Measurement of the $1s2s\,^1S$-$1s2p\,^3P_1$ Interval in Heliumlike Nitrogen

E. G. Myers, J. K. Thompson, E. P. Gavathas, and N. R. Claussen
Department of Physics, Florida State University, Tallahassee, Florida 32306

J. D. Silver and D. J. H. Howie
Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, United Kingdom

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For a large range of Z the $1s2s\,^1S_0$-$1s2p\,^3P_1$ interval in heliumlike ions lies in a wavelength region accessible by infrared lasers. Measurements of this interval will enable exceptionally sensitive tests of calculations of relativistic corrections and QED effects (Lamb shifts) in two-electron ions. This Letter describes a precision measurement of this interval in N^{5+} using a fast ion beam and a CO_2 laser. Our result is compared with recent relativistic and QED calculations.

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Helium and heliumlike ions are the prototypical many electron system and provide an important testing ground for relativistic quantum mechanics. The energy separations of the $n = 2$ levels, shown in Fig. 1, are particularly sensitive to interesting relativistic and quantum-electrodynamic (QED) effects. Recent theoretical developments have included relativistic many-body perturbation theory [1,2] and relativistic configuration interaction theory [3,4], which obtain all "structure," but not all QED contributions to $O(Z\alpha)^4$ atomic units (a.u.). Using highly precise nonrelativistic wave functions and operators derived from QED, Drake and collaborators aim to extend calculations of the $1s2p\,^3P_J$ fine-structure splittings in helium to $O(\alpha^5)$ a.u. [5], and hence by comparison with experiment [6] obtain a new "atomic physics" value for the fine-structure constant. There is also considerable interest, e.g., see [4,7,8], in improving the precision of two-electron Lamb shift calculations.

Because of the different Z scalings of the various theoretical contributions to the energy spacings of the $n = 2$ levels of two-electron ions, it is important to have precision measurements at low, intermediate, and high Z. Recent experimental work has concentrated on the $1s2s\,^3S_1$-$1s2p\,^3P_{2,0}$ transitions, and the results have been compared with theory in Ref. [2]. Precision laser measurements have been carried out up to $Z = 5$ [8–10]. However, for higher Z these intervals lie in the vacuum ultraviolet (VUV), and measurements have been carried out in emission using concave grating spectrometers, e.g., see [11,12]. At the precision currently obtainable with these techniques there is generally good agreement with existing theory.

In contrast to the $1s2s\,^3S$-$1s2p\,^3P$ intervals, the energy separation of the $1s2p\,^3P_1$ and $1s2s\,^1S_0$ levels lies in the infrared for a large range of Z; see Fig. 2. Although the transition is first-order forbidden, relativistic effects cause a mixing of the singlet and triplet states and result in an electric dipole transition matrix element of order $(Z\alpha)^2 a_0$ [13]. (The same mechanism opens up the ground-state decay mode of $2\,^3P_1$.) As proposed several years ago [14], the intercombination transition is therefore accessible to laser spectroscopy, and it is possible to use laser radiation to induce the transition from the metastable $2\,^1S_0$ level to

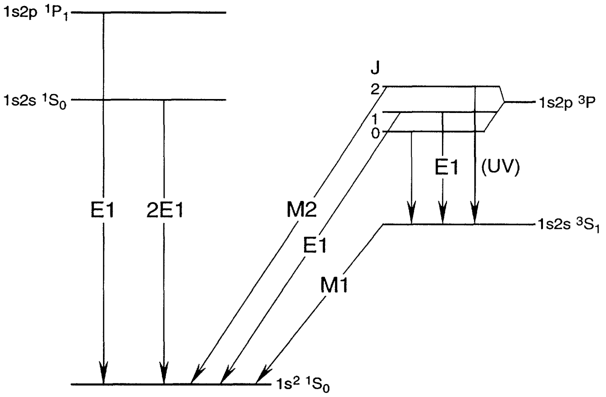

FIG. 1. Schematic of the $n = 2$ levels in heliumlike ions showing their principal decay modes.

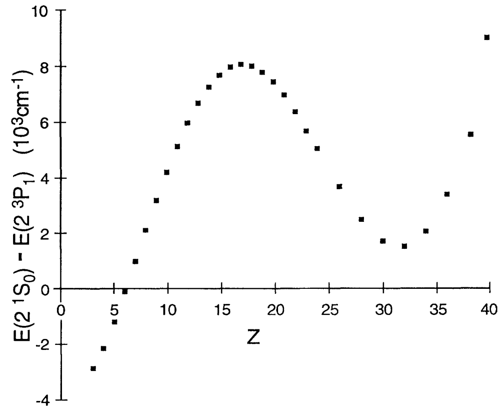

FIG. 2. Z dependence of the $1s2s\,^1S_0$-$1s2p\,^3P_1$ interval in heliumlike ions.

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the shorter-lived $2\,^3P_1$ level. The transition can be monitored by detecting the photon emitted in the decay of $2\,^3P_1$ to $2\,^3S_1$ or to the $1\,^1S_0$ ground state. In the present experiment, the $1s2s\,^1S_0$-$1s2p\,^3P_1$ interval energy in N^{5+} at around 10.1 μm was Doppler tuned into coincidence with 10.4 μm radiation from a CO_2 laser. To our knowledge this is the first measurement of this intercombination transition in a heliumlike ion. Apart from the precision test of theory this measurement provides at $Z = 7$, the experiment demonstrates the feasibility of a technique which can be extended to measurements at higher Z. The use of a laser compared to classical techniques and the fact that the QED contribution is a larger fraction of the total transition energy are both important advantages over VUV measurements of the $1s2s\,^3S_1$-$1s2p\,^3P_J$ transitions. The investigation of QED effects using this interval in the heliumlike system also has an experimental advantage over similar laser-spectroscopic measurements of the Lamb shift in hydrogenlike systems (e.g., see Ref. [15]). This is due to the narrower transition width resulting from the longer lifetime of the $2\,^3P_1$ level compared to the hydrogenic $2P$ levels.

The present experiment was performed at the Florida State University Superconducting Linear Accelerator Laboratory. The experimental setup is shown in Fig. 3. Positive nitrogen ions were produced by a radio-frequency discharge source mounted in the terminal of the model FN tandem Van de Graaff accelerator. A beam of $^{14}N^+$ was accelerated to between 6.1 and 6.6 MeV before being stripped by a single $5-10$ $\mu g\,cm^{-2}$ carbon foil. The foil was placed at the entrance of a 90° energy analyzing magnet, which selected the 5^+ charge state. After charge state and energy analyses, up to 250 nA of N^{5+} was focused at the center of the interaction chamber using a quadrupole doublet. Of these ions an estimated 0.1% were in the $2\,^1S_0$ metastable state, mean lifetime 1.06 μs [16], following a 10 m flight from the foil. The laser was a 200 W continuous-wave CO_2 laser, modified to make it line tunable across the 10.6 μm band by the installation of a concave diffraction grating. Most data were acquired using the P-6 line though the P-10 line was used during some of the initial searches.

Two 5° magnets were used to merge the laser and ion beams over a length of 38 cm. The laser induced transition was observed using two 2.5 cm diameter CsTe photomultiplier tubes, mounted approximately 17 mm above the overlapping beams, which detected the UV photon emitted in the decay of the $2\,^3P_1$ level. This level has a mean lifetime of 4.8 ns with a 30% branch to the $2\,^3S_1$ level [17]. Optimum overlap and alignment of the laser and ion beams is essential for a high transition probability and to minimize any frequency shift due to the angle dependence of the Doppler shift. This was achieved using two 1 mm diameter apertures, 18 cm apart, positioned symmetrically upstream and downstream of the phototubes.

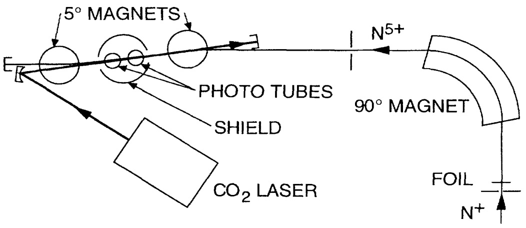

FIG. 3. Experimental arrangement.

Because the CO_2 laser is not continuously tunable, the resonances were scanned by varying the velocity of the N^{5+} beam, $v/c \simeq 0.03$. The transition intervals were then related to the laser wavelength and beam velocity using the relativistic Doppler formula. The beam velocity was scanned by slowly stepping the field of the 90° magnet. This controlled the accelerator voltage via a feedback loop with an error signal derived from the beam current intersected by the magnet exit slits. The beam velocity was determined from the magnetic field of the magnet, as measured by an NMR probe, using a calibration based on the accurately known 14.23 MeV $^{12}C(p,p)^{12}C$ nuclear resonance [18]. The calibration in the region of magnetic fields used for the experiment was carefully investigated using a precision time-of-flight technique. This consisted of bunching the beam at 97 MHz and measuring the phase difference of the beam induced signals from two identical pickup resonators spaced 9092 ± 1 mm apart. As a further test of our energy measurement procedure, we used a $^{15}N^{5+}$ beam to excite the well-known $^1H(^{15}N,\alpha\gamma)^{12}C$ resonance in a thin hydrogen gas target obtaining a resonance energy of 6397.4 ± 2 keV, in good agreement with precise values in the literature [19,20]. More details on these procedures will be published elsewhere.

After the initial resonance search, the three $1s2s\,^1S_0$-$1s2p\,^3P_{1,F}$ hyperfine components of the transition were each scanned an additional 5 or more times. Figure 4 shows survey scans of all three components, and Fig. 5 shows a separate scan of the $F = 2$ component. Depending on analyzing magnet slit settings and foil condition, the FWHM's of the resonances varied from 1 to 2.5 G corresponding to energy spreads in the ion beam of 4 to 10 keV. The 33 MHz natural width of the transition corresponds to a beam energy variation of only 0.4 keV.

The statistical precision of the resonance data is high, enabling a centroid determination in many cases to better than 0.1 G. However, the accuracy of the energy determination is limited by the calibration of the analyzing magnet and the reproducibility of the energy stabilization system. From the investigation using the time-of-flight system we determined a small correction to the original calibration equivalent to 1.6 ± 2 keV in beam energy for our 6 MeV $^{14}N^{5+}$ beam. From the scatter of the individual centroids we estimate a statistical uncertainty of

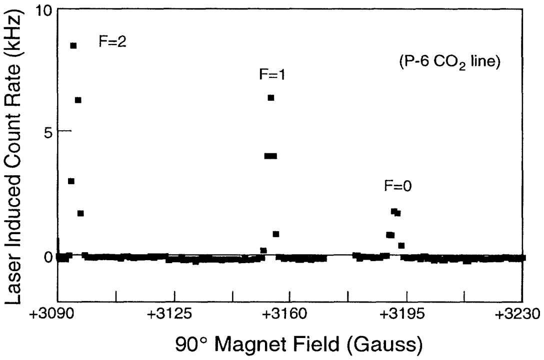

FIG. 4. Survey scans of the $1s2s\,^1S_0$-$1s2p\,^3P_{1,F}$ transitions in $^{14}N^{5+}$.

TABLE I. Our result for the $1s2s\,^1S_0$-$1s2p\,^3P_{1,F}$ interval in $^{14}N^{5+}$ without hyperfine interaction, compared with the hyperfine structure calculations of Ohtsuki and Hijikata [22].

	Our measurements		Theory
F	E_{obs} (cm^{-1})	ΔE_{obs} (cm^{-1})	$\Delta E_{\mathrm{theory}}$ (cm^{-1})
2	986.010(7)		
		0.570(6)	0.572
1	986.581(7)		
		0.365(6)	0.362
0	986.945(7)		

1.6 keV. Combined in quadrature with the calibration uncertainty this leads to an uncertainty in the absolute value of v/c of 7×10^{-6}. The angle of intersection of the ion and laser beams was constrained by the collimators to ±5 mrad. This uncertainty makes a negligible contribution to the present errors. The frequencies of the laser lines were taken from the meterological results of Petersen *et al.* [21]. Although the laser was unstabilized, the difference between the mean output frequency and the values of Petersen *et al.* should be negligible at our present level of precision.

The wave numbers we obtain for the three hyperfine components of the N^{5+} $2\,^1S_0$-$2\,^3P_1$ transition are presented in Table I. Because most of the systematic uncertainty in the velocity measurement cancels for the energy differences, they are quoted with smaller errors. The energy differences do not conform to the simple hyperfine interval rule because of the relatively small $2\,^3P_1$-$2\,^3P_0$ fine-structure interval in N^{5+}. The magnetic dipole hyperfine structure (HFS) has been calculated by Ohtsuki and Hijakata [22]. Their results, which are seen to be in good agreement with our experiment, were used to correct for the shift to the centroid of the multiplet due to hyperfine mixing of the fine-structure levels. The electric quadrupole contribution to the HFS was estimated to be negligible. The resulting component energies were combined with statistical weightings. Our result for the $^{14}N^{5+}$ $2\,^1S_0$-$2\,^3P_1$ interval in the absence of HFS is presented in Table II, along with theoretical values for comparison. Although Drake's "unified" calculations [23] do not include the relativistic corrections of $O(Z\alpha)^4$ a.u. which are obtained in the recent "all-order" many-body perturbation theory calculations of Plante, Johnson, and Sapirstein [2], we see that Drake's calculations are in best agreement with our experiment. This is probably due to a more accurate treatment of nonrelativistic and $O(\alpha^2)$ relativistic electron correlation effects. The larger difference between the relativistic configuration interaction theory results of Cheng *et al.* [4], and the other calculations are mainly due to their different values for the QED corrections. If instead one combines their relativistic energies, which also include the relativistic corrections of $O(Z\alpha)^4$, with Drake's QED corrections [25] one obtains 985.9 cm^{-1}, in better agreement with experiment.

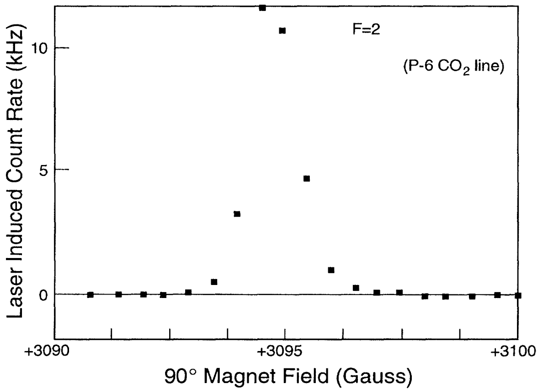

FIG. 5. Scan of the $F = 2$ component.

We have demonstrated that laser spectroscopy of the $2\,^1S_0$-$2\,^3P_1$ transition is a precision probe of energy levels in heliumlike ions. Our measurement on N^{5+} has yielded a result with an uncertainty of 7 ppm, which is equivalent to 0.02% of the QED contribution to the transition energy. By improved measurements of the velocity of the N^{5+} ion beam in our experiment this uncertainty can be reduced. However, further improvements in the

TABLE II. Our result for the $1s2s\,^1S_0$-$1s2p\,^3P_1$ interval in $^{14}N^{5+}$ without hyperfine interaction, compared with recent theory.

	E (cm^{-1})	Ref.
Experiment	986.321(7)	This work
Theory		
Drake	986.579	[23]
Plante, Johnson, and Sapirstein	984.7	[2]
Cheng *et al.*	993.6	[4,24]

calculation of the "correlation" part of the transition energy at this Z are required before the QED part can be tested to the above precision. Signal estimates show the method can be extended up to $Z \sim 20$. Possibilities also exist, particularly at lower Z where the $2\,^1S_0$ is longer lived, for carrying out very high precision spectroscopy of the transition energy using metastable heliumlike ions produced by electron cyclotron resonance and electron beam ion sources. Finally, we note that mixing of the $1s2p\,^3P_0$ and $1s2p\,^3P_1$ levels due to hyperfine interaction in heliumlike ions with nuclei with nonzero spin leads to a small electric dipole transition matrix element for the $1s2s\,^1S_0$-$1s2p\,^3P_0$ transition. In favorable cases this would allow measurement of both $1s2s\,^1S_0$-$1s2p\,^3P_{J=1,0}$ transitions and hence allow a precise measurement of the $J = 1$-0 fine-structure interval.

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[24] Because Cheng *et al.* [4] give results only for even Z, we have obtained values for $Z = 7$ by interpolating the differences between their results and those of Ref. [2] for $Z = 6$ and $Z = 8$.

[25] In comparing the QED corrections of Cheng *et al.* [4] with those of Drake [23], we allow for the difference in definition of the QED terms which applies to singlet states.