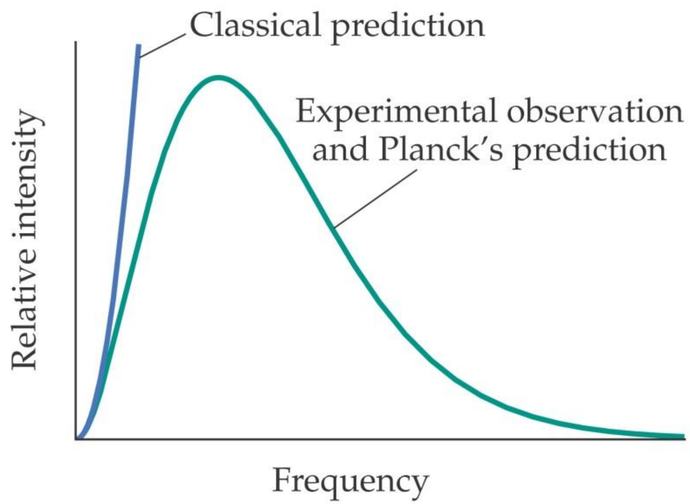
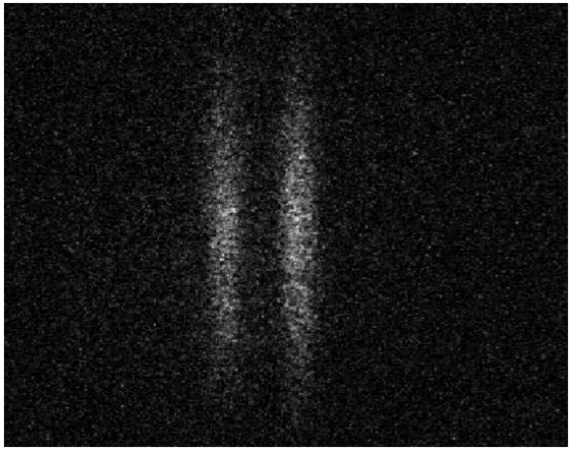
C11 Light Sources

- Photometry and radiometry;
- Blackbody Radiation;
- Photon, photoelectric effect, wave-particle duality.





Light sources

Blackbody radiation

Electrically driven

- Thermal radiation Tungsten halogen lamp
- Gas discharge Mercury lamp, sodium lamp
- Solid luminescence Electroluminescence、Light Emitting Diode (LED), Laser Diode (LD)

Laser

- Solid-state laser Ti-Sapphire laser, semiconductor laser
- Gas laser He-Ne, Ar ion
- Dye molecular laser

X-ray: High-speed electron bombard heavy metal targets (W, Ag, Mo, Cu etc.)

Synchrotron radiation: electromagnetic radiation emitted in the tangential direction as electrons move in a circular motion in the accelerator.

§ 11.1 Blackbody radiation

At room temperature, iron is **black-gray**. At high temperature, it emits a **dark red** light. At very high temperature, it emits **orange** light.
Any object with a temperature above absolute zero can emit thermal radiation.

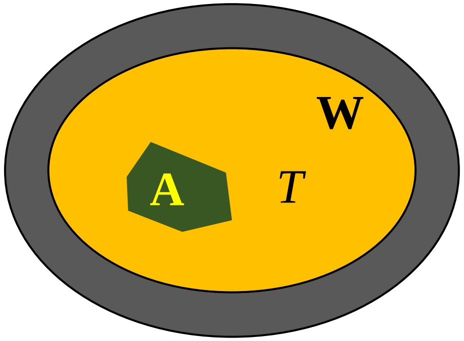
Thermal radiation: The radiation of a heated object. It is generated from random thermal motions of charged particles in a substance.

At equilibrium conditions, the energy **radiated** by an object must equal the energy it **absorbs**.

Objects with a high absorption rate also have a large radiation capability and vs.

Kirchhoff's Radiation Law

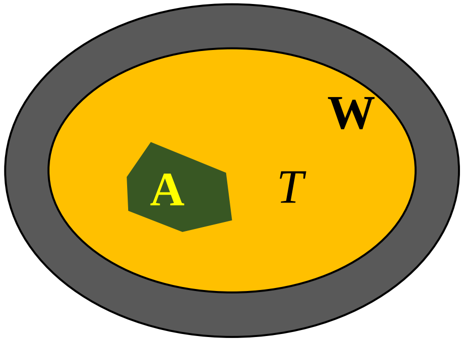
Imagine that the power absorbed by A is only from the radiation it absorbs, without any other way, as shown in the figure.



The object A is placed in an isothermal vacuum chamber. It absorbs the radiation in the cavity while emitting radiation. Finally it should reach the same temperature as the cavity wall. **Whatever the material of A and the cavity wall is, and if they are the same.**

Kirchhoff's Radiation Law

Under the Thermal equilibrium：



For A: $P_{\text{emit}} = P_{\text{abs}}$

$R = \alpha I$ α is absorption rate.

Radiation $\propto$ *Irradiance*

Under thermal equilibrium conditions, the ratio of the irradiance of the object to its absorption rate is equal to the irradiance I in the cavity, independent of the nature of the object.

$$R/\alpha = I$$

Kirchhoff's Radiation Law: At thermal equilibrium, the ratio between the spectral irradiance and the spectral absorption coefficient is only a function of the wavelength of the radiation and the temperature T, independent of the nature of the radiating object itself.

Kirchhoff's Radiation Law

Mathematical representation of Kirchhoff's Radiation Law:

$$\frac{r_{\mathrm{A}}(\lambda,T)}{\alpha_{\mathrm{A}}(\lambda,T)}=\frac{r_{\mathrm{W}}(\lambda,T)}{\alpha_{\mathrm{W}}(\lambda,T)}=f(\lambda,T)$$

$r(\lambda,T)$ Spectral radiance

$\alpha(\lambda,T)$ Spectral absorption rate

$f(\lambda, T)$ is a universal function that is independent of the nature of the object.

$$\boxed{\frac{r(\lambda,T)}{\alpha(\lambda,T)}=f(\lambda,T)}$$

If $\alpha \nearrow \rightarrow R \nearrow$

A good absorber is a good emitter.

If object transmittance $\tau = 0$, then $\alpha = 1 - \rho$ (Reflectivity)

A good emitter must be a weak reflector.

Blackbody radiation

Perfect blackbody (or blackbody): An object with a spectral absorbance of 1 for all wavelengths of radiation at any temperature. It is an ideal model for thermal radiation.

$\alpha \equiv 1$ is independent of λ, T

$$\frac{r(\lambda,T)}{\alpha(\lambda,T)} = f(\lambda,T)$$

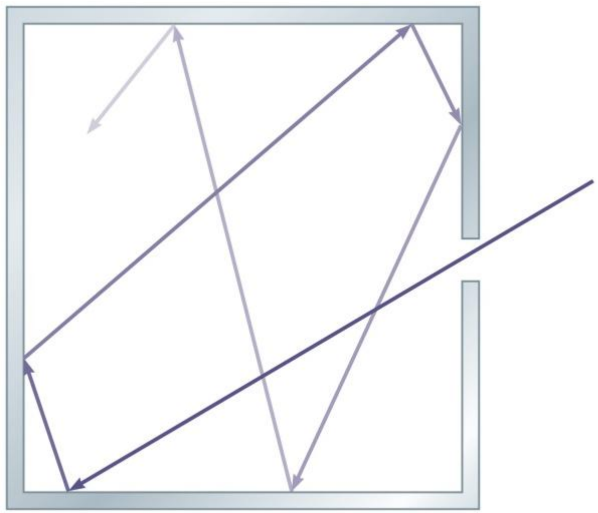
Spectral radiance of blackbody:

$$r_0(\lambda,T) = f(\lambda,T)$$

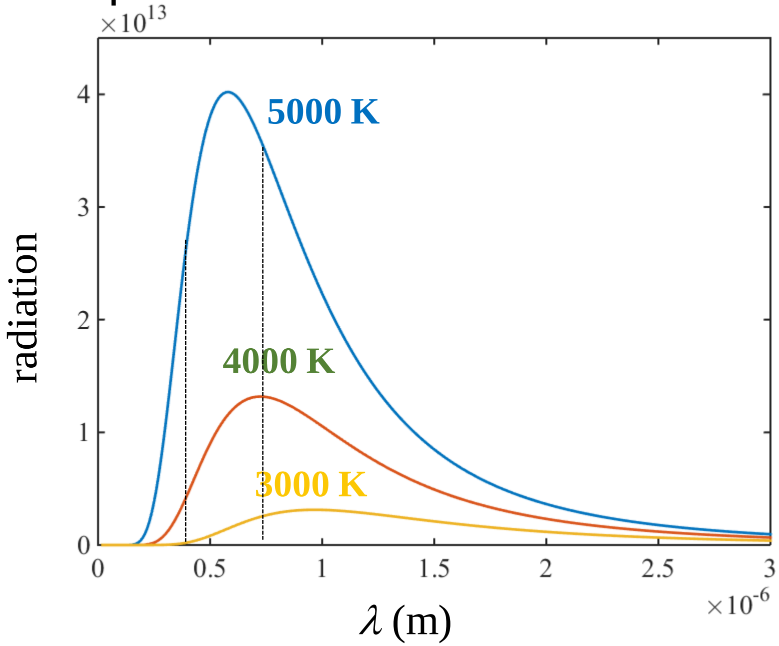
By measuring the spectral radiance of the black body, the universal function $f(\lambda, T)$ can be obtained, and the spectral radiance of any substance can be obtained.

Blackbody radiation

Blackbody $\alpha \approx 1$



Blackbody radiation spectrum experimental curve



If the wall of the chamber is heated, the radiation of the aperture corresponds to the radiation of a black body having an area equal to the area of the aperture.

Relationship between radiance and spectral irradiance

$$R(T) = \int_0^\infty r(\lambda, T)\,\mathrm{d}\lambda$$

Blackbody radiation

1. J. **Stefan** (1835 ~ 1893, Austria) **—** L. **Boltzman** (1844 ~1906, Austria) **law**:

$$R = \sigma T^4 \qquad \sigma = 5.670\times 10^{-8}\ \mathrm{W/m^2\cdot K^4}$$

The radiance of the blackbody is proportional to the fourth power of the absolute temperature.

2. **Wien displacement law**

$$\lambda_{\max} T = b \qquad b = 2.897\times 10^{-3}\ \mathrm{m\cdot K}$$

W. Wien (1864~1928, Germany)

1911 Nobel Prize in Physics

Blackbody radiation

$$\boxed{\lambda_{\max} T = b}$$

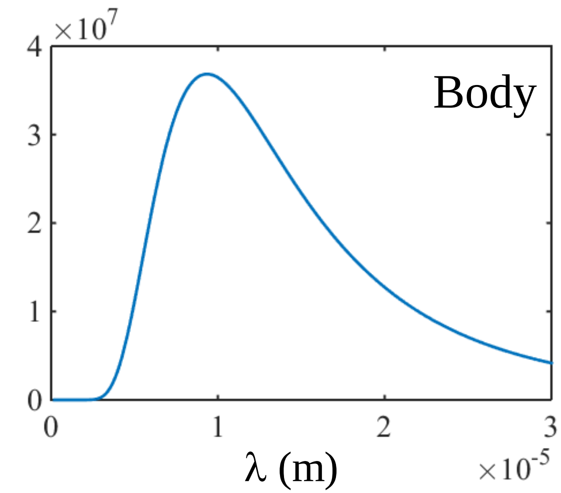
When the object can't be contacted, we can measure the radiation spectrum to obtain the temperature of the object.

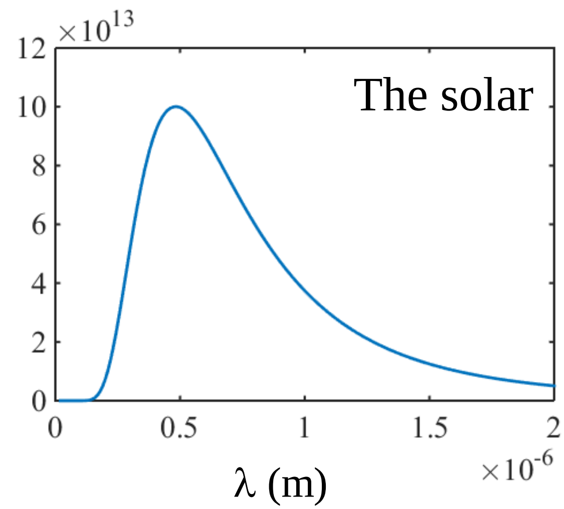
temperature ⇔ color

⇨ Color temperature

The peak wavelength of human/ the solar radiation is 9.4 μm (T = 310 K) /0.48 μm (T = 6000 K)

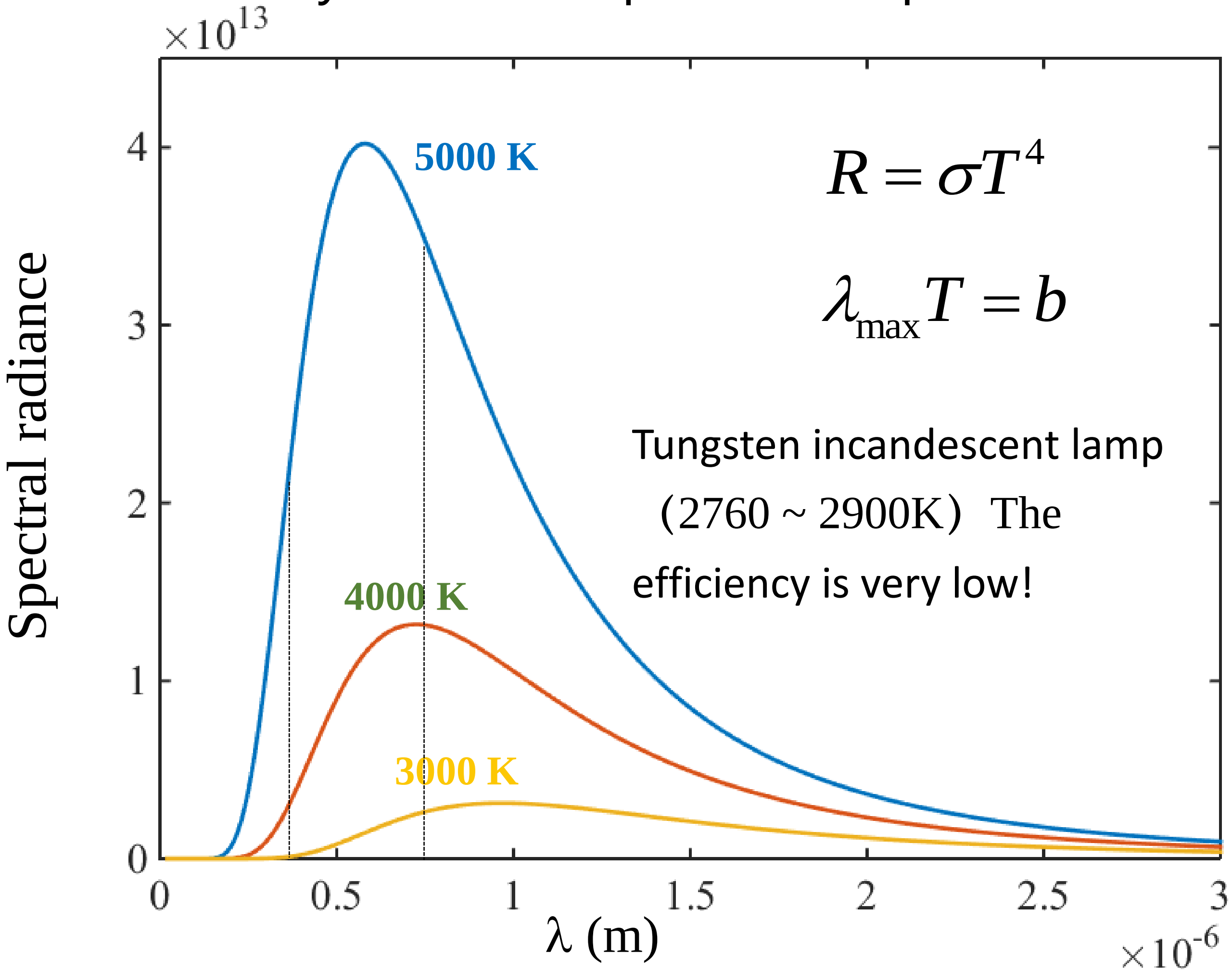
The energy of solar radiation is 50% in the visible and ultraviolet regions.
The energy radiated by the human body is almost entirely in the infrared region.





Blackbody radiation

Blackbody radiation spectrum experimental curve



$$R = \sigma T^4$$

$$\lambda_{max} T = b$$

Tungsten incandescent lamp （2760 ~ 2900K） The efficiency is very low!

Blackbody radiation explanation

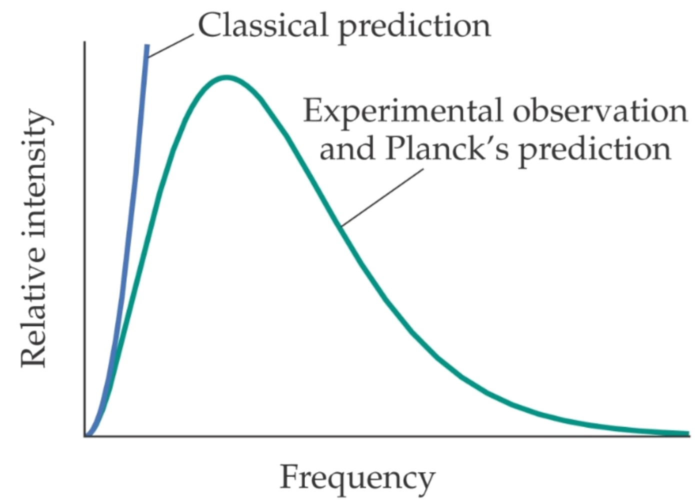
Classical theory of blackbody radiation encounters difficulties

① Wien derives blackbody radiation spectrum from thermodynamics

$$r_0(\lambda, T) = C_1 \lambda^{-5} e^{-C_2/\lambda T}$$

The results are consistent with the experimental results at shorter wavelengths and lower temperatures.

Ultra-violet catastrophe



② Rayleigh-Jeans formula

$$r_0(\lambda, T) = \frac{2\pi c}{\lambda^4} kT$$

Consistent with the experimental results when λ is large and temperature is high. For classical physics, Rayleigh-Jeans formula is impeccable, but it gives a completely different rule from the experiment!

推导过程可参见**崔宏滨**等《光学》第二版，P353-354

Blackbody radiation explanation

Quantum Theory : Planck's Radiation Law

In 1900s, Max Planck (1858 ~ 1947, Germany) assume that: The energy of the resonator in the blackbody cavity only can take a series of discontinuous energy, that is, an integral multiple of a certain minimum energy ε_0.

$$E_n = n\varepsilon_0$$

and $$\varepsilon_0 = h\nu$$

Planck constant

$$h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$$

Thus using the statistical physics to derive the blackbody radiation formula

$$\boxed{r_0(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}}$$

崔宏滨《光学》，P353-354

Blackbody radiation explanation

Planck's Radiation Law $r_0(\lambda,T)=\dfrac{2\pi hc^2}{\lambda^5}\cdot\dfrac{1}{e^{hc/\lambda kT}-1}$

From the Planck formula, the Stein-Boltzmann law and the Wien's displacement law can be obtained.

(1) Smaller λ is, the larger ν is, so $hc/\lambda kT >> 1$ or $h\nu >> kT$

$$e^{h\nu/kT} >> 1 \qquad \frac{1}{e^{h\nu/kT}-1} \approx \frac{1}{e^{h\nu/kT}}$$

$$\Rightarrow \quad r_0(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\cdot e^{-hc/\lambda kT} \qquad r_0(\lambda,T)=C_1\lambda^{-5}e^{-C_2/\lambda T}$$ **Wien formula**

With the decrease of λ (ultraviolet), $r_0 \to 0$ there will be no more "ultraviolet catastrophe". $e^{-hc/\lambda kT} \to 0$

Blackbody radiation explanation

Planck's Radiation Law $r_0(\lambda,T)=\dfrac{2\pi hc^2}{\lambda^5}\cdot\dfrac{1}{e^{hc/\lambda kT}-1}$

(2) In the case of large λ and high temperatures

$h\nu << kT$

i.e. $hc/\lambda kT << 1$

$$\frac{1}{e^{h\nu/kT}-1}\approx\frac{1}{1+\dfrac{h\nu}{kT}-1}=\frac{kT}{h\nu}$$

$r_0(\lambda,T)=\dfrac{2\pi hc^2}{\lambda^5}\cdot\dfrac{kT}{h\nu}=\dfrac{2\pi c}{\lambda^4}kT$ Rayleigh-Jeans formula

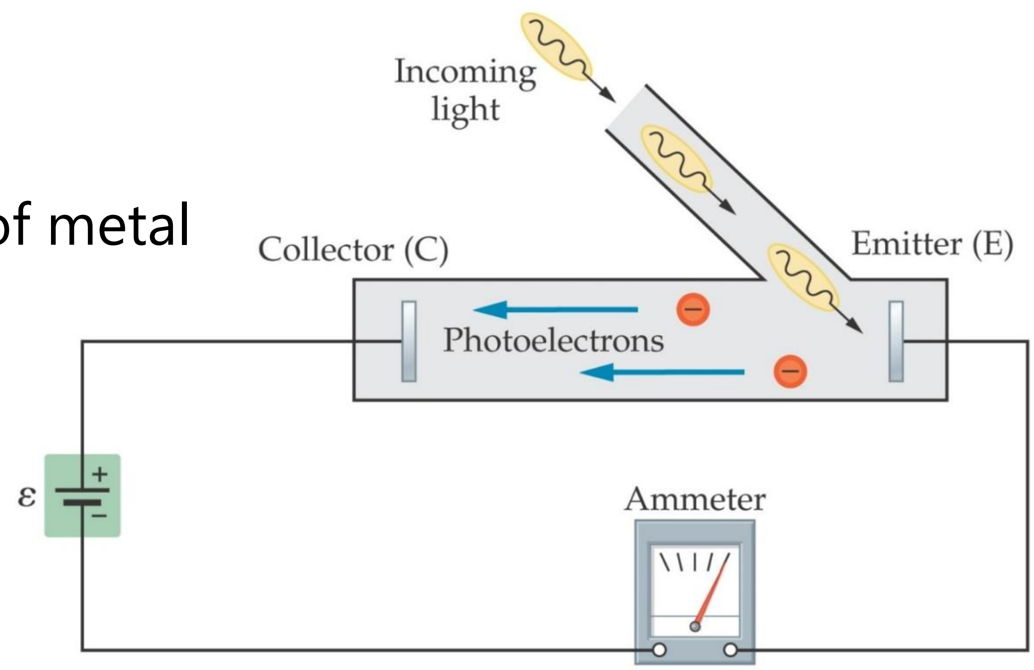
Planck won the 1918 Nobel Prize in Physics for his "discovery of the basic quanta, which made a huge contribution to the development of physics".

§ 11.2 Photons

Einstein proposed the light quanta hypothesis in 1905 and successfully explained all the experimental laws of the (external) photoelectric effect.

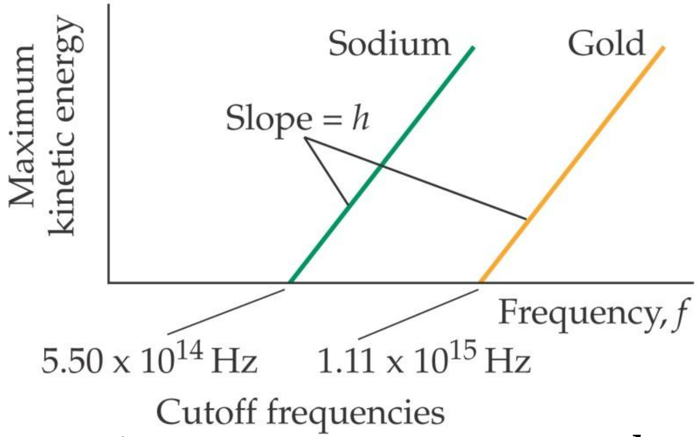
$$h\nu = \frac{1}{2}mv^2 + A$$

A is work function of metal

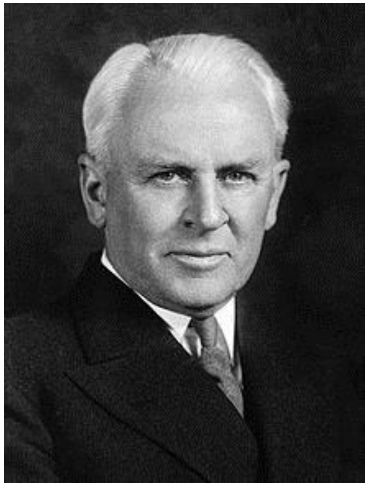


Measurement of Planck constant

Applying a reverse voltage to the vacuum tube electrode, so that the reverse voltage at which the photoelectron cannot reach the anode is the cutoff voltage V_s, there is



$$eV_s = \frac{1}{2}mv^2$$



Robert Andrews Millikan

1868 ~ 1953， USA

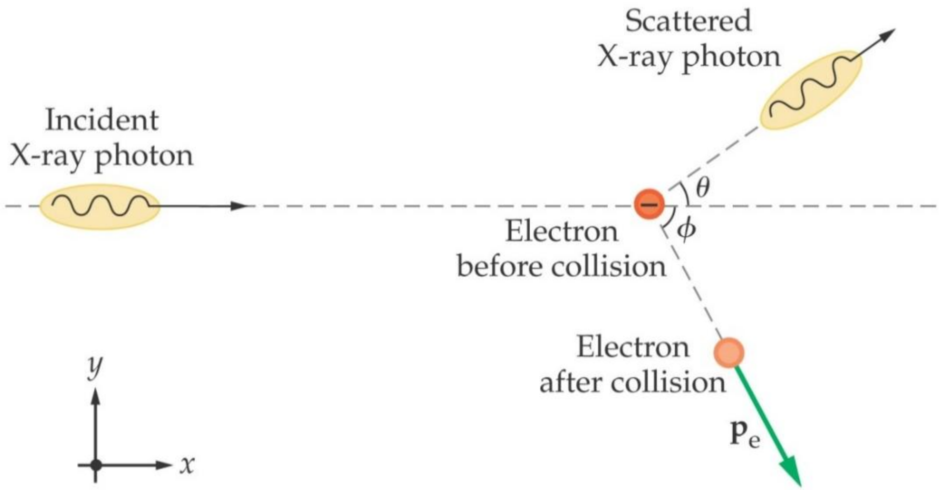
1923 Nobel Prize in Physics (Oil droplet experiment and photoelectric effect)

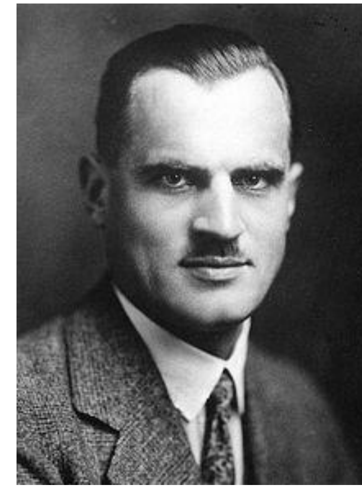
$$hv = \frac{1}{2}mv^2 + A \Rightarrow V_s = \frac{h}{e}v - \frac{A}{e}$$

1914s, Millikan experiment measured the Planck constant, and in 1916 he "had to" accept that Einstein's photoelectric effect equation was fully experimentally confirmed.

Compton scattering

Since a photon is a particle. Is there an experiment to prove the photon momentum?





Arthur Holly Compton,
1892 ~ 1962, USA
1927 Nobel Prize in Physics

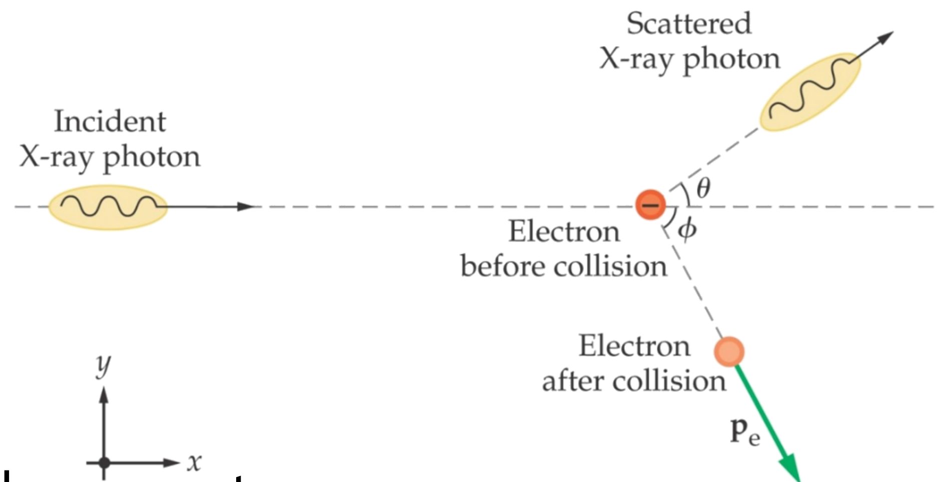
In 1923, Compton discovered that when X-rays passed through materials such as graphite and metals, in addition to wavelength-invariant scattering, there was also scattered photons whose wavelength is larger as the scattering angle increased.

Compton scattering

Momentum：

$$p = m'c = \frac{m'c^2}{c} = \frac{E}{c}$$

$$\Rightarrow \boxed{p = \frac{h\nu}{c}}$$



Energy conservation and momentum conservation during collision:

$$\begin{cases} h\nu + m_0c^2 = h\nu' + mc^2 \\ \mathbf{p} = \mathbf{p}' + mv \end{cases}$$

The derivation process uses relativistic knowledge (omitted), available

$$\Delta\lambda = \frac{h}{m_0c}(1 - \cos\theta)$$

This model successfully explained the Compton effect, and strongly support the theory of light quantum.

Energy and momentum

wave

wavelength λ wave vector $\mathbf{k}$ frequency ν period T
angular frequency ω velocity v

$$\mathbf{k} = \frac{2\pi}{\lambda}\hat{\mathbf{k}} \quad v = \frac{\lambda}{T} = \lambda\nu \quad \omega = 2\pi\nu = \frac{2\pi}{T} = \frac{2\pi}{\lambda}v = kv = k_0 c$$

particle

energy $E = h\nu = \hbar\omega$

momentum $\mathbf{p} = \hbar\mathbf{k} = \frac{h}{\lambda}\hat{\mathbf{k}}$

h Plank constant

$$h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$$

$$\hbar = h/2\pi$$

Light has **wave-particle duality** nature. When related to the propagation of light, the nature of wave is obvious; the nature of particle is significant in the interaction of light and matter.

Comparison: Photon and Electron

Electrons and photons are distinct entities.

	electron	photon
Rest mass	m_0	0
Motion mass	m	$h\nu/c^2$
Motion velocity	$< c$	c
Spin	1/2	1
Distribution law	Fermion	Boson

- Both have the wave –particle duality:

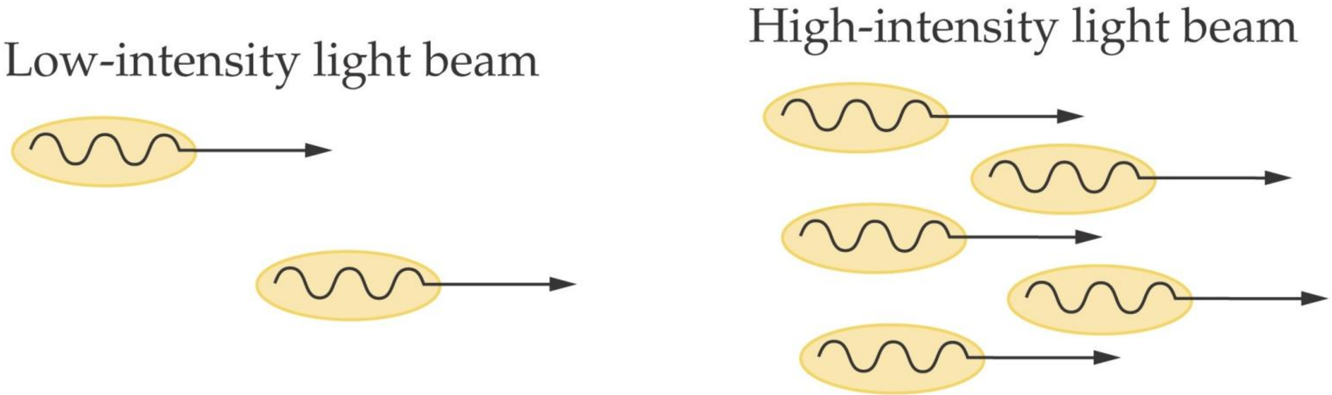
$$E = h\nu \qquad p = h/\lambda$$

$$E\sqrt{1-\frac{v^2}{c^2}} = m_0 c^2$$

- Both can carrying information.

Wave-particle duality

A beam of strong light intensity (fluctuation) contains more photons (particles), but the energy of each photon does not change.

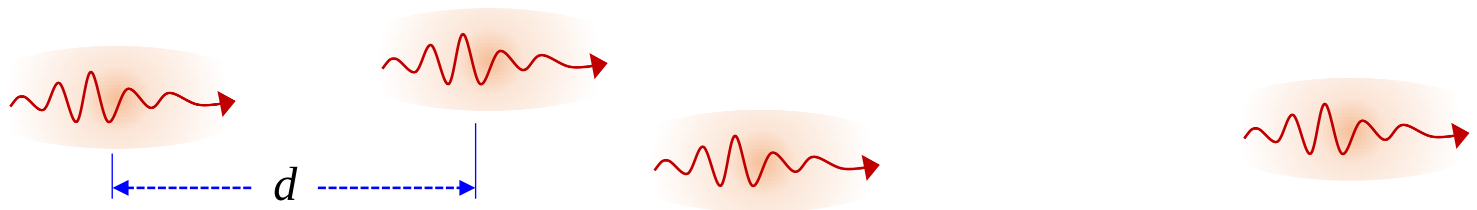


The electric field amplitude of a single photon is obtained by normalizing the energy density of the electromagnetic field to the energy $h\nu$ of a single photon after integration of the space; the electric field amplitude of the entire coherent light wave can be similarly normalized to N photon energies.

Wave-particle duality

For a laser beam, $\lambda = 632.8\ \mathrm{nm}$, $P = 1\ \mathrm{mW}$. Then the number of photons N hit on the tablet per unit time is

$$N \cdot h\nu = P \cdot t \qquad N = \frac{P \cdot t}{h\nu} = \frac{1\mathrm{mW} \times 1\mathrm{s}}{3.1391 \times 10^{-19}\,\mathrm{J}} = 3.1856 \times 10^{15}$$

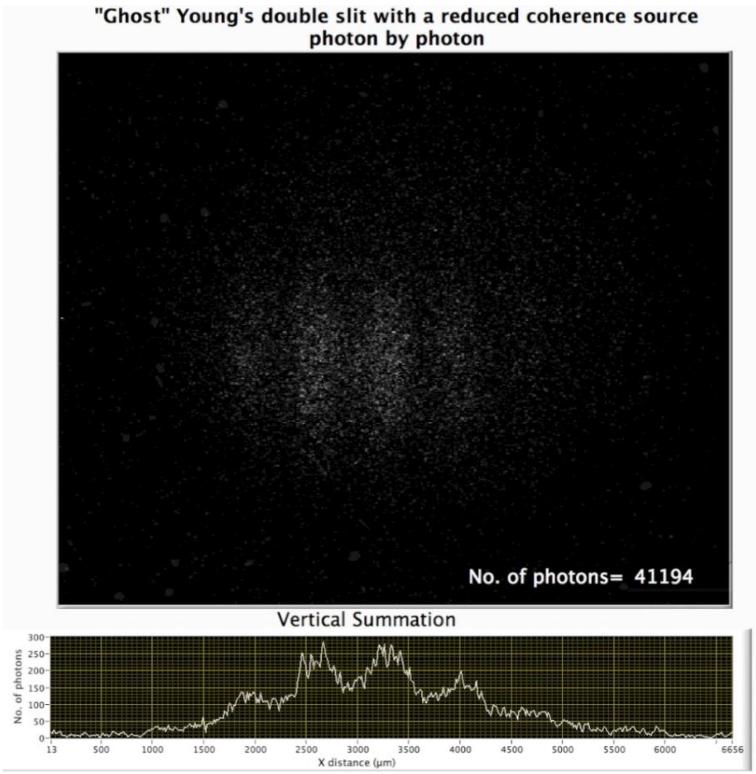


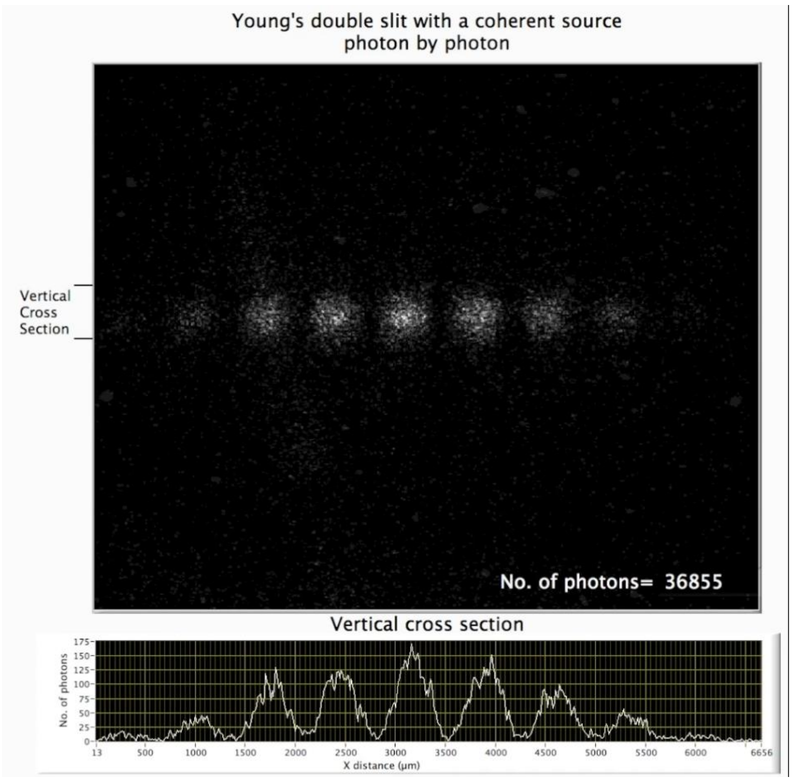
Since the laser is a continuous laser, the photons can be assumed to be evenly distributed over the propagation path, and the average photon-photon distance is

$$\langle d \rangle = \frac{c \cdot t}{N - 1} = \frac{2.99792458\,\mathrm{m/s} \times 1\mathrm{s}}{3.1856 \times 10^{15}} = 9.4109 \times 10^{-8}\,\mathrm{m} \approx 94\ \mathrm{nm}$$

Wave-particle duality

Single photon's Young's double slit interference video





Illinois Wesleyan University http://dx.doi.org/10.5525/gla.researchdata.281

Wave-particle duality

In 1923, de Broglie (1892 ~ 1987, France) proposed that, as waves can exhibit particle-like behavior, particles should exhibit wave-like behavior as well, i.e., **Wave-Particle Duality.**

He proposed that the same relationship between wavelength and momentum should apply to massive particles as well as photons:

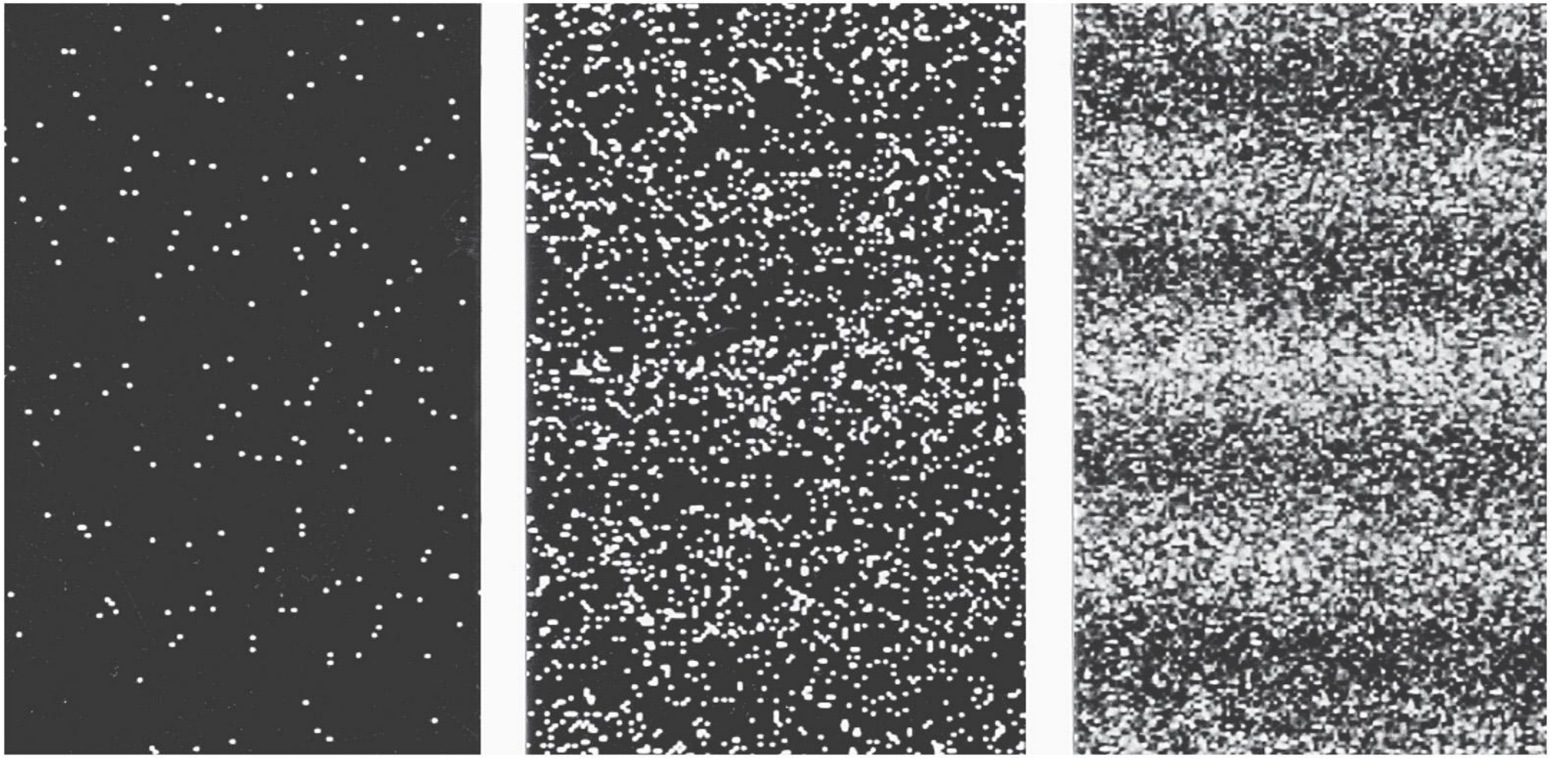
de Broglie Wavelength

$$\lambda = \frac{h}{p}$$

SI unit: m

Wave-particle duality

These images show the ‘growing’ of the diffraction pattern of **electrons**.

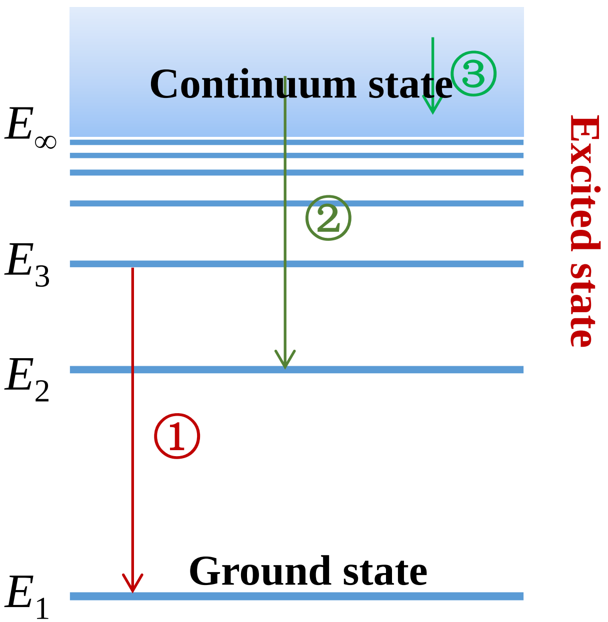


§ 11.3 Laser

① The transition of electrons from a high-excited state to a low-energy level emits a photon. The photons are often called **fluorescence**. The spectra of atoms are generally line spectra.

$$h\nu = E_{\mathrm{H}} - E_{\mathrm{L}}$$

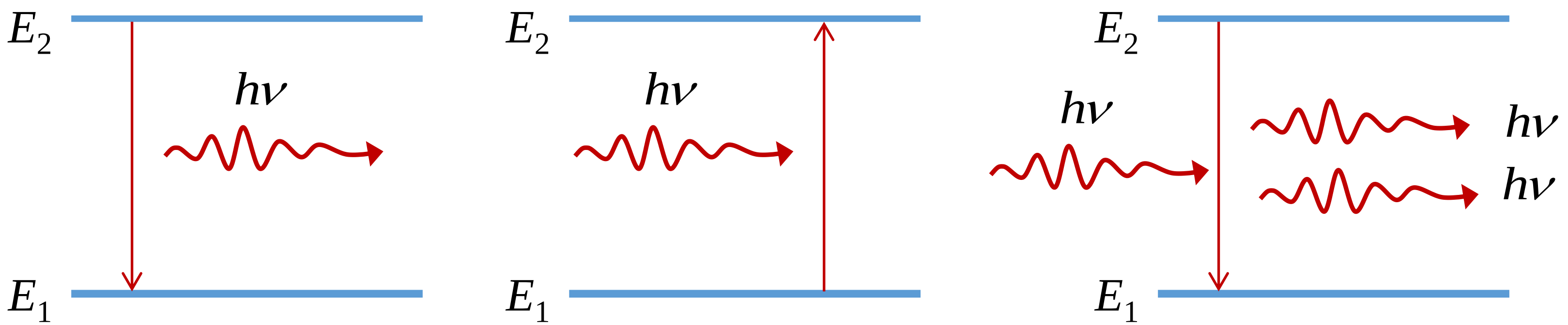
② When electrons transfer from a free state to a bound state, it emits a photon, called radiative recombination. The photons have a continuous spectrum.



③ When the kinetic energy (speed) of a free electron changes, the state of the electron changes >> optical radiation (electrodynamics).
Other example synchrotron radiation.

Spontaneous/stimulated emission

Einstein described the light-matter interaction by three basic processes: spontaneous emission, stimulated emission, and stimulated absorption.



Spontaneous emission | Stimulated absorption | Stimulated emission

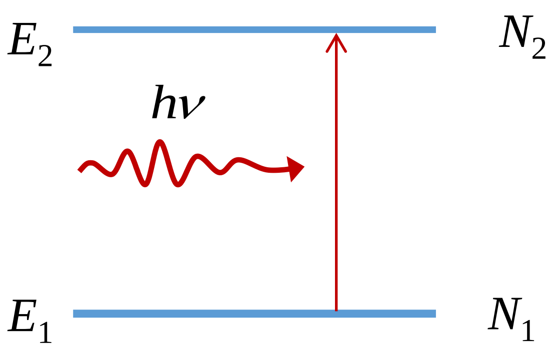
(1) **Spontaneous emission**: In the absence of external photons, atoms may spontaneously and independently transition from a high energy level to a low energy level. The number of atoms that have transitions in dt is proportional to the number of atoms at the E_2 level.

$$\mathrm{d}N_{21} = A_{21}N_2\mathrm{d}t$$

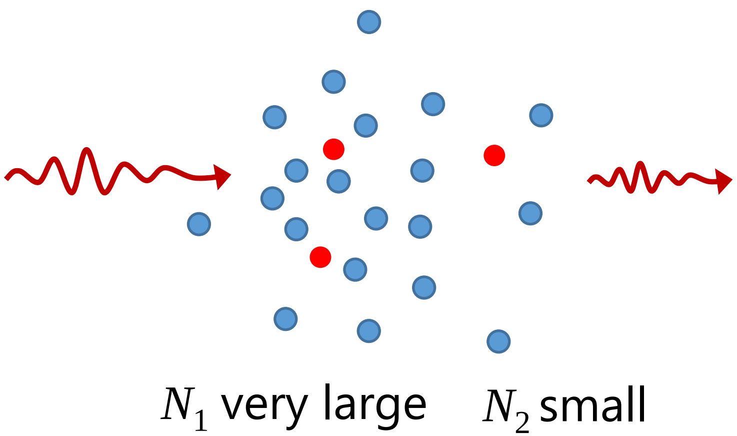
Spontaneous/stimulated emission

(2) **Stimulated absorption**: Atom at low energy E_1 absorbs a photon and jumps to a high energy level E_2. The number of atoms absorbed during the time dt is proportional to the photon number density and the number of atoms at the E_1 level.

$$\mathrm{d}N_{12} = B_{12}\rho\left(\nu\right)N_1\mathrm{d}t$$



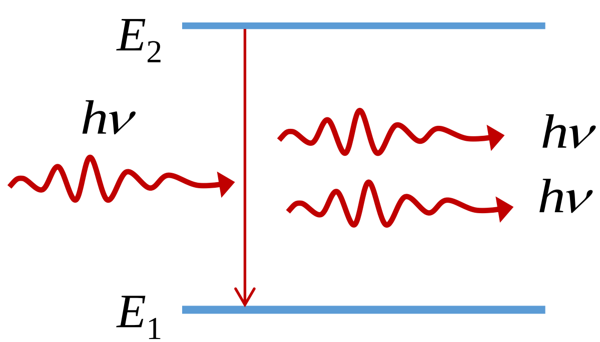
Stimulated absorption



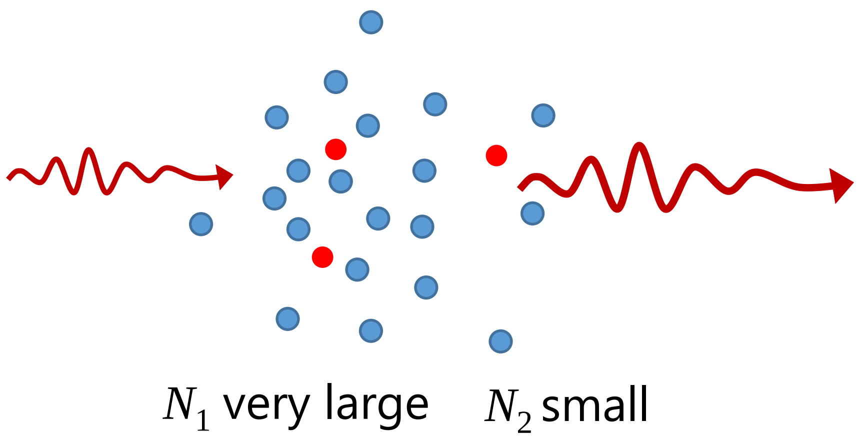
Spontaneous/stimulated emission

(3) **Stimulated emission**: Emitting a photon with the same frequency, phase, polarization, and propagation direction as the external photon. The number of atoms that generate stimulated radiation in $\mathrm{d}t$ is proportional to the photon number density and the number of atoms at the E_2 level.

$$\mathrm{d}N'_{21} = B_{21}\rho(\nu)N_2\mathrm{d}t$$



Stimulated emission



Spontaneous/stimulated emission

When light interacts with atoms, the three processes always exist at the same time. When the atom is in equilibrium, it should have

$$\mathrm{d}N_{21} + \mathrm{d}N'_{21} = \mathrm{d}N_{12}$$

$$\boxed{\mathrm{d}N_{21} = A_{21} N_2 \mathrm{d}t}$$ Spontaneous emission

$$\boxed{\mathrm{d}N_{12} = B_{12} \rho(\nu) N_1 \mathrm{d}t}$$ Stimulated absorption

$$\boxed{\mathrm{d}N'_{21} = B_{21} \rho(\nu) N_2 \mathrm{d}t}$$ Stimulated emission

that is,

$$A_{21} N_2 + B_{21} \rho(\nu) N_2 = B_{12} \rho(\nu) N_1$$

$$\rho(\nu) = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2}$$

In the equilibrium state, the number of atoms at each energy level in the system satisfies the **Boltzmann** distribution.

$$\Rightarrow \rho(\nu) = \frac{A_{21}}{B_{12} e^{h\nu/kT} - B_{21}}$$

$$\frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{kT}\right) = \exp\left(\frac{h\nu}{kT}\right)$$

Spontaneous/stimulated emission

$$\rho(\nu) = \frac{A_{21}}{B_{12}e^{h\nu/kT} - B_{21}}$$

If the spectral density of the external radiation field is described by the black body radiation law,

$$\boxed{\rho(\nu) = \underbrace{\frac{8\pi\nu^2}{c^3}}_{\text{Mode density}} \cdot \underbrace{\frac{h\nu}{e^{h\nu/kT} - 1}}_{\text{average energy of the Planck harmonic oscillator}}}$$

Mode density

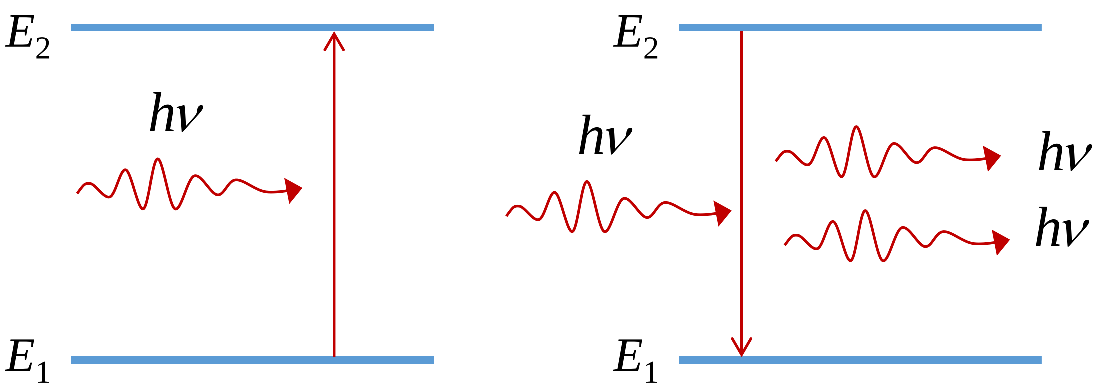
average energy of the Planck harmonic oscillator

So,

$$\frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1} = \frac{A_{21}}{B_{12}} \cdot \frac{1}{e^{h\nu/kT} - \frac{B_{21}}{B_{12}}}$$

$\Rightarrow$ $\boxed{B_{12} = B_{21} = B}$ $\quad$ $\boxed{\frac{A_{21}}{B} = \frac{8\pi h\nu^3}{c^3}}$

Condition for generating Laser



Identical photons (frequency, phase, vibration direction and propagation direction are the same)

Can be used to amplify light! Gain or loss?

$$\mathrm{d}N_{12} = B\rho(\nu)N_1\mathrm{d}t$$ Stimulated absorption

$$\mathrm{d}N'_{21} = B\rho(\nu)N_2\mathrm{d}t$$ Stimulated emission

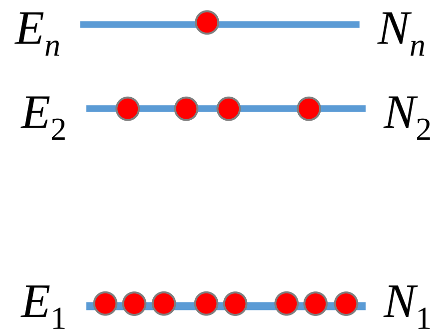
$$B_{12} = B_{21} = B$$

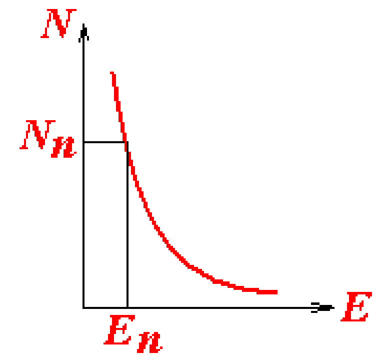
When a beam of light is incident on $h\nu = E_2 - E_1$, if $N_2 > N_1$ (the number of atoms in E_2 is large), the stimulated radiation > absorbed photons. Optical amplification!

Condition for generating Laser

A system consisting of a large number of atoms, obeys the statistical distribution of Boltzmann.

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right) << 1$$





Order of magnitude:

$T \sim 10^3\,\text{K}$

$kT \sim 1.38 \times 10^{-20}\,\text{J} \sim 0.086\,\text{eV}$

$E_2 - E_1 \sim 1\text{eV}$

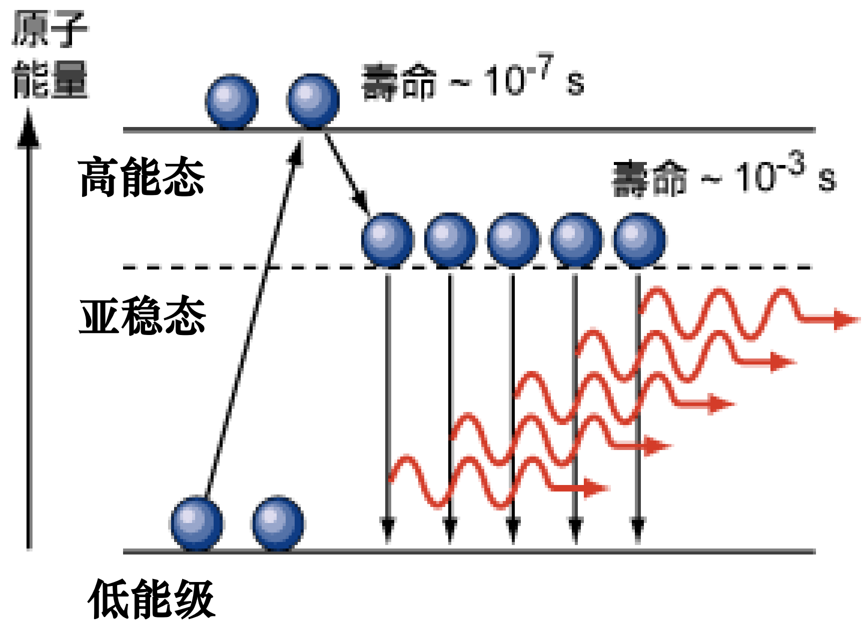
$$\boxed{\frac{N_2}{N_1} = e^{-\frac{1}{0.086}} \approx 10^{-5} << 1}$$

That is, the atom is basically in a low energy state. At this point, the absorbed > stimulated radiation. Light is weaken after passing through the atoms.

Condition for generating Laser

- To produce light amplification, $N_2 > N_1$, that is, the **population is inversed**.

The population inversion state is a non-thermal equilibrium state. In order to promote the occurrence of particle number inversion, a certain means must be used to excite the atomic system. This is called "**pumping**".



The pumping methods include light pumping, electric pumping and pumping by atomic collisions.

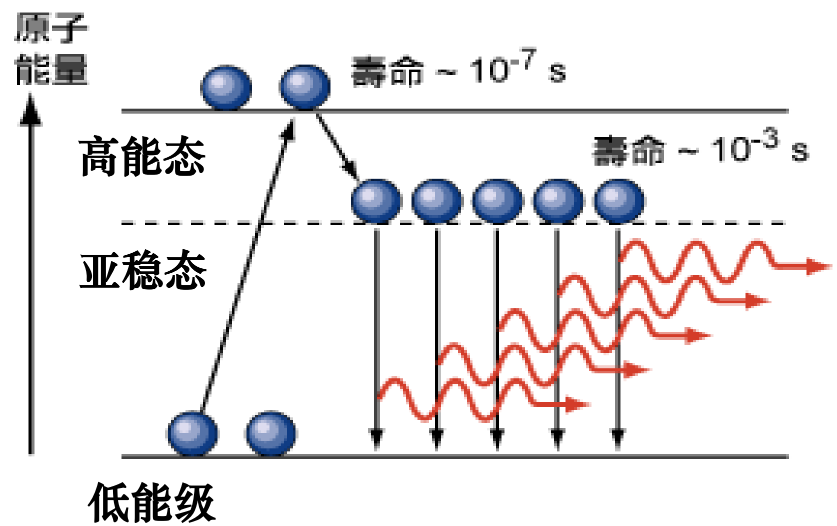
Condition for generating Laser

- To produce light amplification, $N_2 > N_1$, that is, the **population is inversed**.

In order to facilitate the population inversion, the activating substance (gain medium) should satisfy:

✓ An energy level system with three or more levels;

✓ The upper level should be "meta-stable" (small spontaneous emission coefficient);

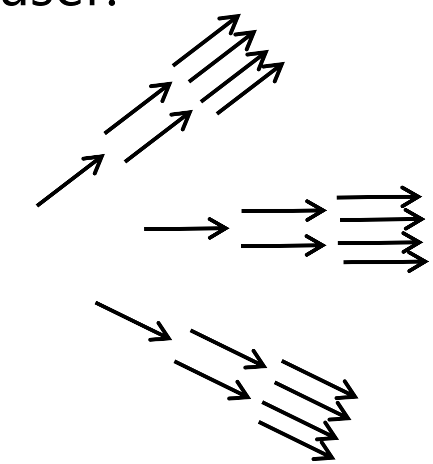


✓ The lower level should not be the ground state, and the spontaneous emission to the lower level should be large.

Condition for generating Laser

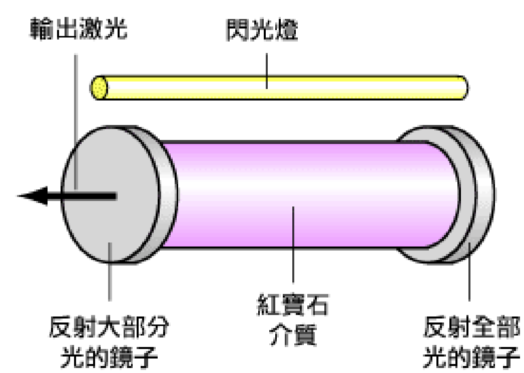
- In addition to the population inversion, the threshold condition must be met to produce the laser.

If population inversion is achieved, the spontaneous emission by **a certain atom** can trigger the simulated emission, but the direction is **messy** and cannot produce a strong laser.



The light must be repeatedly amplified in a certain direction to form a laser, called light oscillation.

This can be accomplished by an optical cavity, such as a **Fabry-Perot resonator** composed of two mirrors.



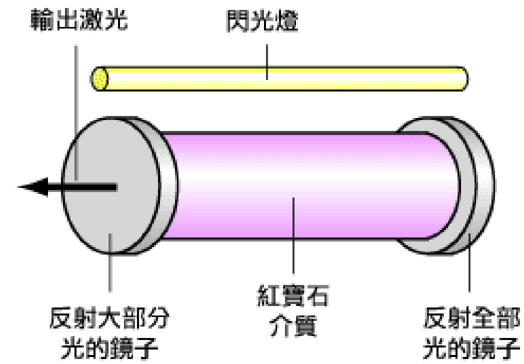
Condition for generating Laser

The role of the optical resonator:

1. directivity (along the axis);

2. optical amplification (extended gain medium);

3. frequency selection (narrow linewidth).



The threshold condition is $G \geq \frac{1}{2L} \ln \frac{1}{R_1 R_2} = G_m$

The pumping intensity is such that the total amplification at least compensates for the loss of light oscillation in the cavity.

Laser

Einstein's theory of stimulated radiation laid the theoretical foundation for experimentally obtaining lasers in the early 1960s.

Laser: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

Condition :

- The particle number reversal distribution is realized between certain energy levels in the working substance of the laser, even $N_2 > N_1$;
- The pumping is above the threshold condition. (To make the total amplification at least compensate for the loss of light oscillation in the cavity)

Laser

The three main components of the laser:

1. **Gain medium**:

   With a suitable energy level structure, particle number inversion can be achieved. Generally use three or four energy level systems. Two energy level systems? ?

2. **Pump**:

   The atoms are excited to maintain the population inversion. Such as electric pumping, optical pumping, etc.

3. **Optical resonantor:**

   Guaranteed light amplification (providing feedback), giving the laser good directionality and monochromaticity (mode selection).

Laser

In 1964, the Nobel Prize in Physics was awarded to three scientists in recognition of their fundamental work in quantum electronics, making an important contribution to the invention of masers and lasers.

Charles H. Townes
USA，1915-2015

Nikolay G. Basov
Soviet Union，1922-2001

Aleksandr M. Prokhorov
Soviet Union，1916-2002

恭喜恭喜，本门课程主体内容到此结束！