Precision Measurement of the $1s2p\,^3P_2$-$^3P_1$ Fine Structure Interval in Heliumlike Fluorine

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Using Doppler-tuned fast-beam laser spectroscopy with co- and counterpropagating beams we have measured the three hyperfine components of the $1s2p\,^3P_2$-$^3P_1$ fine structure interval in $^{19}F^{7+}$. Our result for the centroid is 957.6679(10) cm^{-1}. Allowing for the hyperfine interaction the "pure" fine structure interval is determined to be 957.8730(12) cm^{-1}. This result tests $O(\alpha^7 m_e c^2)$ quantum electrodynamic corrections to high precision calculations which will be used to obtain a new value for the fine structure constant from the fine structure of helium. [S0031-9007(99)09157-7]

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The fine structure constant, α, is the fundamental constant which expresses the elementary charge in dimensionless form and hence plays a crucial role in unifying an enormous range of physical phenomena [1]. There is now a program to obtain a new value for α from comparison of theory and experiment for the $1s2p\,^3P_{J-J'}$ fine structure of atomic helium. Drake and co-workers, using matrix elements of operators derived from the Bethe-Salpeter equation, evaluated with high-precision nonrelativistic wave functions, aim to complete calculations to order α^5 a.u. (or $\alpha^7 m_e c^2$) [2–4]. Independent calculations of the effective operators are also being carried out by Pachucki [5]. This is expected to result in a theoretical value for the larger, approximately 29.6 GHz, $J = 0-1$ interval in helium to better than ± 1 kHz. Combined with measurements aimed at exceeding this precision [6–9], this should yield a value for α at the 16 ppb (parts per 10^9) level. This would be of interest for comparison with the result obtained from QED theory and experiment for the electron magnetic moment, and with results obtained from the various other phenomena reviewed in Ref. [1].

Compared to other methods dependent on QED theory for obtaining α, helium fine structure has an advantage in that the theory, in particular, the evaluation of the complex higher-order relativistic and QED corrections, can be independently tested. This is because there are two 2^3P fine structure intervals and because the same methods used for helium can be used to calculate fine structure in moderate Z heliumlike ions where the relative magnitudes of these higher-order terms are larger. Hence fine structure measurements in moderate Z heliumlike ions [10–15], even though less precise than measurements in helium, can provide sensitive tests of the theory. Here we report a measurement of the three hyperfine components of the $^{19}F^{7+}$ $1s2p\,^3P_2$-$^3P_1$ fine structure interval, obtained by directly inducing the $M1$ transitions using a CO_2 laser, in a fast, foil stripped fluorine ion beam. A novel Doppler shift cancellation technique was used which measures products of the transition energies in pairs. Our result, with a precision of ± 1 ppm for the centroid, improves on a previous measurement in F^{7+} [10] by a factor of 19 and is the most precise fine structure measurement on a heliumlike ion to date. It complements a previous measurement of the $J = 0-1$ interval in $^{14,15}N^{5+}$ [14,15] and tests $O(\alpha^5)$ theoretical contributions at the level of $\pm 5\%$.

A schematic of the experimental setup is shown in Fig. 1 and the relevant energy levels of $^{19}F^{7+}$ are shown in Fig. 2. Beams of 13–17.5 MeV $^{19}F^{4+}$ ions from the

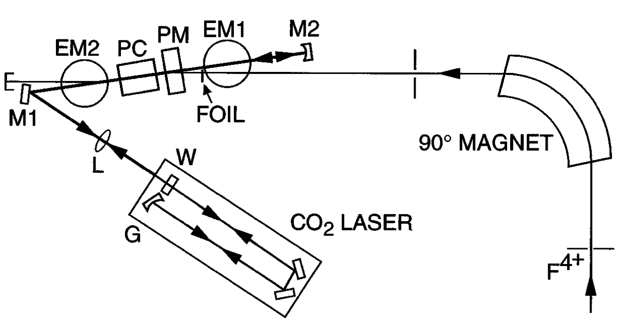

FIG. 1. Schematic of the experimental arrangement. G is a diffraction grating, W is a window, L is a lens, M1, M2 are mirrors, EM1, EM2 are electromagnets, PM is a permanent magnet, and PC is a proportional counter.

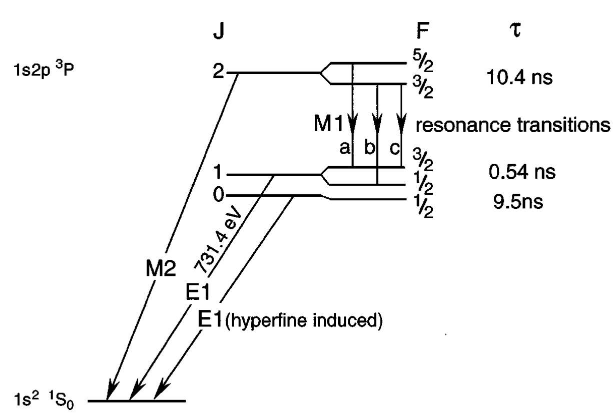

FIG. 2. Schematic of the energy levels of $^{19}F^{7+}$ relevant to the experiment.

TABLE I. CO_2 laser lines and corresponding $^{19}F^{7+}$ beam energies (to the nearest 10 keV) used for the measurements of the $2^3P_{2,F}$-$2^3P_{1,F'}$ transitions using co- and counterpropagating beams. 9P-60 refers to the P-60 line of the 9.4 μm band. The other lines are from the 10.4 μm band.

	Counterpropagating			Copropagating		
Product	F-F′	Line	E (MeV)	F-F′	Line	E (MeV)
ab	5/2-3/2	*P*-40	13.46	3/2-1/2	*R*-48	13.48
	3/2-1/2	*P*-52	17.41	5/2-3/2	9*P*-60	17.49
ac	5/2-3/2	*P*-40	13.46	3/2-3/2	*R*-24	13.37
	5/2-3/2	*P*-42	15.04	3/2-3/2	*R*-28	15.14
bc	3/2-1/2	*P*-48	13.87	3/2-3/2	*R*-26	14.25
	3/2-1/2	*P*-50	15.58	3/2-3/2	*R*-28	15.14
bb	3/2-1/2	*P*-48	13.87	3/2-1/2	*R*-50	14.13

Florida State University tandem electrostatic accelerator were energy analyzed in a 90° magnet and then passed through a 4 μg cm^{-2} carbon foil. The F^{7+} charge state was magnetically deflected 5° bringing it collinear with the laser beam. At a distance 16 cm down-beam of the foil 730 eV x rays were detected using a thin window proportional counter. At this position, which corresponds to a flight time of about 13 ns from the foil, approximately 8% of the K x rays detected originate from the 2^3P_2 level [16]. The total count rate was typically 800 kHz at a beam current of 50 particle-nA. Details of the CO_2 laser and the alignment procedure are given in Ref. [15]. When the ion beam velocity was such that a particular hyperfine component of the F^{7+} 2^3P_2-2^3P_1 transition was Doppler shifted into resonance with the laser radiation, a small, <1%, increase in count rate was observed due to the subsequent x-ray decay of the 2^3P_1 level. This was detected synchronously by switching the laser at 500 Hz.

Key to the final precision obtained was the method of scanning resonances with laser beams parallel and antiparallel to the ion beam, with frequencies chosen so that the resonances occur at very similar beam energies. Let a particular transition in the ion be brought to resonance successively with co- and counterpropagating laser beams with frequencies ω_1, ω_2, at beam velocities $\beta_1 c$, $\beta_2 c$, with laser-ion intersection angles θ_1, 180° − θ_2 (θ_1 and θ_2 are small). Then using the relativistic Doppler formula [15], ω', the transition frequency in the rest frame of the moving ion, can be obtained from

$$\omega'^2 = \omega_1\omega_2[1 + f\{\Delta p, \bar{p}, \Delta(\theta^2), \bar{\theta^2}\}], \quad (1)$$

where $\Delta p = \gamma_2\beta_2 - \gamma_1\beta_1$, $\bar{p} = (\gamma_1\beta_1 + \gamma_2\beta_2)/2$, [$\gamma_1 = (1 - \beta_1^2)^{-1/2}$, etc.], $\Delta(\theta^2) = \theta_2^2 - \theta_1^2$, and $\bar{\theta^2} = (\theta_1^2 + \theta_2^2)/2$. The "correction factor" f can be expressed as a power series and is zero if θ_1, θ_2, and Δp are zero, which can be arranged if the laser is continuously tunable. Here, however, where the laser is line tunable, we are able to arrange that $|\Delta p| \ll 1$. In this case [see Eq. (1) of Ref. [15]], f is mainly sensitive to Δp (which is proportional to the difference in magnetic rigidities of the two beams), and to $\Delta(\theta^2)$, and is relatively insensitive to $\bar{p}$ and $\bar{\theta^2}$. A trivial extension of Eq. (1) is to replace ω'^2 by $\omega_1'\omega_2'$, where ω_1' and ω_2' are frequencies of *different* transitions in the moving ion. In this work we made use of this generalization because it gave a greater number of combinations of useful laser lines and F^{7+} transitions. We could choose resonance pairs much closer in beam velocity, and hence more amenable to a precise measurement of their velocity difference, than if we had required both resonances to correspond to a single transition [17]. In this way we obtained measurements of the products ab, ac, and bc, where a, b, c are the wave numbers of the F-F′ = 5/2-3/2, 3/2-1/2, and 3/2-3/2 components of the 2^3P_2-2^3P_1 transition, respectively. For the 3/2-1/2 component, however, it was possible to find a pair of laser lines which induced resonances with co- and counterpropagating beams at similar beam energies, so we also obtained a measurement of b^2. In

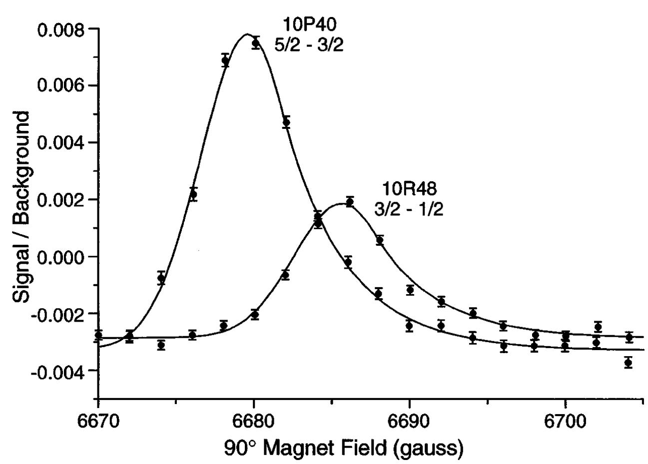

FIG. 3. Single energy scans of the $1s2p\,^3P_{2,F}$-$1s2p\,^3P_{1,F'}$ 5/2-3/2 and 3/2-1/2 components. The vertical axis shows the laser induced signal as a fraction of the x-ray background. The 5/2-3/2 component was induced with the laser tuned to the 10.4 μm band P-40 laser line, with the laser beam antiparallel to the ion beam. The 3/2-1/2 component was induced with the R-48 line, parallel to the ion beam. The curves through the data are least squares fits using Gaussians with exponential tails.

TABLE II. Results and error contributions for the wave number products. All units cm^{-2}.

Product	Result	Fitting	Calibration	Alignment	Total
ab	917 137.2	0.4	0.5	1.7	1.8
ac	905 175.8	0.5	0.6	1.7	1.9
bc	897 500.4	1.0	2.5	1.9	3.3
bb	909 360.4	1.0	2.0	1.9	3.0

Table I we show the combinations of CO_2 laser lines and F^{7+} transitions used in the measurements. For these combinations the magnitude of the correction factor f in Eq. (1) ranged from 4×10^{-5} to 6×10^{-4}.

The procedure was to scan each pair of resonances in a series of up and down scans of beam energy, changing the CO_2 laser line as required. The beam energy was servoed to the 90° analyzing magnet, and a step size of 2 G, approximately equivalent to 8.8 keV in beam energy, was used. The integration time at each point was 60 sec during which the field was periodically measured with an NMR probe. An example of the data obtained in single scans is shown in Fig. 3. In addition to searches for systematic effects, 32 scans of resonance pairs were obtained in two separate, two week periods of accelerator beam time. From the difference ΔB between resonance centroids, combined with a differential magnet calibration $\Delta p/\Delta B$, we obtain the value of Δp between resonances. Hence with estimates of $\bar{p}$, and upper estimates for $\Delta(\theta^2)$ and $\bar{\theta}^2$, together with the accurately known CO_2 laser frequencies [18], we obtain results for the wave number products.

The resonances had FWHM's of 30 keV in beam energy, mainly due to the distribution of energy loss in the foil. To extract centroids the data were fitted with a Gaussian with an exponential tail on a flat background. Because the shapes of the resonances in a pair are similar, the effect of asymmetry cancels for the difference between the centroids. Further, by taking the average of ΔB for up and down scans of a resonance pair, the effects of progressive foil thickening and degradation due to beam irradiation also cancel to first order. (These effects were also reduced by using foils prepared by laser ablation, by repetitively scanning the foil transverse to the ion beam during a measurement, by control of the beam current, and by maintaining the vacuum in the chamber below 3×10^{-7} torr.) The resonances appear on top of a negative laser induced background signal. This is understood to be due to nonresonant laser induced quenching of high n, l Rydberg levels, which reduces the cascade fed x-ray emission in the detection region [19].

Our results for the wave number products with estimates of the error contributions are shown in Table II. Under the heading "Fitting" we give the statistical uncertainty obtained from the fitting routine, combined with estimates of the additional uncertainty due to possible small differences between the shapes of resonances in a pair, and due to imperfect normalization with respect to laser power and its effect on the laser induced background. Since account must be taken of the variation of the momentum lost in the foil with incident beam energy, we measured the effective magnet calibration, $\Delta p(F^{7+})/\Delta B$, by inducing resonance a using the P-42 and P-44 lines, and resonance b using the R-48 and R-50 lines. Using this calibration, the two bc measurements, which have relatively large and opposite sensitivities to an error in calibration, agreed within their fitting errors. But conservatively, we assign an uncertainty equal to the magnitude of the total calibration correction, with respect to a previous calibration of the magnet alone [15], for each resonance product. This error contribution appears under the heading "Calibration" in Table II. Under the heading "Alignment" we include estimates of the uncertainty due to misalignment of the laser and ion beams and to possible systematic variation of the laser beam divergence between the resonances, as discussed in Ref. [15]. Using a least squares procedure we obtain from the four results in Table II best estimates for the three individual wave numbers a, b, c, and for the hyperfine splittings. These are shown in Tables III and IV. The centroid of the three wave numbers, viz. $(3/5)a + (1/3)b + (1/15)c$, is found to be $957.6679(10)\ cm^{-1}$ [20]. This is in good agreement with the earlier measurement which gave a centroid of $957.669(19)\ cm^{-1}$ [10]. The uncertainty in our final result is equivalent to a fraction $1/40$ of the experimental linewidth (FWHM).

In Table IV we also show the results of a relativistic calculation of the hyperfine structure, which does not include QED and nuclear size corrections, by Johnson *et al.* [21], and the results of a calculation based on nonrelativistic wave functions, with relativistic, QED, and nuclear size corrections, by Pan and Drake [13,22]. The agreement of both calculations with our experiment is consistent with their respective approximations. From the hyperfine theory one can obtain the correction to be applied to the measured centroid to obtain the "pure" $1s2p\,^3P$,

TABLE III. Results for the three $^{19}F^{7+}$, $2^3P_{2,F}$-$2^3P_{1,F'}$ fine structure intervals.

F-F′	$\Delta E_{2,F-1,F'}$ (cm^{-1})
5/2-3/2	961.7591(19)
3/2-1/2	953.6039(13)
3/2-3/2	941.1668(22)

TABLE IV. Results for the hyperfine splittings of the $^{19}F^{7+}$, 2^3P_2, and 2^3P_1 levels, compared with recent theory. Units cm^{-1}.

	$^3P_2, 5/2\text{-}3/2$	$^3P_1, 3/2\text{-}1/2$	Difference
This experiment	20.592(4)	12.437(3)	8.155(3)
Johnson *et al.* [21]	20.606	12.442	8.164
Pan and Drake [22]	20.599	12.434	8.165

TABLE V. Result for the $^{19}F^{7+}$, 2^3P_2-2^3P_1 fine structure interval compared with recent theory.

	ΔE_{12} (cm^{-1})
This experiment	957.8730(12)
Previous experiment [10,23]	957.874(19)
Zhang, Yan, and Drake [3]	957.840(80)
Chen, Cheng, and Johnson [24]	957.85
Plante, Johnson, and Sapirstein [25]	957.87

$J = 2-1$ fine structure interval. From the calculations of Johnson *et al.* this correction is $0.205(1)$ cm^{-1}, where the error is based on the number of significant figures quoted in their tabulation. From Pan and Drake's calculations we obtain $0.2051(5)$ cm^{-1}, where the error is based on the comparison between theory and experiment in Table IV.

We choose the latter and the resulting fine structure interval is compared with theory in Table V. The agreement with the relativistic calculations of Chen *et al.* and Plante *et al.* is perhaps better than expected given that these calculations do not include all $O(\alpha^4)$ terms. The agreement with the high precision calculations of Zhang *et al.* is within their estimate (shown in parentheses) of the magnitude of the $O(\alpha^5)$ terms not yet included [4]. Our result will test the total of these contributions at the 5% level. Because there is cancellation between electron-electron and electron-nuclear terms for F^{7+} [3], the sensitivity to these individual contributions is higher.

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