

Syllabus

1. Introduction

2. Fluids

1. General Characteristics
2. Dispersions
3. Thermodynamics
4. Transport Phenomena
5. Solutions
6. Surface Tension
7. Electrical Properties
- 8. Optical Properties**
9. Biological Fluids

Physics of Microfluidic Systems

1. Navier-Stokes Equation
2. Laminar and Turbulent Flow
3. Fluid Dynamics
4. Fluid Networks
5. Transport of Heat
6. Interfacial Surface Tension
7. Electrokinetics

2.8. Optical Properties

- Interaction
 - High-frequency EM-fields
 - Visible light
 - UV
 - IR
 - Matter
- Close relation
 - Optical properties
 - Dielectric properties
- Optical properties often utilized in microfluidic systems for
 - Location & contours of fluids
 - Detection in biomolecular assays



2.8. Optical Properties

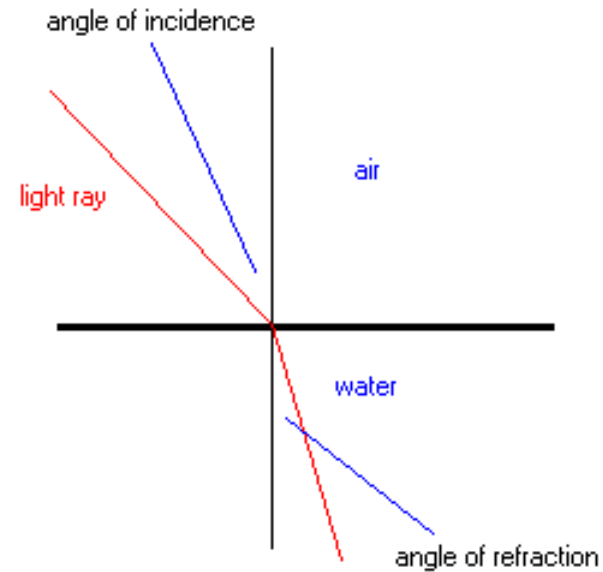
2.8.1. Refractive Index

2.8.2. Absorption

2.8.3. Luminescence

2.8.4. Optical Activity

2.8.5. Scattering



2.8.1. Refractive Index

- **Speed of light in vacuum**

$$c_0 \simeq 3 \times 10^8 \text{ m s}^{-1}$$

- **Maxwell relation**

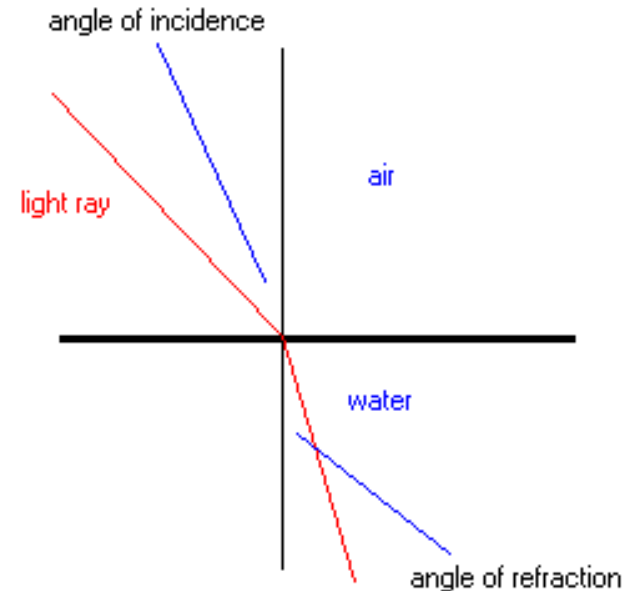
- Speed of light in **dielectric** c_ϵ
- **Refractive index** n_ϵ

$$c_\epsilon = \frac{c_0}{n_\epsilon}$$

- **Refractive index n related to relative permittivity**

$$n_\epsilon = \sqrt{\epsilon}$$

- **Dispersion**
 - Frequency-dependent refractive index $n_\epsilon(\nu)$
- Similar arguments as for permittivity also apply to refractive index



2.8. Optical Properties

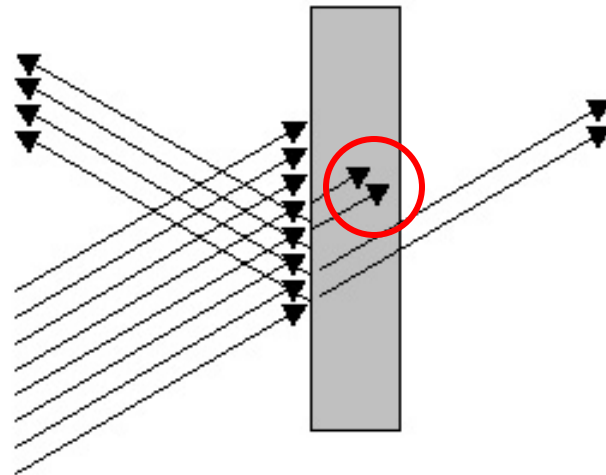
2.8.1. Refractive Index

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2.8.2. Absorption

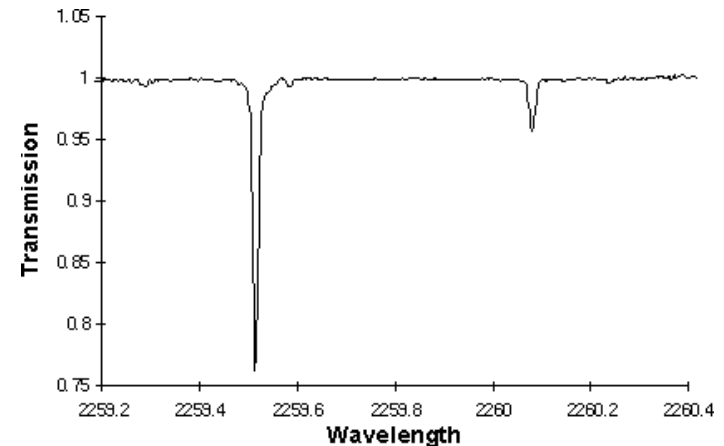
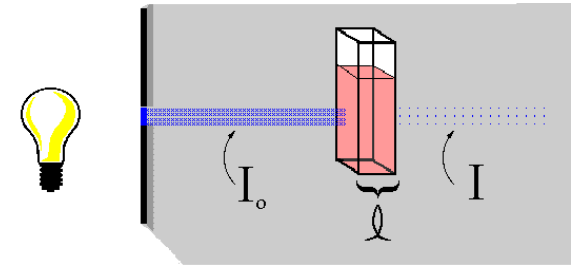
- Transformation of energy
 - From EM-wave
 - Into other forms, e.g., **heat**
- **Attenuation of intensity** at distance x

$$dI = -\Gamma I dx$$

- Absorption coefficient Γ
- Law of **Lambert and Beer**
 - Exponential decay

$$I(x) = I(0)e^{-\Gamma x}$$

- Solutions
 - Absorption coefficient $\Gamma \sim c$ (solute)
- Absorption linked to atomic or molecular properties of substance
 - Maxima at **atomic or molecular resonances**
 - Away from the resonances, absorption rather small
- **μfluidic systems: small optical path lengths x**



2.8. Optical Properties

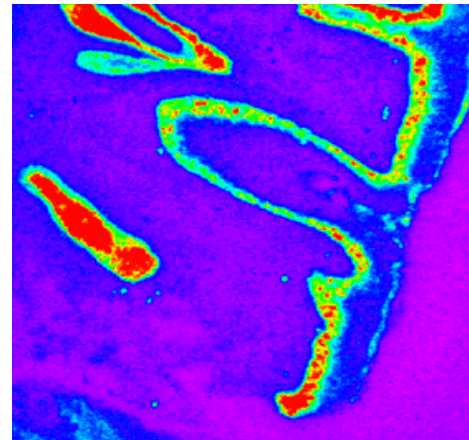
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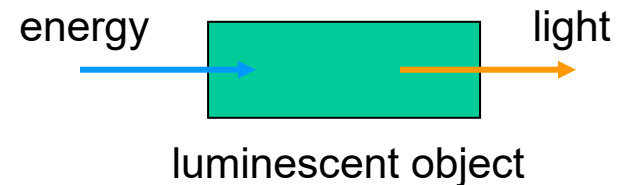
2.8.5. Scattering



2.8.3. Luminescence

- **Emission of light** from all sources other than hot, incandescent bodies like black body radiators

- Excitation of atomic levels
- Intra-atomic relaxation
- Emission of radiation

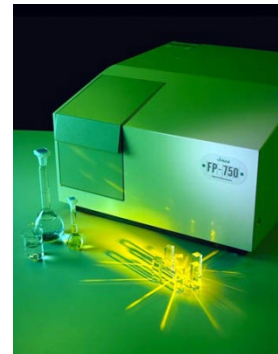
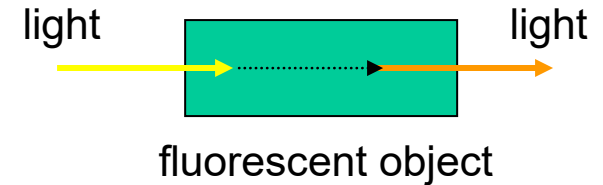


- **Distinction by source of energy** for light emission

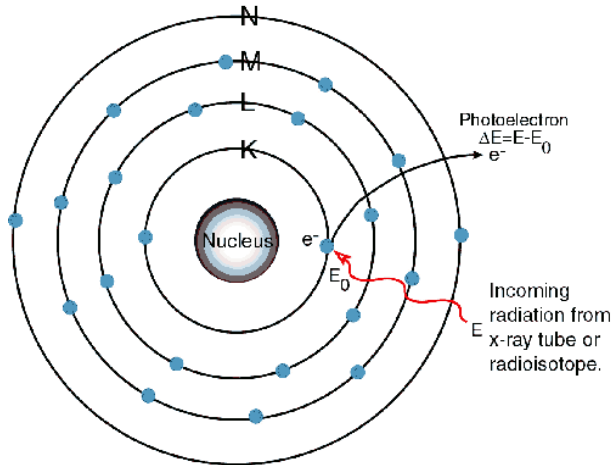
- Fluorescence → EM radiation
- Chemiluminescence → Chemical reaction
- Bioluminescence → Biochemical reaction
- Electroluminescence → Electrical field
 - Gas discharges
- Tribo-luminescence → Mechanical friction

2.8.3. Fluorescence

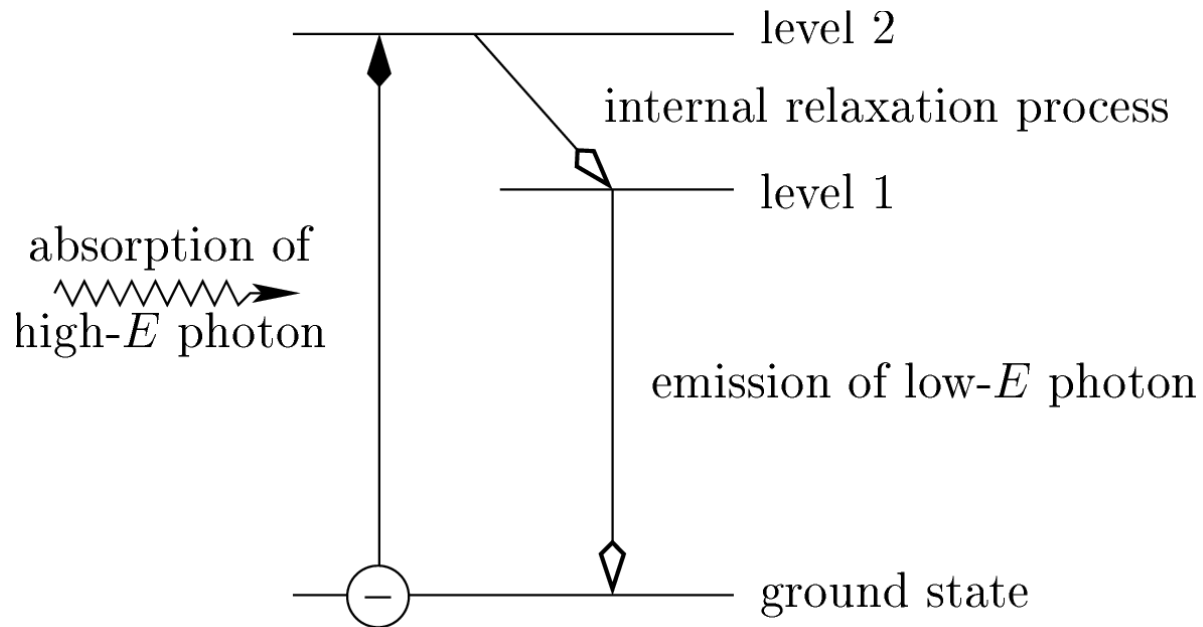
- Characteristics
 - Absorption from some source of energy
 - E.g., UV radiation
 - Emission **ceases** upon **extinction** of external source
 - Contrasts phosphorescence
 - Effect named by Stokes after mineral fluorite
- Detection
 - Fluorescent dye **markers / tags**
 - Identification of macromolecules like DNA in biomolecular assays
 - Fluorescent particles
 - Flow visualization in microstructures
- Laser-Induced Fluorescence
 - **Selective** excitation
 - Laser radiation with appropriate wave length
 - Enforcing **specific molecular transition** in optical spectrum
 - **Exclusive** observation of fluorescently tagged fractions of sample



2.8.3. Laser-Induced Fluorescence

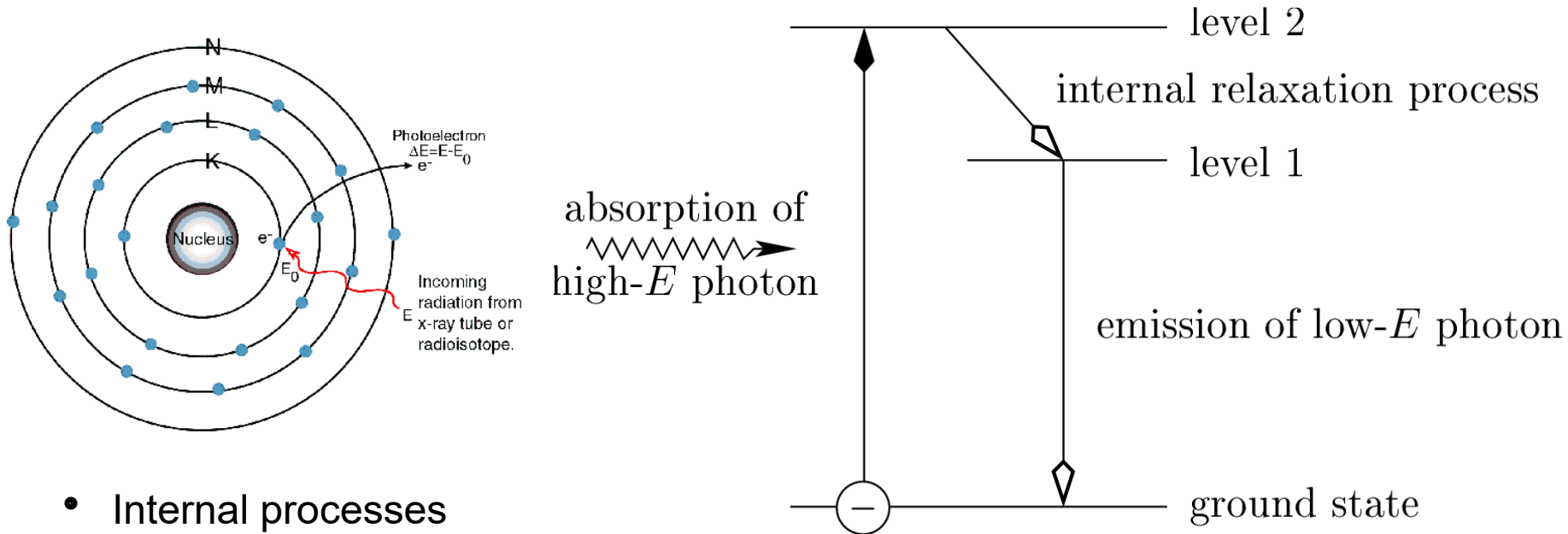


Discrete molecular energy levels



- Laser radiation
 - Strong and **coherent** electric field
 - **Sharp** frequency
- Absorption of photon: $E = h \cdot \nu$
- Excitation of electron in upper level

2.8.3. Laser-Induced Fluorescence

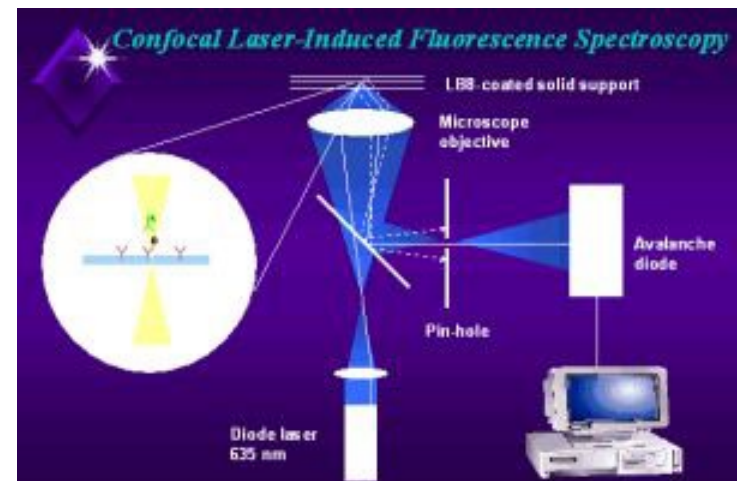
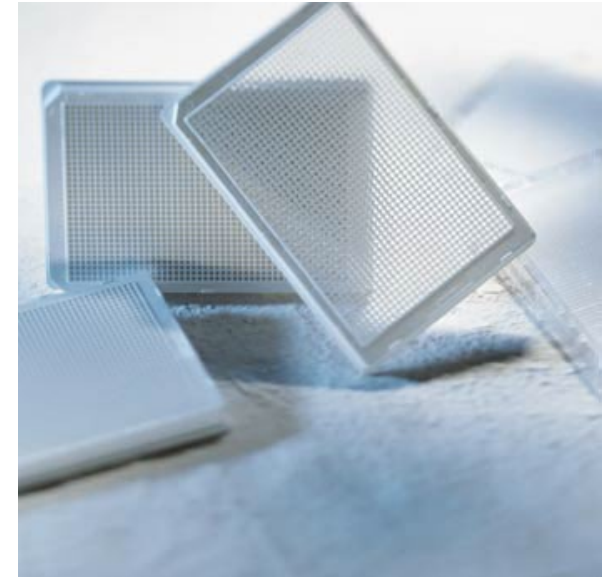


- Internal processes
 - Relaxation into first level
 - Fluorescent transition to ground state as last step of cascade
 - Largest fraction of excitation energy E released
- Fluorescent emission „red-shifted“ (lower E) wrt absorbed photon
- Examples
 - Fluorescein
 - Rhodamine 6G

2.8.3. Laser-Induced Fluorescence

Laser-induced fluorescent detection in microfluidic devices

- Minimize **unspecific fluorescence** from sources other than marker dye
 - Solid support
 - Other dyes
- Confocal microscopy
 - Depth resolution
 - Focal plane: Bound dye molecules



2.8.3. Chemiluminescence

- Mechanisms

- **Chemical energy** into **photons**
- Low-temperature chemical reactions with a „**fuel**“
 - Chiefly **oxidations**
- Product in excited state
- Emission of light

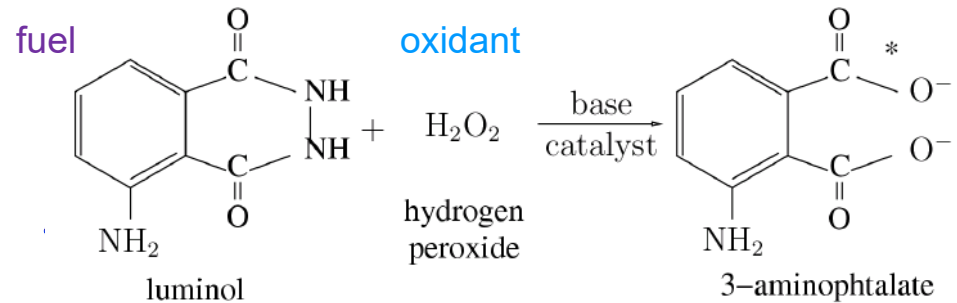
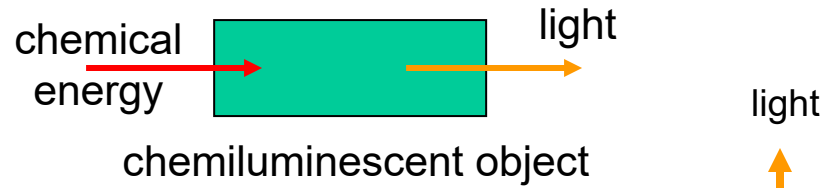
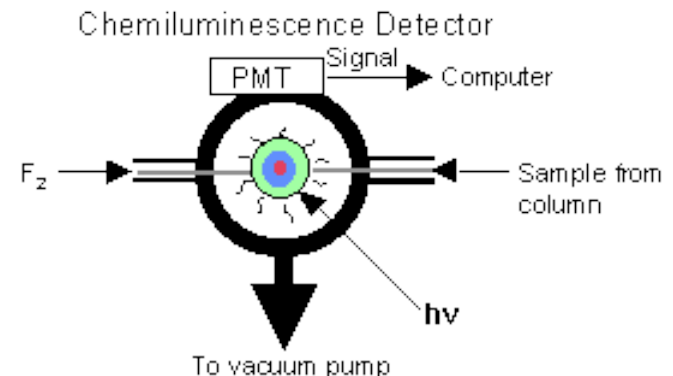


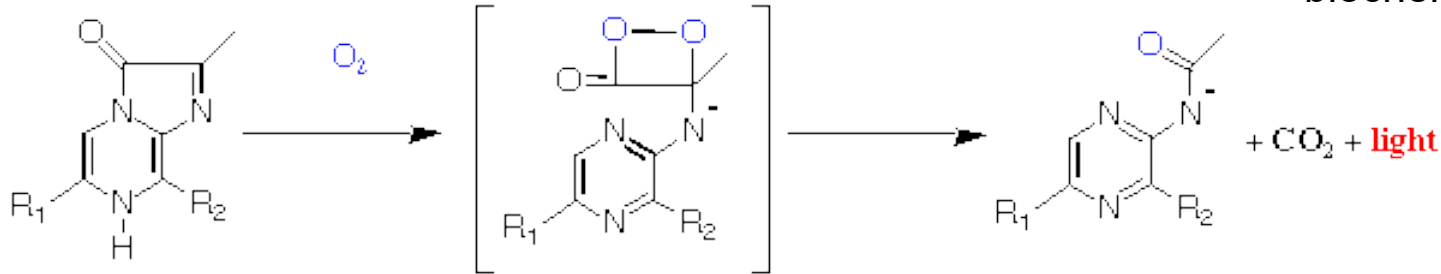
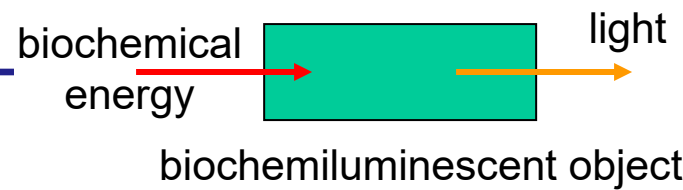
Fig. 2.32. Luminol is excited by an oxidation reaction with hydrogen peroxide. The excited 3-aminophthalate relaxes by the emission of light

- **Simple setup**

- No excitation unit needed
- Simple photometric detector
 - E.g., photomultiplier tube



2.8.3. Bioluminescence



Imidazopyrazinone
(Luciferin Analogue)

Dioxetanone Intermediate

Oxyluciferin Analogue

- **Subtype** of chemiluminescence
- Emission of light by **living**, mostly microscopic organisms
- Prominent examples
 - Glow worms
 - Fire flies
- Analytical tool
 - Luciferin (fire fly)
 - Reacting with oxygen to form excited state



glow worm



fire fly

2.8. Optical Properties

optional

2.8.1. Refractive Index

2.8.2. Absorption

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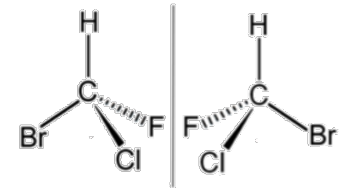
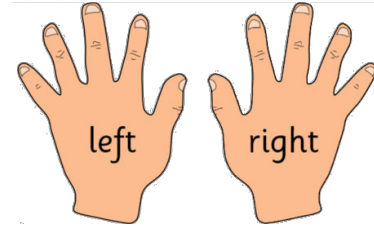
2.8.4. Optical Activity

2.8.5. Scattering

2.8.4. Optical Activity

optional

- Optical isomers or enantiomers
 - Non-superimposable mirror images of each other
 - Asymmetric
 - Name appealing to Greek word meaning hand
 - Coinciding in many properties
 - E.g., melting and boiling points, solubility
 - Cannot be separated by chromatography, IR and NMR spectra
- Optical activity of enantiomer solutions
 - Solutions of one enantiomer rotate plane of polarization in one direction (clockwise, „+“)
 - Solutions of enantiomer rotate plane anticlockwise („-“)
 - At same concentration, absolute value of angle of rotation identical
- Detection
 - Law of Lambert and Beer
 - Coefficient Γ characterizing optical activity
 - **Small optical path length in μ fluidics**



Seldom in μ f!

$$I(x) = I(0)e^{-\Gamma x}$$

2.8. Optical Properties

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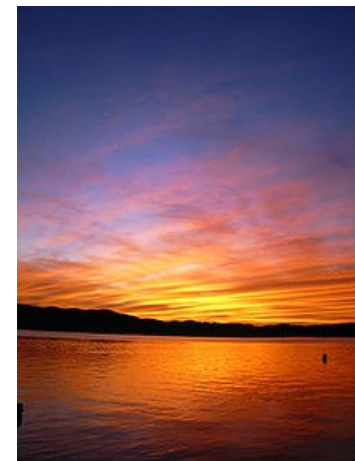
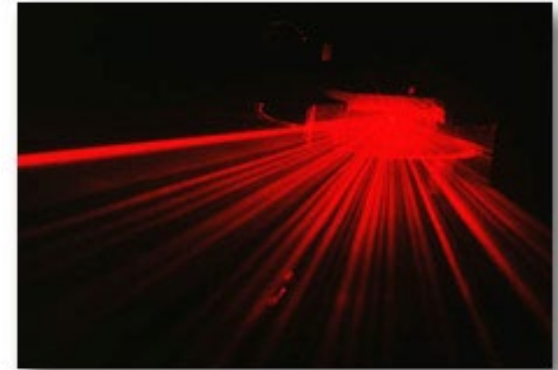
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2.8.5. Scattering

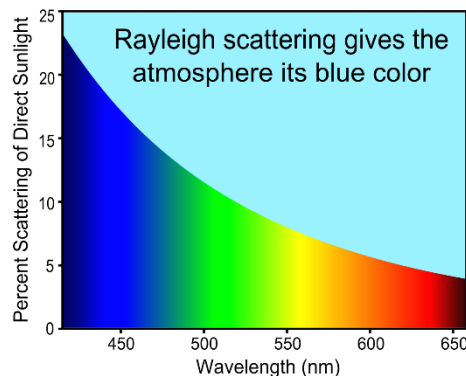
- Interaction of light with media (fluids)
- Scattering behavior governed by ratio
 - Wave length of impinging light λ
 - Diameter of **suspended particles** d_{part}
- Rayleigh scattering ($d_{\text{part}} \ll \lambda$)
 - Wave length exceeds particle dimension (“blue sky”)
- Huygens scattering ($d_{\text{part}} \gg \lambda$)
 - Wave length below particle dimension
- Mie scattering ($d_{\text{part}} \approx \lambda$)
 - Intermediate case (“grey clouds”)



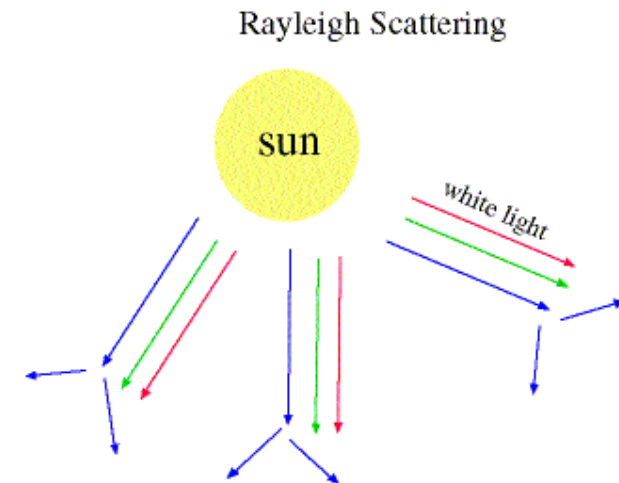
2.8.5. Rayleigh Scattering



- Particle **diameter** well **below wavelength** λ of some 100 nm
- Molecule oscillates like **Hertz dipole** in external field
- External **field** remains roughly **constant** across particle diameter
- Rayleigh's law determines scattering cross section



$$\sigma_{\omega} = \frac{\omega^4 V^2}{6\pi c_0^4}$$

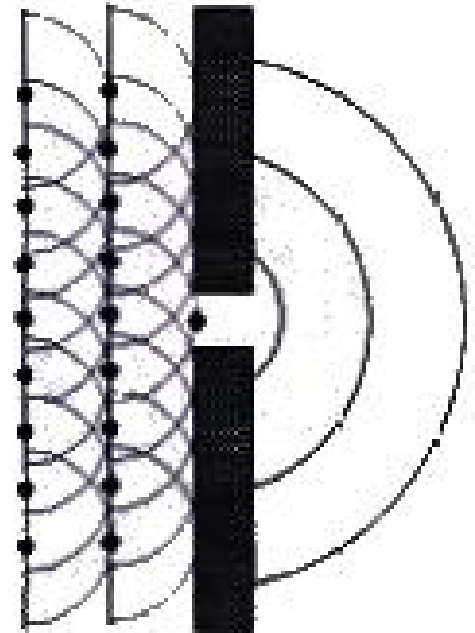


- Strong variation with frequency ω^4
 - Enhanced scattering of ultraviolet compared to red light
 - Blue sky at noon, red sky at dawn
- „Volume“ of molecule V

2.6.5. Huygens Principle

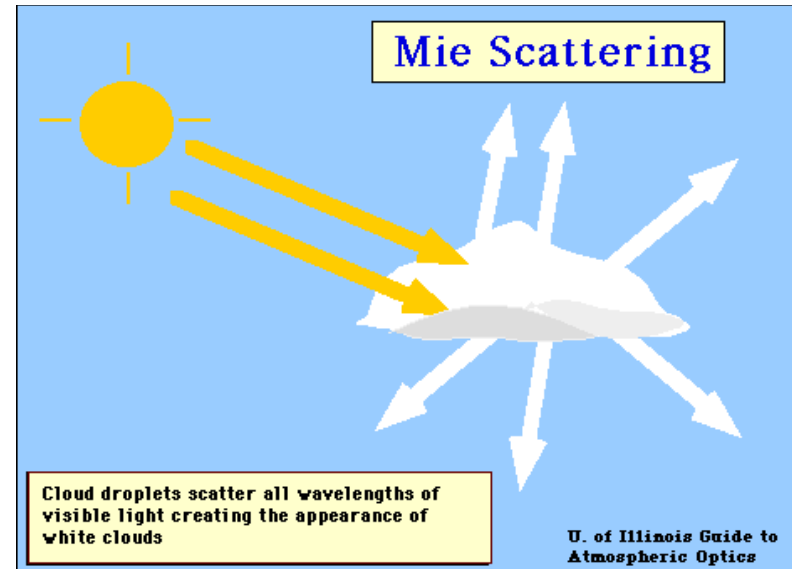


- **Wavelength** λ falls way **below** particle **dimension**
 - Scattering of light on beads or particles measuring several microns or more
- Huygens principle
 - Each inhomogeneity nucleus for secondary wave
- Superposition
 - Typical wave phenomena like reflection
 - Changing the direction of wave propagation at constant energy
- Scattering **cross section** σ_ω roughly **constant for all frequencies**



2.8.5. Mie Scattering

- Particle **diameter** of **same order** as **wave length**
 - Similar rules as for Huygens' scattering apply
- Mathematics of Mie theory straightforward but tedious
 - Computation of potentially large number of series expansions
- Essential result
 - Light interacts with particle over **cross-sectional area larger** than its **geometric** cross section
- Examples for Mie scattering
 - Clouds in sky
 - Small grease particles in emulsions like diluted milk



Summary

In vacuum $c_0 \simeq 3 \times 10^8 \text{ m s}^{-1}$

Speed of light

In medium

$$c_\epsilon = \frac{c_0}{n_\epsilon}$$

Refractive index

$$n_\epsilon = \sqrt{\epsilon}$$

Absorption (Lambert Beer)

$$I(x) = I(0)e^{-\Gamma x}$$

**Rayleigh scattering
(particle smaller than λ)**

$$\sigma_\omega = \frac{\omega^4 V^2}{6\pi c_0^4}$$