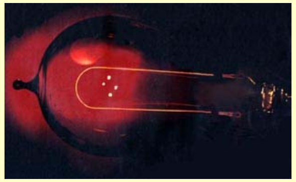
Generation of light – Light sources



Black-body radiation

Luminescence

Laser

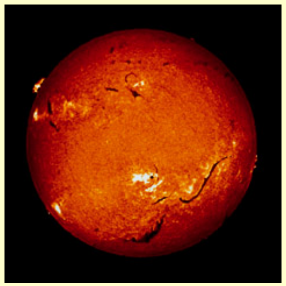
Black-body radiation

or

Thermal Radiation

- Experience: hot bodies

emit
visible light



Thermal Radiation

All material *objects ($T > 0$ K) emit electromagnetic radiation independently from the temperature of its environment*

Radiation originates from specific collective internal vibrations of the composing atoms.

Planck (1900)

1. Some of the atomic vibrations lead to **oscillating charge** separations: source of electromegnetic radiation (EMR)

2. If the oscillators can have any energies the spectrum can not be derived

3. Planck supposed that the internal vibrations can only have discrete energies

$$E_n = nhf$$

(n: integer; f: vibrational frequency)

4. EMR absorption and emission changes the quantum state of vibrations by one quantum

Absorptance (or absorption coefficient) is the fraction of incident light that is absorbed by the body

$$\alpha = \frac{E_{absorbed}}{E_{total\ incident}}$$

Varies with the wavelength

***Black body* absorbs all light that strikes it.**

$$\alpha_{max} = 1$$

Kirchhoff's observation: absorbs more – radiates more

M: radiant emittance [W/m^2]

$$\frac{M_{\lambda i}}{M_{\lambda j}} = \frac{\alpha_{\lambda i}}{\alpha_{\lambda j}}$$

i: arbitrary
j: ideal black body

$$\alpha_{\lambda j} = 1 \qquad \alpha_{\lambda i} < 1$$

$$M_i < M_{\lambda j}$$

Ideal black body has the maximal radiant emittance

$$\alpha_{\lambda(\text{blackbody})} = 1 \qquad \alpha_{\lambda j} < 1$$

$$M_{\lambda j} < M_{\lambda(\text{blackbody})}$$

Ideal black body has the highest radiant emittance

Human body can be considered as a 95% balck body

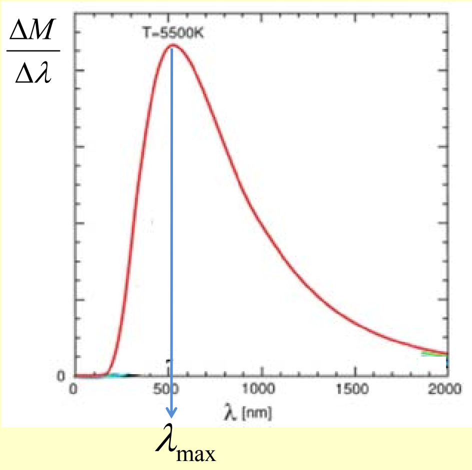
Emission spectrum of thermal radiation

- the spectrum is continuous

- it has one maximum : λ_{max}

- area below the curve:

$$M = \sigma T^4$$



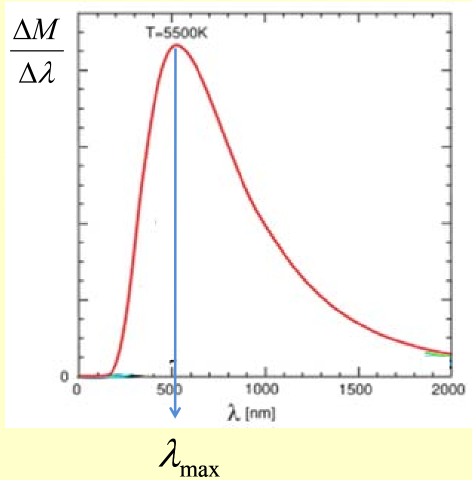
Radiant emittance: total radiant power per unit surface area

Stefan – Boltzmann law

$$M_{blackbody(T)} = \sigma T^4$$

Stefan – Boltzmann constant

$$\sigma = 5.7 \times 10^{-8} [\frac{W}{m^2 K^4}]$$



The role of thermal radiation in the energy release

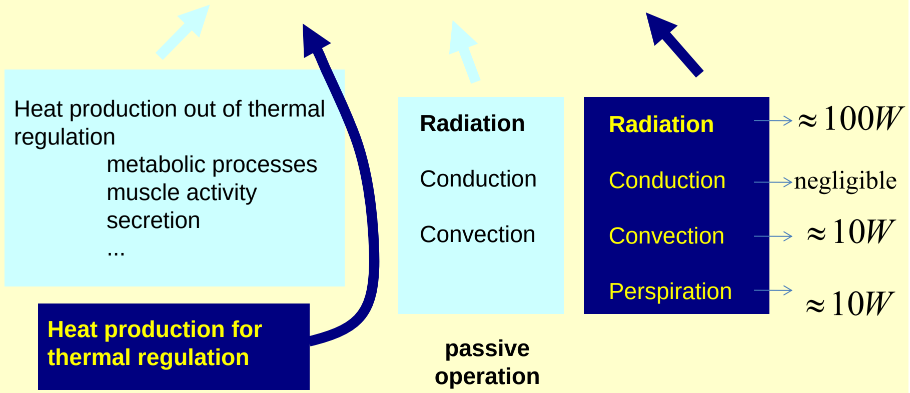
$$\Delta M = \sigma(T^4_{object} - T^4_{environment})$$

It is influenced by

- the temperature of the body
- surface area
- the temperature of the environment (temperature of the surrounding objects)

Temperature regulation and heat exchange

heat production + heat uptake = heat loss



If someone is interested…

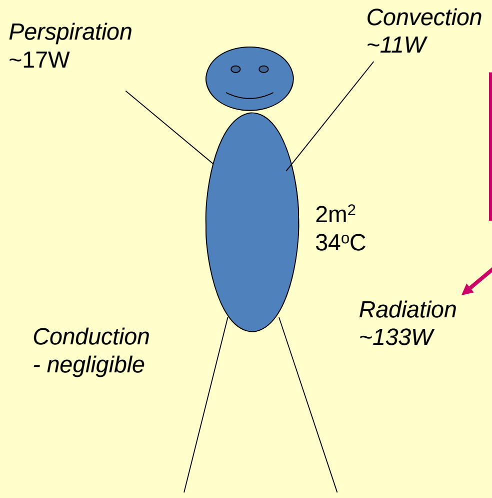
The total energy radiated in one day is about 9 MJ (million joules), or 2000 kcal (food calories). Basal metabolic rate for a 40-year-old male is about 35 kcal/(m²·h), which is equivalent to 1700 kcal per day assuming the same 2 m² area. However, the mean metabolic rate of sedentary adults is about 50% to 70% greater than their basal rate

There are other important thermal loss mechanisms, including convection and evaporation. Conduction is negligible. Evaporation (perspiration) is only required if radiation and convection are insufficient to maintain a steady state temperature. Free convection rates are comparable, albeit somewhat lower, than radiative rates.Thus, radiation accounts for about 2/3 of thermal energy loss in cool, still air. Given the approximate nature of many of the assumptions, this can only be taken as a crude estimate. Ambient air motion, causing forced convection, or evaporation reduces the relative importance of radiation as a thermal loss mechanism.
Also, Applying Wien's Law to humans, one finds that the peak wavelength of light emitted by a person is

$$\lambda_{peak} = \frac{2.898 \times 10^6\ \mathrm{K \cdot nm}}{305\ \mathrm{K}} = 9500\ \mathrm{nm}$$

This is why thermal imaging devices designed for human subjects are most sensitive to 7-14 micrometers wavelength

Heat exchange with the environment



Energy exchange with the environment

$$\Delta M = \sigma \cdot (T_{body}^4 - T_{envir.}^4)$$

Exchange depends on T of the environment

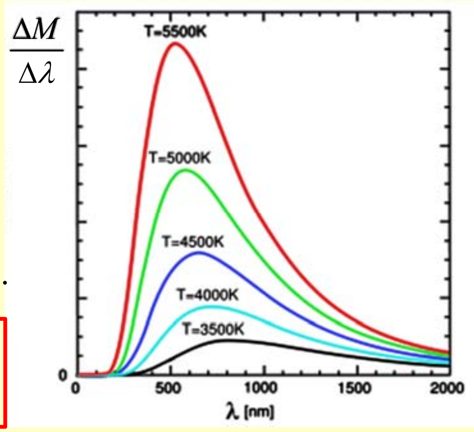
Emission spectrum of thermal radiation at various temperatures

$$T_1 > T_2 > T_3 > T_4 > T_5$$

$$M_1 > M_2 > M_3 > M_4 > M_5$$

$$\lambda_{\max 1} < \lambda_{\max 2} < \lambda_{\max 3} < \ldots$$

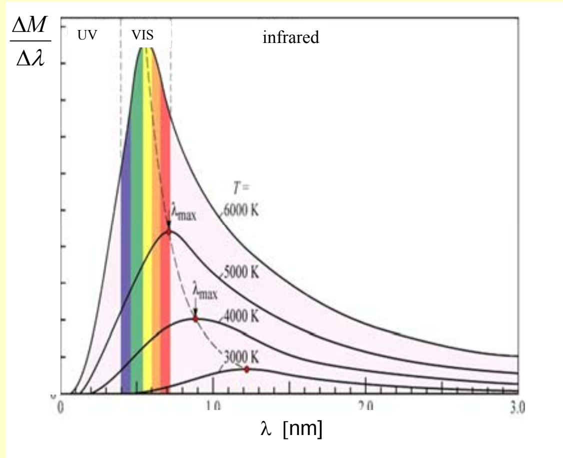
$$\mathrm{T} \times \lambda_{\max} = \mathrm{cons\,tan\,t}$$



Wien's displacement law

$$\mathrm{T} \times \lambda_{\max} = \mathrm{cons\,tan\,t}$$

$$k = 2.898 \times 10^6 [nm \times K]$$



The wavelength of maximum intensity shifts to shorter wavelengths when T is increased

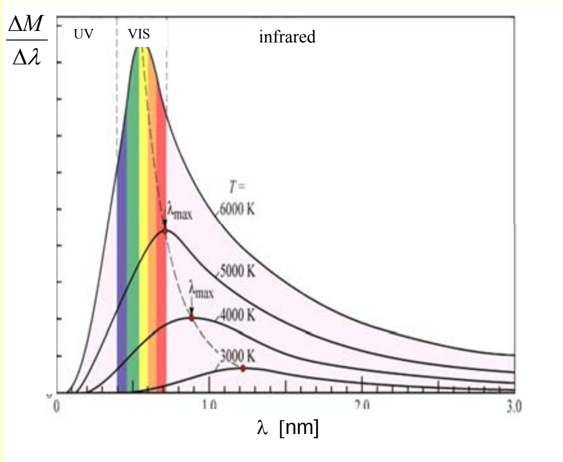
Wien's displacement law

$$T \times \lambda_{max} = \text{cons tan t}$$

$$k = 2.898 \times 10^{6} [nm \times K]$$

$$T_{bodysurface} \approx 305[K]$$

$$\lambda_{max} \approx 9500[nm]$$



Under 700 K the emitted radiation is not visible

Subjective colours

480ºC	faint red glow
580ºC	dark red
730ºC	bright red, slightly orange
930ºC	bright orange
1100ºC	pale yellowish orange
1300ºC	yellowish white
>1400ºC	white

Applications

1. Medical application – telethermography

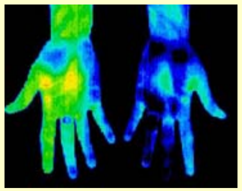
non-invasive imaging technique which can evaluate the body surface thermal gradients

Applying Wien's Law to humans, one finds that the peak wavelength of light emitted by a person is

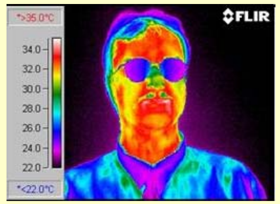
$$\lambda_{peak} = \frac{2.898 \times 10^{6}\ \mathrm{K \cdot nm}}{305\ \mathrm{K}} = 9500\ \mathrm{nm}$$

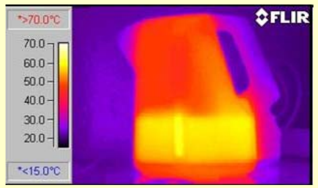
This is why thermal imaging devices designed for human subjects are most sensitive to **7-14 micrometers** wavelength

=> tumours, inflammations, constriction of vessels



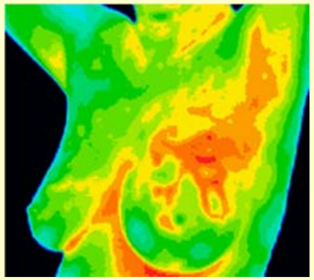
photos by normal and by infra-camera

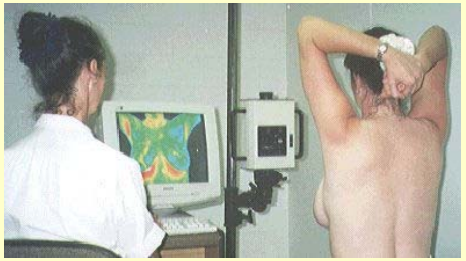




Application fields

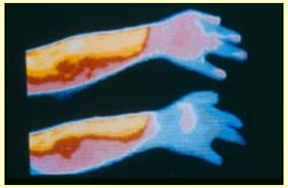
- rheumatology
- diagnostics of breast cancer
- dentistry
- neurology



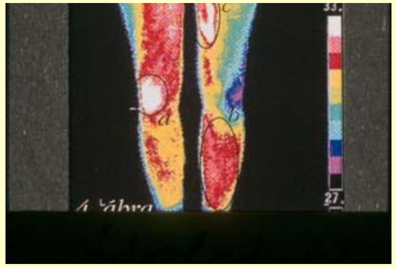


alterations in blood circulation

Effect of smoking

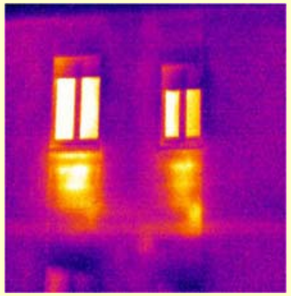


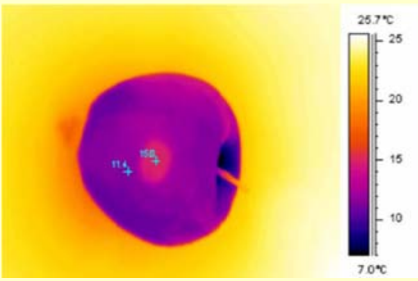
Inflammation and trombosis



2. Non-medical application

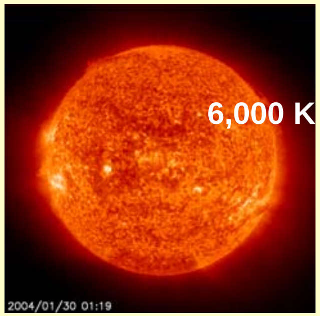
Architecture - insulation techniques





Food industry

Astronomy



	T (K)	λ_{max} (µm)	Spectral range	M (W/m^2)
Sun	6000	0.5	VIS	7 x 10^7
Earth	300	10	infrared	460

Applications

3. Light sources

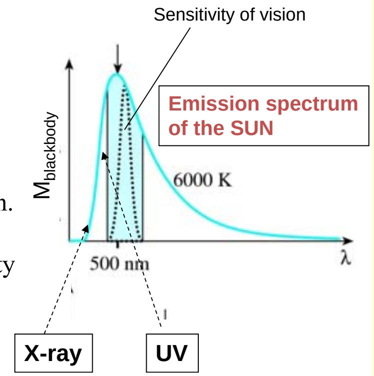
Light sources

based on thermal radiation

The Sun.

40 % of its thermal radiation falls into the sensitivity range of vision.

Its λ_{max} is close to the highest sensitivity of vision.



Emission spectrum on the Earth:
λ < 290 nm is filtered by the atmosphere

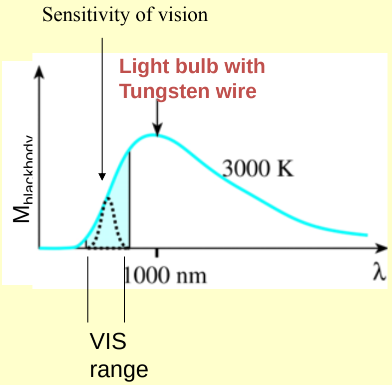
Incandescent lamps

Metal filaments in a glass bulb heated to high temperature to approach the spectrum of the Sun.

Light bulbs
Tungsten at 3000 K

Infralamps
Tungsten at 1300 K

Sollux lamps
High power Tungsten at T>3300 K with filters for long wavelength IR and filters for short wavelength UV -> UVA for tanning



Treatment of

Seasonal Affective Disorder (S.A.D.)

5000 K thermal radiation light source (λ_{max} = 580 nm) with UV filter

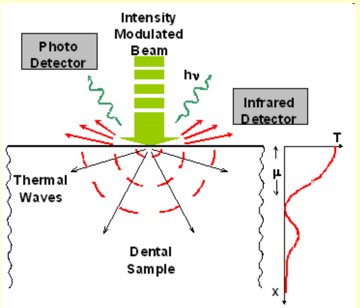
(Sun: about 6000 K, λ_{max} = 480 nm)

Strength of irradiation:
max . 5 - 10 thousand lux

(regular office ~ 50-100 lux, bright sunlight ~ 10^5 lux)

Time period: 10 – 15 minutes / day

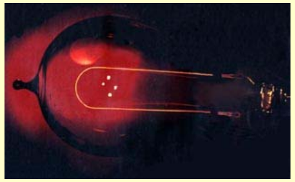
Photothermal detection of dental caries



Damjanovich, Fidy, Szöllősi: Medical Biophysics

II. 2.2
- 2.2.1
- 2.2.2
- 2.2.6

Generation of light – Light sources



Black-body radiation

Luminescence

Laser

Luminescence

Repetition

Types of energy states in atoms and molecules are independent (not coupled)
Energy states are non-continuous, but discrete
Transition between states involves packets (quanta) of energy)

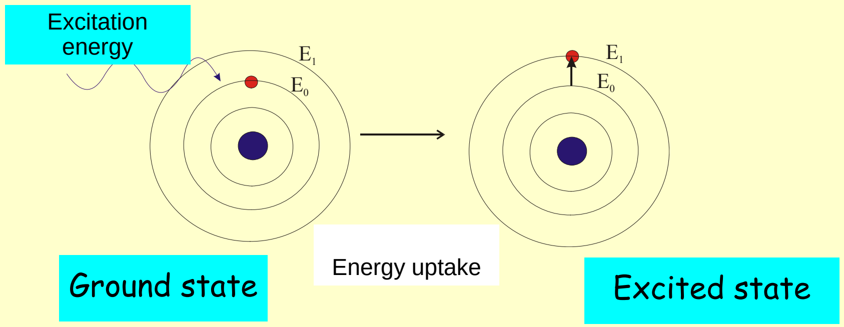
$$E_{total} = E_e + E_v + E_r$$

Scales of transition energies between different states are different:

$$E_e > E_v > E_r$$

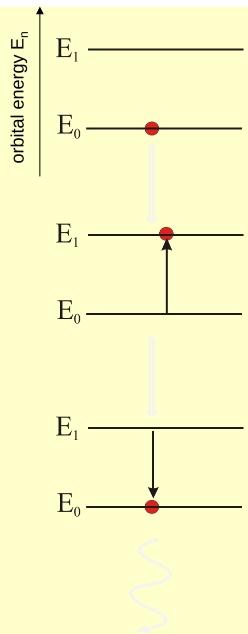
Consider a single atom

- Energy states are discrete
- Electrons occupy the lowest possible energy state (ground state)
- Pauli exclusion principle: no two identical fermions (particles with half-integer spin) may occupy the same quantum state simultaneously



Excitation modes

- absorption of radiation (UV/VIS) : *photoluminescence*
- chemical reaction: *chemo/bio-luminescence*
- Injection of charges: *electroluminescence*
- friction (mechancal deformation: *triboluminescence*
- thermally activated ion recombination: *thermoluminescence*
- Sound waves: *sonouminescence*



Excitation of external electron

De-excitation - elecron relaxation to ground state

spontaneously

Light emission

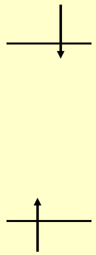
$hf=E_1-E_0$

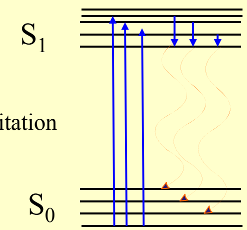
Luminescence: spontaneous light photon emission by electrons when they return from their excited state to their original (ground) state of lower energy

$hf=E_1-E_0$

The emitted photon energy is characteristic for the electronic orbitals, thus for the atom/molecule.

The energy of the electronic orbitals in molecules is perturbed by the discrete states of molecular vibrations





excitation

Non-radiant transitions

Light emission

Fluorescence

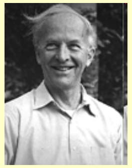
First excited singlet state

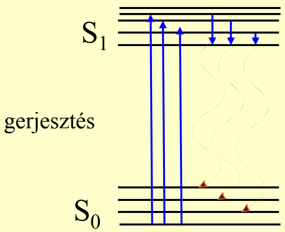
the spin states of the electrons

sum of all e^- spin quantum numbers=0

De-excitation by photon emission between singlet states

Kasha's rule:





fluorescence originates always from the vibrational state of lowest energy within the lowest electronic excited state.

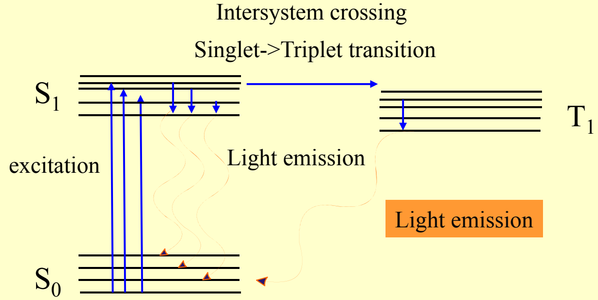
Fluorescence

De-excitation by photon emission between singlet states

$E_{excitation} \geq E_{fluorescence}$

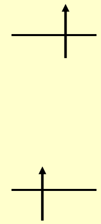
$\lambda_{excitation} \leq \lambda_{fluorescence}$

Stokes-shift



Phosphorescence

spontaneous light photon emission from metastable excited state

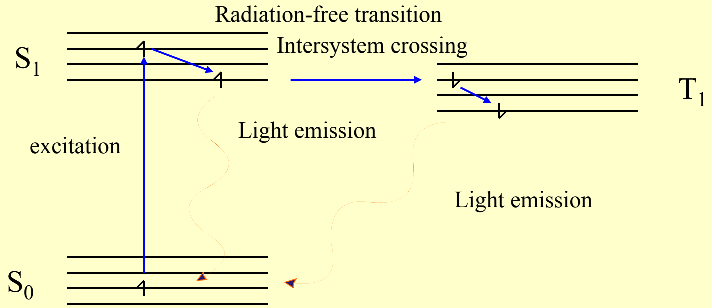


Triplet state

sum of all e^- spin quantum numbers=1

Metastable state

Emitted photon energies



Fluorescence **Phosphorescence**

Stokes-shift

$E_{excitation} \geq E_{fluorescence} > E_{phosphorescence}$

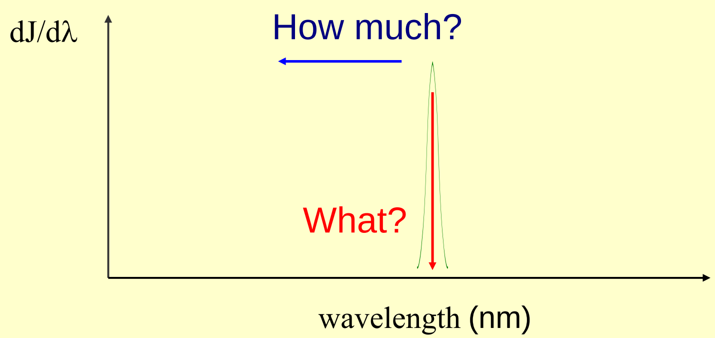
$\lambda_{excitation} \leq \lambda_{fluorescence} < \lambda_{phosphorescence}$

Characteristics of emitted light

Wavelength distribution of emitted light

Emission spectrum

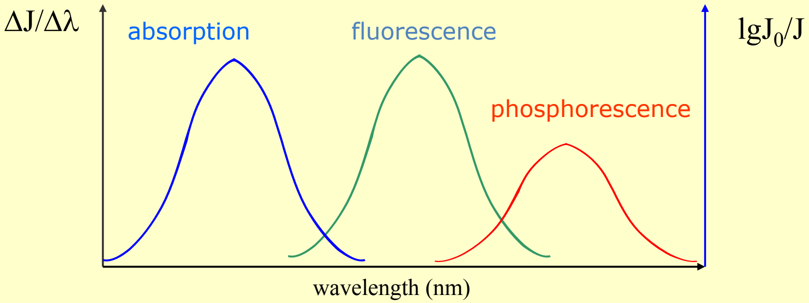
Atoms line spectrum



Wavelength distribution of emitted light

Emission spectrum

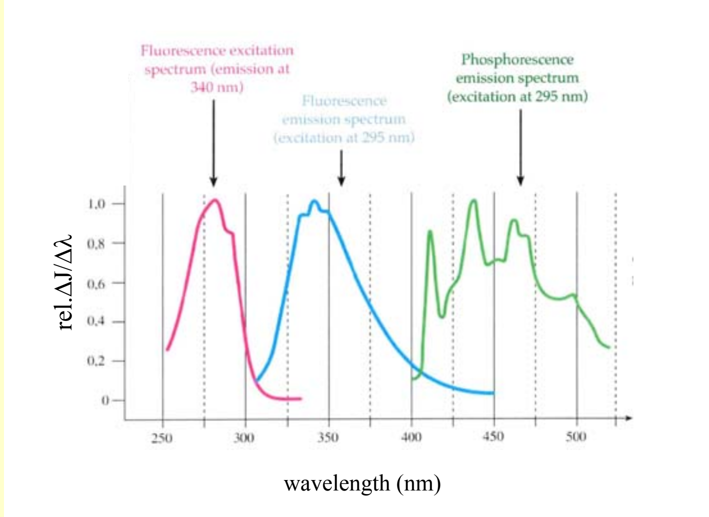
molecules: band spectrum



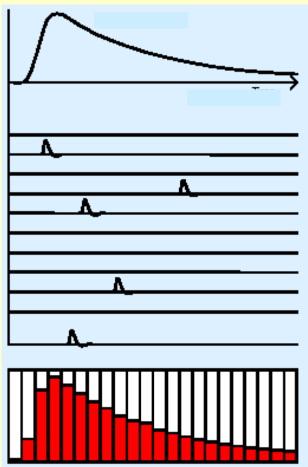
$\lambda_{excitation} \leq \lambda_{fluorescence} < \lambda_{phosphorescence}$

Stokes shift

E.g.: Corresponding spectra of triptophane



Excited-state lifetime



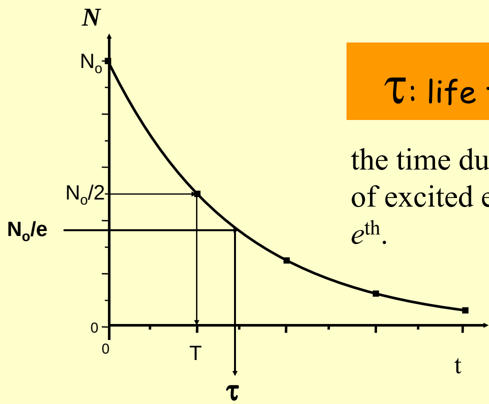
Single photon counting

Measuring of time gap between excitation and photon emission.

Statistical analysis of large number of measurements.

Number of excited electrons → $N = N_0 e^{-\frac{t}{\tau}}$ ← time after excitation

- Exponential function

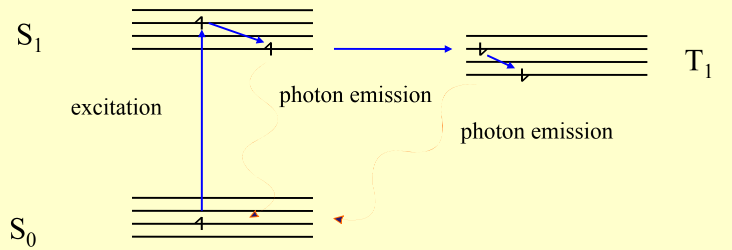


τ: life time

the time during which the number of excited electrons decreases to its e^{th}.

Typical excited-state lifetimes

Lifetime the time during which the number of excited electrons decreases to its e^{th}.



Fluorescence — short — $10^{-9} - 10^{-7}$ s

Phosphorescence — long — $10^{-3} - 10^{2}$ s

Is excitation always followed by photon emission?

Excited state decay can be caused by mechanisms other than photon emission and are therefore often called "non-radiative rates„.

These can include: chemical reaction, dynamic collisional quenching, near-field dipole-dipole interaction, internal conversion and intersystem crossing.

Is excitation always followed by photon emission?

Quantum yield

$$A \xrightarrow{h\nu} B$$

Reciprocal of the number of absorbed photons for one photon emission

Fluorescence quantum yield (Q_F)

$$Q_F = \frac{number.of.photons.emitted}{numbe.of.photons.absorbed}$$

$$Q_F \leq 1$$

Types of luminescence
- fluorescence
- phosphorescence

They can be characterized by
- emission spectrum
  - types
  - position of peaks
  - amplitude
- lifetime
- quantum yield

Application fields of luminescence

Light sources (lightning, fertilization, sunbeds, photomedicine...)

concentration determination (flame photometer)

luminescence spectroscopy

luminescence microscopy

dosimetry (see later)

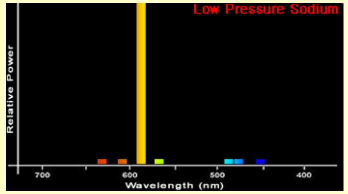
archeology

architecture

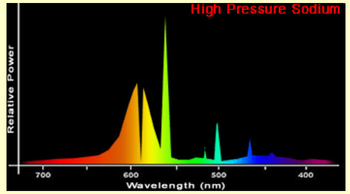
safety controll … many more

Luminescent light sources

Metal vapor lamps

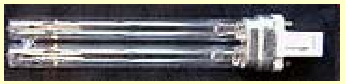


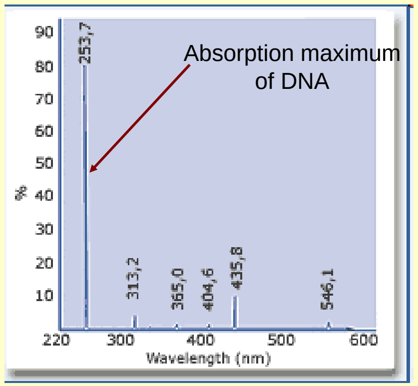
Low-pressure Na-vapor lamp



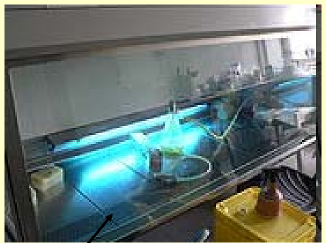
High-pressure Na-vapor lamp

Low-pressure Hg-vapor lamp



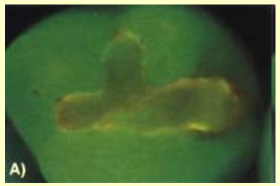


Emission spectrum



„germicid lamp”

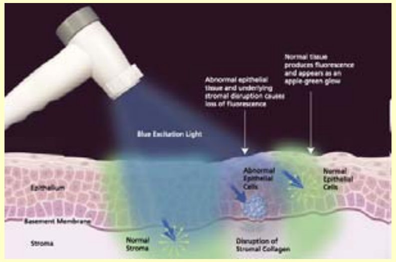
Application in dental medicine



Red fluorescence indicates the activity of identifies cariogenic bacteria

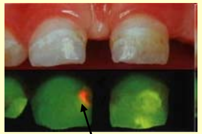
Auto-fluorescence of teeth. When teeth are illuminated with high intensity blue light they will start to emit light in the green part of the spectrum.

amalgam restoration



Healthy and malignant tissues
different fluorescent properties

Teeth
native and fluroescent
images

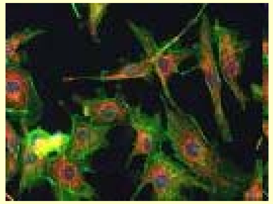


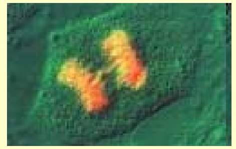
Active caries

caries

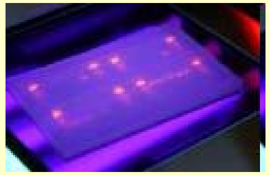
Tooth
native and fluroescent
image

Luminescent microscopy





Laboratory application in many ways



And more...

Damjanovich, Fidy, Szöllősi: Medical Biophysics

II. 2.2
- 2.2.4
- 2.2.6

VI.3.3
- 3.3.1
- 3.3.2 pp. 411-413
- 3.3.3