

Classification of the Nickel-Like Silver Spectrum (AgXX) from a Fast Capillary Discharge Plasma

A. Rahman¹, J. J. Rocca^{1,2,*} and J.-F. Wyart^{3,**}

¹National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology and Department of Electrical and Computer Engineering, Colorado State University.

²Department of Physics, Colorado State University, Fort Collins, CO 80523, USA

³Laboratoire Aimé Cotton, CNRS (UPR 3321), Centre Universitaire, 91405-Orsay, France

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Abstract

A study of the Ni-like silver (AgXX) spectra in the 13.7–20.5 nm wavelength region using a plasma generated by a fast high power capillary discharge is reported. Forty-three AgXX transitions have been identified with the assistance of calculations performed using the Slater–Condon method with generalized least-squares fits of the energy parameters. The average difference between the measured transition wavelengths and the theoretical values is 0.0026 nm.

1. Introduction

Capillary discharge excitation has proven to be an efficient method to create very compact lasers in the 46.9–60.8 nm spectral region using Neon-like ions [1–3]. Several applications demand lasers at even shorter wavelengths. In particular, the metrology associated with extreme ultraviolet lithography for the fabrication of the future generations of integrated circuits motivates the development of lasers emitting at wavelengths in the vicinity of 13.5 nm [4]. Lasing at 13.9 and 13.2 nm in the $3d^9 4d^1 S_0$ – $3d^9 4p^1 P_1$ transitions of nickel-like silver [5–10] and cadmium [8] respectively has been observed in laser-created plasmas. Further, lasing was observed on the $4f^1 P_1$ – $4d^1 P_1$ transition of AgXX at 16.05 nm [10]. The further development of practical lasers operating in this wavelength region generates significant interest in the spectra of these Ni-like ions. Recently, a detailed spectroscopic study of Ni-like Cd has been reported utilizing a capillary discharge plasma [11]. Numerous newly identified Ni-like cadmium transitions were observed and classified in the 12.7–18.4 nm wavelength region in a cadmium plasma excited by such a discharge.

Herein we report the use of a similar discharge in silver vapor to study the spectra of Ni-like silver in the spectral region between 12.7 and 20.5 nm. A highly ionized Ag plasma was obtained with fast capillary discharge excitation of a silver vapor filled capillary channel with discharge current pulses up to 200 kA peak amplitude and a current rate increase of approximately 1.5×10^{13} A/s. Previous work in laser-created plasmas [12] has identified five AgXX lines in the 17.0–19.0 nm spectral region as 4p–4d transitions, in addition to 18 lines of the $3d^9 4s$ – $3d^9 4p$ array from 24.8 to 31.8 nm. In the present spectra, all previously reported 4d–4p and 4d–4f transitions of AgXIX [13] and

AgXX were strong emission lines and this was an incentive to extend the classification to weaker lines.

The plasma generation technique and the set-up utilized in the acquisition of the spectra are discussed in the next section. Section 3 discusses the theoretical computation and the line assignments.

2. Experimental set-up

The highly ionized silver plasmas of interest were generated by rapid electromagnetic compression of a silver vapor plasma column in a capillary channel. In these types of plasmas the contrast between the line and continuum spectra can be significantly larger than in laser created plasma, facilitating the classification of bound–bound atomic transitions. The silver vapor was created by heating and vaporizing a silver electrode with a current pulse. The metal vapor produced by this room-temperature metal vapor gun was injected through a hollow electrode into a 5 mm diameter, 4 cm long channel drilled into a polyacetal rod. The silver vapor injected into the channel was pre-ionized using a moderate current pulse and was subsequently compressed and heated using a fast high current pulse of 160–200 kA peak amplitude and ~ 12 –15 ns risetime. The high current pulse was produced using a three stage pulse-compression system consisting of a conventional eight-stage Marx generator, followed by a 26 nF cylindrical water dielectric capacitor and a radial water-dielectric Blumlein transmission line [14]. The Marx generator was operated at an erected voltage of ~ 650 kV to charge the water dielectric capacitor that in turn was discharged through a self-breaking spark-gap pressurized with SF₆ gas to pulse charge the transmission line. The Blumlein transmission line was discharged through the capillary channel located on its axis triggering an array of seven synchronously triggered spark-gaps. Each stage of pulse compression enables the generation of current pulses of increasingly shorter risetimes, allowing the creation of very fast current risetimes with a current increase rate that exceeds 1.5×10^{13} A/s. The Lorentz force associated with the current pulse rapidly compresses and heats the plasma, generating a narrow plasma column on axis, which reaches the Ni-like stage of ionization. Maximum soft X-ray emission occurs when the column pinches on axis. Pinhole camera measurements of cadmium plasma columns excited under similar discharge conditions show that at this time

* e-mail: rocca@engr.colostate.edu

** e-mail: Jean-Francois.Wyart@lac.u-psud.fr

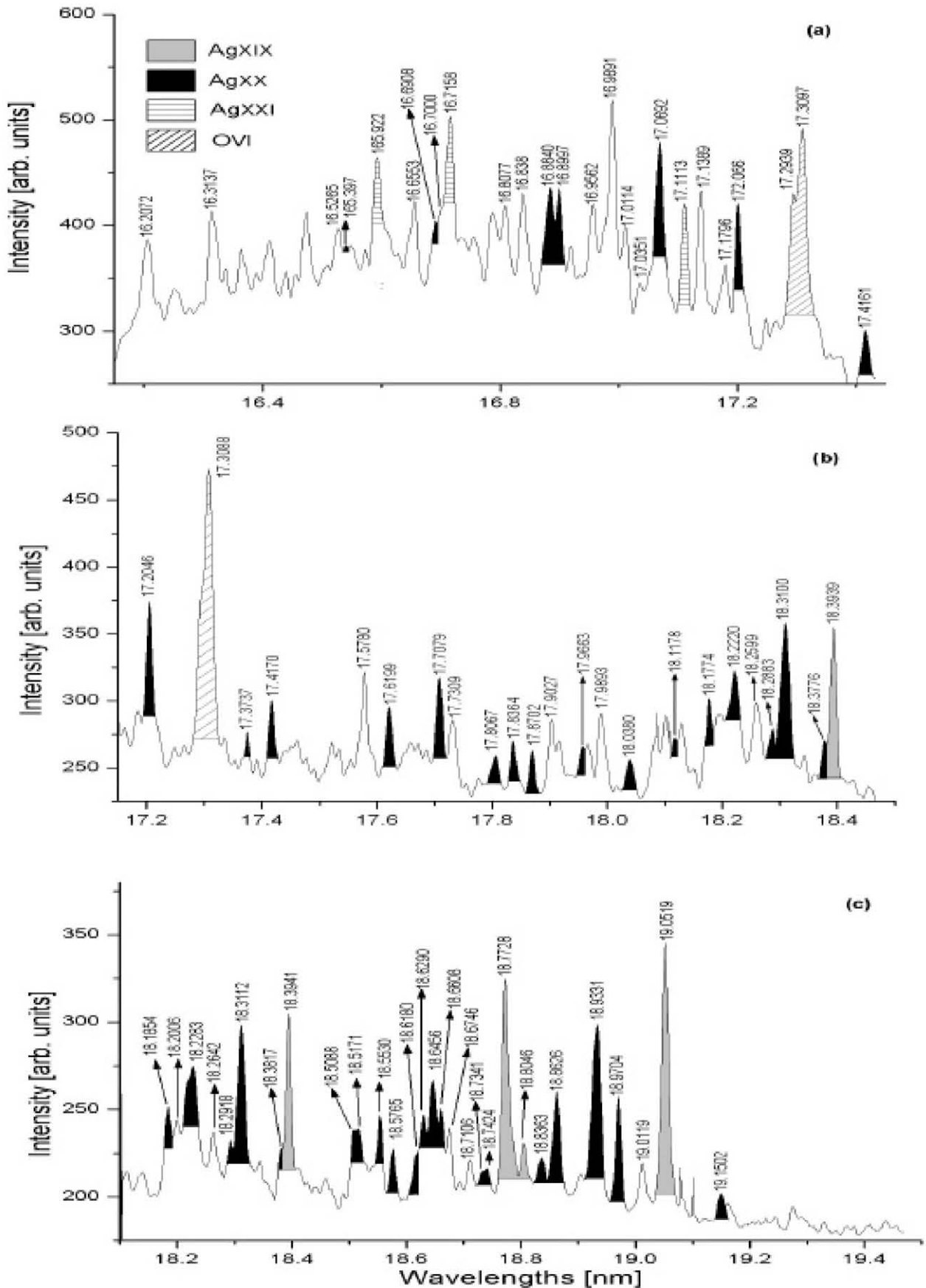


Fig. 1. (a)–(c) Spectra of capillary discharge silver plasma for the 16.2–19.4 nm wavelength region. Each spectrum corresponds to a single discharge shot and was acquired with a time resolution of about 5 ns. The capillary diameter was 5 mm and the discharge current pulse had a peak amplitude of 167 kA, 167 kA and 164 kA respectively. Each spectral line is identified with the experimental wavelength corresponding to that particular discharge shot. The difference in wavelength of the lines appearing in the overlapping regions are illustrative of the error associated with the measurements. Notice that the experimental wavelengths listed in Table II are the result of averaging several spectra. Some of the weak lines listed in Table II which do not appear clearly in these spectra were classified based on their identification in the spectra corresponding to other discharge shots.

Table I Energy levels of *AgXX*. Levels are designated in the (J_1, j_2) coupling scheme with J and N index numbering from the lowest level in its J -value for the configuration. The (J_1, j_2) purity in % is followed by SL leading components and purities. Energy values are in cm^{-1} .

Config.	Multiplet	J	N^{th}	%	$SL\%$	E_{exp}	E_{GLS}
$3d^{10}$		0	1		1S100	0	0
$3d^9 4s$	(5/2,1/2)	3	1	100	$^3D 100$	2807885	2807855
	(5/2,1/2)	2	1	99	$^3D 51$	2814345	2814304
	(3/2,1/2)	1	1	100	$^3D 100$	2859060	2859074
	(3/2,1/2)	2	2	99	$^1D 51$	2864395	2864451
$3d^9 4p$	(5/2,1/2)	2	1	96	$^3P 67$	3122417	3122540
	(5/2,1/2)	3	1	99	$^3F 50$	3129393	3129309
	(3/2,1/2)	2	2	93	$^3F 85$	3175562	3175607
	(3/2,1/2)	1	1	71	$^3P 58$	3181814	3181734
	(5/2,3/2)	4	1	100	$^3F 100$	3191211	3191162
	(5/2,3/2)	2	2	90	$^1D 62$	3201870	3201870
	(5/2,3/2)	1	2	69	$^1P 82$	3206188	3206250
	(5/2,3/2)	3	2	99	$^3D 74$	3209891	3209772
	(3/2,3/2)	0	1	100	$^3P 100$	3229410	3229433
	(3/2,3/2)	3	3	100	$^3F 49$	3248295	3248421
	(3/2,3/2)	1	3	92	$^3D 59$	3251230	3251044
	(3/2,3/2)	2	4	98	$^3D 57$	3258589	3258728
	$3d^9 4d$	(5/2,3/2)	1	1	69	$^3S 79$	3687150
(5/2,3/2)		4	1	98	$^3D 57$	3710770	3710662
(5/2,3/2)		2	1	87	$^3P 51$	3714000	3714179
(5/2,3/2)		3	1	89	$^3D 44$	3721590	3721435
(5/2,5/2)		1	2	71	$^1P 51$	3719060	3718862
(5/2,5/2)		5	1	100	$^3G 100$	3719430	3719454
(5/2,5/2)		3	2	88	$^3D 39$	3732080	3732215
(5/2,5/2)		2	2	83	$^1D 39$	3737110	3736977
(5/2,5/2)		4	2	98	$^3F 78$	3738070	3738186
(5/2,5/2)		0	1	50	$^3P 99$	3743390	3743026
(3/2,3/2)		1	3	69	$^1P 47$	3757490	3757758
(3/2,3/2)		3	3	93	$^3G 74$	3761440	3761250
(3/2,3/2)		2	3	96	$^3F 71$	3780240	3780364
(3/2,3/2)		0	2	51	$^1S 99$	3926590	3926657
(3/2,5/2)		1	4	68	$^3D 56$	3769630	3769578
(3/2,5/2)		4	3	98	$^1G 41$	3777140	3777078
(3/2,5/2)		2	4	93	$^3D 41$	3783160	3783151
(3/2,5/2)	3	4	97	$^3F 53$	3788660	3788801	
$3d^9 4f$	(5/2,5/2)	0	1	100	$^3P 100$		4237753
	(5/2,5/2)	1	1	78	$^3P 90$	4242500	4242766
	(5/2,5/2)	2	1	69	$^3P 64$		4250992
	(5/2,5/2)	5	1	97	$^3H 55$	4257030	4257022
	(5/2,5/2)	3	1	57	$^3D 54$	4265930	4266009
	(5/2,5/2)	4	1	70	$^3F 77$	4270140	4269009
	(5/2,7/2)	6	1	100	$^3H 100$	4255340	4254974
	(5/2,7/2)	2	2	74	$^1D 40$		4264980
	(5/2,7/2)	4	2	67	$^1G 47$	4271600	4272036
	(5/2,7/2)	5	2	96	$^3G 76$	4274400	4274068
	(5/2,7/2)	3	2	56	$^1F 48$	4276550	4276293
	(5/2,7/2)	1	2	48	$^3D 85$	4283940	4283578
	(3/2,7/2)	2	3	85	$^3D 37$		4304534
	(3/2,7/2)	4	3	93	$^3H 73$	4310260	4310013
	(3/2,7/2)	5	3	97	$^3H 39$	4313940	4313746
	(3/2,7/2)	3	4	98	$^3G 63$	4329060	4328895
	(3/2,5/2)	2	4	90	$^3F 63$		4317844
(3/2,5/2)	3	3	99	$^3F 41$	4322160	4322284	
(3/2,5/2)	4	4	95	$^3G 45$	4326960	4327415	
(3/2,5/2)	1	3	66	$^1P 93$	4381930	4382027	

the soft X-ray emitting region has a diameter of 250–350 μm . Shortly after, the soft X-ray emission decreases as the plasma column expands and rapidly cools [15].

Plasma radiation emitted through axial holes in the ground electrode and metal vapor gun was collected and focused onto the slit of a 2.217 m grazing incidence spectrograph using a gold-coated cylindrical mirror placed at a grazing angle of 85.8° . The radiation was dispersed by a 2400 lines/mm gold-coated grating mounted at an angle of incidence of 85.8° along the perimeter of a Rowland circle. The first order diffracted beam was recorded by a two-dimensional array detector system. This detector consists of two micro-channel plates (MCP's) mounted in a chevron configuration, a fiber optics plate coated with phosphorous, and a 1024×1024 pixels CCD camera. The MCP's were gated with a resolution of ~ 5 ns to allow the recording of spectra corresponding to different times of the plasma column evolution. Resolution of the instrument is limited by the MCP/CCD detector. This detector offers lower resolution than photographic plate, however it has the advantage of allowing for single-shot time resolved spectra. Figure 1 shows typical spectra of capillary discharge silver plasma for the 16.2–19.4 nm wavelength region. Calibration of the spectral region between 12.80–14.00 nm was performed using known transitions of OVI, OVII, ArVIII and FVI [16]. A second spectral region of interest, covering the wavelength range between 16.5 and 20.5 nm was calibrated using various known Argon transitions (ArIX through ArXIV) and OVI lines [16]. The calibration was verified by acquiring highly ionized silver spectra and comparing them with previously known lines of AgXIX and AgXX. The measured values of AgXIX lines averaged over several shots were found to deviate by less than 0.004 nm from those previously reported in the literature [13]. The maximum deviation between the AgXX lines reported in the literature [12] and the values measured in the present experiment was found to be 0.013 nm. From these comparisons, from the difference between the wavelength of other known lines and those obtained applying the calibration curve, and from shot to shot variations of the measured wavelengths, the error in the measurement of the transition wavelengths reported herein can be conservatively estimated at 0.01 nm.

3. Interpretation of the silver spectra

The same theoretical methods previously used to classify lines from CdXXI [11] was used for AgXX. The advantages of the Generalized least-squares (GLS) techniques for improving the reliability of multicharged ions predicted energies in the framework of the Racah–Slater method had been stressed in Ref. [11] and will not be repeated. Isoelectronic constraints were applied to the scaling factors of radial parameters of the four excited configurations $3d^9 4l$ ($l = s, p, d, f$). The scaling factor is the ratio of an ‘adjustable’ radial parameter to its *ab initio* (HFR) value, which is derived from the RCN, RCN2 codes by R. D. Cowan [17]. The experimental 4s and 4p levels used in the GLS fits were those of [12] and earlier references. For $3d^9 4d$, the set of E_{exp} values was extended from 228 values in [12] to 239 after inclusion of the new AgXX levels in the final fit. The predicted levels of AgXX are collected in Table I and are compared with energies derived from the classified lines of Table II. As for the case of CdXXI, the (J_1, j_2) coupling is a better approximation than is LS and

Table II *Classification of lines of Nickel-like AgXX. The first column shows the calculated wavelengths (λ_{cal} in nm) as they are derived from the “best” experimental values in Table I. The second and third column show the experimental wavelengths (λ_{exp}) and wavenumbers. Int is the measured relative intensity. The level designations imply the J -value and index N_{th} which numbers the levels from the lowest energy in the same J -value and configuration as used in [12]. The emission transition probability gA (in $10^9 s^{-1}$) in length form is derived by means of Cowan codes for E_{GLS} level values with no C.I. effects included.*

λ_{cal} (nm)	λ_{exp} (nm)	λ (cm^{-1})	Int	gA	$\lambda_{\text{exp}} - \lambda_{\text{cal}}$	$J_0 N_{\text{th}}$	$J_e N_{\text{th}}$	E_{odd}	E_{even}	Comment
13.4269	13.4250	744879	1	16	-0.0019	4p 1 1	4d 0 2	3181814	3926590	
13.8811	13.8830	720305	7	153	0.0011	4p 1 2	4d 0 2	3206188	3926590	
16.5377	16.5390	604617	2	198	0.0013	4p 2 2	4d 2 3	3175562	3780240	
16.5924	16.5919	602704	2	46	-0.0005	4p 3 1	4d 3 2	3129393	3732080	S, AgXXI
16.6898	16.6898	599168	3	249	0.0000	4p 2 1	4d 3 1	3122417	3721590	
16.7105	16.7122	598365	3	100	0.0017	4p 1 1	4d 2 3	3181814	3780240	S, AgXXI
16.8863	16.8870	592171	4	286	-0.0007	4p 3 1	4d 3 1	3129393	3721590	
16.9038	16.8995	591733	4	347	-0.0043	4p 2 1	4d 2 1	3122417	3714000	
17.0684	17.0704	585809	5	517	0.0020	4p 2 2	4d 3 3	3175562	3761440	
17.1055	17.1088	584495	2	73	0.0033	4p 3 1	4d 2 1	3129393	3714000	S, AgXXI
17.2005	17.2039	581264	6	797	-0.0034	4p 3 1	4d 4 1	3129393	3710770	
17.3709	17.3752	575533	1	125	0.0043	4p 1 1	4d 1 3	3181814	3757490	
17.4200	17.4152	574211	3	94	-0.0048	4p 1 2	4d 2 3	3206188	3780240	
17.6174	17.6213	567495	3	97	0.0039	4d 3 3	4f 3 4	3761440	4329060	S
17.7075	17.7074	564736	4	210	-0.0001	4p 2 1	4d 1 1	3122417	3687150	
17.7029	17.7074	564736	4	99	0.0045	4d 1 2	4f 1 2	3719060	4283940	S, AgXXI
17.8070	17.8070	561577	1	85	0.0000	4p 1 1	4d 0 1	3181814	3743390	Tentative, Blend
17.8079	17.8070	561577	1	28	-0.0009	4p 2 2	4d 2 2	3175562	3737110	Tentative, Blend
17.8336	17.8377	560610	2	140	0.0041	4d 4 1	4f 4 2	3710770	4271600	
17.8709	17.8688	559635	2	95	-0.0021	4p 2 3	4d 3 3	3201870	3761440	
17.9689	17.9670	556576	1	78	-0.0019	4p 2 2	4d 3 2	3175562	3732080	
18.0190	18.0216	554890	1b	161	0.0026	4d 5 1	4f 5 2	3719430	4274400	
18.1182	18.1182	551931	2b	248	0.0000	4d 2 1	4f 3 1	3714000	4265930	
18.1815	18.1773	550137	3	194	-0.0042	4d 3 1	4f 4 2	3721590	4271600	
18.2209	18.2205	548832	4b	747	-0.0004	4d 3 3	4f 4 3	3761440	4310260	Tentative, Blend
18.2209	18.2205	548832	4b	442	-0.0004	4d 2 3	4f 3 4	3780240	4329060	Tentative, Blend
18.2299	18.2205	548832	4b	315	-0.0094	4d 3 1	4f 4 1	3721590	4270140	Tentative, Blend
18.2862	18.2868	546849	2	219	0.0006	4p 4 1	4d 4 2	3191211	3738070	
18.3092	18.3094	546174	5	902	0.0002	4d 4 1	4f 5 1	3710770	4257030	
18.3665	18.3803	544040	1b	122	0.0138	4d 3 2	4f 3 2	3732080	4276550	Tentative, Blend
18.3709	18.3803	544040	1b	227	0.0094	4d 3 1	4f 3 1	3721590	4265930	Tentative, Blend
18.3942	18.3941	543653	5	521	-0.0001	4d 3/2	4f 5/2	892277	1435920	AgXIX 18.3942
18.5048	18.5088	540284	2b	60	0.0040	4d 3 4	4f 3 4	3788660	4329060	Tentative, Blend
18.5060	18.5088	540284	2b	142	0.0028	4p 3 3	4d 3 4	3248295	3788660	Tentative, Blend
18.5110	18.5152	540097	2b	126	0.0042	4p 0 1	4d 1 4	3229410	3769630	
18.5350	18.5309	539639	1b	436	0.0041	4d 3 2	4f 4 2	3732080	4271600	q
18.5378	18.5378	539438	1b	373	0.0000	4d 2 2	4f 3 2	3737110	4276550	q
18.5530	18.5530	538996	2	450	0.0000	4d 2 4	4f 3 3	3783160	4322160	
18.5770	18.5770	538300	2	640	0.0000	4d 3 4	4f 4 4	3788660	4326960	
18.6134	18.6166	537155	1b	43	0.0032	4p 1 2	4d 1 2	3181814	3719060	
18.6290	18.6290	536797	3b	894	0.0000	4d 4 3	4f 5 3	3777140	4313940	
18.6451	18.6451	536334	4	747	0.0000	4d 4 2	4f 5 2	3738070	4274400	
18.6599	18.6599	535909	4	1060	0.0000	4d 5 1	4f 6 1	3719430	4255340	
18.7319	18.7341	533786	1b	64	0.0022	4d 3 2	4f 3 1	3732080	4265930	q
18.7441	18.7415	533575	2b	83	-0.0026	4d 3 4	4f 3 3	3788660	4322160	
18.7753	18.7719	532711	7	705	-0.0034	4d 5/2	4f 7/2	904224	1436839	AgXIX 18.7753
18.7995	18.8046	531786	2	205	-0.0051	4p 1 3	4d 2 4	3251230	3783160	blend AgXIX 18.8073
18.8352	18.8368	530876	2	82	0.0016	4p 1 2	4d 2 2	3206188	3737110	
18.8605	18.8626	530150	4	271	0.0021	4p 2 3	4d 3 2	3201870	3732080	Tentative, Blend
18.8654	18.8626	530150	4	405	-0.0028	4p 2 4	4d 3 4	3258589	3788660	Tentative, Blend
18.9092	18.9092a	528843	7c	693	0.0000	4p 3 3	4d 4 3	3248295	3777140	
18.9315	18.9315a	528220	7c	851	0.0000	4p 4 1	4d 5 1	3191211	3719430	
18.9330	18.9230a	528457	7c	496	-0.0100	4p 3 2	4d 4 2	3209891	3738070	
18.9674	18.9704	527137	4	15	0.0030	4p 3 2	4d 2 2	3209891	3737110	S
19.0632	19.0519	524882	8	147	-0.0112	4p 2 4	4d 2 4	3258589	3783160	blend AgXIX 19.0543
19.1502	19.1501	522190	2	159	0.0000	4p 3 2	4d 3 2	3209891	3732080	
19.4980	19.4956	512936	5	103	-0.0024	4p 1 2	4d 1 2	3206188	3719060	blend AgXIX 19.4981
19.5427	19.5420	511718	1	98	-0.0007	4p 3 2	4d 3 1	3209891	3721590	

- Notes:
- a Wavelength from ref [11]. The present spectra lead to an unresolved peak with global intensity 7
 - S line is too strong with regard to the gA value
 - S, Ag XXI This Ag XX transition is probably masked by a AgXXI transition.
 - blend Ag XIX blend with a classified line of Cu-like Ag XIX with wavelength from [13].
 - Ag XIX AgXIX lines with wavelengths from [13].
 - q this line did not appear in all spectra
 - b broad line
 - c only combined intensity can be assigned for all three transitions

the changes in leading components are small in those close elements.

4. Conclusions

A highly ionized silver plasma generated by a fast high current capillary discharge was used to identify forty-three transitions of Ni-like Ag. The average deviation between the measured and theoretical GLS transition wavelength values is 0.0026 nm. The newly identified lines can be of use in the plasma diagnostic necessary to optimize the performance of Ni-like Ag lasers operating at 13.9 nm.

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References

1. Rocca, J. J. *et al.*, Phys. Rev. Lett. **73**, 2192 (1994).
2. Tomasel, F. G., Rocca, J. J., Shlyaptsev, V. N. and Macchietto, C. D., Phys. Rev. A **55**, 1437 (1997).
3. Frati, M., Seminario, M. and Rocca, J. J., Opt. Lett. **25**, 1022 (2000).
4. Attwood, D. T., "Soft X-rays and Extreme Ultraviolet Radiation" (Cambridge University Press, 1999).
5. Li, Y. *et al.*, Phys. Rev. A **58**, 2668 (1998).
6. Zhang, J. *et al.*, Phys. Rev. Lett. **78**, 3856 (1997).
7. Warwick, P. *et al.*, IEEE J. Selected Topics Quantum Electron. **5**, 1447 (1999).
8. Dunn, J. *et al.*, Phys. Rev. Lett. **84**, 4834 (2000).
9. Klisnick, A. *et al.*, J. Opt. Soc. Am. B **17**, 1093 (2000).
10. Kuba, J. *et al.*, Phys. Rev. A **62**, 043808 (2000).
11. Rahman, A., Hammarsten, E. C., Sakadzic, S., Rocca, J. J. and Wyart, J.-F., Physica Scripta **67**, 414 (2003).
12. Churilov, S. S., Ryabstev, A. N. and Wyart, J.-F., Physica Scripta **38**, 326 (1988).
13. Reader, J., Acquista, N. and Cooper, D. N., J. Opt. Soc. Am. **73**, 1765 (1983).
14. Gonzalez, J. J., Frati, M., Rocca, J. J., Shlyaptsev, V. N. and Osterheld, A., Phys. Rev. E. **65**, 026404 (2002).
15. Rahman, A. *et al.*, P 113 "X-ray Lasers 2002", AIP Conf. Proceed. 641 (Edited by J. J. Rocca, J. Dunn and S. Suckewer), (2002).
16. Kelly, R. L. and Palumbo, L. J., "Atomic and Ionic Emission Lines Below 2000 Angstroms," NRL Report 7599 (1973).
17. Cowan, R. D., "The Theory of Atomic Structure and Spectra," (University of Calif. Press, Berkeley 1981) and computer codes.