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Core-excited quartet and doublet states of B III

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A beam-foil study of core-excited states of B III in the wavelength region 36—200 nm is reported. Fourteen new lines are identified in the ^4L system and four in the core-excited ^2L system, confirming the recent theoretical predictions of Chung *et al.* The wavelength accuracy has been improved for most of the transitions already observed between doubly excited states. The previously unknown energies of the $1s2p4s\,^4P^\circ$ and $[(1s2p)^3P5f]^2F$ terms have been determined. Lifetime results for the $[(1s2p)^3Pnd]^2D^\circ$ ($n=3,4$) and for the $[(1s2p)^3Pnf)]^2F$ ($n=4,5$) terms are reported. The autoionization width of the $(1s2p^2)^2D$ state has been measured by analyzing the profile of the broadened $(1s2p^2)^2D$-$[(1s2p)^3P3d]^2D^\circ$ line. The measured width of 44 ± 4 meV is in good agreement with the value calculated by Davis and Chung.

I. INTRODUCTION

Detailed studies of quartet states in B III have been made both theoretically and experimentally[1–4] but only a few transitions predicted between 100 and 200 nm have been observed. Autoionizing and metastable autoionizing states of core-excited doublet states of B III have also been calculated recently to high accuracy.[5,6] However, very few lines have been observed up to now in this system and no lifetimes or autoionization widths for core-excited ^2L states have been measured in B III.

In this work, transitions between core-excited quartet and doublet states of B III are studied in the wavelength region 36—200 nm using foil excitation of B^+ ion beams. The aim of this investigation was to find new transitions in these systems, to improve the wavelength accuracy for transitions previously observed, and to measure lifetimes or autoionization widths for doubly excited ^2L states.

II. EXPERIMENT

B^+ beams of $\approx 1\ \mu A$ (diameter 10 mm) were supplied by a 2-MV Van de Graaff accelerator equipped with a radio-frequency source into which BF_3 gas was admitted. Beam light emitted after the carbon foil ($\approx 10\ \mu g/cm^2$) was observed with a Seya-Namioka-type spectrometer, employing two 1200 1/mm concave gratings, one blazed for normal incidence at 80 nm (Pt coated) and the other at 170 nm (Al-MgF_2 coated). The light was detected with three Mullard (Philips) channeltron detectors ($\lambda < 125$ nm) or with an EMR 542G photomultiplier tube ($\lambda > 105$ nm). The experimental setup is described in detail in Ref. 7.

A typical spectrum of boron recorded between 124.6 and 142.9 nm using the Al-MgF_2-coated grating and the photomultiplier tube is shown in Fig. 1. The lines marked III** are new lines observed in the core-excited system of B III, those marked III^c and IV^c are new lines classified in B III and B IV in Ref. 8, from known level energies. The

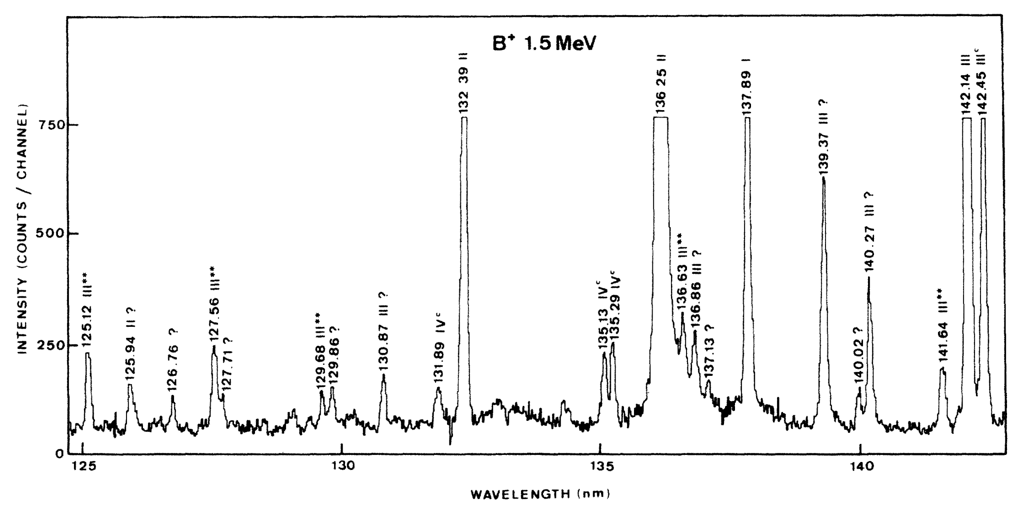

FIG. 1. A section of the beam-foil spectrum of boron between 124.6 and 142.9 nm recorded using 1.5-MeV B^+ ions. (Al-MgF_2-coated grating and EMR 542G photomultiplier tube). The number of counts in each channel corresponds to a preset amount of beam charge equal to 4×10^{-5} C. The slits are 70 μm.

experimental linewidth (full width at half maximum) is about 0.09 nm in the first order of dispersion, for slits of 70 μm.

Most of the short-wavelength lines ($\lambda < 60$ nm), observed previously with grazing-incidence spectrometers, were recorded in several dispersion orders of our spectrometer which leads to a higher accuracy on the wavelength determination than that reported up to now. Moreover, a few lines blended in the first order were resolved in higher orders.

Beam-foil spectra of boron were recorded using at least two different beam energies (0.5 and 1.5 MeV). For light ions such as boron, measurements of line intensities at two energies are generally sufficient for identifying unambiguously the ionization stage of the emitting ion.

III. RESULTS

A. ^4L states

The wavelength values of the lines appearing in our spectra and assigned to transitions between quartet states in B III are reported in Table I together with the most recent experimental and theoretical values available. Estimations of the observed line intensities are also given in Table I. These are not corrected for the sensitivity of the detection system so that comparison of the intensities is relevant only for lines of nearby wavelengths. There is an excellent agreement between our wavelength values and the theoretical predictions of Chung *et al.*[1] and Agentoft *et al.*[2]

TABLE I. Transitions associated with quartet states in B III.

Experimental wavelength (nm)		Intensity	Theoretical wavelength	
This work[a]	Other experiments	This work[b]	(nm)	Assignment
36.762±0.005	36.78,[c]36.74[e]	m	36.75,[d]36.75[f]	$2s2p\,^4P^o$–$2s4d\,^4D$
39.84±0.01	39.82,[c]39.85[g]	m	39.83,[d]39.91[f]	$2s2p\,^4P^o$–$2p3p\,^4P$
39.98±0.01	39.96,[c]39.98[g]	m	39.98[d]	$2p2p\,^4P$–$2p4d\,^4D^o$
40.26±0.01	40.24,[c]40.27[g]	m	40.24,[d]40.22,[f]40.13[h]	$2s2p\,^4P^o$–$2p3p\,^4S$
40.871±0.005	40.86,[c]40.86[g]	m	40.86,[d]40.83[f]	$2s2p\,^4P^o$–$2p3p\,^4D$
41.50±0.01		w	41.47[f]	$2p2p\,^4P$–$2p4s\,^4P^o$
45.751±0.003	45.77,[c]45.76[e]	vs	45.75,[d]45.71[f]	$2s2p\,^4P^o$–$2s3d\,^4D$
49.342±0.005	49.31,[c]49.31[e]	s	49.31,[e]49.23[f]	$2p2p\,^4P$–$2p3d\,^4P^o$
49.957±0.007	49.94,[c]49.94[e]	vs	49.97,[d]49.91[f]	$2p2p\,^4P$–$2p3d\,^4D^o$
51.895±0.005	51.89[e]	m (3d order)	51.90,[d]51.87,[f]51.87[h]	$2s2p\,^4P^o$–$2s3s\,^4S$
56.730±0.005	56.72,[c]56.74[e]	vs	56.71,[d]56.68[f]	$2p2p\,^4P$–$2p3s\,^4P^o$
115.45±0.02		vw	115.42[d]	$2s3p\,^4P^o$–$2s5d\,^4D$
122.41±0.03		vw	122.45,[d]122.32[h]	$2s3p\,^4P^o$–$2s5s\,^4S$
125.12±0.01		w	124.81[i]	$2p3d\,^4F^o$–$2p5f\,^4G$
127.56±0.01		m	127.62[i]	$2s3d\,^4D$–$2s5f\,^4F^o$
136.63±0.02		w	136.66[i]	$2p3d\,^4D^o$–$2p5f\,^4F$
141.64±0.02		w	141.63[d]	$2p3s\,^4P^o$–$2p4p\,^4P$
145.50±0.01		w	145.79[d]	$2p3s\,^4P^o$–$2p4p\,^4D$
155.72±0.02		w	155.86[d]	$2p3p\,^4D$–$2p4d\,^4D^o$
158.85±0.02		s	158.55[d]	$2s3p\,^4P^o$–$2s4d\,^4D$
161.62±0.01		s	161.64[i]	$2p3p\,^4D$–$2p4d\,^4F^o$
170.217±0.005	170.1,[c]170.13,[e]170.14[j]	vs	170.18[d]	$2s2p\,^4P^o$–$2p2p\,^4P$
170.56±0.01		m	170.48[i]	$2p3d\,^4F^o$–$2p4f\,^4G$
172.72±0.01	172.61[e]	m	172.82[d]	$2p2p\,^4P$–$2p4d\,^4D^o$
175.31±0.02	175.4,[k]175.32[e]	w	175.47[e]	$2p3d\,^4F^o$–$2p4f\,^4F$
176.49±0.01	176.51[e]	s	176.54[e]	$2s3d\,^4D$–$2s4f\,^4F^o$
181.70±0.02		vw		$2p3p\,^4D$–$2p4s\,^4P^o$
185.08±0.02		vw	185.09,[d]185.33[h]	$2s3p\,^4P^o$–$2s4s\,^4S$
197.92±0.02	197.9,[k]197.73[e]	vw	198.00[e]	$2p3d\,^4D^o$–$2p4f\,^4F$

[a]The quoted uncertainties represent the error on the position of the line maximum.
[b]vw, very weak; w, weak; m, medium; s, strong; vs, very strong (at 1.5 MeV).
[c]To *et al.*, Ref. 9.
[d]Chung *et al.*, Ref. 1.
[e]Agentoft *et al.*, Ref. 2.
[f]Fairley and Laughlin, Ref. 3.
[g]To *et al.*, Ref. 9, reassigned by Chung *et al.*, Ref. 1.
[h]Larsson and Crossley, Ref. 4.
[i]Calculated from theoretical level energies given by Chung *et al.*, Ref. 1 and Agentoft *et al.*, Ref. 2.
[j]Martinson *et al.*, Ref. 10.
[k]To *et al.*, Ref. 9, reassigned in this work.

When two sufficiently strong lines are originating from the same upper term, intensity decay curves were measured for these lines. These measurements were made (a) for the 36.762- and 158.85-nm lines (upper term: $1s2s4d\,^4D$) and (b) for the 39.98- and 172.72-nm lines (upper term: $1s2p4d\,^4D^{\circ}$). Similar intensity decay curves were obtained for lines belonging to each of these two groups which support the classification of all these lines (see Table I).

The energy of the $2p4s\,^4P^{\circ}$ term was obtained for the first time by classifying the lines at 41.50 and 181.70 nm as the $2p2p\,^4P$–$2p4s\,^4P^{\circ}$ and $2p3p\,^4D$–$2p4s\,^4P^{\circ}$ transi-

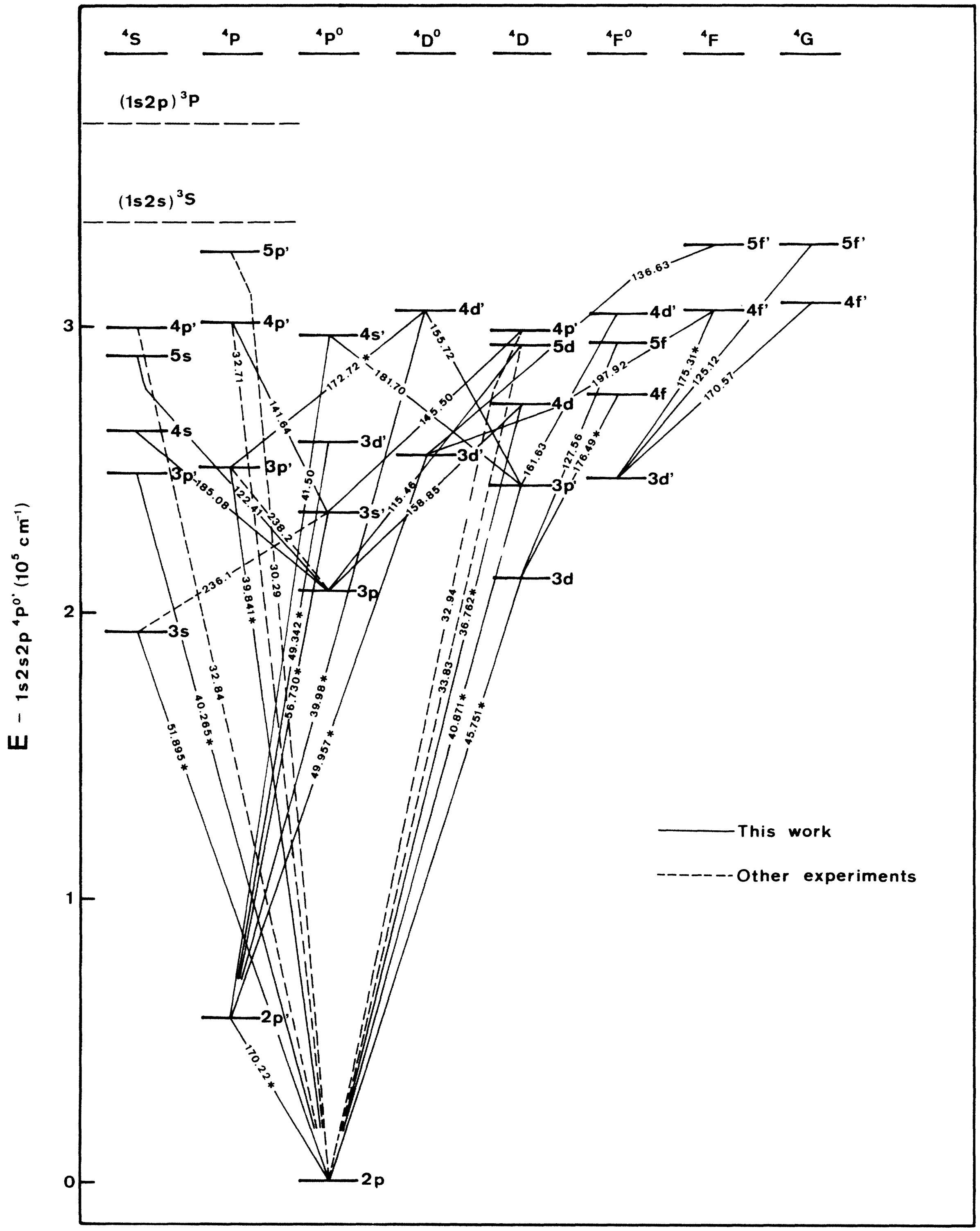

FIG. 2. Term diagram of the quartet system of B III (nl and nl' mean $1s2snl$ and $1s2pnl$, respectively). Observed wavelengths λ are indicated in nm; λ*: values measured in this work for transitions previously observed (see Table I).

tions, respectively. The wavelength of the first transition is in good agreement with the theoretical value of Fairley and Laughlin[3] (see Table I).

The wavelength values obtained in this work are in agreement, within experimental errors, with the other measured values available.[1,2,9,10] Our wavelength results are the mean value of measurements made at two beam energies and generally in different dispersion orders. Note that our wavelength value for the center of gravity of the transition connecting the two lowest quartet states ($\lambda = 170.2$ nm) is significantly larger than the three previously measured values.

Transitions observed in this work in the quartet system of B III are shown on a term diagram in Fig. 2. Transitions reported recently by other authors[1,2] and which are compatible with the present results are also indicated in Fig. 2.

The term energies for B III quartet states, derived by a least-squares calculation from all observed wavelengths indicated in Fig. 2, are listed in Table II. The errors are estimated from the weighted errors on the wavelength values. The term energies are relative to the $1s2s2p\,^4P^\circ$ term. The theoretical energy of this term is given in Ref. 1 as $-3\,571\,203$ cm^{-1}.

TABLE II. Experimental term energies for B III quartets (relative to the $1s2s2p\,^4P^\circ$).

Term	Energy (cm^{-1})
$2s2p\,^4P^\circ$	0
$2p2p\,^4P$	58 749±2
$2s3s\,^4S$	192 688±13
$2s3p\,^4P^\circ$	209 067±24
$2s3d\,^4D$	218 574±14
$2p3s\,^4P^\circ$	235 034±16
$2p3p\,^4D$	244 722±20
$2p3p\,^4S$	248 354±62
$2p3p\,^4P$	251 045±30
$2p3d\,^4F^\circ$	252 430±29
$2p3d\,^4D^\circ$	258 946±28
$2p3d\,^4P^\circ$	261 417±21
$2s4s\,^4S$	263 097±25
$2s4d\,^4D$	272 020±21
$2s4f\,^4F^\circ$	275 234±14
$2s5s\,^4S$	290 759±31
$2s5d\,^4D$	295 679±27
$2s5f\,^4F^\circ$	296 968±15
$2p4s\,^4P^\circ$	299 757±21
$2p4p\,^4D$	303 762±17
$2p4p\,^4S$	304 506±185
$2p4p\,^4P$	305 639±18
$2p4d\,^4F^\circ$	306 593±20
$2p4d\,^4D^\circ$	308 942±22
$2p4f\,^4F$	309 471±28
$2p4f\,^4G$	311 058±29
$2p5p\,^4P$	330 250±220
$2p5f\,^4F$	332 136±30
$2p5f\,^4G$	332 353±30

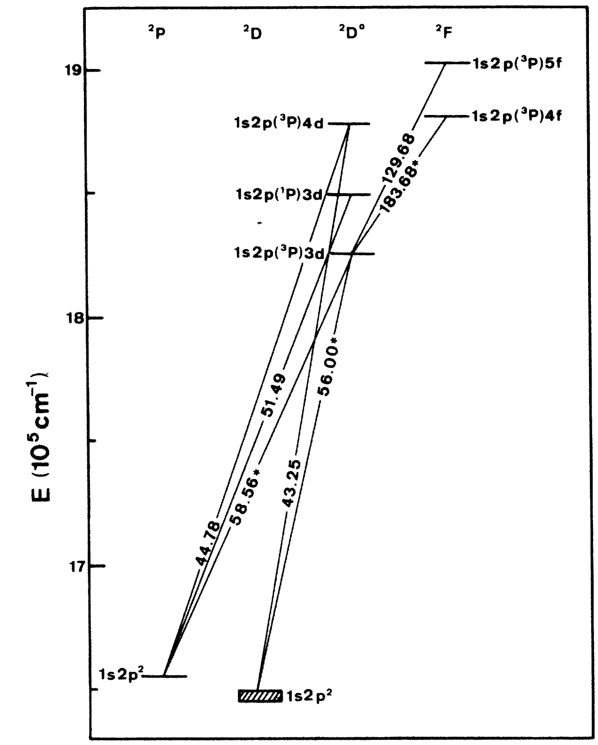

FIG. 3. Term diagram of the core-excited doublet system of B III. Observed wavelengths λ are indicated in nm; λ*: values measured in this work for transitions previously observed (see Table III).

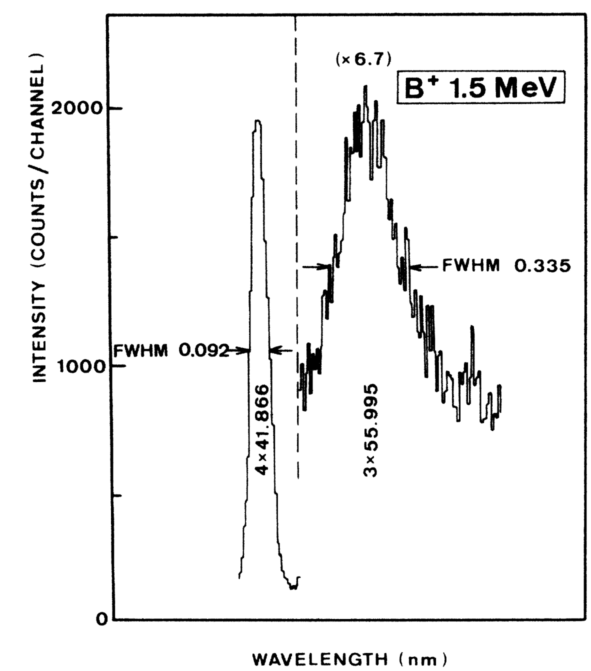

FIG. 4. The broadened 55.995-nm line corresponding to the $[1s2p2p]^2D$-$[(1s2p)^3P3d]^2D^\circ$ transition in B III together with the 41.866-nm line corresponding to the $1s2p\,^1P^\circ$$-$$1s3d\,^1D$ transition in B IV. FWHM: full width at half maximum of the line.

TABLE III. Transitions associated with core-excited doublet states in B III.

Experimental wavelength (nm) This work[a]	Other experiment[b]	Theoretical[c] wavelength (nm)	Assignment
43.25±0.05		43.31	$[1s2p2p]^2D$-$[(1s2p)^3P4d]^2D^\circ$
44.78±0.02		44.76	$[1s2p2p]^2P$-$[(1s2p)^3P4d]^2D^\circ$
51.49±0.02		51.49	$[1s2p2p]^2P$-$[(1s2p)^1P3d]^2D^\circ$
55.995±0.005	56.04±0.03	56.10	$[1s2p2p]^2D$-$[(1s2p)^3P3d]^2D^\circ$
58.56±0.01	58.57±0.02	58.56	$[1s2p2p]^2P$-$[(1s2p)^3P3d]^2D^\circ$
129.68±0.02			$[(1s2p)^3P3d]^2D^\circ$-$[(1s2p)^3P5f]^2F$
183.68±0.01	183.6±0.1	183.66	$[(1s2p)^3P3d]^2D^\circ$-$[(1s2p)^3P4f]^2F$

[a]The quoted uncertainties represent the error on the position of the line maximum.
[b]Agentoft *et al.*, Ref. 2.
[c]Bruch *et al.*, Ref. 5, Davis and Chung, Ref. 6.

B. Doubly excited ^2L states

In Table III wavelength values of the lines we have classified as transitions between core-excited ^2L levels, on the basis of level energies calculated by Bruch *et al.*[5] and by Davis and Chung,[6] are reported. The theoretical wavelengths are also quoted in Table III together with other experimental values available. Four new transitions have been identified in the core-excited doublet system.

The classification of the line at 129.68±0.02 nm as the $[(1s2p)^3P3d]^2D^\circ$-$[(1s2p)^3P5f]^2F$ transition positions the $[(1s2p)^3P5f]^2F$ term (for which no theoretical value has been reported) at 247 880±30 cm^{-1} above the $(1s2p^2)^2P$ term. The experimental excitation energy of this latter term as measured from the B III ground state is 1 654 630 cm^{-1} (Ref. 5).

Lifetimes have been measured by the beam-foil method for sufficiently strong lines. The results are given in Table IV. Note that lifetimes obtained for the $[(1s2p)^3P3d]^2D^\circ$ term using the 55.995- and the 58.56-nm lines are in excellent agreement.

Transitions observed in the core-excited doublet system of B III are shown on a term diagram in Fig. 3. Those involving a lower level which is autoionizing must give rise to broadened lines. Figure 4 shows the lines at 41.866 and 55.995 nm recorded in the fourth and third dispersion order, respectively. The former line corresponds to the $1s2p\ ^1P^\circ-1s3d\ ^1D$ transition in B IV, the latter to the $[1s2p2p]^2D$-$[(1s2p)^3P3d]^2D^\circ$ transition in B III. The broadening of the second line is essentially due to the autoionization width Γ of the lower $[1s2p2p]^2D$ state (the radiative widths of the upper and lower states are negligible). The autoionization width Γ was obtained by deconvoluting the Lorentzian function from the profile of the 3×55.995-nm line using a Gaussian instrumental-response function deduced from the profile of the nearby 4×41.866-nm line. The deconvoluted width Γ was calculated from a tabulation given in Ref. 11. The weighted mean value of Γ, deduced from seven independent measurements, is

$$\Gamma = 44 \pm 4 \text{ meV},$$

where the error represents plus or minus twice the standard deviation of the mean value. If the theoretical fine-structure splitting[12] is included, the value of Γ is reduced to 42 meV. In Table V, the observed autoionizing width Γ is compared to recent theoretical values.[6,13] Results for this width in isoelectronic Li I and Be II ions[6,13–17] are also quoted in Table V. All the experimental values are in good agreement with the theoretical predictions of Davis and Chung.[6]

TABLE IV. Lifetimes for core-excited ^2L terms.

Upper term	Wavelength (nm)	Lifetime (ns)
$[(1s2p)^3P3d]^2D^\circ$	55.995	0.11±0.01
$[(1s2p)^3P3d]^2D^\circ$	58.56	0.11±0.01
$[(1s2p)^3P4d]^2D^\circ$	44.78	0.18±0.02
$[(1s2p)^3P4f]^2F$	183.68	0.9±0.1
$[(1s2p)^3P5f]^2F$	129.68	1.2±0.1

TABLE V. Comparison of autoionization widths (in meV) for the $(1s2p2p)^2D$ state.

	Autoionization width (meV) Experiment	Theory
Li I	10.5±0.3[a]	5,[b]10.0,[c]11.00[d]
Be II	30.3±1.1[e]	23,[b]31.3,[f]27.56[d]
B III	44 ±4[g]	27,[b]42.04[d]

[a]Cederquist and Mannervik, Ref. 14.
[b]Bhatia, Ref. 13.
[c]Nicolaides and Aspromallis, Ref. 15.
[d]Davis and Chung, Ref. 6.
[e]Cederquist *et al.*, Ref. 16.
[f]Aspromallis and Nicolaides, Ref. 17.
[g]This work.

IV. CONCLUSIONS

The present beam-foil study of the B III quartet system leads to a term diagram for this system more complete than those previously reported. 29 lines appearing in our spectra (14 observed for what may be the first time) have been classified in the quartet system of B III on the basis of recent theoretical predictions.[1,2] The experimental wavelengths for transitions between quartet states are in very good agreement with the theoretical values and with other experimental data available. The energy of the $2p4s\,^4P^\circ$ term, not reported previously, has been determined by classifying two new lines.

The energies of the B III core-excited doublet states calculated recently[5,6] have been used to search in our beam-foil spectra for transitions between these states. Seven transitions have been identified (four observed for the first time) in this system. Good agreement is found between theoretical and experimental wavelengths. The energy of the $[(1s2p)^3P5f]^2F$ term has been determined for the first time. Moreover, the autoionization width of the $[1s2p2p]^2D$ state has been measured from the broadening of the line at 55.995 nm ($[1s2p2p]^2D$-$[(1s2p)^3P3d]^2D^\circ$) and compared to theoretical values.

Since submission of this manuscript an experimental study of quartet transitions in B III has been reported by Mannervik, Cederquist, and Martinson.[18] In the wavelength region where overlap occurs the agreement with the results of the present work is excellent.

ACKNOWLEDGMENTS

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