Optical Transitions

The integration absorption coefficient

Area = integrated absorption coefficient

Transitions

Molar absorption coefficient, $\varepsilon$

Wavenumber, $\tilde{\nu}$

Stimulated absorption

Spontaneous emission

Stimulated emission
Einstein Coefficients

\[ \frac{dN_2}{dt} = B_{12} \cdot u(\nu) \cdot N_1 \]

\[ \frac{dN_2}{dt} = -A_{21} \cdot N_2 \]

\[ \frac{dN_2}{dt} = -B_{21} \cdot u(\nu) \cdot N_2 \]

\[ \frac{B_{21}}{B_{12}} = \frac{g_2}{g_1} \]

\[ \frac{A_{21}}{B_{12}} = \frac{8\pi h \nu^3}{c^3} \]
Lambert-Beer Law

Transmittance of the sample:

\[ T = \frac{I}{I_0} \quad T = e^{-\sigma N l} = e^{-\alpha}, \]

where \( \sigma [\text{cm}^2] \) is an absorption cross section, \( N [\text{cm}^{-3}] \), and \( l [\text{cm}] \)

The form which widely used in laboratory practice:

\[ T = 10^{-\varepsilon C l}, \]

where \( \varepsilon [\text{L mol}^{-1} \text{ cm}^{-1}] \) is an extinction coefficient and \( C [\text{mol L}^{-1}] \) is a molar concentration:

\[
C = \frac{\text{Number of molecules}}{N_A V} = \frac{N}{N_A}
\]

\( N_A \) is Avogadro number, \( N_A = 6.022 \times 10^{23} \text{ mol}^{-1} \)
Low Optical Density

In case if the exponent factor $\alpha = \sigma N l$ is small compared to unity, $\alpha \ll 1$, the exponential function can be expanded over $\alpha$. Keeping in this expansion only first two terms one comes to the important for practice particular case called low optical density of the sample:

$$I = I_0 (1 - \sigma N l)$$

Integrating the cross section $\sigma = \sigma(\nu)$ over the light frequency $\nu$ within the absorption peak, one obtains the integrated cross section $\langle \sigma(\nu) \rangle$:

$$\langle \sigma \rangle = \int \sigma(\nu) \, d\nu = B_{mn} \frac{h \nu_0}{c}$$

where $B_{mn}$ is the Einstein absorption coefficient and $\nu_0$ is the center of the molecular absorption line. Thus, the Einstein coefficient $B_{mn}$ can be directly determined from experiment.
Born-Oppenheimer Approximation

\[ \Psi_{\text{tot}} = \Psi_{\text{el}} \Psi_{\text{vib}} \Psi_{\text{rot}} \]

\[ E_{\text{tot}} = E_{\text{el}} + E_{\text{vib}} + E_{\text{rot}} \]

Potential energy curves
Morse Potential

\[ V(R) = D_e \left( 1 - 2^{-\beta (R - R_0)} \right) \]
\[ \beta = \pi v_e \sqrt{\frac{2 \mu}{D_e}} \]

\[ E_v = (v + \frac{1}{2}) \omega_e - (v + \frac{1}{2})^2 \omega_e^2 x_e^2 + (v + \frac{1}{2})^3 \omega_e^3 y_e^3 + \text{higher terms}, \quad v=0,1,2... \]
Born-Oppenheimer Approximation: Electronic transitions in molecules
Molecular Fluorescence Spectroscopy
Jablonski Diagram

- $S_n$, $S_2$, $S_1$, $S_0$: electronic states
- $T_2$, $T_1$: triplet states
- A = photon absorption
- F = fluorescence (emission)
- P = phosphorescence
- S = singlet state
- T = triplet state
- IC = internal conversion
- ISC = intersystem crossing

Excited vibrational states (excited rotational states not shown)
Spectral Line Shape

Uncertainty relation for energy:

\[ \Delta E \approx \frac{\hbar}{\tau} \]

Two main processes which are responsible to the finite lifetime of excited states:

1. Spontaneous decay which is proportional to the corresponding Einstein coefficient \( A_{nm} \). The intensity the spontaneous decay is proportional to the square of the matrix element of interaction with electromagnetic modes of vacuum.

2. Interaction between the molecular quantum states and other particles and fields. In the gas phase this interaction is mostly inelastic collisions with surrounding particles. In the condensed matter there can be interaction with phonons (vibration of the surrounding lattice).

The corresponding line has the Lorentz shape:

\[ I(\nu) = \frac{1}{\pi} \frac{\gamma}{(\nu - \nu_L)^2 + \left(\frac{\gamma}{2}\right)^2} \]

where \( \gamma = \frac{1}{2\pi\tau} \) is the decay rate and \( \Delta \nu_L = \gamma \)
## Homogeneous (Lorentz) Broadening

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\Delta \nu_L$ (Hz)</th>
<th>$\Delta \nu_L$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural lifetimes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas phase, electronic transitions</td>
<td>$\sim 10^7$</td>
<td>$\sim 10^{-4}$</td>
</tr>
<tr>
<td>Natural lifetimes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas phase, rotational transitions</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-15}$</td>
</tr>
<tr>
<td>Collisional lifetimes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas, atmospheric pressure</td>
<td>$\sim 10^9$</td>
<td>$\sim 10^{-2}$</td>
</tr>
<tr>
<td>Collisional lifetimes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid, electronic transitions</td>
<td>$\sim 10^{12}$</td>
<td>$\sim 10^1$</td>
</tr>
</tbody>
</table>
Doppler Broadening

The Doppler effect results in light frequency shift when the source is moving toward, or away from the observer. When a source emitting radiation with frequency $\nu_0$ moves with a speed $v$, the observer detects radiation with frequency:

$$\nu = \nu_0 \left(1 \pm \frac{v_z}{c}\right)$$

Molecules in a gas chaotically move in all directions. In case of the thermal equilibrium, the distribution of molecular velocities along the line of detection, which we designate as $Z$ axis, this velocity distribution is known as Maxwell-Boltzmann distribution:

$$n(\nu_z) \, d\nu_z = \sqrt{\frac{2kT}{\pi m}} \exp\left[-\frac{m\nu_z^2}{2kT}\right]$$

The observer detects the corresponding Doppler-broadened spectral line profile:

$$I(\nu) = \sqrt{\frac{4\ln 2}{\pi}} \frac{1}{\Delta \nu_D} \exp\left[-4\ln 2 \frac{(\nu - \nu_0)^2}{\Delta \nu_D^2}\right]$$

where

$$\Delta \nu_D = \frac{2\nu_0}{c} \sqrt{\frac{2\ln 2kT}{m}}$$

For transitions which belong to the visible or the near-UV spectral range when the gas temperature is around 300 K, the Doppler width is typically within one GHz. For the visible part of the spectrum the Doppler line broadening is usually much larger than the lifetime broadening.
Lorentz and Doppler Line Shapes

Lorentz normalized:

\[ I(\nu) = \frac{1}{2\pi} \frac{\Delta\nu_L}{(\nu - \nu_0)^2 + \left(\frac{\Delta\nu_L}{2}\right)^2} \]

Doppler normalized:

\[ I(\nu) = \frac{4}{\pi \Delta\nu_D} e^{-2\ln^2 \left(\frac{\nu - \nu_0}{\Delta\nu_D}\right)} \]

\[ \Delta\nu_D = \Delta\nu_L = \Delta\nu \]
Synchrotron Radiation

![Diagram of synchrotron radiation setup]

- Experimental stations
- Radiation
- Storage ring
- Linear accelerator
- Booster synchrotron
- 30 m
- 10 m
- Electron beam
- Incidence beam
- Scattered beams
- Diffraction grating
- To detector
- Slit
- $\lambda_1$, $\lambda_2$, $\lambda_3$
LASER
Light Amplification by Stimulated Emission

Nobel Prize, 1964
C.H. Townes,
N.G. Basov,
and A.M. Prokhorov
Properties of Laser Radiation

1. The laser light can be very monochromatic and can be effectively used for high resolution spectroscopy. The best results have been obtained for the low pressure gas lasers: \( \Delta \lambda / \lambda \approx 10^{-15} \).

2. The laser beam can be of very low divergent (spatial coherence), which means that its diameter is increased only slowly in space. In principle, with laser beams it is possible to reach the diffraction limit:

\[
\theta \approx \frac{2\lambda}{\pi d}
\]

Using a lens, it is possible to focus a laser beam on a spot of the diameter:

\[
d \approx \frac{2\lambda f}{\pi D} \approx \frac{\lambda}{2}
\]

where, \( f \) denotes the focal distance of the lens.

3. Extremely short laser pulses can be produced. The pulse duration in the nanosecond \( (10^{-9}) \), picosecond \( 10^{-12} \), and femtosecond \( 10^{-15} \) range are now available commercially. Particularly, femtosecond laser pulses are of great importance, because they allow to investigate chemical reactions in the real-time domain.

4. High power output. The continuous CO\(_2\) lasers are now can produce the high power output up to 100 kW. These technological lasers are now widely used in industry and for military. The pulsed lasers, especially those operating in the pico- and femtosecond time-domain can have the pick power from \( 10^9 \) to \( 10^{12} \) Watt. High power pulsed lasers are widely used for investigation of nonlinear and multiple photon processes.
Rotational Spectra: Moment of Inertia

Energy of Rotation: $E_{\text{rot}} = \frac{1}{2} I \omega$, where $I$ is the moment of inertia: $I = m r^2$.

For arbitrary object rotation energy is written as:

$$E_{\text{rot}} = \frac{1}{2} I_A \omega_A^2 + \frac{1}{2} I_B \omega_B^2 + \frac{1}{2} I_C \omega_C^2 = \frac{J_A^2}{2I_A} + \frac{J_B^2}{2I_B} + \frac{J_C^2}{2I_C}$$

where A, B, and C are principal axes of rotation and

$J_i = I_i \omega_i$ is angular momentum
### Rigid Rotator: examples

\[
E_{\text{rot}} = \frac{J^2_A}{2I_A} + \frac{J^2_B}{2I_B} + \frac{J^2_C}{2I_C}
\]

<table>
<thead>
<tr>
<th>Type</th>
<th>Conditions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical Top</td>
<td>( I_A = I_B = I_C = I )</td>
<td>( \text{CH}_4, \text{CCl}_4, \text{CF}_6 )</td>
</tr>
<tr>
<td>Symmetric Top</td>
<td>( I_A = I_A = I_\perp, \quad I_C = I_\parallel ) ( I_\perp &lt; I_\parallel ) oblate ( I_\perp &gt; I_\parallel ) prolate</td>
<td>( \text{C}_6\text{H}_6, \text{CH}_3\text{I}, \text{NH}_3 )</td>
</tr>
<tr>
<td>Linear Rotor</td>
<td>( I_A = 0, \quad I_B = I_C )</td>
<td>All diatomic molecules, ( \text{CO}_2, \text{N}_2\text{O}, \text{C}_2\text{H}_2 )</td>
</tr>
<tr>
<td>Asymmetric Top</td>
<td>( I_A \neq I_B \neq I_C )</td>
<td>( \text{H}_2\text{O}, \text{NO}_2, \text{H}_2\text{CO}, \text{CH}_3\text{OH} )</td>
</tr>
</tbody>
</table>
Moments of Inertia

Diatomics, \( \text{CO}_2, \text{N}_2\text{O}, \text{C}_2\text{H}_2 \)

\( \text{CH}_4, \text{CCl}_4, \text{SF}_6 \)

\( \text{NH}_3, \text{CH}_3\text{I}, \text{C}_6\text{H}_6 \)

\( \text{H}_2\text{O}, \text{NO}_2, \text{H}_2\text{CO}, \text{CH}_3\text{OH} \)
Spherical Top: Energy States

The corresponding quantum mechanical expression:

\[ E_{rot} = \frac{J_A^2}{2I} + \frac{J_B^2}{2I} + \frac{J_C^2}{2I} = \frac{J^2}{2I} \]

because the eigenvalue of the operator \( J^2 \) is

\[ J^2 \Psi = \hbar^2 J(J + 1) \Psi \]

In spectroscopy the rotational energy is usually written as:

\[ E_{rot} = \hbar c B \cdot J(J + 1) \]

where the rotational constant \( B \) in cm\(^{-1}\)

\[ B = \frac{\hbar}{4\pi c I} \]

The rotational term:

\[ F(J) = B \cdot J(J + 1) \]
Symmetric Top

\[ E_{\text{rot}} = \frac{J_A^2}{2I \perp} + \frac{J_B^2}{2I \perp} + \frac{J_C^2}{2I \parallel} = \frac{J_A^2 + J_B^2}{2I \perp} + \frac{J_C^2}{2I \parallel} \]

where \[ J_A^2 + J_B^2 + J_C^2 = J^2 \]

\[ E = \frac{J^2}{2I \perp} + J_C^2 \left( \frac{1}{2I \parallel} - \frac{1}{2I \perp} \right) \]

using \[ J^2 \rightarrow J(J+1) \hbar^2 \] and \[ J_C \rightarrow K \hbar \]

We get the corresponding quantum mechanical expression for the rotational term:

\[ F_{JK} = B J(J+1) + (A - B) K^2 \]

where \[ J = 0, 1, 2 \ldots \] and \[ K = 0, \pm 1, \pm 2, \pm J. \]

Oblate top: \( A - B < 0 \)

Prolate top: \( A - B > 0 \)

\[ A = \frac{\hbar}{4\pi c I \parallel} \quad B = \frac{\hbar}{4\pi c I \perp} \]
Symmetric Top: \( F(J) = B J (J + 1) + (A - B)K^2 \)

Role of the quantum number \( K \):

- if \( K = J \gg 1 \), \( F(J) \approx A K^2 \)
- if \( K = 0 \), \( F(J) = B J (J + 1) \)

Role of the quantum number \( M_J \)
Asymmetric Top

The diagram illustrates the relationship between the moments of inertia $I_A$ and $I_c$ for an asymmetric top, with $I_c = \frac{1}{2}I_B$.

The figure shows the quantum numbers $K_a$, $K_c$, and $J_{K_aK_c}$, with specific levels labeled as $3_{03}$, $3_{31}$, $3_{21}$, $3_{22}$, $3_{13}$, and $3_{12}$. The diagram indicates the transition regions from oblate to prolate shapes as $I_A$ and $I_c$ vary.
Elastic Rotator: Centrifugal Distortion

So far, we assumed that rotation does not affect the shape of a molecule (rigid rotor). However, in general there are centrifugal forces that stretch the bonds of a rotating molecule.

An increased length of the bond corresponds to a higher moment of inertia ($I = \mu r^2$). In turn, the rotational constant $B$ decreases ($B \sim I^{-1}$), i.e. we would expect a rotational energy in the form:

$$F(J) \approx BJ(J+1) - DJ^2(J+1)^2 + \ldots$$

where the coefficient $D$ is a small correction, which is called centrifugal distortion constant.
Pure Rotational Transitions

The pure rotational transitions are possible in polar molecules which have a permanent dipole moment and a transitional dipole moment within a pure rotational spectrum is not equal to zero.

In contrast, no rotational spectra exists for homonuclear diatomics; the same is true for spherical tops.

Selection rules: $\Delta J = \pm 1; \Delta M_J = 0, \pm 1$

For a symmetric top, an existing dipole moment is always parallel to the molecular axis:

$\Delta K = 0$
\[ \nu( J ) = B( J + 1)(J + 2) - B J (J + 1) \]
\[ = 2B (J + 1) \]

\[ \Delta \nu = \nu(J + 1) - \nu(J) = 2B \]

That is, the spectrum consists of **equidistant lines**.

The intensities of spectral lines first increase with increasing \( J \) and pass through a maximum. The reason for the maximum in intensity is the existence of a maximum in the population of rotational levels. According to the **Boltzmann distribution** the population of a rotational level at temperature \( T \) is given by:

\[ N( J ) = N_0 g_J \exp\left( - \frac{E_J}{kT} \right) \]
Vibrational Levels

\[ E_v = \left(v + \frac{1}{2}\right) \omega_e \]

\[ E_v = (v+\frac{1}{2}) \omega_e - (v+\frac{1}{2})^2 \omega_e^2 x_e^2 + (v+\frac{1}{2})^3 \omega_e^2 y_e^2 + \cdots \]

\[ v = 0, 1, 2, \ldots \]
Vibrational Transitions

If the molecule in its equilibrium position has a dipole moment, as is always the case for the heteroatomic molecules, this dipole moment will in general change if the internuclear distance changed. The molecular vibration would lead to the emission of light at the oscillation frequency. Therefore, all heteroatomic molecules in principle are said to be infrared active, that is they can absorb or emit infrared radiation. Contrary, all homoatomic diatomic molecules do not have any dipole moment and cannot set in vibration by absorption the infrared light. These molecules are said to be infrared inactive. The selection rules for the vibrational transitions in a harmonic oscillator-like molecule are:

$$\Delta v = v' - v'' = \pm 1$$

As the energy difference between each two neighbor vibrational energy levels is $\hbar \omega$, the vibrational spectrum would contain only one line. This line is called fundamental line. The wavelength of this line for different diatomic molecules usually lies in near IR spectral range $\lambda = 2 \ldots 20 \text{ mkm}$.

However, for high lying vibrational energy states the harmonic oscillator approximation in is not valid any more. For anharmonic oscillator the selection rule above is not valid and additional lines appear in the molecular vibration spectra corresponding to transitions $\Delta v = v' - v'' = \pm 1, \pm 2, \pm 3$ and so on. These transitions are called second harmonic, third harmonic, and so on. The intensity of the harmonic transitions transitions is usually much smaller than the intensity of the fundamental line.
The quantum mechanical analysis of simultaneous vibrational and rotational transitions shows that the rotational quantum number $J$ changes by $\pm 1$ during the vibrational transition. If the molecule also possesses angular momentum about its axis, (for instance, NO($^2\Pi$)), then the selection rule also allows $\Delta J = 0$. In general, the vibrational-rotational spectrum of the $v' \rightarrow v'' \pm 1$ transition can contain three rotational branches: $\Delta J = -1$, $\Delta J = 0$, and $\Delta J = 1$ branches which are called P, Q, and R branches, respectively.
Vibrational–Rotational Transitions: Π Electronic State
Electronic Transitions

Diagram showing electronic transitions with rotational and vibrational levels.
Electronic Transitions

In the Born-Oppenheimer Approximation:

Wavefunction:

\[ \Psi(r_e, R(\theta, \phi)) \approx \Psi_{el}(r_e, R) \Psi_{vib}(R) \Psi_{rot}(\theta, \phi) \]

Energy:

\[ E = E_{el} + E_{vib} + E_{rot} \]

Term [ cm\(^{-1}\) ]:

\[ F = T_e + \omega_e (v + \frac{1}{2}) + B_e J (J+1) \]

where \( T_e \gg \omega_e \gg B_e \)

\[ \Delta F = T_e' - T_e'' + \omega_e' (v' + \frac{1}{2}) - \omega_e'' (v'' + \frac{1}{2}) + B_e' J' (J'+1) - B_e'' J'' (J'' + 1) \]
Electronic Transitions: Franck–Condon factors

Transition dipole moment:

\[ \langle \Psi' | d_q | \Psi'' \rangle \approx \langle \Psi'_{el} \Psi'_{vib} \Psi'_{rot} | d_q | \Psi''_{el} \Psi''_{vib} \Psi''_{rot} \rangle \approx \langle \Psi'_{rot} | \Psi''_{rot} \rangle \langle \Psi'_{vib} | \Psi''_{vib} \rangle \langle \Psi'_{el} | d_q | \Psi''_{el} \rangle \]

Where

\[ \langle \Psi'_{vib} | \Psi''_{vib} \rangle \]

is a Frank-Condon Factor

and

\[ \langle \Psi'_{el} | d_q | \Psi''_{el} \rangle \]

is an electronic transition dipole moment
Electronic Transitions: selection rules

Diatomc Molecule Electronic Terms:
\[ \frac{2S+1}{\Lambda_\Omega} \]

Additional quantum numbers:
- \( g \), \( u \) for homonuclear molecules
- \( \pm \) for \( \Sigma \) states

Examples: \( ^1\Sigma_0^+ \), \( ^3\Sigma_{1u}^+ \), \( ^1\Pi_1 \), \( ^1\Pi_{1g} \)

\[ \Lambda = \sum_i \lambda_i \quad \Sigma = \sum_i \sigma_i \quad \Omega = \Lambda + \Sigma \]

<table>
<thead>
<tr>
<th>Allowed Transitions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \Lambda = 0, \pm 1 )</td>
<td>( \Sigma \rightarrow \Sigma, \Pi \rightarrow \Pi ), ( \Sigma \rightarrow \Pi, \Delta \rightarrow \Pi )</td>
</tr>
<tr>
<td>( \Delta S = 0 )</td>
<td>( ^1\Sigma \leftrightarrow ^1\Sigma ), ( ^2\Sigma \leftrightarrow ^2\Pi ), ( ^3\Pi \leftrightarrow ^3\Pi ), ( ^1\Sigma \leftrightarrow ^1\Pi )</td>
</tr>
<tr>
<td>(+ \leftrightarrow + )</td>
<td>( \Sigma^+ \leftrightarrow \Sigma^+ )</td>
</tr>
<tr>
<td>(- \leftrightarrow - )</td>
<td>( \Sigma^- \leftrightarrow \Sigma^- )</td>
</tr>
<tr>
<td>( g \leftrightarrow u )</td>
<td>( \Sigma_g^+ \leftrightarrow \Sigma_u^+ ), ( \Sigma_u \leftrightarrow \Pi_g )</td>
</tr>
</tbody>
</table>
### Rotational Structure of Electronic Transitions: Selection Rules

<table>
<thead>
<tr>
<th>Electron Transition</th>
<th>Allowed Transitions</th>
<th>Name</th>
</tr>
</thead>
</table>
| $\Sigma \leftrightarrow \Sigma$ | $\Delta J = -1$  
$\Delta J = +1$ | P branch  
R branch       |
| All others          | $\Delta J = -1$  
$\Delta J = 0$  
$\Delta J = +1$ | P branch  
Q branch  
R branch       |
Rotational Structure of Electronic Transitions

(a) $B' < B$

(b) $B' > B$

Red shadowed

Blue shadowed

band head
Dissociation and Predissociation
Photoelectron Spectroscopy: CO Molecule
Absorption Spectroscopy with a Frequency Modulated Laser
Intracavity Absorption Technique
Cavity Ring-Down Spectroscopy
Fig. 6.13. Photoacoustic spectroscopy (a) level scheme (b) schematic experimental arrangement.
Fig. 6.15. Optoacoustic overtone absorption spectrum of acetylene around $\tilde{\nu} = 15600$ cm$^{-1}$ corresponding to the excitation of a local mode by 5 quanta vibrations [6.45]
Laser Induced Fluorescence (LIF)

Fig. 6.33a,b. Laser-induced fluorescence: (a) Level scheme and (b) experimental arrangement for measuring LIF spectra.
Laser Induced Fluorescence: Na$_2$

Fig. 6.34. Laser-induced fluorescence of the Na$_2$ molecule excited by argon laser lines (a) term diagram (b) fluorescence lines with $\Delta J = 0$ (Q-lines) emitted from the upper level ($v' = 3, J' = 43$) of the $B^1\Pi_u$ state, excited at $\lambda = 488$ nm. (c) P and R doublets, emitted from the upper level ($v' = 6, J' = 27$).
Laser Induced Fluorescence: NO$_2$
Ionization Spectroscopy

ionization potential

$\lambda_1$

$\lambda_2$

$\lambda_3$

autoionizing level

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www.scimedia.com
Rydberg States Ionization

Photo-ionisation

\[
\begin{align*}
\nu_2 & \quad E_k \\
\nu_1 & \quad E_i
\end{align*}
\]

Feld-ionisation

\[
\begin{align*}
\nu_2 & \quad E_k \\
\nu_1 & \quad E_i
\end{align*}
\]

Laser

Molekular-strahl
Raman Laser Spectroscopy

(a) Stokes radiation

(b) Anti-Stokes radiation

Sample cell

Laser

Detector

Monochromator or interferometer
Fig. 8.3. Rotational Raman spectrum of $\text{C}_2\text{N}_2$ excited with the 488 nm line of the argon laser in the experimental setup of Fig. 8.2 and recorded on a photographic plate with 10 min exposure time [8.20]
Ultra Short Laser Pulses: mode locking

Fig.11.3. Intensity modulation using a Pockels cells. a) Schematic experimental arrangement. b) Transmitted intensity. c) Frequency spectrum of transmitted intensity.
Quantum Beat Spectroscopy
Femto-Second Laser Spectroscopy

1999 Nobel Prize
Ahmed Zewail

Pump-and-probe Technique
Femto-Second Laser Spectroscopy

H₂O

Pump-and-probe technique
Spectroscopy of size-selected molecular clusters: \((O_n)^-\)

Ahmed Zewail Lab
Spectroscopy of size-selected molecular clusters