Hyperfine-Induced $1s2s\,1S_0-1s2p\,3P_0$ Transition and Fine-Structure Measurement in Heliumlike Nitrogen

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We have observed the $1s2s\,1S_0-1s2p\,3P_0$ transition in $^{14}N^{5+}$ using Doppler-tuned fast-beam laser spectroscopy. This transition, absolutely forbidden for atoms with zero nuclear spin, occurs due to mixing of states of different $J$ by the hyperfine interaction. By measuring the difference between the $2\,^1S_0-2\,^3P_{1/2}$ and $2\,^1S_0-2\,^3P_0$ transition energies, we have obtained a value for the $1s2p\,3P_{1/2}P_0$ fine-structure splitting in $N^{5+}$. Our result will test quantum-electrodynamic corrections to recent high precision calculations [Z.-C. Yan and G. W. F. Drake, Phys. Rev. Lett. 74, 4791 (1995)].

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In a recent Letter [1] we reported a measurement of the $1s2s\,1S_0-1s2p\,3P_0$ intercombination transition in $^{14}N^{5+}$ by Doppler-tuned laser spectroscopy using a CO$_2$ laser on a fast, foil-stripped nitrogen beam. It was subsequently realized, because of the excellent signal-to-noise ratio obtained in that measurement, that it would be possible to observe the even more “forbidden” $2\,^1S_0-2\,^3P_0$ hyperfine-induced transition in this ion, and hence obtain a precise measurement of the $N^{5+}\,2\,^3P_0-2\,^3P_1$ fine-structure splitting $\Delta E_{01}$; see Fig. 1. Such fine-structure measurements are of considerable interest in that they test basic atomic theory and, in particular, the recent high precision calculations of Drake and co-workers [2]. These calculations when extended to $O(\alpha^7\ln\alpha)me^2$ and $O(\alpha^7)me^2$ [3] will enable $\Delta E_{01}$ in helium to be calculated to better than $\pm$ 1 kHz, and hence, by comparison with accurate experiment [4], should yield a new atomic physics value for the fine-structure constant. Because certain higher-order QED corrections scale with high powers of $Z$, fine-structure measurements in heliumlike ions, though of lower precision than those in helium, can provide important independent tests of the theory. Here we report a measurement with sufficient precision to provide a quantitative test of the new contributions of order $\alpha^7\ln\alpha$ [3] to be added to the order $\alpha^6$ calculations of Ref. [2].

Hyperfine-induced transitions are themselves relatively rare [5] and interesting in atomic physics. In atoms or ions with zero nuclear spin, single-photon electromagnetic transitions in which $J = 0 \rightarrow J' = 0$, e.g., transitions of the type $1sns\,1S_0-1sn'd\,3P_0$ in heliumlike ions, are absolutely forbidden. However, the hyperfine interaction, by mixing levels of different total electronic angular momentum $J$, in our case the $2\,^3P_0$ and $2\,^3P_1$ levels, can produce finite electric-dipole matrix elements for these transitions. In heliumlike ions this enables the $2\,^3P_0$ level to decay to the ground state [6], and measurements of the resulting “hyperfine-quenched” lifetime of the $2\,^3P_0$ level in higher $Z$ heliumlike ions have been used to infer the $J = 1-0$ fine-structure splitting [7–9]. But to our knowledge the present work is the first spectroscopic measurement to utilize a laser-and-hyperfine induced $J = 0 \rightarrow J' = 0$ transition.

The measurements were carried out using the arrangement described in Ref. [1]. This consisted of a 200 W, continuous wave, line tunable CO$_2$ laser, the output from which was merged at 180° with a nominally 6 MeV foil excited N$^+$ ion beam from a Van de Graaff accelerator equipped with a terminal ion source [10]. Since on a given line the laser frequency is fixed, frequency scanning was accomplished via the Doppler effect by varying the beam velocity. The ion velocity was determined by a 90° analyzing magnet whose field was determined using a NMR gaussmeter. Laser-induced transitions from the metastable $1s2s\,1S_0$ level to the $2\,^3P_0$ and $2\,^3P_{1/2}$ levels, mean lifetimes 14.7 and 4.8 ns, respectively [11,12], were observed by

![FIG. 1. Schematic of the energy levels of $^{14}N^{5+}$ relevant to the experiment. The hyperfine induced transition is indicated. Approximate spacings are given in units of cm$^{-1}$.](Image 349x110 to 524x274)
detecting UV photons from their decays to the $2^3S_1$ level, using a pair of photomultiplier tubes. The collinear alignment of the laser and ion beam was achieved by optimizing the transmission of the ion beam through approximately 1 mm diameter holes in a pair of retractable quartz discs, spaced 18 cm apart, the holes having been previously ablated using the laser beam.

Several significant improvements have occurred since the previous work. The accelerator has been upgraded by the installation of a new charging system resulting in improved energy and positional stability of the ion beam. This, together with more stable ion source operation, allowed more accurate and repeatable alignment of the laser and ion beams. Improved control of the analyzing magnet enabled scanning with 1 keV steps, while the use of narrower analyzing magnet slits and more consistent, nominally 5 µg/cm², carbon foils resulted in approximately Gaussian line shapes with FWHM of 3.4(8) keV, corresponding to Doppler widths of 0.0085(20) cm⁻¹. The magnetic shield surrounding the photomultiplier tubes, see Fig. 3 of Ref. [1], has been extended to provide a low magnetic field region over a distance greater than the $1/e$ decay length of the $2^3P_0$ level, before the ions reach the down-stream laser phototube.

A considerable reduction in the dependence of our measurements on the energy calibration of our analyzing magnet was achieved by inducing pairs of resonances at similar beam energies in a continuous energy scan. For the fine-structure measurement the procedure was to scan first the relatively strong $2^1S_0-2^3P_{1,F=2}$ transition which occurs near 6.15 MeV with the P6, 956.1850 cm⁻¹ CO₂ laser line. The laser line was then changed to R4, 964.7690 cm⁻¹ to scan the $2^1S_0-2^3P_0$ transition at a beam energy approximately 75 keV higher. The scan was then repeated in the opposite direction. The procedure for measuring the $2^3P_1$ hyperfine intervals was the same except that only the P6 laser line was used. A typical energy scan for the fine-structure measurement is shown in Fig. 2. The observed relative strength of the $2^1S_0-2^3P_0$ transition compared to $2^1S_0-2^3P_{1,F=2}$ is in good agreement with a theoretical estimate based on the hyperfine mixing coefficients of Ref. [6].

The resonances were fitted with Gaussians and the centroids were converted into beam velocity using a magnet calibration based on an accurately measured nuclear resonance energy [14], together with small corrections; see below. Using the relativistic Doppler formula and the known CO₂ laser frequencies, these velocities were converted into transition wave numbers. Even though these wave numbers are subject to systematic offsets in the absolute magnet calibration at the level of 0.005 cm⁻¹ [1], the error from this source for the wave-number differences, for pairs of nearby resonances scanned sequentially, is smaller by more than an order of magnitude. Our analysis, excluding measurements used to estimate systematic effects, used five scans for the measurement of the $2^3P_{1,F=2}-2^3P_0$, interval and 12 and 8 scans, respectively, for the $2^3P_1$, $F = 2-1$ and $F = 1-0$ hyperfine intervals.

Small corrections and the error budget for the three measured intervals are shown in Table I. An important source of systematic error was the observed small variation in the energy of the ions with horizontal position across the ion beam at the interaction region, $dE/dx$, of about 2.5 keV/mm. Because there was also a small systematic movement of the ion beam with increasing energy, we carefully realigned the ion beam before each transition was scanned. However, a correction to the centroid energy remains because the alignment was necessarily done a few gauss away from the actual centroid. We have assigned an uncertainty equal to the correction in each case. After allowing for this effect the local differential magnet calibration was checked by measuring the $2^1S_0-2^3P_{1,F=2}$ transition using the P4, P6, and P8 CO₂ laser lines.

![Image](https://example.com/image.png)

**FIG. 2.** A single energy scan showing the $1s2s \,^1S_0-1s2p \,^3P_{1,F=2}$ transition and the hyperfine induced $1s2s \,^1S_0-1s2p \,^3P_0$ transition.

![Image](https://example.com/image.png)

**FIG. 3.** Differences between experiment, Refs. [4–21] and this work, and the $O(a^9)$ theory [2], scaled by $Z(Z-1)a^2m_ec^2$, for the $2^3P$ fine-structure intervals $\Delta E_{01}$ and $\Delta E_{12}$. Also shown are the hyperfine-quenching measurements of Ref. [9] compared to the theory of Ref. [17] which uses QED corrections from Ref. [22]. Data for $\Delta E_{01}$ and $\Delta E_{12}$ are indicated by bullets and crosses, respectively. We have used the sign convention of Ref. [2] in which both intervals are taken to be positive for helium.
The results were consistent with each other and implied a deviation from the slope of the one point nuclear calibration of $8(4) \times 10^{-4}$, which is probably due to differential hysteresis. The corresponding corrections to the wave-number intervals have been included in Table I. Despite the consistency of these checks, we have assigned an error equal to the total calibration correction. For the $2\,^3P_{1,0} - 2\,^3P_{0,0}$ measurement we have included an estimate of the error due to possible systematic movement of the laser beam as the line is changed, coupled with the observed $dE/dx$, and also estimates of errors due to the difference in lifetimes between the $2\,^3P_0$ and $2\,^3P_1$ states. These include the effects of possible angular misalignment between the laser and ion beam coupled with $dE/dx$, and also small corrections to the Doppler formula due to departures of the laser mode from a plane wave. The errors due to the angular dependence of the Doppler formula, and the estimated systematic angular misalignment of the laser and ion beams ($<5$ mrad), and systematic change in the angular alignment between a pair of resonances in a scan ($<1$ mrad), are negligible. The uncertainties in Table I have been combined in quadrature, except for the ion beam movement and magnet calibration corrections which we have combined linearly.

Our final value for the $2\,^3P_{1,0} - 2\,^3P_{0,0}$ interval is $9.0339(7)$ cm$^{-1}$. In Table II we compare our results for the $2\,^3P_1$ hyperfine splittings with theoretical results of Ohtsuki and Hijikata [15], which we have corrected for relativistic, QED, and nuclear size effects, and also for the small quadrupole interaction, using the procedures detailed in Ref. [16]. The agreement is reasonable but an improved hyperfine calculation would be interesting. In order to extract a value for the fine-structure interval $\Delta E_{01}$, we must allow for the hyperfine shifts of the two levels involved in our measurement. Using the calculations of Ref. [15], corrected in the same way as the hyperfine intervals in Table II, we obtain a correction of $0.3624$ cm$^{-1}$ to be subtracted from our measured interval. Alternatively, it can be shown that the required correction is equal to the $F = 1 - 0$ hyperfine interval, with small corrections for the quadrupole interaction ($-0.0010$ cm$^{-1}$) and mixing with the $J = 2$ fine-structure level ($-0.0004$ cm$^{-1}$). Using our experimental result from Table II, we obtain a correction of $0.3630(7)$ cm$^{-1}$. Since this is less dependent on the numerical accuracy of the results in Ref. [15], and on the relativistic, QED, and nuclear size corrections, we use this as the required correction.

Our final result for $\Delta E_{01}$ is compared in Table III with the recent calculations of Yan and Drake [2], and also with the relativistic configuration interaction calculations of Chen, Cheng, and Johnson [17], and the relativistic many-body perturbation theory calculations of Plante, Johnson, and Sapirstein [18]. We note that the approximate cancellation of the lowest order $O(\alpha^4)$ contribution for $\Delta E_{01}$ in $N^+$ leads to particular sensitivity to higher order corrections, and in fact the $O(\alpha^6)$ second-order Breit term represents 28% of the total interval [2]. In Fig. 3 we plot the difference between existing precise measurements [4,16,19–21] and the results of Ref. [2] for $\Delta E_{01}$ and $\Delta E_{12}$, for $Z < 10$. We have also included the results of the hyperfine-quenching measurements at $Z = 47$ and 64 [9]. Since the calculations of Ref. [2] do not extend beyond $Z = 9$, these two results are compared with the calculations of Ref. [17], which use the QED corrections of Ref. [22]. As suggested by Eq. (4) of Ref. [2], we have scaled the differences between experiment and theory by $Z(Z - 1)^3\alpha^3m_e^2c^2$, corresponding to the estimated $Z$ scaling of the spin-dependent part of the one-electron Lamb shift. We note that the estimate provided by this term is in agreement with the differences between the $O(\alpha^6)$ theory and the experimental data for

### Table I. Systematic corrections and error budget for the three measured $2\,^3P_{1,F} - 2\,^3P_{0,F'}$ intervals. Units $10^{-4}$ cm$^{-1}$.

<table>
<thead>
<tr>
<th>$j,F - j',F'$</th>
<th>1,2-0,1</th>
<th>1,2-1,1</th>
<th>1,1-1,0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical ($\sigma/\sqrt{n}$)</td>
<td>0 ± 3.8</td>
<td>0 ± 2.4</td>
<td>0 ± 3.0</td>
</tr>
<tr>
<td>Ion beam movement, $dE/dx$</td>
<td>3.4 ± 3.4</td>
<td>1.0 ± 1.0</td>
<td>2.9 ± 2.9</td>
</tr>
<tr>
<td>Magnet calibration</td>
<td>1.5 ± 1.5</td>
<td>4.7 ± 4.7</td>
<td>3.0 ± 3.0</td>
</tr>
<tr>
<td>Laser beam movement, $dE/dx$</td>
<td>0 ± 2</td>
<td>0 ± 2</td>
<td></td>
</tr>
<tr>
<td>Lifetime dependent effects</td>
<td>0 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.9 ± 6.8</td>
<td>5.7 ± 6.2</td>
<td>5.9 ± 6.6</td>
</tr>
</tbody>
</table>

### Table II. Our results for the $^{14}N^+$, $2\,^3P_1$ hyperfine splittings compared with theory. Units cm$^{-1}$.

<table>
<thead>
<tr>
<th>$F-F'$</th>
<th>2-1</th>
<th>1-0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohtsuki and Hijikata [15]</td>
<td>0.5725</td>
<td>0.3620</td>
</tr>
<tr>
<td>Rel., QED, Nuc. [16]</td>
<td>0.0013</td>
<td>0.0008</td>
</tr>
<tr>
<td>Quadrupole [16,15]</td>
<td>−0.0004</td>
<td>0.0010</td>
</tr>
<tr>
<td>Total</td>
<td>0.5734</td>
<td>0.3638</td>
</tr>
<tr>
<td>This experiment</td>
<td>0.5726(7)</td>
<td>0.3644(7)</td>
</tr>
</tbody>
</table>

### Table III. Our results for the $^{14}N^+$, $2\,^3P_0 - 2\,^3P_1$ fine-structure interval compared with recent theory.

<table>
<thead>
<tr>
<th>$\Delta E_{01}$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This experiment</td>
</tr>
<tr>
<td>Yan and Drake[2]</td>
</tr>
<tr>
<td>Chen, Cheng, and Johnson [17]</td>
</tr>
<tr>
<td>Plante, Johnson, and Sapirstein [18]</td>
</tr>
</tbody>
</table>
He [4] and F$^{7+}$ [21], for $\Delta E_{12}$. However, for $\Delta E_{01}$, our present result for N$^{3+}$ disagrees with the $O(\alpha^6)$ theory by approximately three times this estimate, and has the opposite sign. This indicates, as for He, that there are larger contributions from other operators of this order [3]. Although the measurements at $Z = 47$ and 64 provide strong confirmation of the relativistic theories [17,18], severe cancellations result in QED contributions to $\Delta E_{01}$ [22] smaller than the experimental errors.

In conclusion, we have observed ultraviolet fluorescence following the laser-induced, hyperfine-induced $2^1S_0 - 2^3P_0$ transition in $^{14}N^{3+}$. We have applied this to a measurement of the $2^3P_0 - 2^3P_1$ fine structure and have obtained agreement with the recent $O(\alpha^6)$ calculations of Yan and Drake [2]. Our result should provide a test, at the 10% level, of the results of $O(\alpha^7)$ and $O(\alpha^7 \ln \alpha)$ calculations now in progress [3].

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