
The text under the slides was written by

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Related book chapters:
- I/1.1.3. The electron as a wave (pp. 26-27)
- I/1.2.2. The Heisenberg uncertainty relation (pp. 29-31)
- II/2.1.4-2.1.5. Interference of light. Light deflection and diffraction (pp. 115-118)
- II/2.1.8. Light as an electromagnetic wave and as photon radiation of light particles (pp. 121-123)
- II/2.2.1.-2.2.3. Thermal radiation (pp. 123-128)
The slide summarizes the main aims and topics of the lecture.

- Light is one of the most important radiation form for living organisms. Besides the perception through our eyes light has some important medical applications such as various microscopic methods or therapeutic applications (e.g. photodynamic therapy etc.). Moreover, electromagnetic waves are widely used in medical imaging methods such as computer tomography, positron emission tomography and magnetic resonance imaging.

- You are going to get introduced to the dual nature of light and the experimental demonstration of the duality during the lecture. Furthermore, we are going to talk about the de Broglie hypothesis regarding the matter waves and the Heisenberg uncertainty principle.

- The major aims are to understand that in some experiments light acts as a wave and in others it acts as a particle as well as the conclusion that light is composed of corpuscles, or discontinuous quanta of energy that are called photons, and as the consequence of the Heisenberg uncertainty principle that is the quantum world does not exist in a deterministic form, but rather as a collection of probabilities.
The nature of light

velocity in vacuum: \( c = 3 \times 10^8 \text{ m/s} \)

in other materials: \( v = \frac{c}{n} \), \( \left( \lambda = \frac{c}{f} \right) \) where \( n \) is the index of refraction

End of the 19th century

electromagnetic wave

transversal wave propagating with the speed of light \( (c) \), having two components, electric and magnetic

proof for the wave nature of light: \textit{interference} phenomena

Beginning of the 20th century

particle (photon)

\[ E = hf = \frac{hc}{\lambda}, \] where \( h \) = Planck’s constant = \( 6.63 \times 10^{-34} \text{ Js} \)

proof for the particle nature of light: \textit{photoelectric} effect

All electromagnetic waves such as light \textit{travel in a vacuum with the speed of light}, that is \( 3 \times 10^8 \text{ m/s} \). In other media its speed is calculated as \( v = \frac{c}{n} \), where \( n \) is the index of refraction of the given medium. At the end of the 19th century it was shown that \textit{electromagnetic waves are transverse waves} because their components, the electric and magnetic fields are \textit{perpendicular} to the direction of propagation of the wave. The first clear demonstration of the wave nature of light was provided by \textit{Thomas Young}, who \textit{showed that} under appropriate conditions, light \textit{exhibits interference behavior}. At the beginning of the 20th century it was concluded that light \textit{is composed of corpuscles, or discontinuous quanta of energy}. These corpuscles or quanta are now \textit{called photons} to emphasize their particle-like nature. \textit{According to Einstein’s theory}, the energy of a photon is proportional to the frequency of the electromagnetic wave associated with it, or \( E = hf \), where \( h = 6.63 \times 10^{-34} \text{ Js} \) is Planck’s constant. The experimental proof for the particle nature of light is the \textit{photoelectric} effect. \textit{Electron volt} is the unit of energy. It is equivalent to the \textit{amount of kinetic energy gained by} a single electron \textit{when accelerated through} a potential difference of \( 1 \text{ V} \).
The wave nature of light is demonstrated by the Young’s double slit experiment. In this experiment there are two narrow, parallel slits on a non-transparent plate (in reality Young used pinholes rather than slits in his original experiments). A monochromatic light source is placed on one side of the plate and a screen on the other side. The light emerging from the two slits produces a visible pattern consisting of a series of bright and dark parallel bands called fringes. According to the Huygens’ principle the elementary waves start in identical phases from both slits, meeting later at different locations of the screen in different phases depending on the distance they travelled. When the light waves arriving from the slits at a point on the viewing screen are in phase constructive interference occurs and a bright fringe appears (the path difference is either zero or some integral multiple of the wavelength). When the light waves from the two slits combine destructively, that is the waves are out of phase at any location on the screen, a dark fringe results (the path difference is an odd multiple of ½ of the wavelength). Interference is a crucial proof for the wave nature of light. We generally use the term interference to refer to phenomena that occur when two or more waves meet. Observable interference at the appropriate points of the illuminated surface can only be produced by coherent light waves. Two waves are said to be coherent if the difference of their phases is constant.
Photoelectric effect is the most important experimental proof for the particle nature of light. The first discovery of this phenomenon was made by Hertz. Illuminating a metallic surface by light having a wavelength shorter than a certain limiting value causes the emission of electrons from the surfaces. The emitted electrons are called photoelectrons. The apparatus is an evacuated glass tube, which contains a metal plate (the emitter) connected to the negative terminal of a variable power supply. Another metal plate (the collector), is maintained at a positive potential by the power supply. When the emitter is illuminated by light electrons are ejected from the surface of the emitter and collected at the collector. If the wavelength of the incident light is short enough (or the energy is high enough), the photon has an adequate amount of energy to eject an electron from the metal. The value of the limiting wavelength is characteristic of the different metals. If the energy of the photon is higher than the energy required to remove an electron, the excess of energy is converted to kinetic energy of the electron according to the following equation: \( hf = A + E_{el,kin} \), where \( A \) is the work function, that is the minimum energy needed to remove an electron and \( E_{el,kin} \) is the kinetic energy of an ejected electron. If we apply a negative potential to the collector electrode and gradually increase it, the photoelectric current decreases, since electrons ejected from the metal surface can only reach the collector electrode if their kinetic energy is sufficient for overcoming the decelerating electric field. At a certain potential even the most energetic electrons (i.e. electrons with the highest speed) fail to reach the collector electrode.
and the photoelectric current drops to zero. In this case \[ \frac{1}{2}mv_{\text{max}}^2 = eU, \] where \( U \) is the stopping potential. The figure below shows that the shorter the wavelength the more negative the stopping potential is. The figure also shows that the stopping potential is independent of the radiation intensity but depends on the frequency (or wavelength) of light. The maximum kinetic energy of the photoelectrons is independent of light intensity but increases with increasing light frequency. The number of photoelectrons (i.e. the photoelectric current) at voltages exceeding the stopping potential depends on the intensity of the illuminating light.
In his doctoral dissertation in 1924, Louis de Broglie postulated that because photons have wave and particle characteristics, perhaps all forms of matter have both properties. This highly revolutionary idea did not have experimental confirmation at that time. de Broglie suggested that all material particles such as an electron with momentum $p$ should have a characteristic wavelength, that is $\lambda = h/p$, where $h$ is the Planck’s constant. That wavelength is called as de Broglie wavelength. The Davisson–Germer experiment (in 1927) confirmed de Broglie’s hypothesis by showing that electrons scattering off crystals form a diffraction pattern. The regularly spaced planes of atoms in crystalline regions of a nickel target act as a diffraction grating for electron matter waves. Based on the equation discussed above the de Broglie wavelength of an electron that moves at a speed of $v$ is approximately $729000/v$ nm.
Electromagnetic waves are transverse waves since the oscillations of the electric and magnetic fields take place in planes perpendicular to the direction of travel of the wave. All electromagnetic waves travel in vacuum with the speed of light, that is $3 \times 10^8$ m/s. The various types of electromagnetic waves are presented in the figure showing the wide and overlapping range of frequencies and wavelengths. The basic properties of the individual components of the electromagnetic spectrum are the same even though they show significant differences in their interaction with the material and in their practical use. The components of the electromagnetic spectrum according to their energy in ascending order are the following: radiowaves, microwaves, infrared, visible light, ultraviolet, X-ray, gamma radiation. Electromagnetic radiation with a higher frequency, i.e. shorter wavelength, is cosmic radiation from space. The visible light, the most familiar form of electromagnetic waves, may be defined as the part of the spectrum that is detected by the human eye (approximately 400-750 nm). The wavelengths of visible light are classified as colors ranging from violet to red.
Objects emit electromagnetic radiation whose spectrum depends on their temperature only, and is independent of the material of the object. This radiation is called thermal radiation.

Kirchhoff’s law of thermal radiation:

\[
\frac{M_{\lambda,i}}{\alpha_{\lambda,i}} = \frac{M_{\lambda,\text{black}}}{\alpha_{\lambda,\text{black}}} \quad \text{M}_{\lambda,i} - \text{the intensity of radiation emitted by object ‘i’ at wavelength ‘\lambda’},
\]

\[
\alpha_{\lambda,i} - \text{the absorption coefficient of object ‘i’ (the ratio of the absorbed radiation to the total radiation the body is exposed to)}
\]

If the emission of an object at a given wavelength is higher, it absorbs more efficiently at that wavelength.

The object whose absorption coefficient (\(\alpha\)) is 1, i.e. it absorbs all the radiation it is exposed to, is called black-body.

\[
\frac{M_{\lambda,i}}{\alpha_{\lambda,i}} = \frac{M_{\lambda,\text{black}}}{\alpha_{\lambda,\text{black}}} = \frac{M_{\lambda,\text{black}}}{1} = M_{\lambda,\text{black}}
\]

Therefore the spectrum of thermal radiation emitted by any object can be determined with the knowledge of the spectrum of a black body radiation and the absorption coefficient.

An object at any temperature emits electromagnetic radiation, called thermal radiation. The spectrum of the radiation depends on the temperature of the object. At low temperatures, the wavelengths of the thermal radiation are mainly in the infrared region and hence not observable by the eye. As the temperature of an object increases, the object eventually begins to glow red. At sufficiently high temperatures, it appears to be white. Kirchhoff’s law of thermal radiation, postulated by a German physicist Gustav Robert Kirchhoff, states that the intensity of radiation emitted („emissivity”) and the absorption („absorptivity”) of a surface at a given temperature and wavelength are equal. If the emission of an object at a given wavelength is higher, it absorbs more efficiently at that wavelength. The object whose absorption coefficient (\(\alpha\)) is 1, that is it absorbs all the radiation it is exposed to is called a blackbody. By definition, a blackbody is an ideal system that absorbs all radiation incident on it. A good approximation of a blackbody is a small hole leading to the inside of a hollow object. Therefore, the spectrum of thermal radiation emitted by any object can be determined with the knowledge of the spectrum of a black body radiation and the absorption coefficient.
All objects radiate energy continuously in the form of electromagnetic waves. The rate at which an object radiates energy is proportional to the fourth power of its absolute temperature. This is known as Stefan’s law, expressed in equation form as $M_{\text{black}}(T) = \sigma T^4$. The radiated energy varies with wavelength and temperature. As the temperature of the blackbody increases, the total amount of energy (area under the curve) it emits increases. Also, with increasing temperature, the peak of the distribution shifts to shorter wavelengths. This shift obeys the following relationship, called Wien’s displacement law that is $\lambda_{\text{max}} T = \text{constant}$, where $\lambda_{\text{max}}$ is the wavelength at which the curve peaks and $T$ is the absolute temperature of the object emitting the radiation. Thermal radiation is due to thermal vibrations of the electrons in the body at non-zero absolute temperature. As the frequency increases the number of the states (modes) of the oscillator increases. According to the equipartition theorem each mode of oscillation has the same amount of energy that is $kT$. Rayleigh and Jeans determined the concrete form of the spectral emission function of the radiation volume $E(f,T)$. In other words the Rayleigh–Jeans law attempts to describe the spectral radiance of electromagnetic radiation at all wavelengths from a black body at a given temperature through classical arguments. The figure at bottom shows an experimental plot.
of the blackbody radiation spectrum together with the theoretical picture of what this curve should look like based on classical theories. At long wavelengths (i.e. at low frequencies), classical theory is in good agreement with the experimental data. At short wavelengths (i.e. at high frequencies) however, major disagreement exists between classical theory and experiment. As $\lambda$ approaches zero, classical theory erroneously predicts that the intensity should go to infinity, when the experimental data show it should approach zero. In 1900, Max Planck developed a formula for blackbody radiation that was in complete agreement with experiments at all wavelengths, leading to an observed experimental curve shown by the figure at bottom. Planck hypothesized that the energy of the oscillators (he called them as resonators) was limited to a set of discrete integer multiples of a fundamental unit of energy called the action quantum that is equal to $hf$. The idea of Planck’s set the stage for the development of quantum physics, which fundamentally changed not only the natural sciences but the entire world. Combining these two counteracting principles we can deduce the Planck’s Radiation Law that can be used to derive both the Wien’s law and the Stefan’s law.
Is it possible to know where the electron is in an atom at a given moment? Or at an instant what is its momentum? In other words, is it possible to determine precisely the position and momentum of an electron at the same time? If you were to measure the position and speed of a particle at any instant, you would always be faced with experimental uncertainties in your measurements. According to classical mechanics, no fundamental barrier to an ultimate refinement of the apparatus or experimental procedures exists. In other words, it’s possible, in principle, to make such measurements with arbitrarily small uncertainty. Quantum theory predicts, however, that such a barrier does exist. In 1927, Werner Heisenberg introduced this notion, which is now known as the uncertainty principle: if a measurement of the position of a particle is made with precision $\Delta x$ and a simultaneous measurement of linear momentum is made with precision $\Delta p_x$, the product of the two uncertainties can never be smaller than the Planck’s constant. In other words, it is physically impossible to measure simultaneously the exact position and exact linear momentum of a particle. If $\Delta x$ is very small, then $\Delta p_x$ is large, and vice versa. Another form of the uncertainty relationship sets a limit on the accuracy with which the energy $E$ of a system can be measured in a finite time interval $\Delta t$. It is important to note that during each experiment, the measurement errors (such as the inaccuracy of the measurement) are not related to the Heisenberg uncertainty principle. One consequence of the Heisenberg uncertainty relationship is that the quantum world does not exist deterministically, but statistically (e.g.
an interference pattern can be predicted accurately, but the exact path of photons cannot). This so-called Copenhagen interpretation of quantum mechanics was disputed by Einstein („I cannot believe that God would choose to play dice with the universe”).
Take-home message

- The dual nature of light can be demonstrated experimentally.
- According to de Broglie, electrons, just like light, have a dual particle-wave nature, thus duality is a general characteristic of matter.
- A de Broglie wavelength can be defined for particles having a mass of $m$ and moving at a speed of $v$.
- Light consists of tiny particles called photons whose energy is proportional to the frequency of the electromagnetic wave associated with it.
- As an MD
  - The medical application of light is widespread in both diagnostics and therapy
  - The wave nature of an electron is used in electron microscopy to produce high-resolution microscopic images that opens up the possibility of imaging sub-cellular details.