Spectra and energy levels of Br XXV, Br XXIX, Br XXX, and Br XXXI

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Emission lines of highly ionized bromine in the wavelength region 17–93 Å have been identified in spectra recorded at the University of Rochester's OMEGA laser facility. The wavelengths of $2s$–$2p$ transitions in nitrogenlike Br XXIX, carbonlike Br XXX, and boronlike Br XXXI are presented. The wavelengths of the magnetic dipole transitions within the $2s^22p^3$ ground configurations of Br XXIX are predicted from the experimental energy levels. Transitions from the $n = 4$ and 5 levels of sodiumlike Br XXV were also identified, and the ionization energy of Br XXV was determined to be 9 027 600 ± 2000 cm^{-1} (1119.3 ± 0.2 eV).

INTRODUCTION

In previous experiments[1] performed at the University of Rochester's OMEGA laser facility, RbBr targets were spherically irradiated by six frequency-tripled (351-nm) Nd:glass laser beams. Transitions of the type $2s$–$2p$ in fluorinelike Br XXVII and oxygenlike Br XXVIII were identified. During a more recent series of experiments, $RuBr_3$ targets were spherically irradiated by 24 frequency-tripled OMEGA beams, and $2s$–$2p$ transitions in nitrogenlike Br XXIX, carbonlike Br XXX, and boronlike Br XXXI have been identified. The n = 3–4, 3–5, and 4–5 transitions in sodiumlike Br XXV have also been identified. In this paper, we report the measured wavelengths of the transitions in Br XXIX, Br XXX, Br XXXI, and Br XXV. The wavelengths of the magnetic dipole transitions within the $2s^22p^3$ ground configuration of Br XXIX are predicted from the experimental energy levels. The ionization energy of Br XXV is also determined.

EXPERIMENT

The targets were solid crystals of $RuBr_3$ and were approximately 600 μm in diameter. The targets were attached to thin glass stalks by using silicone adhesive. Each of the 24 OMEGA laser beams was focused by an $f/3.7$ lens to a point eight target radii beyond the center of the target.[2,3] Each beam delivered an energy of approximately 50 J in a pulse of 500-psec duration. The average laser intensity at the surface of the target was typically 2×10^{14} W/cm^2.

The spectra were photographed by a 3-m grazing-incidence spectrograph that was described in detail in Ref. 4. The spectrograph was fitted with a 1200-line/mm gold-coated Bausch & Lomb replica grating with a 2° 35′ blaze angle. The angle of incidence was 88°, and at this angle the blaze wavelength was 60 Å.

Light from the target was focused astigmatically onto the spectrograph entrance slit by a cylindrical beryllium mirror that was positioned 50 cm in front of the entrance slit and 1.3 m from the target. The image formed by the mirror was adjusted to cross the entrance slit at an angle of 1°, and this provided some spatial resolution in the recorded spectrum. The spectra were recorded on Kodak 101-05 plates, and the radiation from two laser shots was accumulated onto one exposure.

Spectral lines were observed from 6.7 to 230 Å. The n = 2–3 transitions[5–8] in neonlike Br XXVI and fluorinelike Br XXVII were observed between 7 and 8 Å, and the $2s^22p^6$ $^1S_0$–$2s^22p^53d(1/2, 3/2)_1$ transition of Br XXVI at 7.173 Å was used as a wavelength reference. Other wavelength references were transitions in C VI, O VIII, and Si XII. These latter transitions were from elements in the glass stalk and the silicone adhesive. Our previous experience[9] with this type of target support indicates that there is no significant wavelength shift between transitions from the target and transitions from the stalk and the adhesive. The estimated uncertainty of the measured wavelengths is 0.015 Å.

RESULTS

The identifications of the transitions in Br XXIX, Br XXX, and Br XXXI are based on the predicted wavelengths of Edlén.[10–12] These predicted wavelengths are based on ex-

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trapolations from the observed spectra of the elements with atomic numbers $Z = 32$ and below and on the systematic differences between the observations and the Dirac–Fock calculations of Cheng *et al.*[13] The predicted wavelengths and the currently measured wavelengths for transitions in Br XXIX, Br XXX, and Br XXXI are listed in Table 1. The line intensities based on visual estimates of photographic plate darkening are also given in Table 1.

The energy levels derived from the measured wavelengths are presented in Table 2. The uncertainty of these energies is estimated to be 500 cm^{-1}. For levels not connected to the ground state by observed transitions, the energies are based on the predicted energies of the levels within the ground configuration. These levels are designated by $+x$, $+y$, and $+z$.

The wavelengths of the magnetic dipole transitions within the $2s^22p^3$ ground configuration of Br XXIX were derived from the experimental energy levels. These wavelengths and the predicted wavelengths of Edlén[10] are presented in Table 3.

Table 1. Wavelengths (in angstroms) and Classifications of Spectral Lines in Br XXIX, BR XXX, and Br XXXI

Ion	Transition		Int.	Observed	Predicted[a]
Br XXIX	$2s^22p^3\ ^4S_{3/2}$–$2s2p^4$	$^4P_{5/2}$	8	76.573	76.60
	$^4S_{3/2}$	$^4P_{3/2}$	8	64.960	64.86
	$^4S_{3/2}$	$^4P_{1/2}$	10	64.326[b]	64.31
	$^4S_{3/2}$	$^2P_{3/2}$	1	46.114	46.09
	$^2D_{5/2}$	$^2D_{5/2}$	8	66.839	66.82
	$^2D_{3/2}$	$^2S_{1/2}$	8	57.241	57.15
	$^2D_{3/2}$	$^2P_{3/2}$	4	54.662	54.63
	$^2D_{5/2}$	$^2P_{3/2}$	12	57.712	57.69
	$^2P_{1/2}$	$^2S_{1/2}$	4	65.724	65.63
	$^2P_{3/2}$	$^2P_{1/2}$	8	60.474	60.52
	$^2P_{1/2}$	$^2P_{3/2}$	8	62.353[c]	62.32
	$2s2p^4\ ^2P_{3/2}$–$2p^5$	$^2P_{3/2}$	2	92.418	92.31
	$^2P_{3/2}$	$^2P_{1/2}$	10	67.135[d]	67.10
	$^2P_{1/2}$	$^2P_{1/2}$	6	89.468	89.66
	$^2D_{3/2}$	$^2P_{3/2}$	2	69.981	70.08
	$^2D_{5/2}$	$^2P_{3/2}$	8	75.836	75.75
Br XXX	$2s^22p^2\ ^3P_0$–$2s2p^3$	$^3D_1$	2	69.718	69.76
	$^3P_1$	$^3D_2$	1	84.550	84.60
	$^3P_1$	$^3P_0$	1	68.163	68.12
	$^3P_1$	$^3P_1$	4	66.366	66.37
	$^3P_2$	$^3P_2$	10	67.135[d]	67.16
	$^3P_2$	$^3S_1$	4	63.212	63.19
	$^1D_2$	$^1P_1$	8	60.170[b]	60.15
	$2s2p^3\ ^3P_2$–$2p^4$	$^3P_1$	2	74.916	74.94
Br XXXI	$2s^22p\ ^2P_{1/2}$–$2s2p^2$	$^2D_{3/2}$	2	74.646	74.53
	$^2P_{3/2}$	$^2D_{5/2}$	2	90.193	90.10
	$^2P_{1/2}$	$^2S_{1/2}$	1	70.480	70.45
	$^2P_{3/2}$	$^2P_{3/2}$	2	68.519	68.47
	$^2P_{3/2}$	$^2P_{1/2}$	1	69.023	69.17
	$2s2p^2\ ^2D_{3/2}$–$2p^3$	$^2D_{3/2}$	6	88.031	87.98
	$^2D_{3/2}$	$^2P_{1/2}$	2	70.685	70.62

[a] Predicted wavelengths from Edlén.[10–12]
[b] Blended with the Br XXV transition.
[c] Blended with the Br XXVIII transition.
[d] Blended Br XXIX and Br XXX transitions.

Table 2. Energy Levels (in cm^{-1}) for Br XXIX, Br XXX, and Br XXXI

Ion	Level	Observed[a]	Predicted[b]
Br XXIX	$2s^22p^3\ ^4S_{3/2}$	0	0
	$^2D_{3/2}$	339 100	338 942
	$^2D_{5/2}$	435 800	436 248
	$^2P_{1/2}$	564 700	564 870
	$^2P_{3/2}$	886 800	892 308
	$2s2p^4\ ^4P_{5/2}$	1 305 900	1 305 451
	$^4P_{3/2}$	1 539 400	1 541 852
	$^4P_{1/2}$	1 554 600	1 554 876
	$^2D_{3/2}$	1 821 600	1 826 071
	$^2D_{5/2}$	1 931 900	1 932 889
	$^2S_{1/2}$	2 086 100	2 088 577
	$^2P_{3/2}$	2 168 500	2 169 596
	$^2P_{1/2}$	2 540 400	2 544 588
	$2p^5\ ^2P_{3/2}$	3 250 600	3 252 939
	$^2P_{1/2}$	3 658 100	3 659 857
Br XXX	$2s^22p^2\ ^3P_0$	0	0
	$^3P_1$	345 246 + x	345 246
	$^3P_2$	423 460 + y	423 460
	$^1D_2$	828 500 + z	828 075
	$2s2p^3\ ^3D_1$	1 434 400	1 433 398
	$^3D_2$	1 528 000 + x	1 527 265
	$^3P_0$	1 812 300 + x	1 813 193
	$^3P_1$	1 852 000 + x	1 852 003
	$^3P_2$	1 913 000 + y	1 912 502
	$^3S_1$	2 005 400 + y	2 006 021
	$^1P_1$	2 490 473 + z	2 490 473
	$2p^4\ ^3P_1$	3 247 800 + y	3 246 909
Br XXXI	$2s^22p\ ^2P_{1/2}$	0	0
	$^2P_{3/2}$	435 644 + x	435 644
	$2s2p^2\ ^2D_{3/2}$	1 339 700	1 341 790
	$^2S_{1/2}$	1 418 800	1 419 360
	$^2D_{5/2}$	1 544 400 + x	1 545 539
	$^2P_{1/2}$	1 884 400 + x	1 881 276
	$^2P_{3/2}$	1 895 100 + x	1 896 231
	$2p^3\ ^2D_{3/2}$	2 475 600	2 478 360
	$^2P_{1/2}$	2 754 400	2 757 741

[a] The estimated accuracy of the observed energy levels is 500 cm^{-1}.
[b] Predicted energy levels from Edlén.[10–12]

Table 3. Predicted Wavelengths (in angstroms) for Magnetic Dipole Transitions within the $2s^22p^3$ Configuration of Br XXIX

Transition	Present	Previous[a]
$2s^22p^3\ ^2P_{3/2}$–$^4S_{3/2}$	112.8 ± 0.2	112.1
$^2P_{3/2}$–$^2D_{3/2}$	182.6 ± 0.4	180.7
$^2P_{3/2}$–$^2D_{5/2}$	221.8 ± 0.6	219.3
$^2P_{3/2}$–$^2P_{1/2}$	310.5 ± 1.0	305
$^2P_{1/2}$–$^4S_{3/2}$	177.1 ± 0.3	177.0
$^2P_{1/2}$–$^2D_{3/2}$	443.3 ± 2.0	443
$^2D_{5/2}$–$^4S_{3/2}$	229.5 ± 0.4	229.2
$^2D_{5/2}$–$^2D_{3/2}$	1034 ± 10	1028
$^2D_{3/2}$–$^4S_{3/2}$	294.9 ± 0.5	295.0

[a] Predicted wavelengths from Edlén.[10]

The wavelengths and intensities of the observed transitions in sodiumlike Br XXV are listed in Table 4. These are transitions of the type n = 3–4, 3–5, and 4–5. The measured wavelengths of Kononov et al.[14] and Fawcett and Hayes[15] and the calculated wavelengths of Ivanov and Ivanova[16] are also included in Table 4.

The Br XXV energy levels derived from the measured wavelengths are given in Table 5. We have adopted the values of Kononov et al.[14] for the 3p and 3d levels.

The Br XXV ionization energy has been determined by using the polarization calculations of Edlén.[17] As shown in Table 6, Δ_p is the energy shift resulting from the polarization of the atomic core, T_H is the relativistic hydrogenic term value, and E is the experimentally determined excitation energy. The ionization energy is the sum of these three values. The ionization energies determined from the 4f, 5f, and 5g levels are listed in the last column in Table 6. The adopted value, 9 027 600 ± 2000 cm^{-1}, is in excellent agreement with the value 9 027 477 cm^{-1} recommended by Edlén[17] and 3500 cm^{-1} lower than the value 9 027 280 cm^{-1} calculated by Ivanov and Ivanova.[16] Based on the currently determined ionization energy, the effective quantum numbers n^* of the energy levels of Br XXV are listed in Table 5.

Table 4. Wavelengths (in angstroms) and Classification of Spectral Lines in Br XXV

Transition	Int.	Observed: Present Work	Observed: Ref. 14	Observed: Ref. 15	Calculated[a]
$3s\ ^2S_{1/2}$–$3p\ ^2P_{3/2}$			189.620		189.62
$^2S_{1/2}$ $^2P_{1/2}$			229.22		229.19
$3p\ ^2P_{1/2}$–$3d\ ^2D_{3/2}$			148.406		148.40
$^2P_{3/2}$ $^2D_{5/2}$			166.772		166.74
$3p\ ^2P_{1/2}$–$5d\ ^2D_{3/2}$	4	17.308			17.281
$^2P_{3/2}$ $^2D_{5/2}$	4	17.570			17.545
$3d\ ^2D_{3/2}$–$5f\ ^2F_{5/2}$	6	19.372			19.373
$^2D_{5/2}$ $^2F_{7/2}$	8	19.430			19.431
$3s\ ^2S_{1/2}$–$4p\ ^2P_{3/2}$	8	22.758		22.739	22.763
$^2S_{1/2}$ $^2P_{1/2}$	6	22.951		22.959	22.952
$3p\ ^2P_{1/2}$–$4d\ ^2D_{3/2}$	14	23.950		23.910	23.954
$^2P_{3/2}$ $^2D_{5/2}$	14	24.441		24.465	24.444
$3p\ ^2P_{1/2}$–$4s\ ^2S_{1/2}$	4	26.709			26.715
$^2P_{3/2}$ $^2S_{1/2}$	6	27.377			27.381
$3d\ ^2D_{3/2}$–$4f\ ^2F_{5/2}$	16	27.660	27.669	27.678	27.667
$^2D_{5/2}$ $^2F_{7/2}$	18	27.768	27.779	27.781	27.772
$^2D_{5/2}$ $^2F_{5/2}$	1	27.796			27.797
$3d\ ^2D_{5/2}$–$4p\ ^2P_{3/2}$	6	30.612			30.619
$^2D_{3/2}$ $^2P_{1/2}$	8	30.794			30.799
$4d\ ^2D_{3/2}$–$5f\ ^2F_{5/2}$	2	60.170[b]			60.207
$^2D_{5/2}$ $^2F_{7/2}$	4	60.396			60.415
$4f\ ^2F_{5/2}$–$5g\ ^2G_{7/2}$	6	64.226	64.242		
$^2F_{7/2}$ $^2G_{9/2}$	10	64.326[c]	64.331		

[a] Ref. 16.
[b] Blended with the Br XXX transition.
[c] Blended with the Br XXIX transition.

Table 5. Observed Level Values (in cm^{-1}) of Br XXV

Term	J	Energy	Interval	n^*	Δn^*
$3s\ ^2S$	1/2	0		2.7563	
$3p\ ^2P$	1/2	436 260[a] ± 40		2.8254	
			91 110[a] ± 50		0.0152
	3/2	527 370[a] ± 30		2.8405	
$3d\ ^2D$	3/2	1 110 090[a] ± 60		2.9432	
			16 900[a] ± 80		0.0031
	5/2	1 126 990[a] ± 50		2.9464	
$4s\ ^2S$	1/2	4 180 200 ± 1000		3.7615	
$4p\ ^2P$	1/2	4 357 500 ± 1000		3.8322	
			36 200 ± 500		0.0150
	3/2	4 393 700 ± 1000		3.8472	
$4d\ ^2D$	3/2	4 611 600 ± 1000		3.9410	
			7 300 ± 500		0.0032
	5/2	4 618 900 ± 1000		3.9442	
$4f\ ^2F$	5/2	4 725 200 ± 1000		3.9926	
			3 100 ± 500		0.0015
	7/2	4 728 300 ± 1000		3.9941	
$5d\ ^2D$	3/2	6 213 900 ± 2000		4.9372	
			5 000 ± 1000		0.0044
	5/2	6 218 900 ± 2000		4.9416	
$5f\ ^2F$	5/2	6 273 200 ± 2000		4.9900	
			1 200 ± 500		0.0011
	7/2	6 274 400 ± 2000		4.9911	
$5g\ ^2G$	7/2	6 282 200 ± 2000		4.9982	
			600 ± 600		0.0006
	9/2	6 282 800 ± 2000		4.9988	
Limit		9 027 600 ± 2000			

[a] The 3p and 3d energies are from Kononov et al.[14]

Table 6. Ionization Energies (in cm^{-1}) for Br XXV

Level	Δ_p[a]	T_H[b]	T[c]	E[d]	E_l[e]
$4f\ ^2F_{5/2}$	10 631	4 291 786	4 302 417	4 725 200	9 027 600
$^2F_{7/2}$	10 631	4 288 814	4 299 445	4 728 300	9 027 700
$5f\ ^2F_{5/2}$	7 531	2 746 762	2 754 293	6 273 200	9 027 500
$^2F_{7/2}$	7 531	2 745 240	2 752 771	6 274 400	9 027 200
$5g\ ^2G_{7/2}$	544	2 745 240	2 745 784	6 282 200	9 028 000
$^2G_{9/2}$	544	2 744 327	2 744 871	6 282 800	9 027 700

[a] Core polarization energy from Edlén.[17]
[b] Relativistic hydrogenic term value.
[c] Calculated term value $T = \Delta_p + T_H$.
[d] Experimentally determined excitation energy.
[e] Limit $E_l = \Delta_p + T_H + E$. The adopted ionization energy is 9 027 600 ± 2000 cm^{-1}.

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