

Spin & Symmetry

Fermions (spin $1/2$, $3/2$, $5/2$ etc) must have antisymmetric wave functions with respect to interchange of 2 identical particles.

Bosons (spin 0, 1, 2, etc) must have symmetric wave functions with respect to interchange of 2 identical particles.

Two electrons in infinite square well: lowest energy state?

Both electrons in $n = 1$, one with $m_s = 1/2$ the other with $-1/2$

$$\psi = \psi_1(x_1) \psi_1(x_2) (|s_1, 1/2\rangle |s_2, -1/2\rangle - |s_1, -1/2\rangle |s_2, 1/2\rangle) / 2^{1/2}$$

Without symmetry requirement there are 4 lowest states.

Spin & Symmetry

Two electrons in infinite square well: first excited state?

One electron in $n = 1$, the other in $n = 2$. There are 4 independent states with the same energy:

$$\psi = [\psi_1(x_1) \psi_2(x_2) + \psi_2(x_1) \psi_1(x_2)] (|1/2\rangle|-1/2\rangle - |-1/2\rangle|1/2\rangle)/2$$

$$\psi = [\psi_1(x_1) \psi_2(x_2) - \psi_2(x_1) \psi_1(x_2)] (|1/2\rangle|-1/2\rangle + |-1/2\rangle|1/2\rangle)/2$$

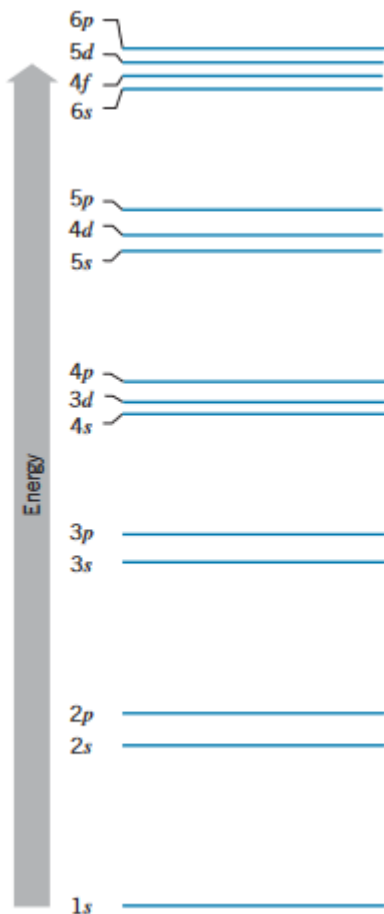
$$\psi = [\psi_1(x_1) \psi_2(x_2) - \psi_2(x_1) \psi_1(x_2)] |1/2\rangle|1/2\rangle/2^{1/2}$$

$$\psi = [\psi_1(x_1) \psi_2(x_2) - \psi_2(x_1) \psi_1(x_2)] |-1/2\rangle|-1/2\rangle/2^{1/2}$$

Order for adding electrons

TABLE 8.1 Filling of Atomic Subshells

n	l	Subshell	Capacity $2(2l+1)$
1	0	1s	2
2	0	2s	2
2	1	2p	6
3	0	3s	2
3	1	3p	6
4	0	4s	2
3	2	3d	10
4	1	4p	6
5	0	5s	2
4	2	4d	10
5	1	5p	6
6	0	6s	2
4	3	4f	14
5	2	5d	10
6	1	6p	6
7	0	7s	2
5	3	5f	14
6	2	6d	10



n	1	2	3	4	5
Shell	<i>K</i>	<i>L</i>	<i>M</i>	<i>N</i>	<i>O</i>

The order of energies for electrons in atoms determines the periodic table.

The potential energy vs. r goes strongly negative as r goes to 0.

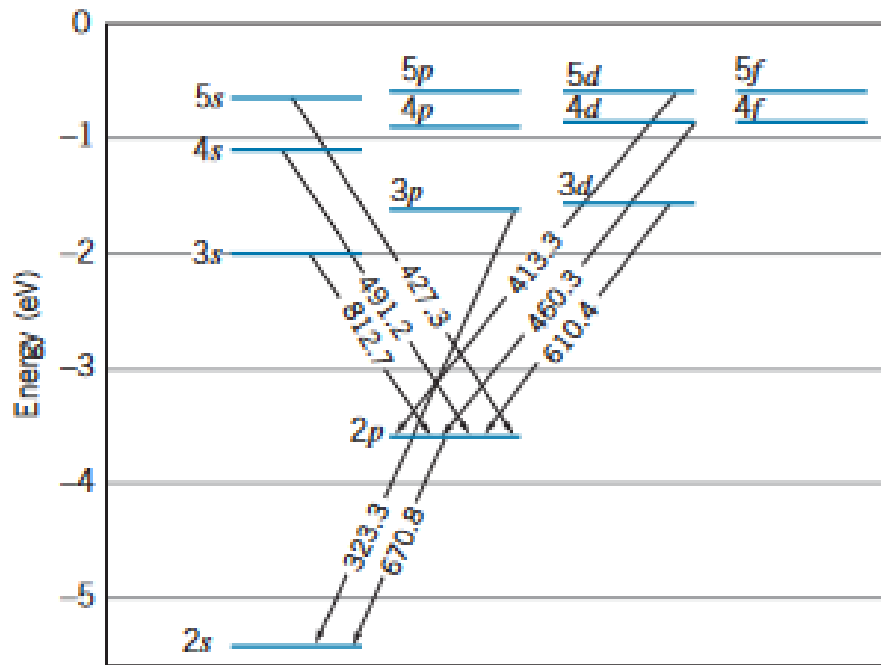
Angular momenta that can get to small r are more strongly shifted to more deeply bound.

Periodic Table of the Elements

1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1s ¹		s	p	d	f												2 He Helium 1s ²
3 Li Lithium [He]2s ¹	4 Be Beryllium [He]2s ²											5 B Boron [He]2s ² 2p ¹	6 C Carbon [He]2s ² 2p ²	7 N Nitrogen [He]2s ² 2p ³	8 O Oxygen [He]2s ² 2p ⁴	9 F Fluorine [He]2s ² 2p ⁵	10 Ne Neon [He]2s ² 2p ⁶
11 Na Sodium [Ne]3s ¹	12 Mg Magnesium [Ne]3s ²	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 Al Aluminum [Ne]3s ² 3p ¹	14 Si Silicon [Ne]3s ² 3p ²	15 P Phosphorus [Ne]3s ² 3p ³	16 S Sulfur [Ne]3s ² 3p ⁴	17 Cl Chlorine [Ne]3s ² 3p ⁵	18 Ar Argon [Ne]3s ² 3p ⁶
19 K Potassium [Ar]4s ¹	20 Ca Calcium [Ar]4s ²	21 Sc Scandium [Ar]3d ¹ 4s ²	22 Ti Titanium [Ar]3d ² 4s ²	23 V Vanadium [Ar]3d ³ 4s ²	24 Cr Chromium [Ar]3d ⁵ 4s ¹	25 Mn Manganese [Ar]3d ⁵ 4s ²	26 Fe Iron [Ar]3d ⁶ 4s ²	27 Co Cobalt [Ar]3d ⁷ 4s ²	28 Ni Nickel [Ar]3d ⁸ 4s ²	29 Cu Copper [Ar]3d ¹⁰ 4s ¹	30 Zn Zinc [Ar]3d ¹⁰ 4s ²	31 Ga Gallium [Ar]3d ¹⁰ 4s ² 4p ¹	32 Ge Germanium [Ar]3d ¹⁰ 4s ² 4p ²	33 As Arsenic [Ar]3d ¹⁰ 4s ² 4p ³	34 Se Selenium [Ar]3d ¹⁰ 4s ² 4p ⁴	35 Br Bromine [Ar]3d ¹⁰ 4s ² 4p ⁵	36 Kr Krypton [Ar]3d ¹⁰ 4s ² 4p ⁶
37 Rb Rubidium [Kr]5s ¹	38 Sr Strontium [Kr]5s ²	39 Y Yttrium [Kr]4d ¹ 5s ²	40 Zr Zirconium [Kr]4d ² 5s ²	41 Nb Niobium [Kr]4d ⁴ 5s ¹	42 Mo Molybdenum [Kr]4d ⁵ 5s ¹	43 Tc Technetium [Kr]4d ⁵ 5s ²	44 Ru Ruthenium [Kr]4d ⁷ 5s ¹	45 Rh Rhodium [Kr]4d ⁸ 5s ¹	46 Pd Palladium [Kr]4d ¹⁰	47 Ag Silver [Kr]4d ¹⁰ 5s ¹	48 Cd Cadmium [Kr]4d ¹⁰ 5s ²	49 In Indium [Kr]4d ¹⁰ 5s ² 5p ¹	50 Sn Tin [Kr]4d ¹⁰ 5s ² 5p ²	51 Sb Antimony [Kr]4d ¹⁰ 5s ² 5p ³	52 Te Tellurium [Kr]4d ¹⁰ 5s ² 5p ⁴	53 I Iodine [Kr]4d ¹⁰ 5s ² 5p ⁵	54 Xe Xenon [Kr]4d ¹⁰ 5s ² 5p ⁶
55 Cs Cesium [Xe]6s ¹	56 Ba Barium [Xe]6s ²	57-71	72 Hf Hafnium [Xe]4f ¹⁴ 5d ² 6s ²	73 Ta Tantalum [Xe]4f ¹⁴ 5d ³ 6s ²	74 W Tungsten [Xe]4f ¹⁴ 5d ⁴ 6s ²	75 Re Rhenium [Xe]4f ¹⁴ 5d ⁵ 6s ²	76 Os Osmium [Xe]4f ¹⁴ 5d ⁶ 6s ²	77 Ir Iridium [Xe]4f ¹⁴ 5d ⁷ 6s ²	78 Pt Platinum [Xe]4f ¹⁴ 5d ⁹ 6s ¹	79 Au Gold [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	80 Hg Mercury [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	81 Tl Thallium [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	82 Pb Lead [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	83 Bi Bismuth [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	84 Po Polonium [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	85 At Astatine [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	86 Rn Radon [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶
87 Fr Francium [Rn]7s ¹	88 Ra Radium [Rn]7s ²	89-103	104 Rf Rutherfordium [Rn]5f ¹⁴ 6d ² 7s ²	105 Db Dubnium [Rn]5f ¹⁴ 6d ³ 7s ²	106 Sg Seaborgium [Rn]5f ¹⁴ 6d ⁴ 7s ²	107 Bh Bohrium [Rn]5f ¹⁴ 6d ⁵ 7s ²	108 Hs Hassium [Rn]5f ¹⁴ 6d ⁶ 7s ²	109 Mt Meitnerium [Rn]5f ¹⁴ 6d ⁷ 7s ²	110 Ds Darmstadtium [Rn]5f ¹⁴ 6d ⁹ 7s ²	111 Rg Roentgenium [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	112 Cn Copernicium [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	113 Uut Ununtrium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	114 Fl Flerovium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	115 Uup Ununpentium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	116 Lv Livermorium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	117 Uus Ununseptium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	118 Uuo Ununoctium [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶

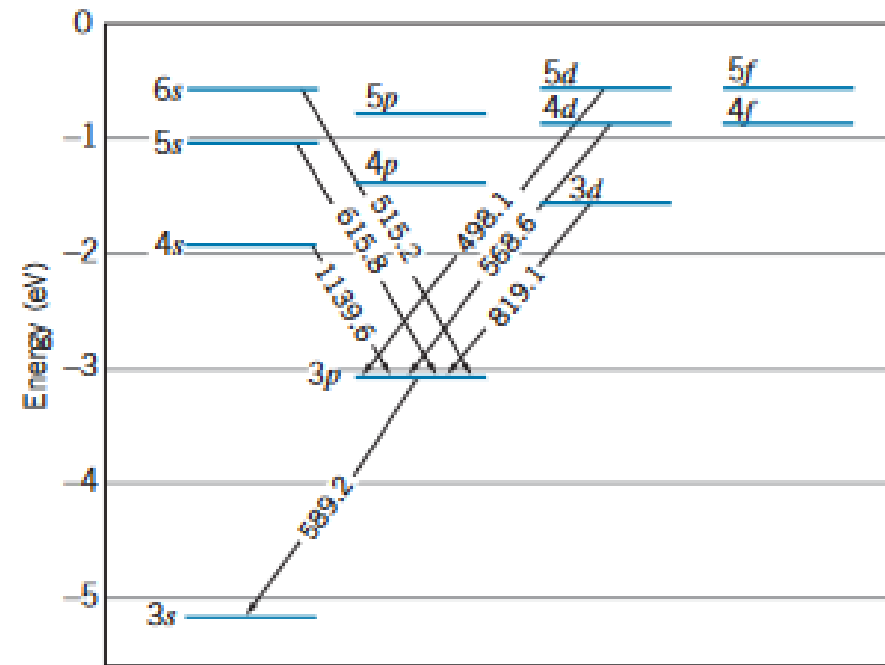
Lanthanide Series	57 La Lanthanum [Xe]5d ¹ 6s ²	58 Ce Cerium [Xe]4f ¹ 5d ¹ 6s ²	59 Pr Praseodymium [Xe]4f ³ 6s ²	60 Nd Neodymium [Xe]4f ⁴ 6s ²	61 Pm Promethium [Xe]4f ⁵ 6s ²	62 Sm Samarium [Xe]4f ⁶ 6s ²	63 Eu Europium [Xe]4f ⁷ 6s ²	64 Gd Gadolinium [Xe]4f ⁷ 5d ¹ 6s ²	65 Tb Terbium [Xe]4f ⁹ 6s ²	66 Dy Dysprosium [Xe]4f ¹⁰ 6s ²	67 Ho Holmium [Xe]4f ¹¹ 6s ²	68 Er Erbium [Xe]4f ¹² 6s ²	69 Tm Thulium [Xe]4f ¹³ 6s ²	70 Yb Ytterbium [Xe]4f ¹⁴ 6s ²	71 Lu Lutetium [Xe]4f ¹⁴ 5d ¹ 6s ²
Actinide Series	89 Ac Actinium [Rn]6d ¹ 7s ²	90 Th Thorium [Rn]6d ² 7s ²	91 Pa Protactinium [Rn]5f ² 6d ¹ 7s ²	92 U Uranium [Rn]5f ³ 6d ¹ 7s ²	93 Np Neptunium [Rn]5f ⁴ 6d ¹ 7s ²	94 Pu Plutonium [Rn]5f ⁶ 7s ²	95 Am Americium [Rn]5f ⁷ 7s ²	96 Cm Curium [Rn]5f ⁸ 6d ¹ 7s ²	97 Bk Berkelium [Rn]5f ⁹ 7s ²	98 Cf Californium [Rn]5f ¹⁰ 7s ²	99 Es Einsteinium [Rn]5f ¹¹ 7s ²	100 Fm Fermium [Rn]5f ¹² 7s ²	101 Md Mendelevium [Rn]5f ¹³ 7s ²	102 No Nobelium [Rn]5f ¹⁴ 7s ²	103 Lr Lawrencium [Rn]5f ¹⁴ 6d ¹ 7s ²

Dipole allowed, alkali



(a)

Li



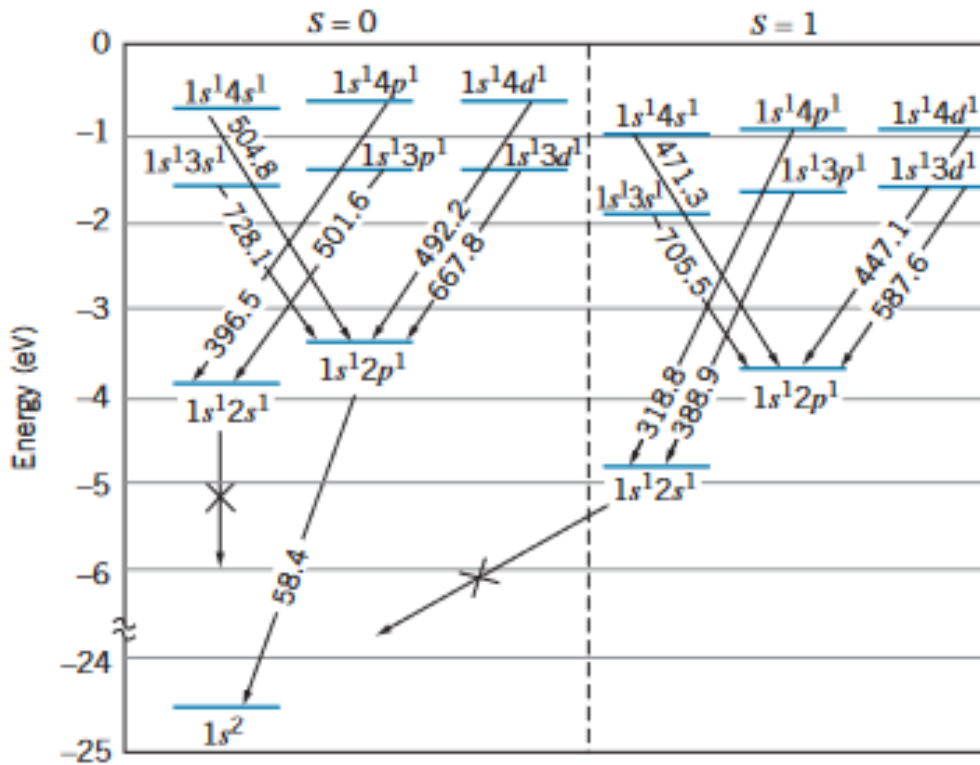
(b)

Na

Quadrupole transitions allowed (but slower)

Li: 3d can go directly to 2s with 1 photon

Dipole allowed, He

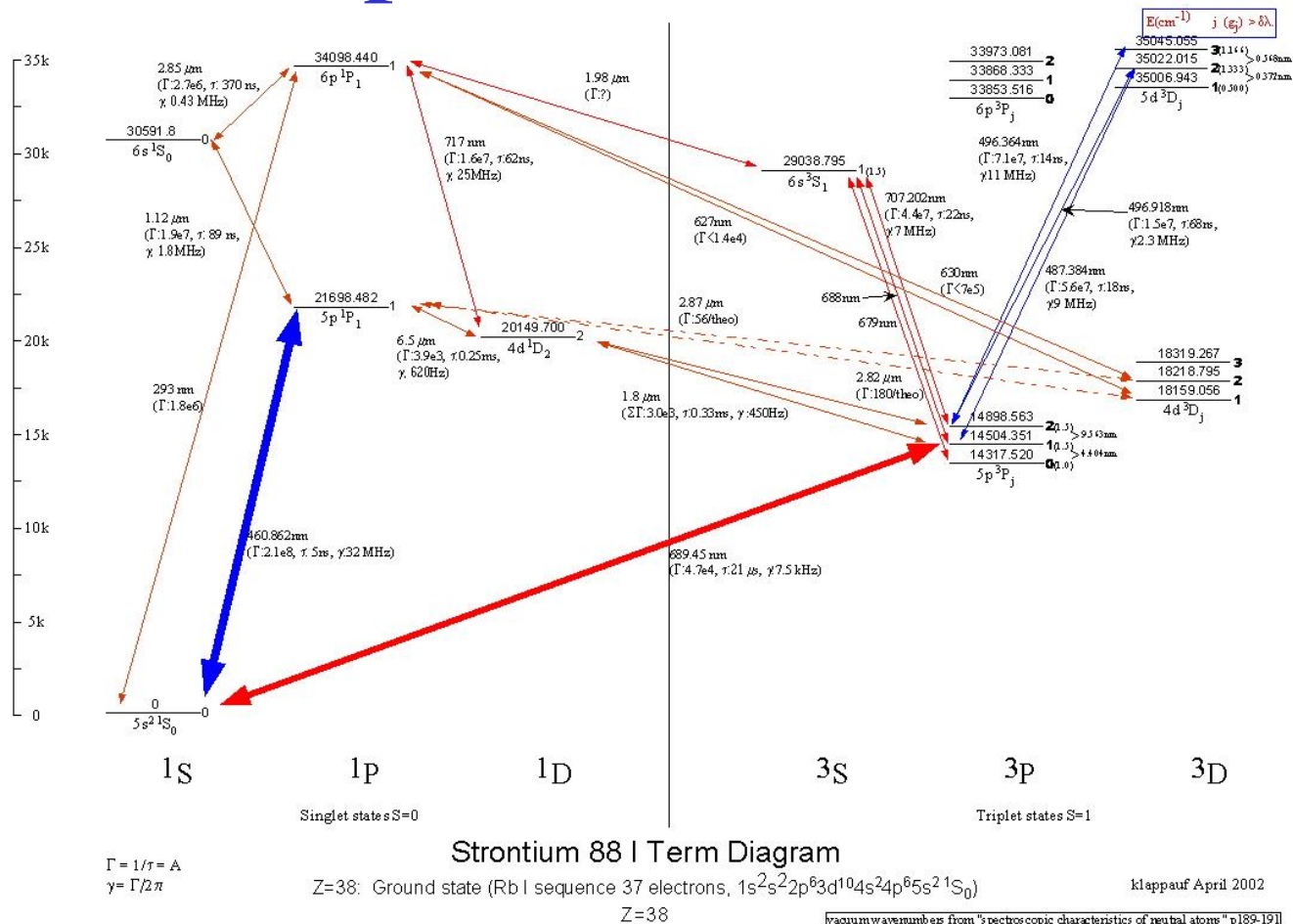


The $1s2s$ states are “metastable”. They go to the ground state by emitting 2 photons. The $S=1$ $1s2s$ state has a much longer lifetime because the ground state has $S=0$

In plasma, a lot of population can get trapped in the $1s2s$ states.

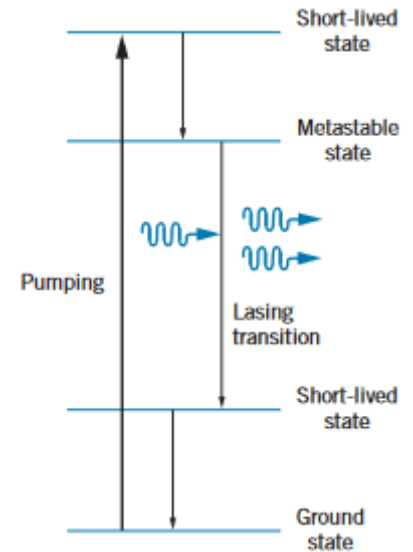
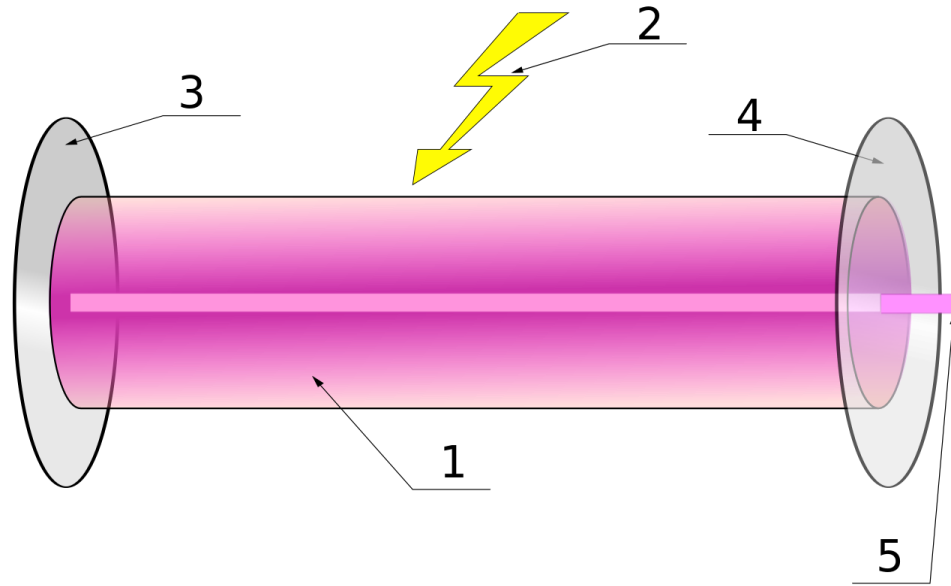
$1s3d \rightarrow$ ground state is allowed but slow

Dipole allowed, Sr



Sr is used in some of the most accurate atomic clocks. The 5s5p S=1 state with J=0 **cannot** emit a photon unless the Sr isotope has nuclear spin (lifetime 1000's of seconds).

Laser Basic

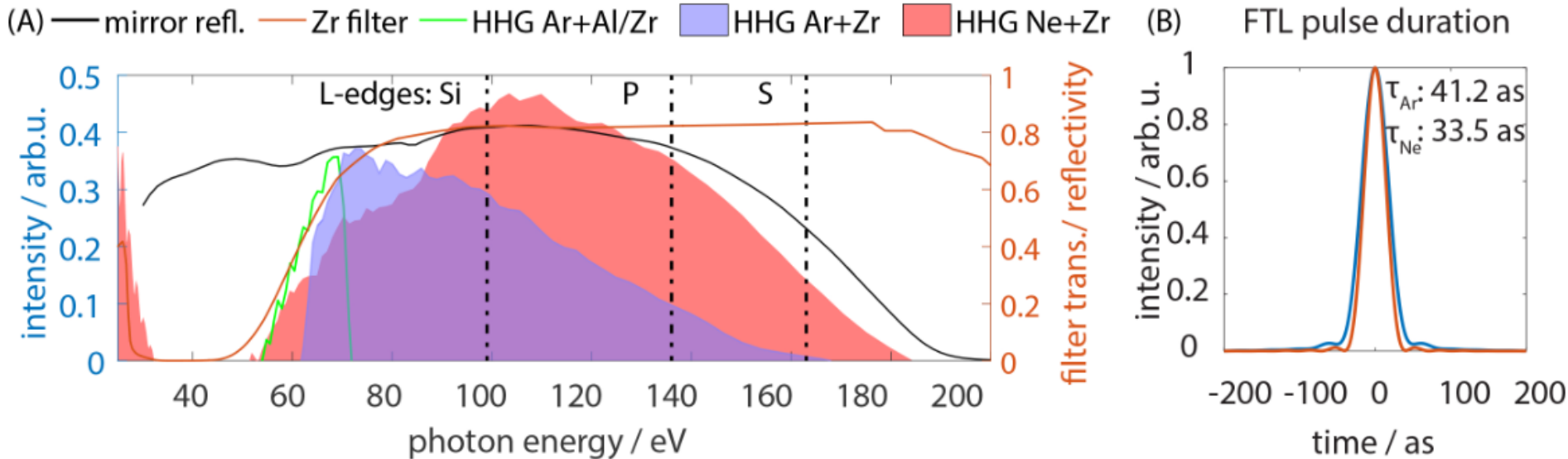


Light builds up between the mirrors leading to more stimulated light.

Coherent light with small frequency uncertainty

- 1=Gain medium
- 2=Pump energy in
- 3=Reflector
- 4=Reflector/output coupler
- 5=Laser beam

Shortest Laser Pulse



Many claims of shortest laser pulse (faster & faster)

Example of 43 attosec pulse

Why big photon energy range???

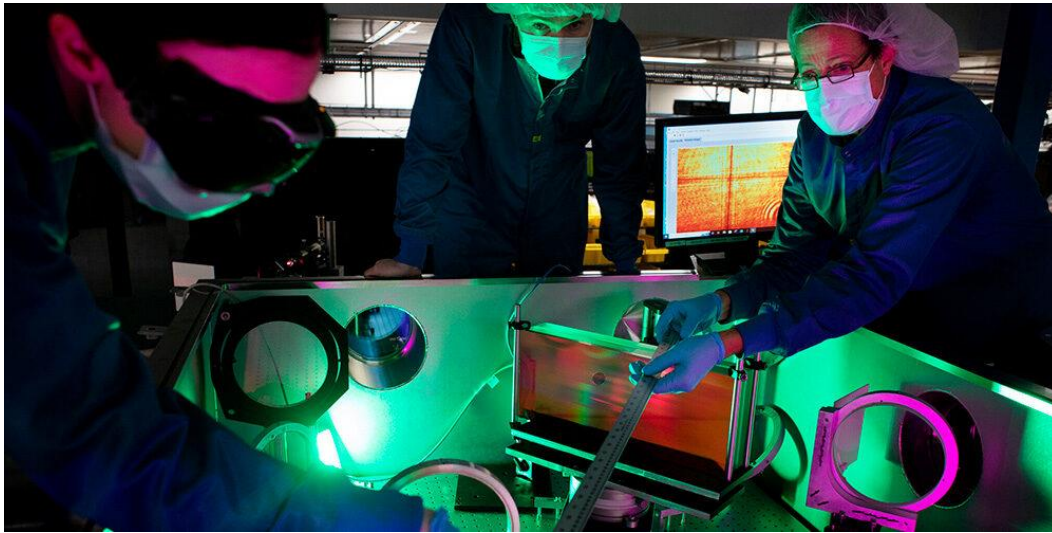
<https://ethz.ch/en/news-and-events/eth-news/news/2017/10/worlds-shortest-laser-pulse.html>

<https://opg.optica.org/oe/fulltext.cfm?uri=oe-25-22-27506&id=375881>

Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver

Thomas Gaumnitz, Arohi Jain, Yoann Pertot, Martin Huppert, Inga Jordan, Fernando Ardana-Lamas, and Hans Jakob Wörner

Strongest Laser Pulse



Many claims of strongest laser pulse (stronger & stronger)

Example of 500 Terrawatts w/ max power 3 PetaW

Many different metrics for strongest

Highest intensity 10^{23} W/cm²

<https://www.sciencedaily.com/releases/2021/05/210506105445.htm>

<https://michigantoday.umich.edu/2022/09/23/first-light-at-the-most-powerful-laser-in-the-u-s-2/>

<https://www.sciencealert.com/scientists-are-about-to-fire-up-the-most-powerful-laser-in-the-us>

<https://www.nobelprize.org/prizes/physics/2018/summary/>