Precision Measurements of Relativistic and QED Effects in Heliumlike Boron

T. P. Dinneen,[a] N. Berrah-Mansour, H. G. Berry, L. Young, and R. C. Pardo
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 31 August 1990)

We have made precision wavelength measurements on the $1s2s\ ^3S_1$–$1s2p\ ^3P^o_{0,1,2}$ transitions in heliumlike boron using fast-beam laser excitation. These measurements are accurate to 2 parts in 10^7 of the transition energy and test the most recent calculations at a level of 0.1% of the Lamb shift. The relatively high Z of boron, in comparison to helium, makes the transition energies sensitive to higher powers of αZ in the calculations, and our measurements show discrepancies which may be due to these uncalculated higher-order terms.

PACS numbers: 32.70.Jz, 12.20.Fv, 32.30.Jc, 35.10.Fk

The two-electron atom is one of the simplest many-body systems available for testing our understanding of relativistic quantum mechanics. The lack of a complete Hamiltonian[1] to describe the bound states in such a system leads to the need to solve the correlation between the two electrons and the quantum electrodynamic (QED) corrections perturbatively. Unlike the case of hydrogen, the $2s \rightarrow 2p$ transitions in heliumlike ions are not degenerate, even in the nonrelativistic approximations, due to the electron-electron correlation energy. This nonrelativistic correlation dominates the energy difference of the levels in light ions, while relativistic corrections become larger in the heavier ions of the sequence. In the transitions of interest here, $1s2s\ ^3S_1$–$1s2p\ ^3P^o_{0,1,2}$, the ^3S state is metastable and the $^3P^o$ state is spin forbidden from decaying to the ground $1s^2\ ^1S_0$ state. The resulting narrow linewidth of the $2s \rightarrow 2p$ transition enables the QED part to be experimentally resolvable and separated from the nonrelativistic part.

In recent years, experimental tests in heliumlike ions have involved high-precision measurements in light ions, for example, helium,[2] lithium,[3] and beryllium,[4] which test the best available calculations for the nonrelativistic parts of the interaction, and lower-precision measurements in heavy ions[5,6] which test the relativistic and QED parts of the interaction. The best of the latter measurements provide tests at a little better than 1% of the one-electron Lamb shift. A complete list of recent experiments is given by Drake[7] along with his most recent calculations.

The measurements in lithium test relativistic corrections to higher precision than helium but are limited at present by uncertainties in the nonrelativistic calculations of the energy. New, soon-to-be-published calculations of Drake will remedy this problem. We decided to attempt high-precision laser measurements of the $2s \rightarrow 2p$ transition in higher-Z two-electron systems where the relativistic and QED corrections, which scale as Z^4 and higher, are a larger fraction of the transition energy. Our goal is to provide experimental tests of the QED and relativistic many-body corrections in cases where the nonrelativistic energy calculations are sufficiently precise not to limit the experimental precision.

In this paper we present a set of precision measurements of the $1s2s\ ^3S_1$–$1s2p\ ^3P^o_{0,1,2}$ transitions in heliumlike B IV. The first observations in this spectrum were made by Edlén[8] in 1934. More recent measurements (e.g., Eidelsberg[9]) have not improved on Edlén's precision of 0.5 cm^{-1} for this transition.

The B^{3+} ions in the metastable $1s2s\ ^3S$ level were produced in the Positive Ion Injector Electron Cyclotron Resonance (PII-ECR) source at the ATLAS facility of the Argonne National Laboratory. The ions were accelerated, mass analyzed in a 90° magnet, and passed through a short section of beam line to the interaction region (Fig. 1). For this experiment a 10-kV source extractor voltage was used to accelerate the ions. Beam current in the interaction region ranged from 0.5 to 1.5 μA during the experiment.

The 282-nm light required for the $1s2s\ ^3S$–$1s2p\ ^3P^o$ transitions was generated by intracavity frequency doubling of the 564-nm fundamental of a Coherent 699 ring dye laser. The maximum doubled output obtained from the dye laser was 7 mW with chilled dye and 7 W pumping from an argon-ion laser.

The ion beam and 282-nm laser light were overlapped collinearly to take advantage of the increased interaction time and velocity compression provided by the accelerated beam. The Doppler width (FWHM) obtained by this method was 1 GHz, corresponding to a beam energy spread of 21 eV (7 V per charge).

The excited $^3P^o$ states decay primarily back to the $^3S_1$ state and this radiation was the signal monitored during the experiment. The fluorescence was collected by a light collector of elliptical cross section with high solid-angle coverage, passed through a 280-nm interference filter (10-nm bandwidth), to eliminate most unwanted light, and detected with a photomultiplier. Since there is no frequency discrimination between the true fluorescence and the scattered laser light, careful collimation of the laser is essential before passing through the interaction region and all optics need to be completely clean.

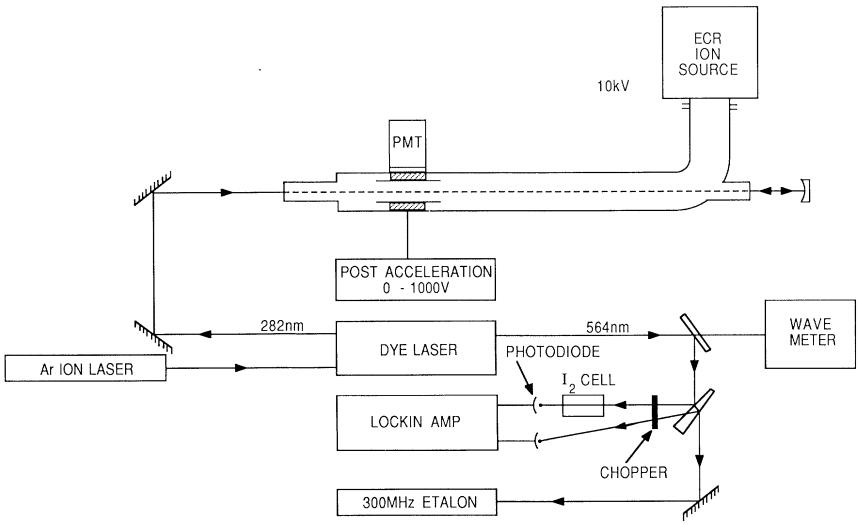

FIG. 1. A schematic of the apparatus. Two bending magnets deflect the beam into and out of the path of the laser. The interaction region is usually biased at −100 V which Doppler shifts the transition enough to confine the fluorescence to that region.

Our high sensitivity allowed most of the hyperfine components to be observed (^{11}B has nuclear spin $I=\frac{3}{2}$).

The absolute wavelength of one hyperfine component in the $^3S_1$-$^3P_2^o$ transition was measured by scanning the frequency-doubled laser over both the red and blue Doppler-shifted transitions and simultaneously measuring an iodine absorption spectrum[10] with the fundamental output of the dye laser (Fig. 2). The expression for the Doppler shift is $E_{B,R}=E_0\gamma(1\pm\beta)$ and hence $E_0=(E_RE_B)^{1/2}$, where $E_{B,R}$ are the transition energies observed with the parallel and antiparallel laser excitation, E_0 is the rest-frame transition energy to be determined in the experiment, and β and γ are the standard relativistic factors. All other transitions were measured relative to this $^3S_1$-$^3P_2^o$ transition.

The red-blue sequence of measurements was repeated many times to remove the effects of voltage drifts in the accelerating potential. A 1-V drift is sufficient to cause a 130-MHz change in the Doppler shift for the boron ion at 30 keV. The variations in the positions of the

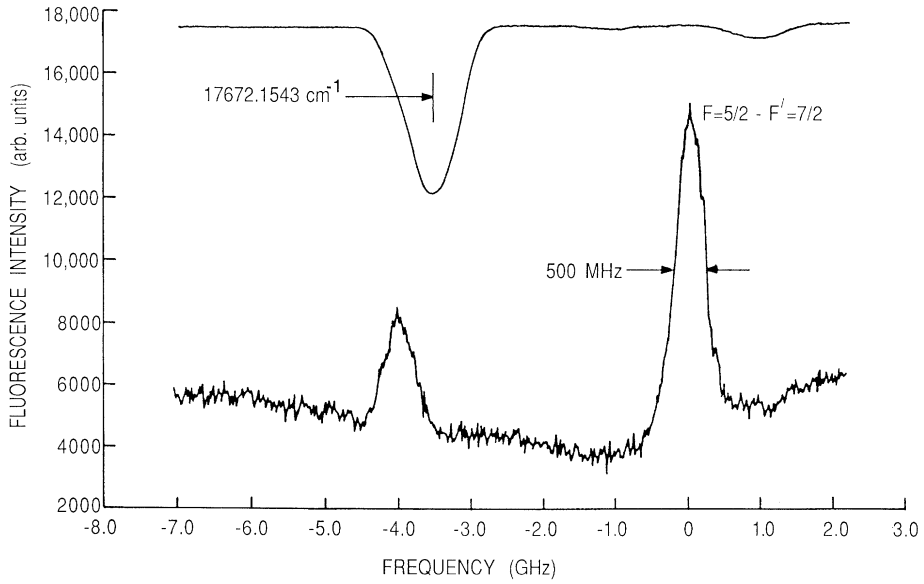

FIG. 2. A typical laser frequency scan of the $^3S_1$-$^3P_2^o$ transition showing two hyperfine components, and the iodine calibration line. The frequency scale is calibrated in terms of the fundamental of the laser. The laser background has also been suppressed by monitoring the laser power during the run.

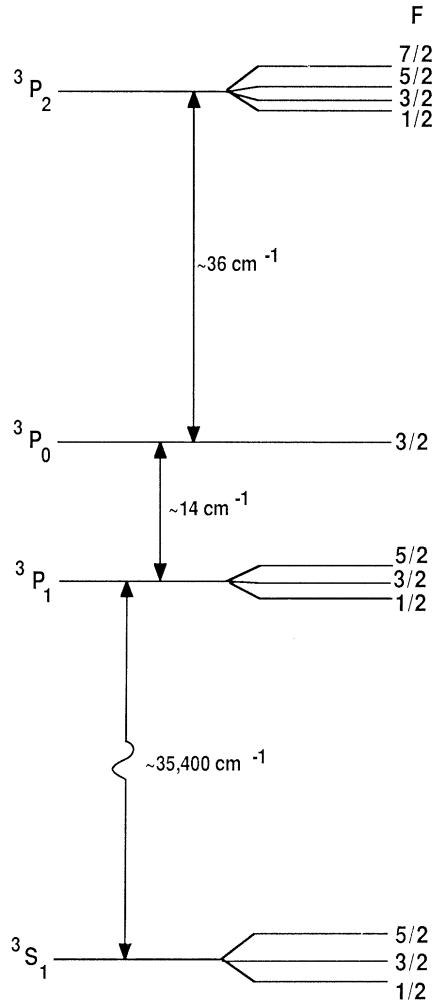

FIG. 3. The level diagram (approximately to scale) shows the fine and hyperfine splitting in the $^3P°$ states. Cancellations in the spin-orbit and spin-spin contributions to the fine structure result in a splitting not much greater than the hyperfine structure.

Doppler-shifted lines relative to the fixed iodine lines were used to monitor the voltage drifts during the measured periods and showed the drifts to be less than 1 V per hour. The connection to the iodine lines was made by also passing the fundamental of the dye laser through a Fabry-Pérot etalon which produced frequency markers at 300-MHz intervals. This eliminated any nonlinearities in the laser frequency scan and allowed the final uncertainty in the boron transition energy to be comparable to the uncertainty of the iodine calibration lines.

To obtain hyperfine-free wavelengths it is necessary to measure the hyperfine structure in both the upper and lower states. The laser power stability, however, was found to be poor over large frequency-scan ranges and so the hyperfine structure was determined by a slightly different technique: The interaction region was used as a postacceleration section, the laser frequency being held fixed while the ion beam was velocity tuned through the resonances by varying the interaction-region voltage. In this way all hyperfine components were obtained in a single spectrum and the relative frequencies yield the hyperfine structure.

The first step in the analysis is the evaluation of the hyperfine energies. Lurio, Mandel, and Novick[11] provide a complete description for the hyperfine structure of these configurations in terms of single-electron wave functions,[12] involving the single-electron dipole moments a_{1s}, a_{2s}, $a_{1/2}$, $a_{3/2}$, quadrupole moment $b_{3/2}$, plus relativistic corrections and spin-orbit interaction effects. It is not possible to fit all the parameters to the data and some simplifications are made. The $a_{1/2}$ and $a_{3/2}$ are related through $\langle r^{-3}\rangle$ integrals of the $p_{1/2}$ and $p_{3/2}$ states. For low Z the relativistic corrections are small[13] and $a_{1/2}=5a_{3/2}$. The $b_{3/2}$ and $a_{3/2}$ terms contain the same radial integrals and using the tabulated[14] nuclear dipole and quadrupole moments gives $b_{3/2}=a_{3/2}/27.3$. Experimental measurements of the hyperfine structure in neutral boron[15] directly measure the $a_{1/2}$, $a_{3/2}$, and $b_{3/2}$ parameters of the p electron and provide confirmation of these nonrelativistic ratios. The departure from LS coupling must also be taken into account in the analysis. The $^1P°$-$^3P°$ mixing angle $\sin\theta$ is small for low Z but directly affects the a_{1s} term. This dipole term dominates the hyperfine structure and any corrections to it must be included. This parameter was not fitted but taken to be $-0.003\,221$.[16]

The hyperfine structure was finally fitted with three parameters, a_{1s}, a_{2s}, and $a_{1/2}$, the other parameters being fixed as described above. Hyperfine levels of a given total angular momentum F, but different J, mix through the hyperfine interaction. The small fine-structure splittings of the $^3P°$ levels (Fig. 3) result in a large perturbation of the hyperfine levels from off-diagonal components of this interaction. The Hamiltonian $(H_{FS}+H_{HFS})$ was thus diagonalized in the fitting procedure, using the experimental fine-structure splittings, to account for the fine-structure perturbations. The results are $a_{1s}=56\,518(60)$ MHz, $a_{2s}=5648(60)$ MHz, $a_{1/2}=1580(80)$ MHz, with the mixing angle $\sin\theta=-0.003\,221$. These parameters are converted to the more usual hyperfine parameters $A(^3P_2^o)$, $A(^3P_1^o)$, and

TABLE I. A comparison of the A values of the measured hyperfine structure with the nonrelativistic variational calculation of Aashamar and Hambro (Ref. 17). All units are in GHz.

Parameter	Experiment	Theory	Expt. − Theory
$A(^3P_2^o)$	14.366(20)	14.302	0.064
$A(^3P_1^o)$	14.788(40)	14.648	0.140
$A(^3S_1)$	31.084(40)	30.930	0.154

TABLE II. A comparison of the fine-structure splitting of the $^3P^\circ$ levels with theory (Refs. 7, 16, and 18). All units are in cm^{-1}. Uncertainties quoted are 3 standard deviations of the mean.

	$^3P_2^\circ \rightarrow {}^3P_0^\circ$	Δ_{E-T}	$^3P_2^\circ \rightarrow {}^3P_1^\circ$	Δ_{E-T}
Expt.	36.457(9)		52.660(9)	
Drake	36.320	0.137	52.624	0.036
Accad	36.416	0.041	52.613	0.047

TABLE III. The absolute transition energies, after subtraction of the hyperfine structure, compared with theory (Ref. 7). All units are in cm^{-1}. Experimental uncertainties quoted are 3 standard deviations of the mean. The theoretical uncertainties represent estimates of contributions from higher-order terms.

Transition	Experiment	Theory	Expt. − Theory
$^3S_1$-$^3P_2^\circ$	35430.084(9)	35430.056(70)	+0.028
$^3S_1$-$^3P_0^\circ$	35393.627(13)	35393.736(70)	−0.109
$^3S_1$-$^3P_1^\circ$	35377.424(13)	35377.432(70)	−0.008

$A(^3S_1)$ and are compared with nonrelativistic variational calculations[17,18] in Table I.

The above analysis ensures that the subtraction of the hyperfine structure can be performed with little uncertainty. The hyperfine contributions to the final uncertainty vary from 6 MHz in the case of the experimental fine-structure measurements of the $^3P_2^\circ$ level to 35 MHz in the case of the $^3P_0^\circ$ level. This compares to approximately 100 MHz from statistical uncertainties and the iodine calibration. The experimental fine-structure measurements of the $^3P^\circ$ state are listed in Table II. The absolute energies of the ^3S-$^3P^\circ$ transitions are listed in Table III. The nonrelativistic (variational calculation) part of the theory makes up over 99% of the transition energy but it is the relativistic terms that lead to the fine-structure splittings. The better agreement of the experiment with the fine-structure calculations of Accad and co-workers in Table II would seem to be fortuitous as Drake has included terms ignored by Accad. At present, terms of order $\alpha^4 Z^4$ remain to be calculated. From Table III it can be seen that the $^3P_2^\circ$ and $^3P_1^\circ$ levels are in good agreement with theory[7] but the $^3P_0^\circ$ level is outside the theoretical uncertainty. This result is in accord with the previous measurements in lithium[3] also using the newer calculations of Drake. In contrast to these measurements, the recent precise measurement by Scholl, Holt, and Rosner[4] of the ^1S-^1P transition in beryllium shows agreement within the experimental error. Calculations of the spin-dependent and spin-independent terms of order $\alpha^4 Z^4$ are currently underway.

In conclusion, we have made precision laser measurements of the fine structure, hyperfine structure, and absolute wavelengths of the $1s2s\ ^3S$-$1s2p\ ^3P^\circ$ transitions in heliumlike boron. The energy of the $1s2p\ ^3P_0^\circ$ level disagrees with theory by 24 standard deviations of the experimental precision, and by 1.5 times the estimated theoretical precision. This latter is an estimate of uncalculated higher-order terms. The use of an ECR ion source to produce the metastable ions opens up the possibility of producing many other heliumlike ions for laser studies with equivalent resolution. These measurements are precise to 0.1% of the Lamb shift for the $2s \rightarrow 2p$ transition and, as the first precision laser measurements in this system, have potential for much improvement.

The authors would like to thank C. Kurtz and P. Billquist for technical assistance, and A. E. Livingston for illuminating discussions. This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

[a]Present address: Department of Physics, University of Connecticut, Storrs, CT 06269.

[1]I. Lindgren, Nucl. Instrum. Methods Phys. Res., Sect. B **31**, 102 (1988).

[2]P. Zhao, J. R. Lawall, A. W. Kam, M. D. Lindsay, F. M. Pipkin, and W. Lichten, Phys. Rev. Lett. **63**, 1539 (1989).

[3]E. Riis, H. G. Berry, O. Poulsen, S. A. Lee, and S. Y. Tang, Phys. Rev. A **33**, 3023 (1986).

[4]T. J. Scholl, R. A. Holt, and S. D. Rosner, Phys. Rev. A **39**, 1163 (1989).

[5]C. T. Munger and H. Gould, Phys. Rev. Lett. **57**, 2927 (1986).

[6]R. DeSerio, H. G. Berry, R. L. Brooks, J. Hardis, A. E. Livingston, and S. J. Hinterlong, Phys. Rev. A **24**, 1872 (1981).

[7]G. W. F. Drake, Can. J. Phys. **66**, 586 (1988); (private communication).

[8]B. Edlén, Nova Acta Regiae Soc. Sci. Ups. **9**, 30 (1934).

[9]M. Eidelsberg, J. Phys. B **7**, 1476 (1974).

[10]S. Gerstenkorn and P. Luc, *Atlas du Spectre d'Absorption de la Molecule d'Iode* (Editions du CNRS, Paris, 1978); (private communication).

[11]A. Lurio, M. Mandel, and R. Novick, Phys. Rev. **126**, 1758 (1962).

[12]C. Schwartz, Phys. Rev. **97**, 380 (1955).

[13]C. Schwartz, Phys. Rev. **105**, 173 (1957).

[14]H. Kopfermann, *Nuclear Moments* (Academic, New York, 1958).

[15]G. Wessel, Phys. Rev. **92**, 1581 (1953).

[16]G. W. F. Drake, Phys. Rev. A **19**, 1387 (1979).

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

[18]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).