z\leq 10$, the experimental precision for the 2^3P_J intervals has been insufficient to show any systematic deficiency in the lowest relativistic order fine-structure calculations of Accad, Pekeris, and Schiff (APS).[5] By performing a direct laser-resonance measurement of two of the $2^3P_{1,F}$-$2^3P_{2,F}$ fine-structure transitions in $^{19}F^{7+}$ (Fig. 1), a fractional precision for the fine structure of 3×10^{-5} has been achieved. This precision is the highest to be obtained of all fine-structure measurements on fast beams to date and is capable of testing higher-order corrections to the calculations of APS. In addition, the measurements are the first direct observation of hyperfine structure in a heliumlike ion for $Z>3$.

The exploitation of the near coincidence of the frequencies of the 10.4-μm band of the CO_2 laser and the 2^3P_1-2^3P_2 fine structure in F^{7+} has been discussed previously by Andrä *et al.*[7] Similar techniques have been used to measure the $n=2$ Lamb shift in F^{8+} and Cl^{16+}.[8,9] The setup used in the present experiment is shown in Fig. 2. Beams of 11–17 MeV $^{19}F^{3+,4+}$ were obtained at the University of Oxford EN tandem Van de Graaff accelerator at typical currents of 300 nA. After charge-state momentum analysis by a 90° bending magnet, the ion beam was focused and collimated to a spot (2 mm^2) with a divergence of 1.5 mrad before passing through a 5-$\mu g/cm^2$ carbon foil where it was stripped and excited.

At a distance of 11 cm downstream from the foil, the beam crossed an intracavity focus of the laser at an intersection angle of 5°. The modified coherent Everlase-325 industrial CO_2 laser was line tuned using a 75-1/mm concave grating and the experiment was performed using the $P(40)$,

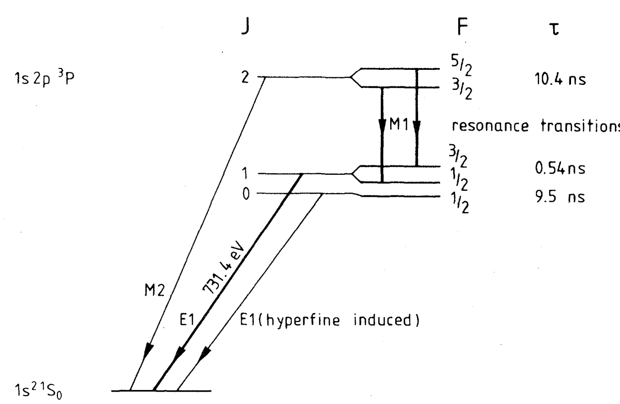

FIG. 1. Energy level diagram of the F^{7+} $1s2p\ ^3P$ fine and hyperfine structure. The resonance transitions, principal x-ray decay modes, and lifetimes are indicated. Theoretical x-ray decay rates are $A(2^3P_2)=9.16\times 10^5\ s^{-1}$, $A(2^3P_1)=1.85\times 10^9\ s^{-1}$, and $A(2^3P_0)=1.3\times 10^7\ s^{-1}$ (see Ref. 6).

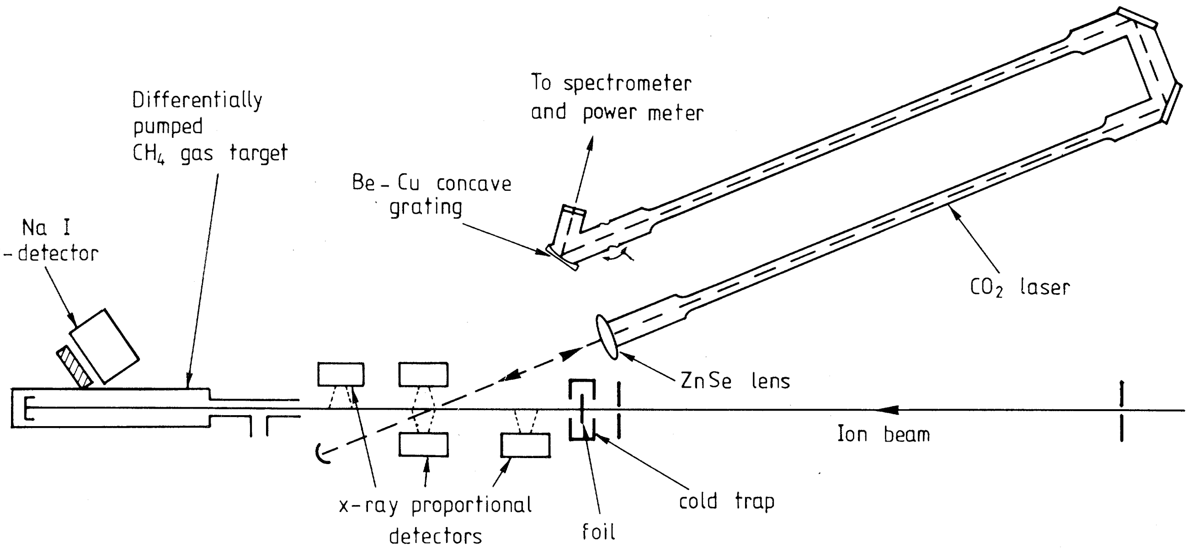

FIG. 2. Schematic diagram of the apparatus. The additional normalization detectors placed 6-cm upstream and downstream of the interaction region aided the identification of the true 2^3P_1-2^3P_2 resonance signal (which appears in the signal detectors only) during the initial search.

$P(44)$, $P(48)$, and $P(50)$ lines of the 00°1–10°0 (10.4 μm) band of CO_2. Typically, intracavity average powers of 300 W in each direction, at a 50% duty cycle, with a laser spot size at the interaction region of 1.7 mm full width at half maximum were obtained. Approximately 1 cm downstream from the center of the interaction region, the K–x-ray intensity from the beam was monitored using two gas-flow proportional counters. By purging with pure methane at 350 mbar the efficiency of the proportional counters was optimized for 730-eV photons at count rates of ~ 1 MHz.

The resonance signal was obtained by making use of the large difference in lifetimes of the 2^3P_2 and 2^3P_1 levels due to the fast $E1$ x-ray intercombination decay $2^3P_1 \rightarrow 1^1S_0$ [see Fig. 1]. After a delay of about 10 ns following excitation by the foil, most of the original 2^3P_1 population has decayed away, while approximately 40% of the 2^3P_2 population still remains. When on resonance, the laser drives the $M1$ $^3P_2 \rightarrow {}^3P_1$ transition, resulting in a small increase in the observed x-ray intensity due to the subsequent $2^3P_1 \rightarrow 1^1S_0$ decay. The increase in the x-ray yield was detected by switching the laser at 500 Hz and gating a set of scalers synchronously. Typical x-ray count rates per detector were 500 kHz with a fractional increase at the peak of the resonance of around 10^{-3}. Combined with estimates of the expected laser-induced transition probability, this signal is consistent with the total x-ray background, with significant contributions from cascading through 2^3P_1 and 2^1P_2,[10] exceeding the inherent x-ray background of the $M2$ decay of 2^3P_2 by a factor of ~ 10.

With the intersection angle between the ion and laser beams fixed, the ion-beam velocity (in the region of 48% c) was ramped by stepping the current of the momentum-analyzing magnet, the field of which was measured with an NMR fluxmeter. Only the laser beam intersecting at 175° was resonant and the beam in the opposite direction could be neglected.

An example of a resonance scan is shown in Fig. 3. The dominant contribution to the observed widths of the resonances (0.04–0.08 cm^{-1} full width at half maximum) is Doppler broadening due to the velocity spread in the ion beam. Energy loss straggling in the foil accounts for a contribution of about 0.03 cm^{-1}; the rest is due to energy fluctuations in the ion beam from the accelerator. The laser-induced background signal seen in Fig. 3 was found not to be completely reproducible and to be very sensitive to small electric fields (~ 50 V/cm) applied after the foil. Though not fully understood, this effect is thought to be due to an interaction of the laser field with high-n, high-l states in F^{7+} and F^{8+}.[11] Because of the constraint imposed by the Doppler formula, a scan of the weakest $\frac{3}{2}$-$\frac{3}{2}$ component with this set-

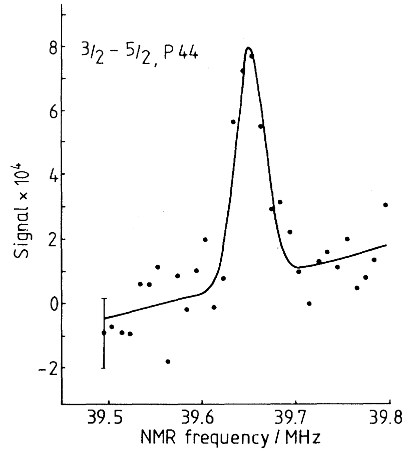

FIG. 3. Example of a resonance spectrum showing the $\frac{3}{2}$-$\frac{5}{2}$ component scanned with the $P(44)$ CO_2 laser line. The horizontal scale of analyzing magnet NMR frequency corresponds to an incident beam energy range of 16.78–17.03 MeV. The signal is defined by $S = (N_{on} - N_{off})/(N_{on}+N_{off})$, where N_{on} (N_{off}) are the total x-ray counts recorded by the signal detectors in the laser on (off) counting periods. The error bar indicates the counting statistics and the total scan time was 3 h. The solid curve is a least-squares fit to the data points.

up would have required the use of a combination of a weak laser line and low-velocity ion beam with a low heliumlike yield and so was not attempted.

To extract the resonance frequencies from the observed resonance curves it is necessary to know the ion-beam velocity as it emerges from the foil, the angle of intersection, and the laser frequency. The resonance curves were fitted with Gaussians on linear backgrounds and their centroids were converted into a beam velocity using a previous magnet calibration.[12] This calibration was checked and the energy loss in the foil, typically 60 keV, measured by exciting $^{19}F(p,\alpha\gamma)$ resonances in a thin (10^{-2} mbar) methane gas target.[13,14] The intersection angle could be measured to within a few milliradians and the narrowness of the laser lines ensures the unstabilized output frequency lies within 3 ppm of the highly accurate results of Petersen *et al.*[15]

The results for the wave numbers of the hyperfine components are

$$2^3P_{1,1/2}\text{-}2^3P_{2,3/2}, \quad 953.60(3)\ \text{cm}^{-1};$$

$$2^3P_{1,3/2}\text{-}2^3P_{1,5/2}, \quad 961.77(3)\ \text{cm}^{-1}.$$

The errors include 1 standard deviation in the results for the centroid NMR frequencies (corrected for foil energy loss) of seven scans for each transition (0.012 and 0.014 cm^{-1}, respectively), and, in addition, allowance for the uncertainties in the energy loss associated with the heliumlike charge state (0.02 cm^{-1}), the nuclear calibration used (0.005 cm^{-1}), the intersection angle (0.007 cm^{-1}), and the laser frequency (0.003 cm^{-1}).

TABLE I. Hyperfine-structure contributions to the measured F^{7+} 2^3P_2 intervals. All values are in inverse centimeters.

	1/2-3/2	3/2-5/2
Nonrelativistic[a]	-4.626	4.076
BDLSC	0.385	-0.212
Rel. wave function, QED, etc.	-0.035	0.024
Total shift	-4.276	3.888

[a]Ref. 16.

Contributions to the theoretical hyperfine-structure shifts to the measured transitions are given in Table I. Aashamar and Hambro[16] have calculated the complete hyperfine matrix for the 2^3P state using nonrelativistic wave functions. This matrix has been diagonalized using the theoretical fine structure of APS. In F^{7+}, there is significant breakdown of *LS* coupling (BDLSC) with admixture of the 2^3P_1 and 2^1P_1 states and the hyperfine splitting of 2^3P_1 is modified accordingly. This effect is not included in the calculations of Aashamar and Hambro and the estimate given in the table was obtained by modifying their matrix using the singlet-triplet mixing coefficient of Drake.[17] Also shown are the sum of small corrections to the dominant contact term due to relativistic, quantum electrodynamical (QED), and Bohr-Weisskopf effects and the reduced mass.[18] The difference of the total theoretical hyperfine contributions to the $\frac{1}{2}$-$\frac{3}{2}$ and $\frac{3}{2}$-$\frac{5}{2}$ intervals is 8.164 cm^{-1} which is in good agreement with the experimental value (obtained by subtracting the two transition energies) of 8.16(4) cm^{-1}.

Subtracting the theoretical hfs from the measured wave numbers yields a value for the 2^3P_1-2^3P_2 fine structure for a (hypothetical) spin-zero nucleus. This value is compared with the theoretical result of APS in Table II. Also shown are some of the previous experimental values from uv spectroscopy.[19,20] The discrepancy between our experimental result and APS is of order $(Z\alpha)^6mc^2$ corresponding to the next order of relativistic corrections. Calculation of some of these corrections, using a method based on both relativistic and nonrelativistic expressions for the

TABLE II. Theory and experiment for the 2^3P fine structure intervals in $^{19}F^{7+}$. All values in inverse centimeters.

	$^3P_0-^3P_1$	$^3P_1-^3P_2$
Engelhardt and Sommer[a]	158 ± 3	957 ± 3
Klein *et al.*[b]	149 ± 2	958 ± 2
This work		957.88 ± 0.03
APS (theory)[c]	151.04	955.26

[a]Ref. 19.
[b]Ref. 20.
[c]Ref. 5.

Breit interaction, are currently in progress.[21]

The authors wish to acknowledge the advice and encouragement of M. A. Grace, the assistance of J. Billowes with the nuclear electronics, and the continuous support of the staff of Oxford Nuclear Physics. Two of us (P.K. and H.J.A.) also wish to acknowledge a grant from the Deutsche Forschungsgemeinschaft.

(a)Present address: Institut für Kernphysik, Universität Münster, Münster, West Germany.

(b)Present address: Central Electricity Generating Board, Marchwood Engineering Laboratories, Marchwood, Southampton, England.

(c)Present address: Institut für Experimentalphysik, Ruhr-Universität, Bochum, West Germany.

[1]W. E. Frieze, E. A. Hinds, V. W. Huges, and F. M. J. Pichanick, Phys. Lett. 78A, 332 (1980), and references therein.

[2]R. Bayer, J. Kowalski, R. Neumann, S. Noehte, H. Suhr, K. Winkler, and G. zu Putlitz, Z. Phys. A292, 329 (1979).

[3]R. A. Holt, S. D. Rosner, T. D. Gaily, and A. G. Adam, Phys. Rev. A 22, 1563 (1980).

[4]For example, I. A. Armour, E. G. Myers, J. D. Silver, and E. Träbert, Phys. Lett. 75A, 45 (1979).

[5]Y. Accad, C. L. Pekeris, and B. Schiff, Phys. Rev. A 4, 516 (1971); B. Schiff, Y. Accad, and C. L. Pekeris, Phys. Rev. A 8, 2272 (1973).

[6]L. Engström *et al.*, Phys. Scr. 22, 570 (1981).

[7]H. J. Andrä, J. Macek, J. Silver, N. Jelley, and L. C. McIntyre, in *Beam-Foil Spectroscopy*, edited by I. A. Sellin and D. J. Pegg (Plenum, New York, 1966), Vol. 2. p. 877.

[8]H. W. Kugel, M. Leventhal, D. E. Murnick, C. K. N. Patel, and O. R. Wood, II, Phys. Rev. Lett. 35, 647 (1975).

[9]D. E. Murnick, C. K. N. Patel, M. Leventhal, O. R. Wood, II, and H. W. Kugel, J. Phys. (Paris), Colloq. 40, C1-34 (1979).

[10]P. Richard, R. L. Kauffman, F. F. Hopkins, C. W. Woods, and K. A. Jamison, Phys. Rev. Lett. 30, 888 (1973).

[11]P. Richard, C. L. Cocke, S. J. Czuchlewski, K. A. Jamison, R. L. Kauffman, and C. W. Woods, Phys. Lett. 47A, 355 (1974).

[12]S. H. Chew, J. Lowe, and H. R. H. McK. Hyder, unpublished.

[13]J. B. Marion, Rev. Mod. Phys. 38, 660 (1966).

[14]F. Ajzenberg-Selove, Nucl. Phys. A300, 179 (1978).

[15]F. R. Petersen, D. G. McDonald, J. D. Cupp, and B. L. Danielson, *Laser Spectroscopy* (Plenum, New York, 1975), p. 555.

[16]K. Aashamar and L. Hambro, J. Phys. B 10, 553 (1977).

[17]G. W. F. Drake, Phys. Rev. 181, 23 (1969).

[18]A. N. Jette, T. Lee, and T. P. Das, Phys. Rev. A 9, 2337 (1974).

[19]W. Engelhardt and J. Sommer, Astrophys. J. 167, 201 (1971).

[20]H. A. Klein, E. G. Myers, and J. D. Silver, unpublished.

[21]G. W. F. Drake, Phys. Rev. A 19, 1387 (1979), and private communication.