Combining laser light with synchrotron radiation

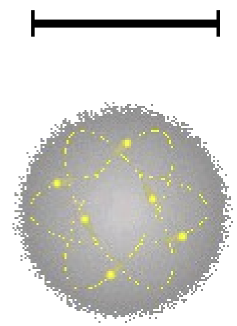
Part 5

Optical pumping

Interaction of Atoms with visible Light

Green light wavelength 5000Å

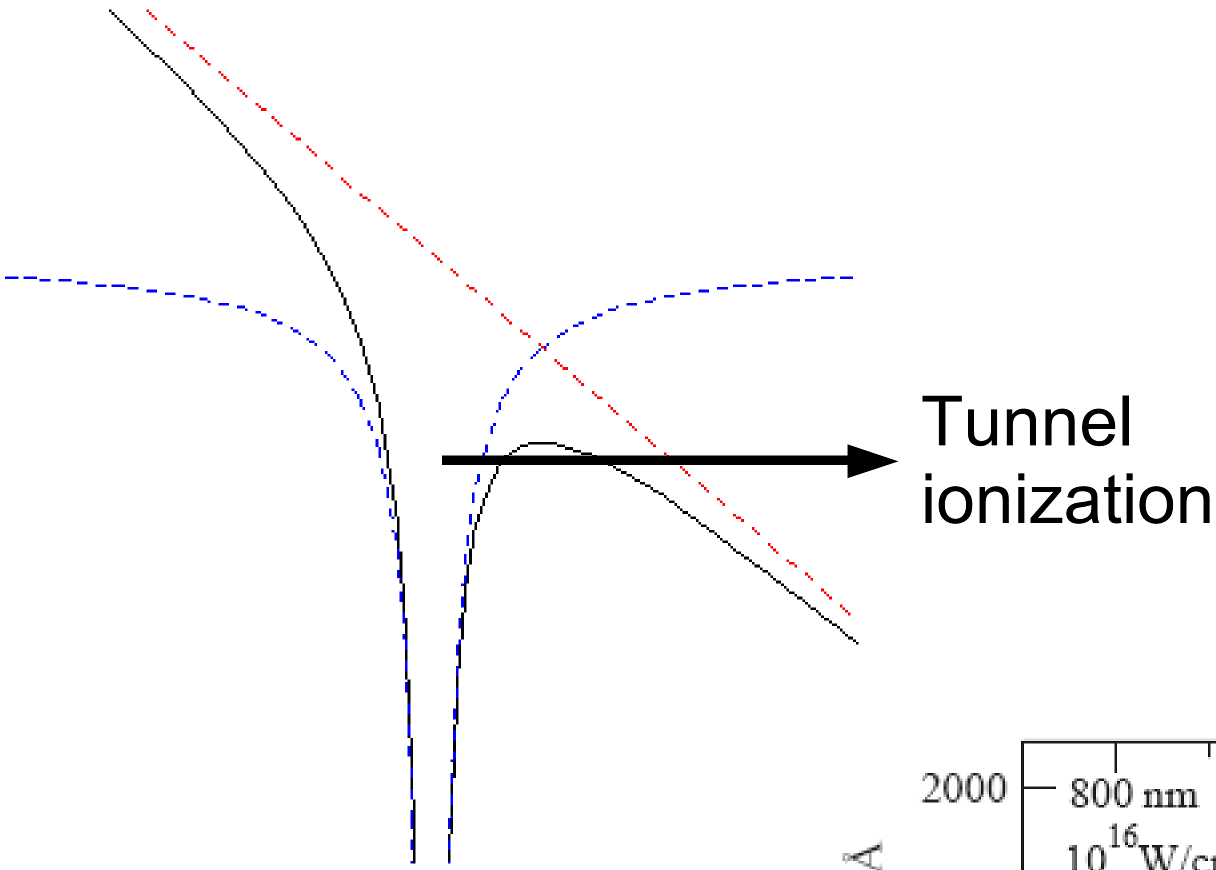
~1Å

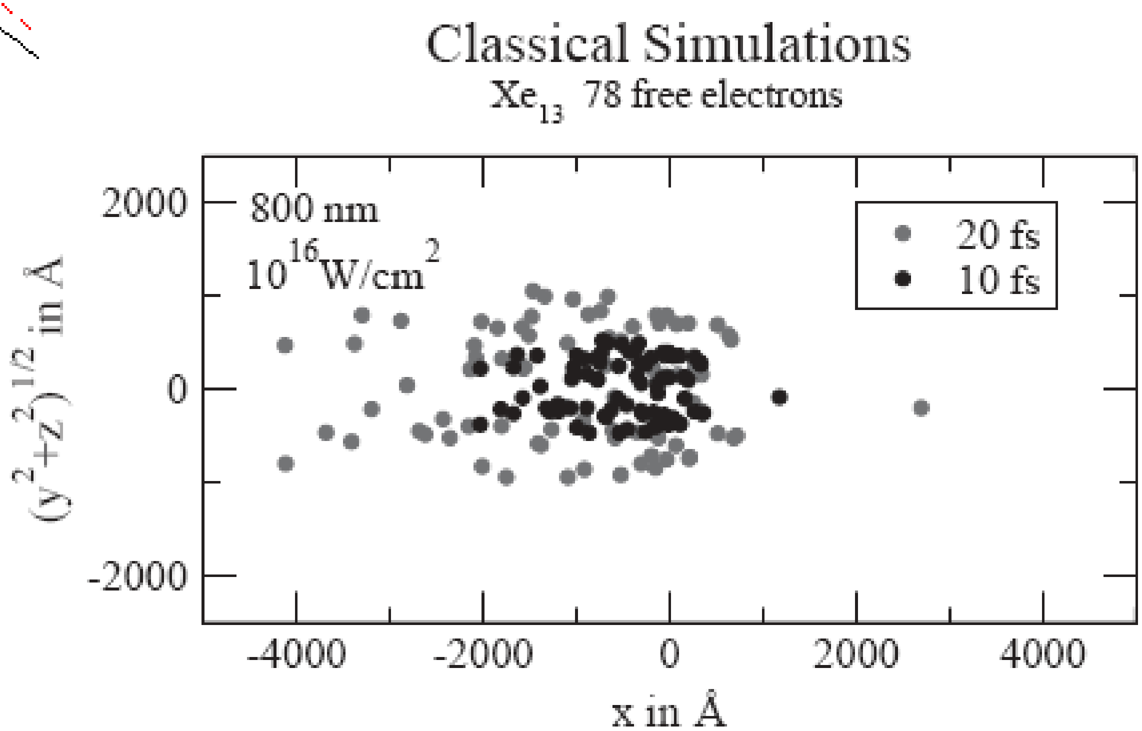


The wavelength is much larger then the atom

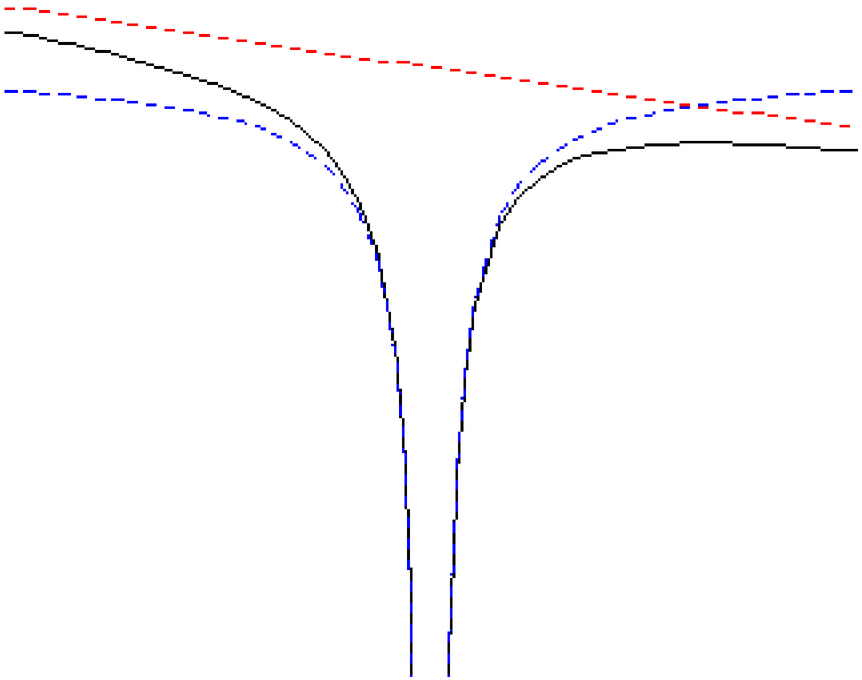
The light electric field is weak with respect to the coulomb force

Strong electric field





Weak electric field



The light field is only a weak perturbation of the coulomb field

Perturbation theory → Part 1 of this lecture

Oscillator Model

Hooke's Law:

If a material body is slightly deformed,
the restoring force is linear to the deformation.

If the electron shell of an atom is slightly deformed,
the restoring force is linear to the deformation.

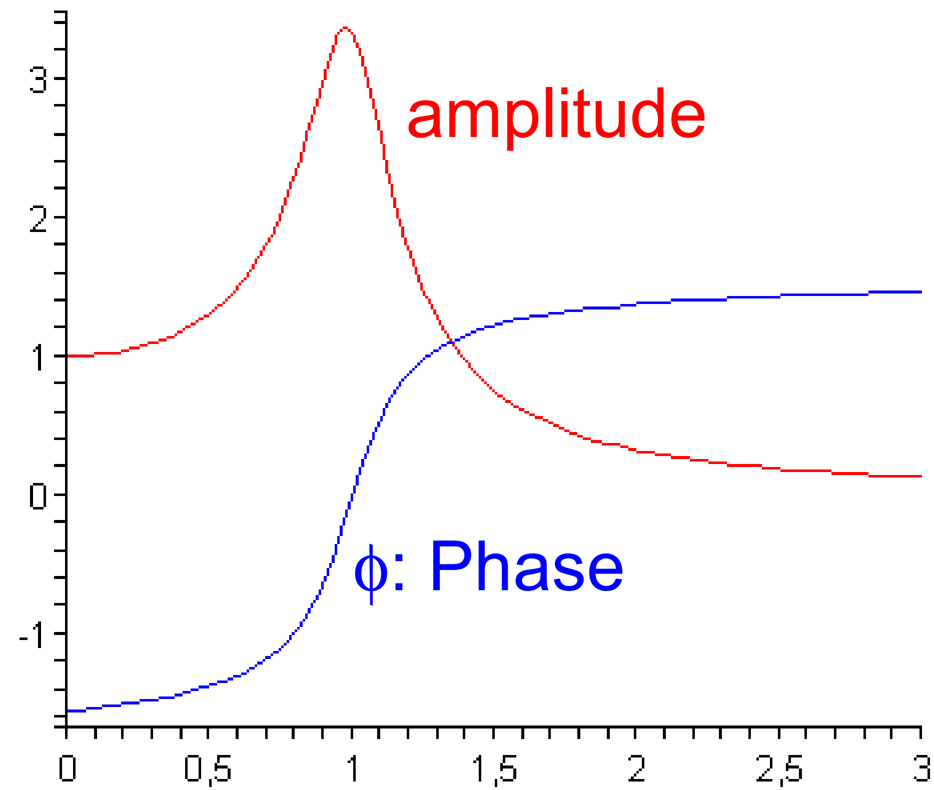
A linear restoring force leads to harmonic oscillations.

Driven harmonic oscillator

$$m\frac{d^2x}{dt^2}+r\frac{dx}{dt}+kx=F_0\cos(\omega t)$$

$$x(t)=\frac{F_0}{\omega\sqrt{r^2+(\omega m-k/\omega)^2}}\sin(\omega t-\phi)$$

$$\phi=\arctan\left(\frac{\omega m-k/\omega}{r}\right)$$



Atomic wave functions

Two energy eigenstates of an atomic system:

$$\Psi_1(\vec{r},t) = u_1(\vec{r})\exp\left[-i(E_1/\hbar)t\right]$$

$$\Psi_2(\vec{r},t) = u_2(\vec{r})\exp\left[-i(E_2/\hbar)t\right]$$

Superposition of eigenstates is a solution of the time dependent Schrödinger-equation:

$$\Psi = a_1\Psi_1 + a_2\Psi_2$$

with $|a_1|^2 + |a_2|^2 = 1$

Atomic Susceptibility

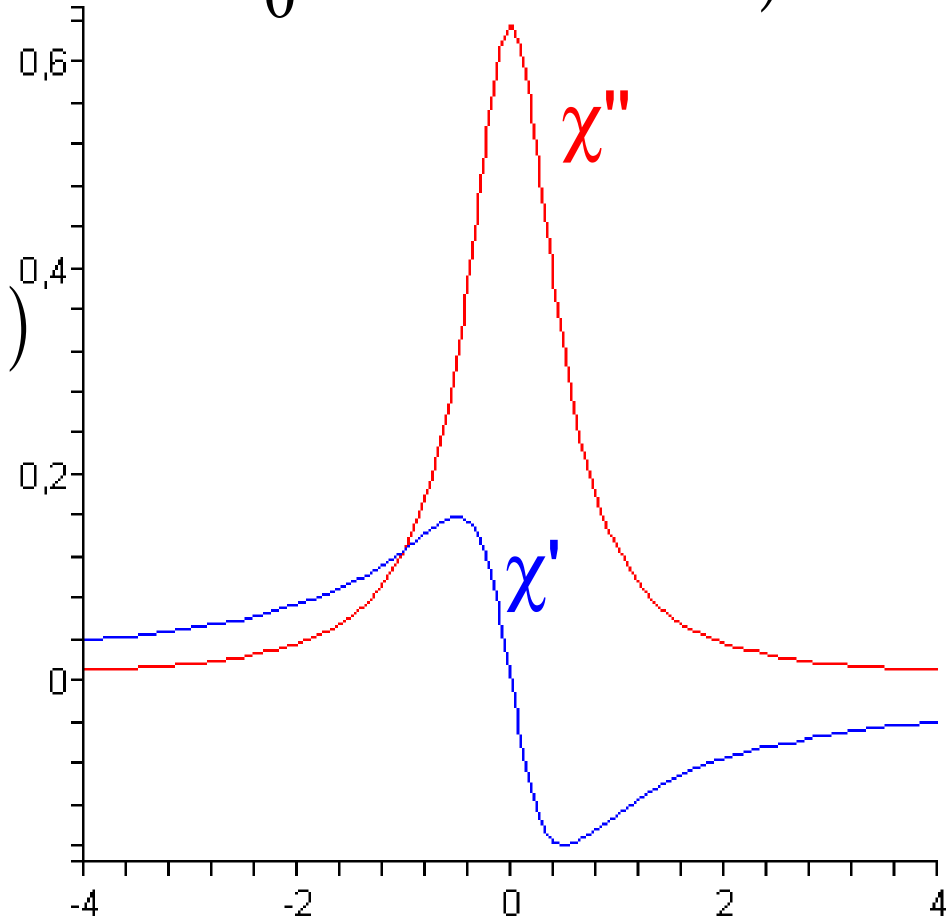
$$\vec{E}(t)=\vec{E}_0\cos\omega t$$

$$\vec{P}(t)=\vec{E}_0(\epsilon_0\chi'\cos\omega t+\epsilon_0\chi''\sin\omega t)$$

$$\chi''(\nu)\propto\Delta N g(\nu)$$

$$\chi'(\nu)\propto\Delta N(\nu_0-\nu)g(\nu)$$

$$g(\nu)=\frac{\Delta\nu/2\pi}{(\nu-\nu_0)^2+\left(\frac{\Delta\nu}{2}\right)^2}$$



$\nu-\nu_0$

In phase response

$$\chi'(\nu) \propto \Delta N (\nu_0 - \nu) g(\nu)$$

$$\epsilon = (1 + \chi')\epsilon_0$$

Dispersive signal.

Influences the speed of light far from the resonance

No energy transfer

Out of phase response

$$\chi''(\nu) \propto \Delta N g(\nu)$$

Absorption signal

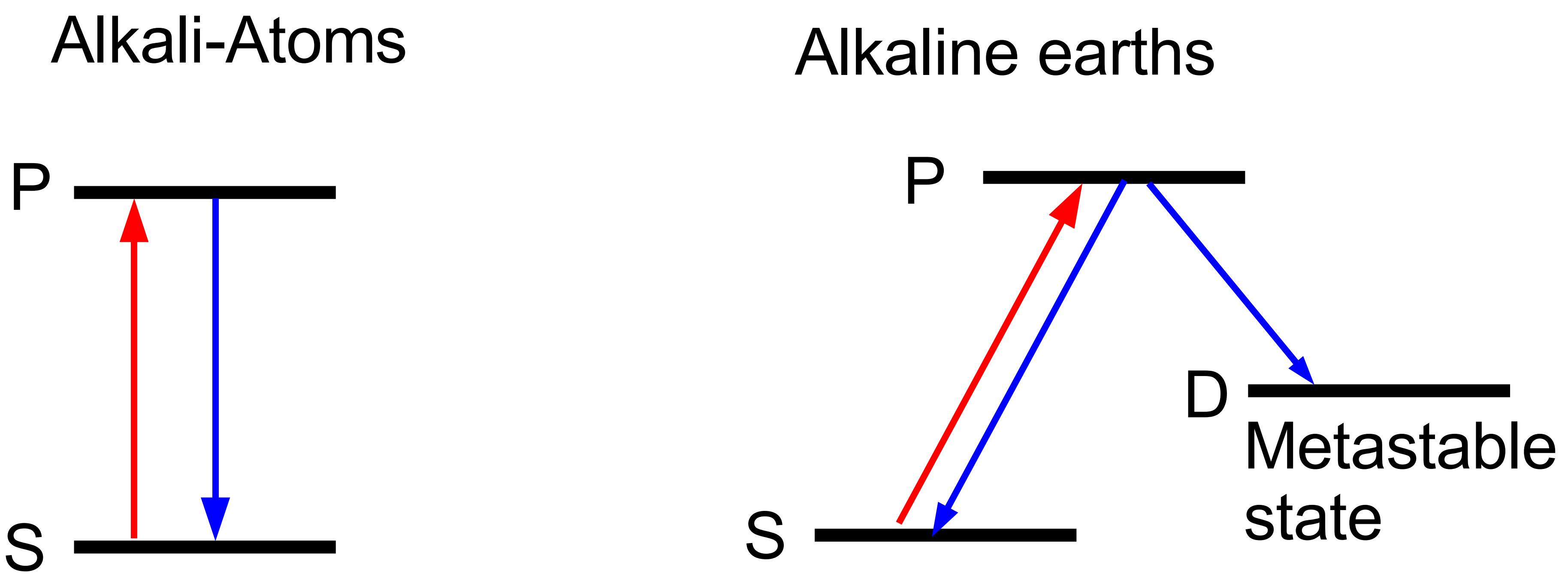
Lorentzian line shape

Proportional to transition probability

Both signals saturate if $\Delta N \rightarrow 0$

Optical pumping

Excitation of atoms into different states

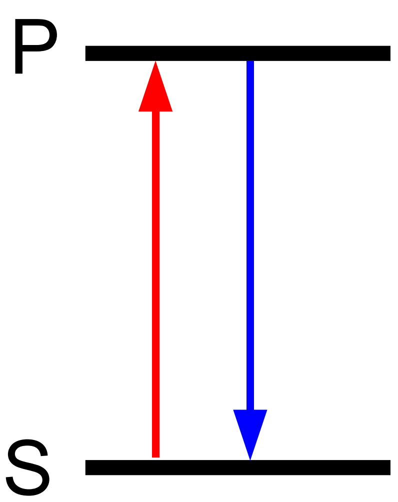


Two level system

Λ-Type three level system

Two Level Systems
Alkali Metals

Two fine structure levels in the upper state,
but no allowed transition between them.



Na: $3s \rightarrow 3p_{3/2}$: 589.0 nm, $A=6.2\ 10^7\ s^{-1}$
$3s \rightarrow 3p_{1/2}$: 589.6 nm, $A=6.1\ 10^7\ s^{-1}$

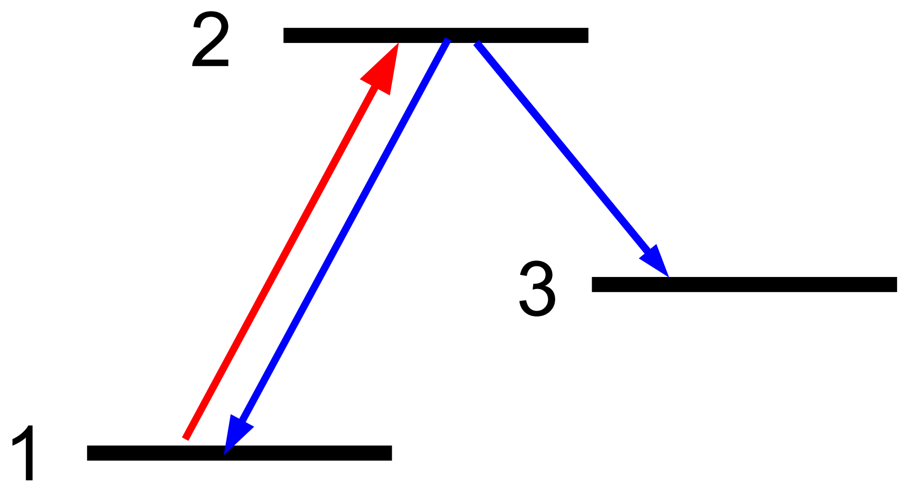
K: $4s \rightarrow 4p_{3/2}$: 766.5 nm, $A=3.8\ 10^7\ s^{-1}$
$4s \rightarrow 4p_{1/2}$: 769.9 nm, $A=3.7\ 10^7\ s^{-1}$

Rb: $5s \rightarrow 5p_{3/2}$: 780.0 nm, $A=3.7\ 10^7\ s^{-1}$
$5s \rightarrow 5p_{1/2}$: 794.8 nm, $A=3.4\ 10^7\ s^{-1}$

Cs: $6s \rightarrow 6p_{3/2}$: 852.1 nm, $A=3.3\ 10^7\ s^{-1}$
$6s \rightarrow 6p_{1/2}$: 894.3 nm, $A=2.9\ 10^7\ s^{-1}$

Web-source: http://physics.nist.gov/PhysRefData/Handbook/index.html

Λ-Type Three level System

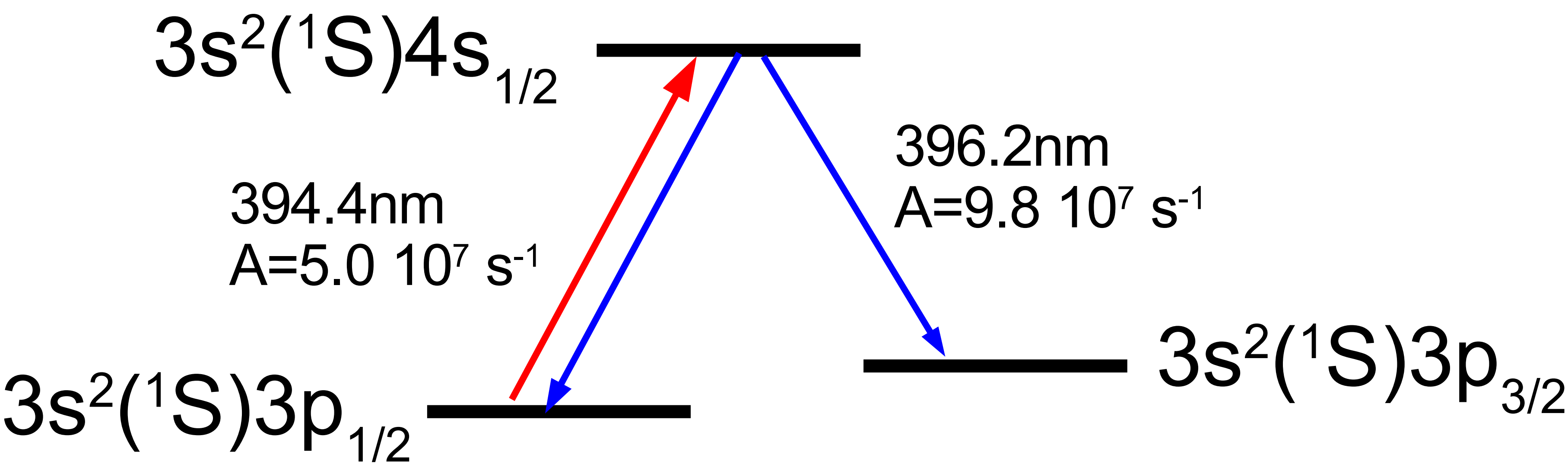


$$\frac{dN_3}{dt} = N_2 A_{23}$$

$$\frac{dN_2}{dt} = +(N_1 - N_2) B_{12} \rho \quad -N_2 A_{21} \quad -N_2 A_{23}$$

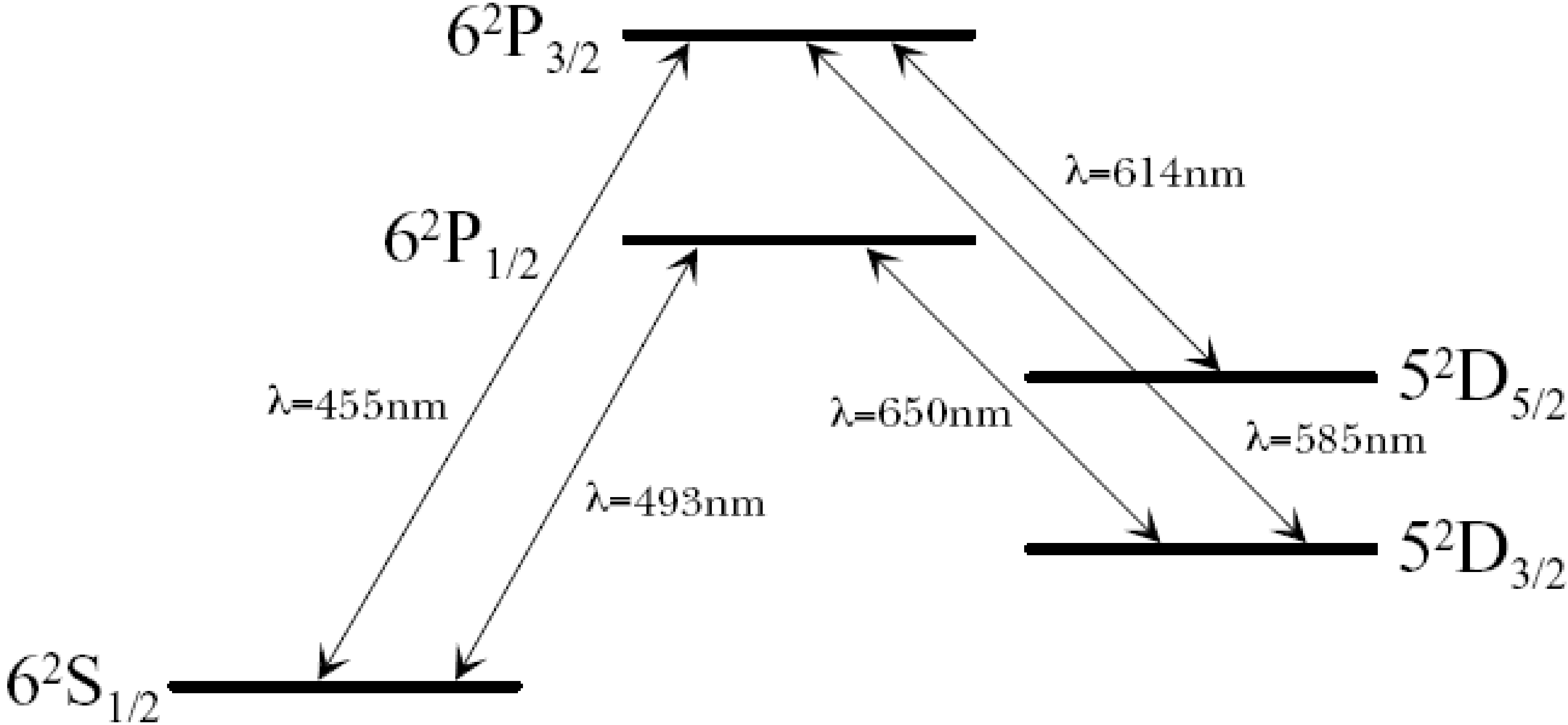
$$\frac{dN_1}{dt} = -(N_1 - N_2) B_{12} \rho \quad +N_2 A_{21}$$

Λ-Type Three level Systems
Aluminum

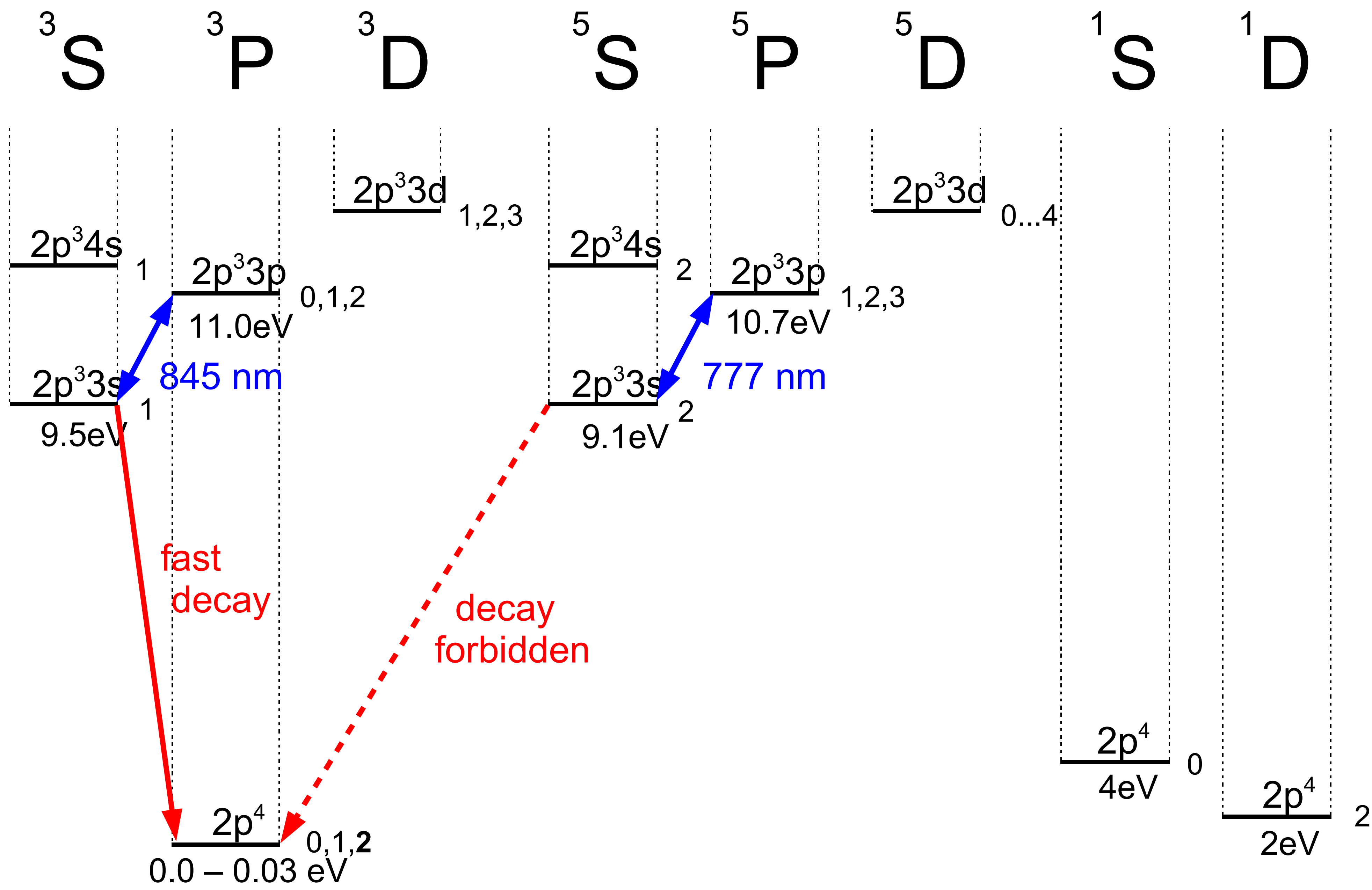


Similar systems: Ga, In

Λ-Type Three level Systems
Barium Ion

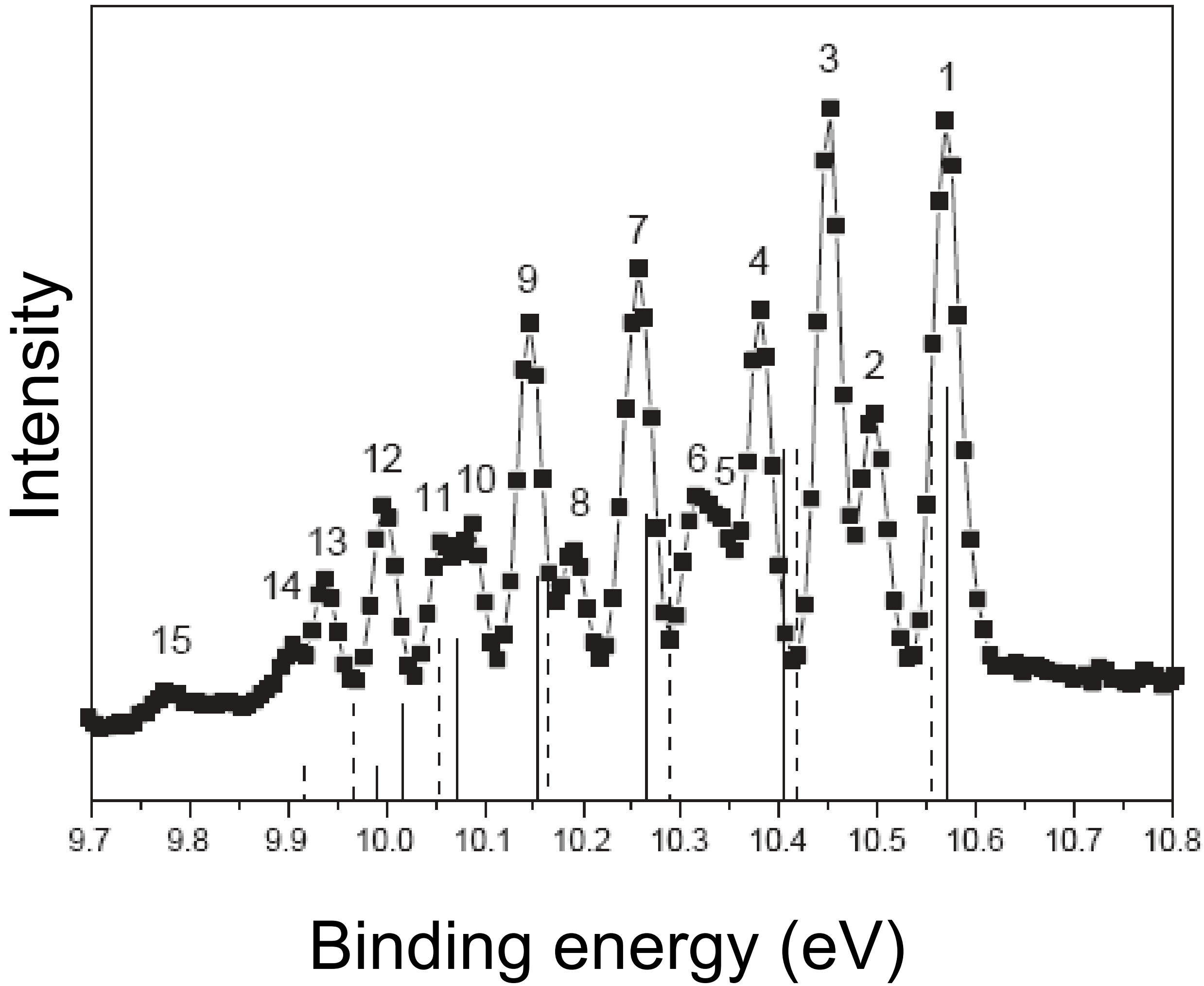


Oxigen Term Scheme



Fine Structure

With 3rd generation synchrotron sources the fine structure of photoelectron emission can be studied in great detail.



Eu 4f photoemission

Ground state:

$4f^7 6s^2\ {}^8S_{7/2}$

Final states:

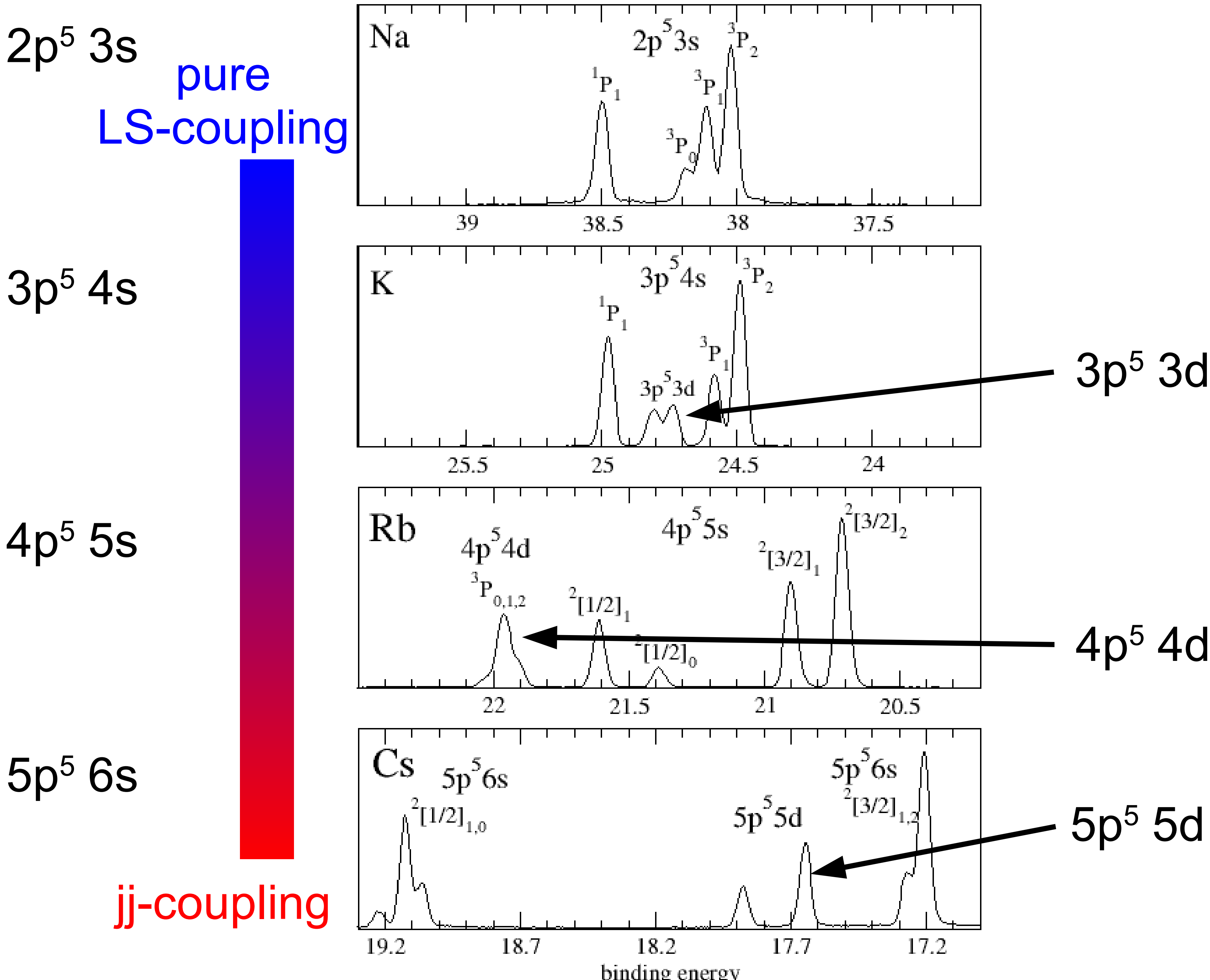
$4f^6\ 6s^2\ {}^7F_{0..6}$

$4f^6\ 5d6s\ {}^9P_{3..5}$

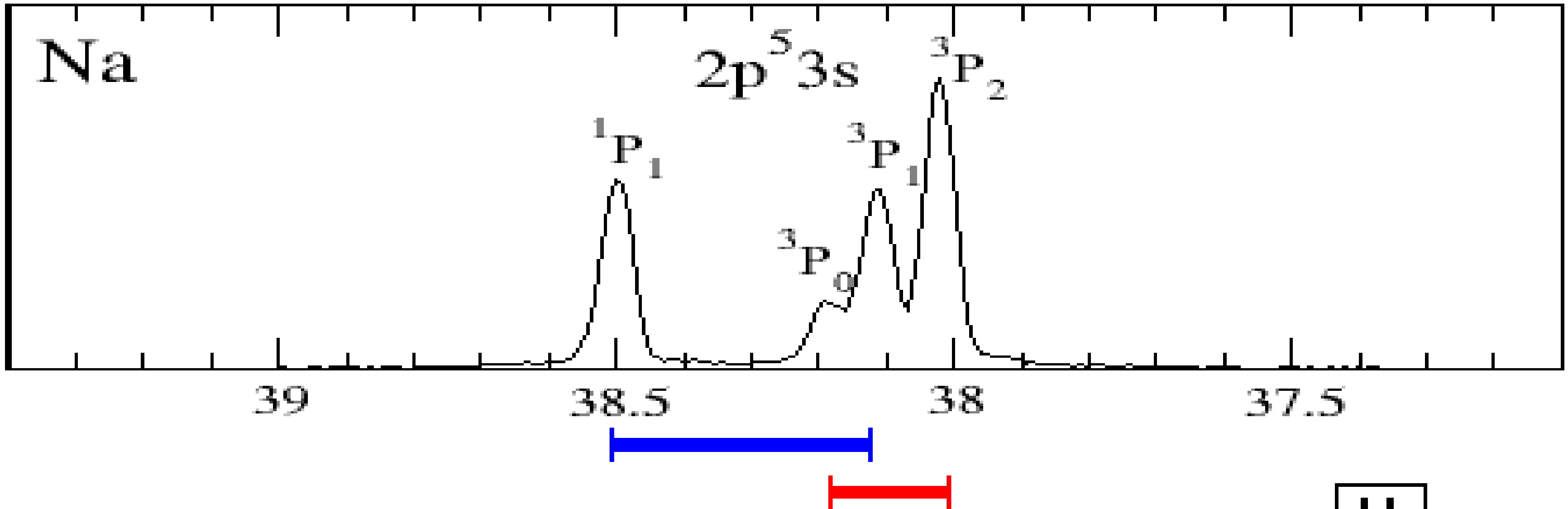
$4f^6\ 5d^2\ {}^{7,9}P_{2..5}$

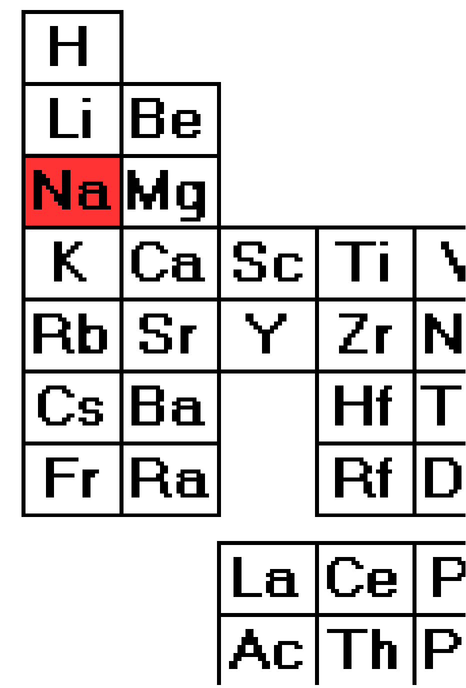
...and unclassified lines

The fine structure of alkali metals



Na: LS coupling





Couple a 2p hole to a 3s electron:

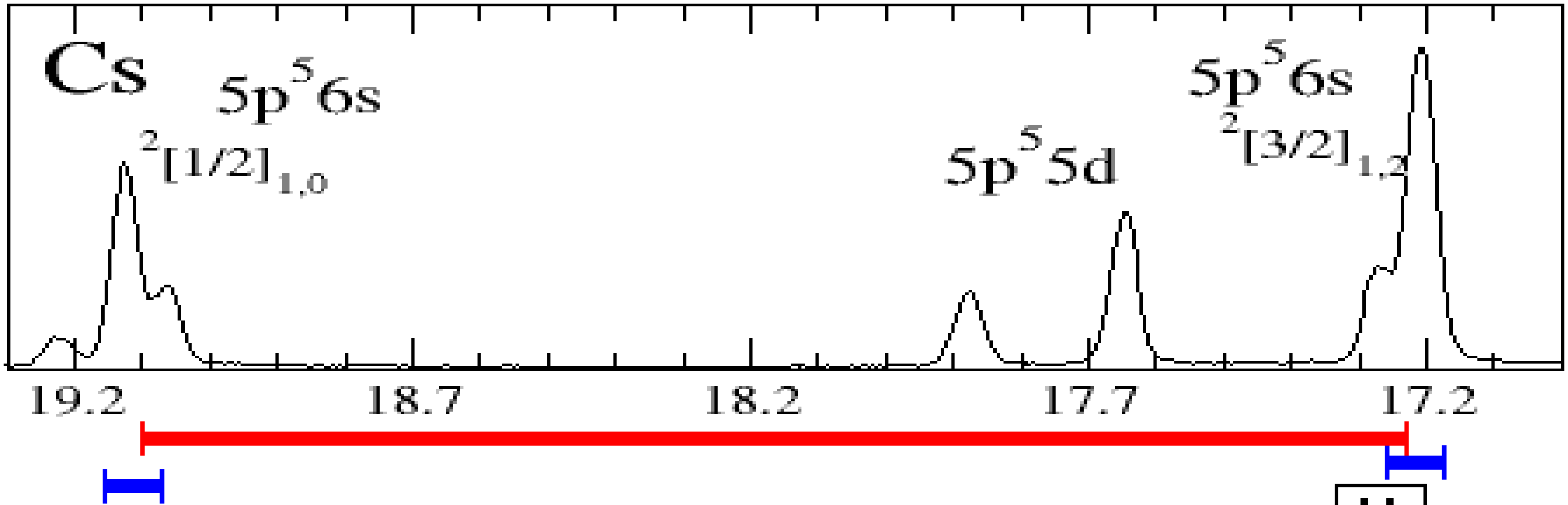
Coupling of two spin ½ leads to 0 and 1

$^1P \leftrightarrow {}^3P$: Coulomb exchange splitting

Coupling of the spin to orbit P=1 gives

J=0,1,2: relativistic Spin-Orbit splitting

Cs: jj coupling



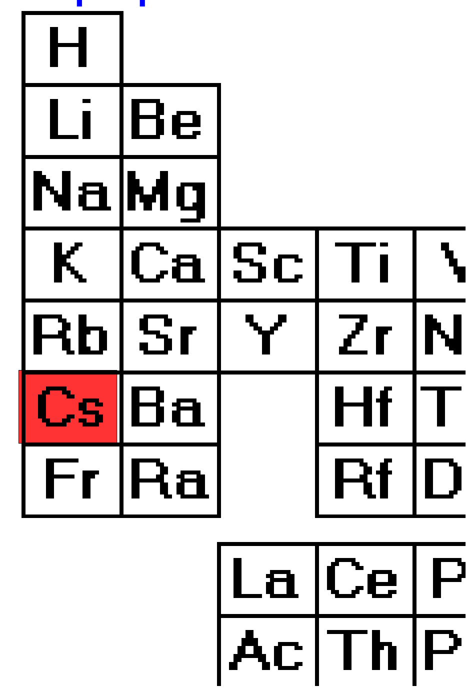
Couple a 2p hole to a 3s electron:

Coupling of the 2p spin to it's orbit gives

j=1/2,3/2: relativistic Spin-Orbit splitting

Coupling to the spin of the 6s electron

$^2[3/2]_1 \leftrightarrow {}^2[3/2]_2$



Orientation and Alignment

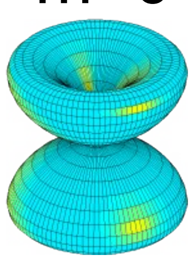
Every fine structure state with l>0 splits up into magnetic substates

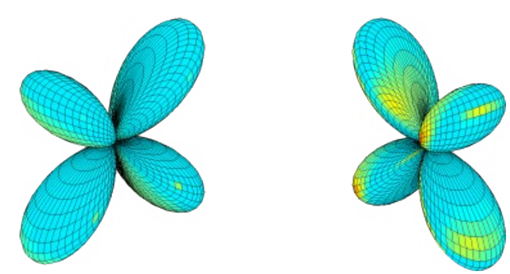
Magnetic quantum number

d-Orbitals

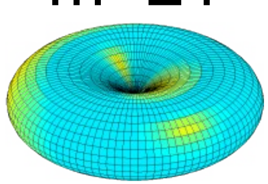
Direction in space (alignment)

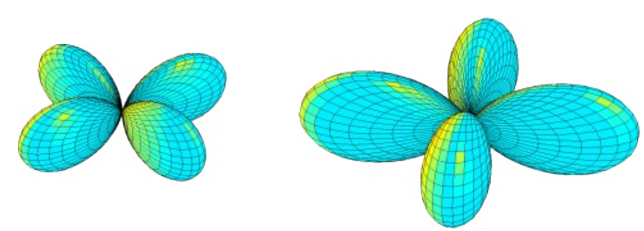
m=0





m=±1

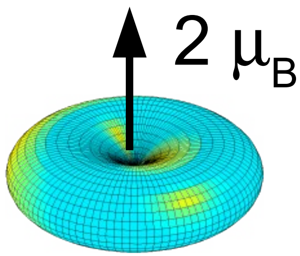




m=±2

Orientation

The magnetic moments of the atoms show in a defined direction

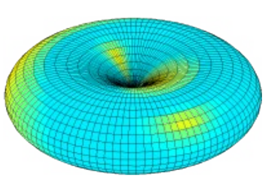


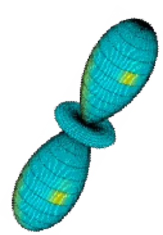
Pumped with circularly polarized light

m=2

Alinment

No magnetic field, but an axis in space is preferred or avoided



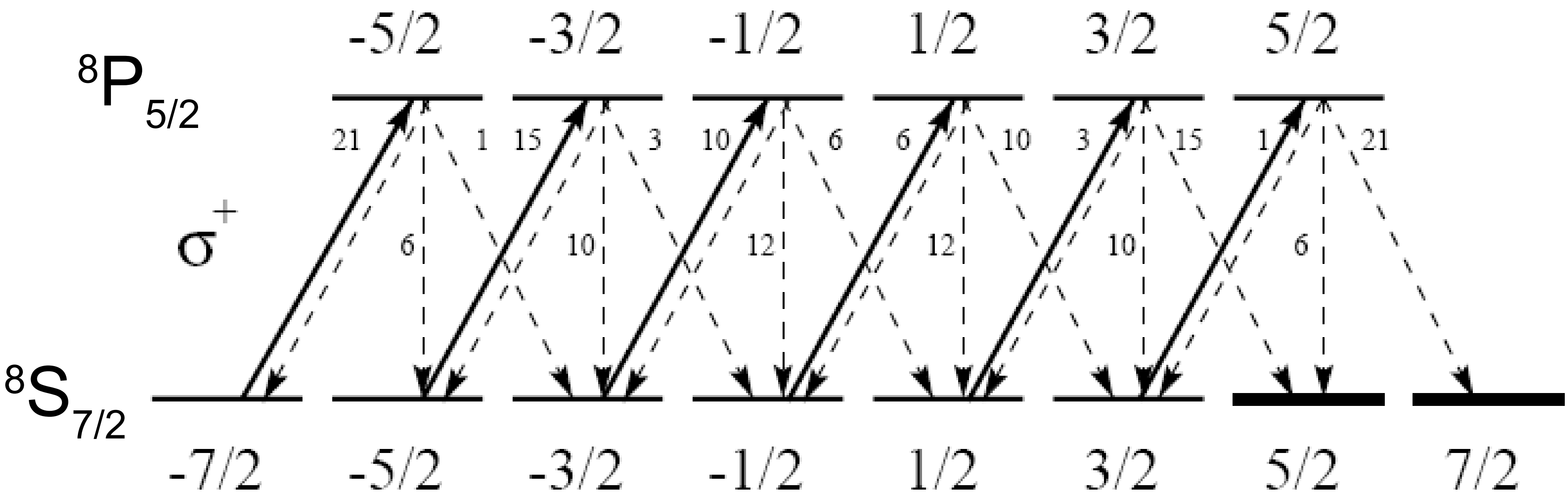


Pumped with linearly polarized light

m=2 & m= -2

Pumping into Orientation

Example: Europium $6s^2 \rightarrow 6s6p$



All atoms are pumped into the m_J=5/2,7/2 states

The final states are **spin** polarized

Multipole moments

Normalized dipole moment (orientation)

$$A_{10} = K_1(J) \sum_{m_J} m_J N_{J m_J}$$

Normalized quadrupole moment (alignment)

$$A_{20} = K_2(J) \sum_{m_J} \left(J(J+1) - 3\mathrm{m}_J^2 \right) N_{J m_J}$$

with:

Normalization constants: K_1, K_2,..

Occupation numbers: N_{Jm}

General definition of Multipole moments

$$\rho_{k_0 q_0}(J) = \sum_{m_J, m'_j} (-1)^{J - m'_J} (J\, m_J, J - m'_J | k_0\, q_0) \langle J\, m'_J | \rho | J\, m_J \rangle$$

$$\rho_{00}(J) = \frac{1}{\sqrt{2J+1}} \sum_{m_J} \langle J\, m_J | \rho | J\, m_J \rangle$$

$$A_{k_0 0}(J) = \frac{\rho_{k_0 0}}{\rho_{0\,0}}$$