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Section 5: Other Lasers

Section 5.1

EXTREME ULTRAVIOLET AND SOFT X-RAY LASERS

Introduction to the Table

In Table 5.1.1 soft x-ray and extreme ultraviolet lasers are listing in order of increasing wavelength. The highly ionized lasing medium is specified by its oxidation state. The electron configurations of these highly ionized states are similar to those of neutral atoms with the same number of electrons. Thus Al^{10+}, for example, which has only three electrons is described as "Li-like" and Se^{24+} (with ten electrons) is described as "Ne-like". The lasing transition and references to the experiments are given in the two final columns of Table 5.1.1.

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Table 5.1.1
Extreme Ultraviolet and Soft X-Ray Lasers
Arranged in Order of Increasing Wavelength

Wavelength (nm)	Ion	Transition	Reference
3.560	Ni-like Au^{51+}	$4d \rightarrow 4p$	1,2
4.318	Ni-like W^{46+}	$4d \rightarrow 4p$	1,3
4.483	Ni-like Ta^{45+}	$4d \rightarrow 4p$	1,3
4.553	H-like Mg^{11+}	$3 \rightarrow 2$	4
4.607	Co-like Ta^{46+}	$4d \rightarrow 4p$	5
5.023	Ni-like Yb^{42+}	$4d \rightarrow 4p$	1,6
5.097	Ni-like Ta^{45+}	$4d \rightarrow 4p$	1,6
5.176	Co-like Yb^{43+}	$4d \rightarrow 4p$	5
5.419	H-like Na^{10+}	$3 \rightarrow 2$	4
5.611	Ni-like Yb^{42+}	$4d \rightarrow 4p$	1,6
5.77	Li-like Ca^{17+}	$4f \rightarrow 3d$	7
5.88	Ni-like Dy^{38+}	$4d \rightarrow 4p$	8
6.11	Ni-like Tb^{37+}	$4d \rightarrow 4p$	8
6.37	Ni-like Dy^{38+}	$4d \rightarrow 4p$	8
6.39	Ni-like Gd^{36+}	$4d \rightarrow 4p$	8
6.583	Ni-like Eu^{35+}	$4d \rightarrow 4p$	9
6.67	Ni-like Tb^{37+}	$4d \rightarrow 4p$	8
6.832	Ni-like Sm^{34+}	$4d \rightarrow 4p$	10
6.92	Ni-like Gd^{36+}	$4d \rightarrow 4p$	8
7.100	Ni-like Eu^{35+}	$4d \rightarrow 4p$	9
7.24	Ni-like W^{46+}	$4d \rightarrow 4p$	1,3
7.331	Ni-like Sm^{34+}	$4d \rightarrow 4p$	8,10,53
7.442	Ni-like Ta^{45+}	$4d \rightarrow 4p$	1,3
7.535	Ni-like W^{46+}	$4d \rightarrow 4p$	1,3
7.747	Ni-like Ta^{45+}	$4d \rightarrow 4p$	1,3
7.906	Ni-like Nd^{32+}	$4d \rightarrow 4p$	8,11,51
8.091	H-like F^{8+}	$3 \rightarrow 2$	12
8.107	Ni-like Yb^{42+}	$4d \rightarrow 4p$	1
8.156	Ne-like Ag^{37+}	$3p \rightarrow 3s$	13
8.2	Ni-like Pr^{31+}	$4d \rightarrow 4p$	51

Table 5.1.1—*continued*
Extreme Ultraviolet and Soft X-Ray Lasers
Arranged in Order of Increasing Wavelength

Wavelength (nm)	Ion	Transition	Reference
8.440	Ni-like Eu^{35+}	4d→4p	9
8.441	Ni-like Yb^{42+}	4d→4p	1,6
8.6	Ni-like Ce^{30+}	4d→4p	51
8.73	Li-like Si^{11+}	5d→3p	14
8.89	Li-like Si^{11+}	5f→3d	14
8.9	Ni-like La^{29+}	4d→4p	14
9.936	Ne-like Ag^{37+}	3p→3s	13
10.0	Ni-like Xe^{26+}	4d→4p	15
10.038	Ne-like Ag^{37+}	3p→3s	13
10.039	Ni-like Eu^{35+}	4d→4p	9
10.243	H-like O^{7+}	3→2	16
10.456	Ni-like Eu^{35+}	4d→4p	9
10.508	Ne-like Ag^{37+}	3p→3s	13
10.57	Li-like Al^{10+}	5f→3d	12,17,18
10.64	Ne-like Mo^{32+}	3p→3s	19
11.1	Ni-like Te^{24+}	4d→4p	51
11.25	Ne-like Nb^{31+}	3p→3s	20
11.473	Ni-like Sn^{22+}	4d→4p	21
11.7	Ne-like Ru^{34+}	3p→3s	22
11.8	Ne-like Ru^{34+}	3p→3s	22
11.89	Ne-like Zr^{30+}	3p→3s	20
11.910	Ni-like Sn^{22+}	4d→4p	21
12.300	Ne-like Ag^{37+}	3p→3s	13
12.989	Li-like Si^{11+}	4f→3d	17,23
12.35	Be-like Al^{9+}	5d→3p	18
13.1	Ne-like Mo^{32+}	3p→3s	19
13.27	Ne-like Mo^{32+}	3p→3s	19
13.86	Ne-like Nb^{31+}	3p→3s	20
13.94	Ne-like Mo^{32+}	3p→3s	19
14.04	Ne-like Nb^{31+}	3p→3s	20

Table 5.1.1—*continued*
Extreme Ultraviolet and Soft X-Ray Lasers
Arranged in Order of Increasing Wavelength

Wavelength (nm)	Ion	Transition	Reference
14.16	Ne-like Mo^{32+}	3p→3s	19
14.3	Ni-like Ag^{19+}	4d→4p	51
14.590	Ne-like Nb^{31+}	3p→3s	20
14.66	Ne-like Zr^{30+}	3p→3s	20
14.76	Ne-like Nb^{31+}	3p→3s	20
14.86	Ne-like Zr^{30+}	3p→3s	20
15.040	Ne-like Zr^{30+}	3p→3s	20
15.466	Li-like Al^{10+}	4f→3d	12,17,18,23
15.4985	Ne-like Y^{29+}	3p→3s	24–27
15.63	Ne-like Zr^{30+}	3p→3s	21
15.71	Ne-like Y^{29+}	3p→3s	24,25
15.98	Ne-like Sr^{28+}	3p→3s	28
16.41	Ne-like Sr^{28+}	3p→3s	28
16.490	Ne-like Y^{29+}	3p→3s	25
16.65	Ne-like Sr^{28+}	3p→3s	28
16.867	Ne-like Se^{24+}	3p→3s	29
17.35	Ne-like Rb^{27+}	3p→3s	30
17.455	Ne-like Sr^{28+}	3p→3s	28
17.61	Ne-like Rb^{27+}	3p→3s	30
17.63	Ne-like Br^{25+}	3p→3s	20
17.78	Be-like Al^{9+}	4f→3d	18
18.210	H-like C^{5+}	3→2	31–33
18.243	Ne-like Se^{24+}	3p→3s	24,25,29,34
18.52	Ne-like Rb^{27+}	3p→3s	30
19.47	Ne-like Br^{25+}	3p→3s	20
19.606	Ne-like Ge^{22+}	3p→3s	35
19.78	Ne-like Br^{25+}	3p→3s	20
20.25	Ne-like Nb^{31+}	3p→3s	20
20.42	Ni-like Nb^{13+}	4d→4p	36
20.465	Ne-like Fe^{16+}	3p→3s	37

Table 5.1.1—*continued*
Extreme Ultraviolet and Soft X-Ray Lasers
Arranged in Order of Increasing Wavelength

Wavelength (nm)	Ion	Transition	Reference
20.638	Ne-like Se^{24+}	3p→3s	24,25,38
20.65	Li-like S^{13+}	5g→4f	39
20.79	Ne-like Br^{25+}	3p→3s	20
20.96	Ne-like Zr^{30+}	3p→3s	20
20.978	Ne-like Se^{24+}	3p→3s	24,25
21.217	Ne-like Zn^{20+}	3p→3s	39–41
21.884	Ne-like As^{23+}	3p→3s	40
22.028	Ne-like Se^{24+}	3p→3s	24,29
22.111	Ne-like Cu^{19+}	3p→3s	35,42
22.256	Ne-like As^{23+}	3p→3s	40
22.49	Ne-like Sr^{28+}	3p→3s	28
23.11	Ne-like Ni^{18+}	3p→3s	42,43
23.224	Ne-like Ge^{22+}	3p→3s	35
23.35	Ne-like Rb^{27+}	3p→3s	30
23.626	Ne-like Ge^{22+}	3p→3s	35,44
24.02	Ne-like Cr^{14+}	3p→3s	37
24.24	Ne-like Co^{17+}	3p→3s	43
24.670	Ne-like Ga^{21+}	3p→3s	40
24.732	Ne-like Ge^{22+}	3p→3s	35
25.111	Ne-like Ga^{21+}	3p→3s	40
25.24	Ne-like Br^{25+}	3p→3s	20
25.487	Ne-like Fe^{16+}	3p→3s	37
26.1	Ne-like V^{13+}	3p→3s	45
26.232	Ne-like Zn^{20+}	3p→3s	40,41
26.294	Ne-like Se^{24+}	3p→3s	24,29
26.723	Ne-like Zn^{20+}	3p→3s	40,41
27.931	Ne-like Cu^{19+}	3p→3s	35,42,43
28.467	Ne-like Cu^{19+}	3p→3s	35,42,43
28.538	Ne-like Cr^{14+}	3p→3s	37
28.646	Ne-like Ge^{22+}	3p→3s	35

Table 5.1.1—*continued*
Extreme Ultraviolet and Soft X-Ray Lasers
Arranged in Order of Increasing Wavelength

Wavelength (nm)	Ion	Transition	Reference
29.62	Ne-like Cu^{19+}	3p→3s	35,42,43
29.77	Ne-like Ni^{18+}	3p→3s	42,43
30.36	Ne-like Ni^{18+}	3p→3s	42,43
30.4	Ne-like V^{13+}	3p→3s	45
31.2	Ne-like Sc^{11+}	3p→3s	46
31.48	Ne-like Ni^{18+}	3p→3s	42,43
31.80	Ne-like Co^{17+}	3p→3s	43
32.45	Ne-like Co^{17+}	3p→3s	43
32.63	Ne-like Ti^{12+}	3p→3s	37,43,47
33.15	Ne-like Cu^{19+}	3p→3s	35,42,43
34.75	Ne-like Ni^{18+}	3p→3s	42,43
34.796	Ne-like Fe^{16+}	3p→3s	37
35.2	Ne-like Sc^{11+}	3p→3s	46
36.73	Ne-like Co^{17+}	3p→3s	43
38.3	Ne-like Ca^{10+}	3p→3s	46
38.93	Ne-like Fe^{16+}	3p→3s	37
40.235	Ne-like Cr^{14+}	3p→3s	37
41.8	Pd-like Xe^{8+}	5d→5p	52
42.1	Ne-like K^{9+}	3p→3s	46
44.077	Ne-like Cr^{14+}	3p→3s	37
45.1	Ne-like Ar^{8+}	3d→3p	48
46.9	Ne-like Ar^{8+}	3p→3s	15,48,49
47.22	Ne-like Ti^{12+}	3p→3s	43
50.76	Ne-like Ti^{12+}	3p→3s	43
52.9	Ne-like Cl^{7+}	3p→3s	46
60.1	Ne-like S^{6+}	3d→3p	50
60.8	Ne-like S^{6+}	3p→3s	50
87.4	Ne-like Si^{4+}	3p→3s	50

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Section 5.2

FREE ELECTRON LASERS

Introduction to the Table

Free electron lasers are arranged in order of increasing wavelength in Table 5.2.1. When a range of wavelengths was reported, lasers are listed in order of the lowest lasing wavelength. For each laser the operating configuration (oscillator, amplifier, single pass, amplified spontaneous emission) and the accelerator (rf linac, induction linac, storage ring, electro-static, pulse line, microtron, modulator, ignition coil) used are given, together with the primary reference or references to laser action. The operating and performance characteristics of these lasers are summarized in recent reviews by Colson and by Freund and Granatstein (see Further Reading below).

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Table 5.2.1
Free Electron Lasers Arranged in Order of Wavelength

Wavelength (μm)	Configuration	Accelerator	Reference
0.244–0.69	oscillator	storage ring	1
0.25	oscillator	rf linac	2
0.3	oscillator	storage ring	3
0.35	oscillator	storage ring	4
0.35	oscillator	storage ring	5
0.37	oscillator	rf linac	6
0.46–0.68	oscillator	storage ring	7
0.5	oscillator	rf linac	2
0.5145	amplifier	storage ring	8
0.525	oscillator	rf linac	9
0.598	oscillator	storage ring	10
0.63	oscillator	rf linac	11
0.662	oscillator	rf linac	12
1.57	oscillator	rf linac	13
1.88	oscillator	rf linac	14
1.9–8.1	oscillator	rf linac	15
2–100	oscillator	rf linac	33
2.2–9.6	oscillator	rf linac	16
3	amplifier	rf linac	17
3	oscillator	rf linac	18
3–10	oscillator	rf linac	19
3–53	oscillator	rf linac	73
3.04	oscillator	rf linac	20

Table 5.2.1—*continued*
Free Electron Lasers Arranged in Order of Wavelength

Wavelength (μm)	Configuration	Accelerator	Reference
4–6	oscillator	rf linac	21
4–40	oscillator	rf linac	22
4.2	oscillator	rf linac	23
5	oscillator	rf linac	24
5–35	oscillator	rf linac	25
5.5	oscillator	rf linac	14
8	oscillator	rf linac	26
10	oscillator	rf linac	27
10.6	amplifier	induction linac	28
12–21	oscillator	rf linac	29
15	oscillator	rf linac	30
16–110	oscillator	rf linac	25
19–65	oscillator	rf linac	32
20	oscillator	rf linac	31
40	oscillator	rf linac	34
40	oscillator	rf linac	35
43	oscillator	rf linac	36
47	oscillator	rf linac	74
60	oscillator	electrostatic	37
65	oscillator	rf linac	75
80–200	oscillator	rf linac	38
120–800	oscillator	electrostatic	39
340	oscillator	electrostatic	37
400	single pass	electrostatic	40
400	oscillator	electrostatic	41
640	–	electrostatic	42
1000	oscillator	electrostatic	43
1500	ASE	electrostatic	44, 45
2000	amplifier	pulse line	46
2000	oscillator	microtron	47
2000	amplifier	induction linac	48
2100–2600	oscillator	mircotron	49
≤2500	oscillator	electrostatic	50
2700	oscillator	rf linac	51
3000	ASE	pulse line	52

Table 5.2.1—*continued*
Free Electron Lasers Arranged in Order of Wavelength

Wavelength (μm)	Configuration	Accelerator	Reference
3000	oscillator	pulse line	53
3200	ASE	electrostatic	54
3500	amplifier	pulse line	55
4000	oscillator	pulse line	56
6000	amplifier	induction linac	57
6700	oscillator	pulse line	58
8000	amplifier	pulse line	59
8000	ASE	pulse line	60
8000	amplifier	induction linac	61
8000	oscillator	induction linac	62
8000	amplifier	pulse line	63
8700	amplifier	induction linac	64, 65
26,000	oscillator	pulse line	66
30,000	ASE	pulse line	67
30,000	oscillator	modulator	68
32,000	ASE	induction linac	69
35,000	oscillator	modulator	70
68,000	ASE	electrostatic	71
300,000	oscillator	ignition coil	72

(S)ASE – (self) amplified spontaneous emission

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Section 5.3

NUCLEAR PUMPED LASERS

Introduction to the Table

Table 5.3.1 lists nuclear pumped lasers in order of increasing wavelength for both reactor-pumped lasers and nuclear-device-pumped lasers. The lasing medium (gas or gas mixtures) is given in the second column and the nuclear reaction giving rise to excitation of the lasing medium is given in the third column. Primary references are included in the final column. This table was adapted from a table provided by G. H. Miley and E. G. Batyrbekov (private communication and to be published).

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Table 5.3.1
Nuclear Pumped Lasers Arranged in Order of Wavelength

Wavelength (μm)	Active medium	Pumping reactions	Reference
Reactor Pumped Lasers			
0.4416	He–Cd	$U^{235}(n,f)F$	1
0.4416	^3He–Cd	$^3He(n,p)T$	2,3
0.5337	He–Cd	$U^{235}(n,f)F$	1
0.5337	^3He–Cd	$^3He(n,p)T$	2, 3
0.5378	He–Cd	$U^{235}(n,f)F$	1
0.5378	^3He–Cd	$^3He(n,p)T$	2, 3
0.5461	He–Xe–Hg–H_2	$U^{235}(n,f)F$	4
0.5852	He–Ne–Ar	$^3He(n,p)T$	5
0.5852	He–Ne–H_2	$B^{10}(n,\alpha)Li^7$	8
0.5853	He–Ne–Ar	$U^{235}(n,f)F$	1,6,7
0.615	He–Hg	$B^{10}(n,\alpha)Li^7$	9,10
0.7032	Ne–Kr(Ar)	$U^{235}(n,f)F$	5,7
0.7245	(He)–Ne–Kr	$U^{235}(n,f)F$	1
0.7245	Ne–Kr(Ar)	$U^{235}(n,f)F$	5,7
0.7479	He–Zn	$^3He(n,p)T$	11
0.7479	He–Zn	$U^{235}(n,f)F$	1
0.8066	He–Cd	$U^{235}(n,f)F$	1
0.8531	He–Cd	$U^{235}(n,f)F$	1
0.8629	Ne–N_2	$B^{10}(n,\alpha)Li^7$	12–14
0.9393	Ne–N_2	$B^{10}(n,\alpha)Li^7$	12–14
1.149	He–Ar	$U^{235}(n,f)F$	15
1.190	He–Ar	$U^{235}(n,f)F$	15
1.27	^3He–Ar	$^3He(n,p)T$	16,17,37
1.4300	He–Cd	$U^{235}(n,f)F$	1
1.45	He–CO,He–CO_2,Ar–CO_2	$B^{10}(n,\alpha)Li^7$	18–20
1.4550	Ne–CO, Ne–CO_2	$B^{10}(n,\alpha)Li^7$	18,21
1.587	^3He–Cd	$^3He(n,p)T$	17
1.6500	He–Cd	$U^{235}(n,f)F$	1
1.69	^3He–Ar	$^3He(n,p)T$	37
1.69	^3He–Ne	$^3He(n,p)T$	37

Table 5.3.1—*continued*
Nuclear Pumped Lasers Arranged in Order of Wavelength

Wavelength (μm)	Active medium	Pumping reactions	Reference
1.73	Ar–Xe	$B^{10}(n,\alpha)Li^{7}$	22
1.73	Ar–Xe	$U^{235}(n,f)F$	23
1.732	Ar–Xe	$U^{235}(n,f)F$	24
1.732	He–Ar–Xe	$U^{235}(n,f)F$	1,25
1.78	He–Kr	$U^{235}(n,f)F$	15,26
1.79	^{3}He–Ar	$^{3}He(n,p)T$	16,17,27,37
1.79	^{3}He–Ne	$^{3}He(n,p)T$	37
2.026	^{3}He–Xe	$^{3}He(n,p)T$	17,28–30
2.026	Ar–Xe	$U^{235}(n,f)F$	15
2.03	He–Ar–Xe	$U^{235}(n,f)F$	23
2.19	^{3}He–Ar	$^{3}He(n,p)T$	17,30
2.19	^{3}He–Kr	$^{3}He(n,p)T$	17
2.397	He–Ar	$U^{235}(n,f)F$	15
2.48	He–Ar–Xe	$U^{235}(n,f)F$	36
2.482	Ar–Xe	$U^{235}(n,f)F$	25
2.5	^{3}He–Kr	$^{3}He(n,p)T$	30
2.52	^{3}He–Ar	$^{3}He(n,p)T$	17,30
2.52	He–Kr	$U^{235}(n,f)F$	15,26
2.60	He–Ar–Xe	$U^{235}(n,f)F$	1,25
2.627	Ar–Xe	$U^{235}(n,f)F$	1
2.627	He–Xe	$U^{235}(n,f)F$	15,31
3.07	He–Kr	$U^{235}(n,f)F$	15,26
3.508	^{3}He–Xe	$^{3}He(n,p)T$	17,28
3.5080	He–Xe	$U^{235}(n,f)F$	32
3.652	^{3}He–Xe	$^{3}He(n,p)T$	17,28
5.1–5.6	CO	$U^{235}(n,f)F$	33,34
Nuclear Device Pumped Lasers			
0.17	Xe_2	gamma rays	35
2.7	HF	gamma rays	35

f and F denote light and heavy fission fragments emitted in the reaction of neutrons (n) with ^{235}U.

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Section 5.4

NATURAL LASERS

Introduction to the Table

Natural lasers are listed by increasing wavelength (in micrometers) in Table 5.4.1. The transition and active gas molecule, the object from which the radiation was observed, and the original reference(s) are given in the subsequent columns.

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Table 5.4.1
Natural Lasers Arranged in Order of Increasing Wavelength

Wavelength (μm)	Gas – Object	Transition	Reference
10.4[a]	CO_2 – Venus	ν_3–$2\nu_2$	1,2
10.4[a]	CO_2 – Mars	ν_3–$2\nu_2$	1,2,3
52.5	H – Cygnus MWC349	H10α	4
88.8	H – Cygnus MWC349	H12α	4
169.4	H – Cygnus MWC349	H15α	4
453	H – Cygnus MWC349	H21α	5
456	H_2O – stars[b]	ν_2=1, 1_{10}–1_{01}	6
636.6	H_2O – [c]	6_{42}–5_{51}	7
682.7	H_2O – [c]	6_{43}–5_{50}	7
844.9	H_2O – VY CMa	$17_{4,13}$–$16_{7,10}$	8
850	H – Cygnus MWC349	H26α	9
885.4	CH_3OH – S231	7_{-4}–6_{-4}	8
885.4 885.5	H_2O – S269	7_3–6_3 E_1 [d] 7_{-3}–6_{-3} E_2	8
885.5	H_2O – S252	7_3–6_3	8
885.6	CH_3OH – S252	7_3–6_3	8
891.6	H_2O – VY CMa	$5_{2,3}$–$6_{1,6}$	8
922.0	para-H_2O – SFR[e]	5_{15}–4_{22}	10
933.4	ortho-H_2O – SFR[e]	10_{29}–9_{36}	11
1635	H_2O[f]	3_{13} – 2_{20}	12

(a) Predicted amplifications are very small (≤ 1.1)
(b) VY CMa, R Leo, R Crt, RT Vir, W Hya, RX Boo, S CrB, U Her, VX Sgr, NML Cyg
(c) Interstellar and circumstellar water
(d) Ambiquity of the line identification
(e) SFR – star forming regions
(f) Various molecular clouds, star forming regions, and evolving stars

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Section 5.5

INVERSIONLESS LASERS

Introduction to the Table

Table 5.5.1 presents experiments involving either lasing or amplification in inversionless systems arranged in order of increasing wavelength. The lasers have been operated continuous wave; the amplifier experiments have measured transient gain or gain on a probe laser pulse. The lasing atomic species is given in the second column. The operative transition and lasing without inversion (LWI) scheme are also given. Primary references to the experiments are listed in the final column.

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Table 5.5.1
Inversionless Lasers and Amplifiers

Wavelength (nm)	Medium	Transition	Scheme	Reference
Lasers:				
589.76	^{23}Na vapor atomic beam	$3^2S_{1/2} - 3^2P_{1/2}$	Λ	1
794	^{87}Rb vapor, magnetic field	D_1:$5^2S_{1/2} - 5^2P_{1/2}$	V	2
Amplifiers:				
479	^{112}Cd vapor, magnetic field	$^3S_1 - {}^3P_1$	Λ	3
571	Sm vapor, magnetic field		Λ	4,9
589	^{23}Na vapor, magnetic field	$3^2S_{1/2} - 3^2P_{1/2}$ D_1 $(2\rightarrow2)$	Λ	7
589.0	^{23}Na vapor magnetic field	D_1:$3^2S_{1/2} - 3^2P_{1/2}$	V	5,6
770	K vapor, He buffer gas	D_1:$^4S(F=2) - {}^4P_{1/2}$	*	8
~821	Ba, atomic beam	$^1D_2 - {}^1P_1$	**	10

* Four-level Raman driven amplification

** Three-level cascade system.

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