An Introduction to AMO Physics

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What is AMO?

= Atomic, molecular, and optical physics

Linked because share basic approach:
- Study “simple” quantum systems with high precision
- Learn to control systems for applications
- Central tool: laser

Purpose of Talk

Introduce key background ideas of AMO
Helpful for subsequent talks

Aimed at new students
Outline

I. Atoms and molecules
   Hierarchy of structures, notation

II. Driving transitions
   Transition rate, saturation, coherent evolution

III. Lasers
   Basic theory, types of laser

IV. Frequency conversion
   Nonlinear response, phase matching

V. AMO at UVA
   Groups, courses
Atoms

Simplest atom: hydrogen

Energy levels have hierarchy

Highest level: Coulombic

\[ E_n = -\frac{mc^2}{2n^2} \alpha^2 \]

fine structure constant \( \alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{137} \)

Often write \( E_n = -\frac{1}{2n^2} \) using \textit{atomic units}

unit of energy = \( mc^2\alpha^2 \) = Hartree = 27.2 eV

Label states with \( n, l \): 3d state has \( n = 3, l = 2 \)
Fine structure

Spin orbit coupling correlates $L$ and $S$
Use $J = L + S$

Relativistic effects shift energy levels
Fractional shift $\sim (Z\alpha)^2$ for atomic number $Z$

More important for heavier atoms

Energy levels split by $J$

3d $\Rightarrow$  
(10 states)  

J = 5/2  (6 states)  
J = 3/2  (4 states)

Notation: $n^{2S+1}L_J$

So “3 $^2D_{3/2}$” means $n = 3$, $S = \frac{1}{2}$, $L = 2$, $J = 3/2$
Hyperfine structure

Electronic angular momentum \( J \) coupled to nuclear angular momentum \( I \) via magnetic moments

\[ \Rightarrow \text{Total momentum } F = I+J \]

Hydrogen has \( I = \frac{1}{2} \):

\[ 3 \ ^2D_{3/2} \quad \Rightarrow \quad F = 2 \]

\[ 3 \ ^2D_{3/2} \quad \Rightarrow \quad F = 1 \]

Energy scale \( \approx \frac{\text{nuclear moment}}{\text{electron moment}} \times \text{FS scale} \)

Typically about \( 10^{-3} \)
Other atoms

Alkali atoms (Li, Na, K, Rb, Cs) have one valence electron + core electrons. Act like H, but levels shifted due to core.

**Rb:**

- $6 S_{1/2}$: $-13500 \text{ cm}^{-1}$
- $4 D_{3/2}$: $-14300 \text{ cm}^{-1}$
- $4 D_{5/2}$: $-20800 \text{ cm}^{-1}$
- $5 P_{3/2}$: $-21000 \text{ cm}^{-1}$
- $5 P_{1/2}$: $-33600 \text{ cm}^{-1}$

Units $\text{cm}^{-1}$ = wave numbers. $1 \text{ eV} = 8050 \text{ cm}^{-1}$ = inverse of corresponding wavelength.
Multielectron Atoms

More than one valence electron = more complex
Multiple $s_i$’s and $\ell_i$’s, couple in different ways

Typically

$$L = \sum \ell_i, \quad S = \sum s_i, \quad J = L + S$$

Label state with $L$, $S$ and $J$:

Calcium:

$^1S_0$ (4s5s) \quad 33300 cm$^{-1}$

31500 \quad $^3S_0$ (4s5s)

23700 \quad $^1P_1$ (4s4p)

21900 \quad $^1D_2$ (4s3d)

300 nm \quad 422 nm \quad 653 nm

20300 \quad $^3D_{1,2,3}$ (4s3d)

15300 \quad $^3P_{0,1,2}$ (4s4p)
Molecules

Put two atoms together, even more fun!
Interact via molecular potential \( V(R) \)
\[ = \text{energy as function of nuclear separation} ~ R \]

Born-Oppenheimer approximation:
- Fix nuclei at spacing \( R \)
- Find electronic energies \( E_n(R) \)
- Use \( E_n(R) \) as potential for nuclear motion

Usually valid \( (m_e << m_N) \)

At large \( R \), \( E_n(R) \rightarrow E_{n1} + E_{n2} \) atomic energies
lots of quantum numbers!
Alkali diatom ground state potential:

Nuclei move in $V(r)$: have own eigenstates and energies vibrational and rotational quantum numbers
Transitions

What do we do with atoms and molecules? Typically, drive transitions using perturbation

\[ H' = \hat{V} \cos \omega t \]

Basic result: Fermi’s Golden Rule:

\[ R_{i \rightarrow f} = \frac{2\pi}{\hbar} \left| \langle f \mid \hat{V} \mid i \rangle \right|^2 \delta(\hbar \omega - \Delta E) \]

where \( |i\rangle = \text{initial state} \)
\( |f\rangle = \text{final state} \)
\( \Delta E = |E_f - E_i| \)
In real life, delta function $\rightarrow$ peak with finite line width $\hbar\Gamma$

Various reasons:

- Finite lifetime $\tau$: $\Gamma \approx \tau^{-1}$
- Thermal atoms at temperature $T$: $\Gamma \approx \omega \sqrt{\frac{k_B T}{mc^2}}$
  (Doppler broadening)
- Collision rate $t_c$: $\Gamma \approx t_c^{-1}$
- Finite duration of drive pulse $t_p$: $\Gamma \approx t_p^{-1}$
On resonance $\hbar \omega = \Delta E$, 

$$\delta(\hbar \omega - \Delta E) \rightarrow \frac{1}{\hbar \Gamma}$$

and

$$R = \frac{2\pi}{\Gamma} \frac{|V_{if}|^2}{\hbar^2}$$

Typically $V = \text{interaction with laser}$

Strongest interaction: dipole coupling $V = e \mathbf{E} \cdot \mathbf{r}$
Dipole coupling

Only couples certain states: selection rules

$$\Delta F, \Delta m_F = 0, \pm 1 \text{ (photon has } \ell = 1)$$
$$\Delta S = 0 \text{ (no coupling to spin)}$$
$$\Delta L = \pm 1 \text{ (require opposite parity)}$$

Can violate with higher order interactions
(magnetic dipole, electric quadrupole)
or higher order perturbations (two–photon transition)
Saturation

Easy to see that $R_{i\rightarrow f} = R_{f\rightarrow i}$

Transition goes both ways

This limits population transfer

Simple model: $N_1 + N_2 = N$

$$\frac{dN_2}{dt} = +RN_1 - RN_2 - \frac{N_1}{\tau}$$

In steady state, get $N_2 = N \frac{R\tau}{2R\tau + 1}$

Population saturates
Coherent Excitation

If $R_{i \rightarrow f} \geq \Gamma$ and drive field is $\approx$ monochromatic, Fermi’s golden rule is inadequate

Need full solution to Schrodinger Eqn

Solution simple if just two levels coupled and if

$$\Omega \equiv \frac{V_{if}}{\hbar} \omega_0 \quad |\Delta| \equiv |\omega - \omega_0| \quad \omega_0$$

with $\omega_0 \equiv \frac{E_f - E_i}{\hbar}$

$\Omega$ called Rabi frequency

$\Delta$ called detuning

Get Rabi oscillation:

$$P_2 = \frac{\Omega^2}{\Omega^2 + \Delta^2} \sin \left( \frac{\sqrt{\Omega^2 + \Delta^2}}{2} t \right)$$
Rabi Oscillation

If \( \Delta = 0 \), get perfect transfer at \( t = \frac{\pi}{\Omega} \)
called “\( \pi \)-pulse”

Make superposition \( |\psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \) at \( t = \frac{\pi}{2\Omega} \)
called “\( \pi/2 \)-pulse”

Oscillation damps on time scale \( \Gamma^{-1} \)
Approaches steady state value from saturation
Lasers

So what do we drive these transitions with?
  Sometimes microwaves
  More often lasers

Lasers are basic tool for much modern physics
  Nearly all AMO physics

Involves three ingredients:
  - Gain medium
  - Pumping mechanism
  - Mirrors
Gain medium = collection of atoms, molecules, etc with well a defined transition

\[ |2\rangle \quad \stackrel{\omega_0}{\longrightarrow} \quad |1\rangle \]

Relatively narrow linewidth, long excited state life time

Pumping = energy source driving atoms to upper state

Need inversion: \( N_2 > N_1 \)

Easiest to achieve in “four level” system
As long as $N_2 > N_1$, light at $\omega$ drives $2 \rightarrow 1$ more than $1 \rightarrow 2$
Number of photons increases: gain!

Mirrors: light at $\omega$ passes through medium many times builds up to high intensity

Eventually saturates transition: gain $\rightarrow 0$
laser has steady state output
Types of lasers

Most important distinction: pulsed vs. continuous

Pulsed laser: output on for brief time

Various methods:
- Switch pumping on/off (flash pumped)
- Add “shutter” to cavity (Q-switched)
- Use nonlinear effects (mode-locked)

Can get short pulse durations:
- picoseconds (Q-switched)
- femtoseconds (mode-locked)

Typically use as strobe or marker to study fast events (chemical reactions, electronic motion, etc.)
Get high peak power
Continuous (CW) laser: on all the time

Typically frequency is very stable

Frequency determined by mirrors: need $n\lambda = L$
$\lambda = \text{round trip path length}$

Put one mirror on piezoelectric translator
"lock" to Fabry-Perot cavity and/or atomic transition

Readily get $\Delta f \sim \text{few MHz}$
As low as 1 Hz

Use for spectroscopy, laser cooling

Most types of laser can be pulsed or CW, depending on setup
Common lasers

Classify by gain medium:

- Solid state (Ti-Sapphire, Alexandrite) – doped crystal
  Fiber laser – doped optical fiber
- Gas laser (HeNe, Argon ion, CO$_2$) – gas discharge
  Excimer laser – reactive gases
- Dye laser – liquid dye
- Diode laser – semiconductor

Wavelengths: incomplete coverage from UV to IR

Power: typically 1-10 W average output
  lower for diode lasers, some gas lasers
Frequency Conversion

Incomplete wavelength coverage is annoying.
Often no laser at the frequency you need

Solution: use nonlinear optics to change $\omega$

Simplest example: second harmonic generation
$= \text{frequency doubling}$

$\omega \rightarrow 2\omega$
nonlinear crystal

Can also combine, split, or mix frequencies:

$\omega_1 + \omega_2 \rightarrow \omega_3$ \hspace{1cm} $\omega_3 \rightarrow \omega_2 + \omega_3$ \hspace{1cm} $\omega_1 + \omega_2 \rightarrow \omega_3 + \omega_4$
Why does it work?

**Quantum picture:**
Off-resonant two-photon transition

**Classical picture:**
Electron in anharmonic potential
Response to drive at $\omega$:

Component at $2\omega$
Why don’t you see this all the time?
1. Need medium with large nonlinearity
2. Need high intensity at $\omega$
3. Need phase matching

Phase matching:
Harmonic wave produced all along crystal

But waves travel at different speeds: $\lambda_1 \neq 2\lambda_2$ since $n = n(\omega)$
$\rightarrow$ Waves get out of phase
Wave produced at one place cancels wave from another
Net output small
A few ways to solve:

- Select and adjust crystal so \( n(\omega) = n(2\omega) \)
  "phase matching"
- Engineer periodic structure in crystal to keep phase
  "periodically poled crystal"
- Use a thin crystal
  Need very high intensity → pulsed laser

Some common crystals:
   KDP, KTP, LBO, BBO, LiNbO\(_3\)

Can typically get ~10% conversion efficiency
depends a lot on medium, phase matching, input power
AMO at UVA

Groups (in physics):

Gallagher: Rydberg atoms
  - Microwave spectroscopy and control
  - Multi-electron excitations
  - Interactions between atoms

Bloomfield: Clusters
  - Magnetism
  - Structure and isomerization

Jones: Rydberg atoms
  - Observation of electronic, nuclear motion
  - Control of electronic, nuclear motion
  - Simulation of collisions
  - Ultrafast laser technology
Pfister: Quantum optics
  - Nonclassical light generation and characterization
  - Quantum information
  - Quantum measurements

Sackett: Bose-Einstein condensation
  - Laser cooling
  - Atom interferometry

Arnold: Particle physics theory
  - BEC phase transition

Kolomeisky: Condensed matter physics theory
  - BEC theory
  - Atomic properties

Cates: Nuclear and medical physics
  - Optical pumping techniques
AMO Classes

Phys 531 – Optics
Phys 532/822 – Photonics
Phys 842 – Atomic Physics
Phys 826 – Ultrafast Lasers
Phys 888 – Quantum Optics

\{ \text{One per year} \}

Also useful:
Phys 519 – Electronics
Phys 553 – Computational Physics

Other departments:
ECE 541 – Optics and Lasers
MAE 687 – Applied Engineering Optics
AMO Journals

General science:

Science, Nature

General physics:


AMO specific:


AMO overlaps with physical chemistry:


and optics:

Optics Lett., JOSA A, JOSA B, Applied Optics

General interest physics:

Physics Today – free with APS membership!
Conclusions

Tried to provided introduction/reminder about a few key ideas in AMO physics

- Atomic and molecular states
- Transitions
- Lasers and frequency conversion

and introduced opportunities for AMO here

As we have more seminars, keep these ideas in mind