Blackbody radiation, the Planck relation, and the photoelectric effect

Blackbody radiation is a phenomenon whereby every object emits light due to its heat. For example, the Sun mainly emits kinds of light that are visible to our human eyes. Such a type of light is called "visible light." Another example of objects that emit blackbody radiation would be human beings, which emit infrared rays, a type of light that is not visible to our eyes and has longer wavelengths than the ones of visible light; however, these infrared rays are visible using an infrared camera or a device such as night-vision goggles.

A natural question that one may ask is: why is the light emitted by the Sun visible light, while the light emitted by human beings is not visible light, but infrared rays?

The answer is because the Sun is much hotter than the human beings, so the Sun emits light with shorter wavelengths, which has higher energies than infrared rays, and their wavelengths (380 nm $\sim$ 700 nm, as mentioned in the last article) happen to fall in the range of visible light, while infrared rays don't. In fact, it is known that the wavelength of light that an object radiates by blackbody radiation depends only on the object's temperature. To be more precise, an object emits all kinds of light - that is, light of all wavelengths - by blackbody radiation, but it emits light with certain wavelengths more than light with other wavelengths. The relative proportions of these different kinds of emitted light depend only on the temperature of the object.

However, when these relative proportions, also called the "blackbody radiation spectrum," were first measured and compared with the classical theory then available, there were some discrepancies. The classical theory matched well for long wavelengths, but it did not match at all for short wavelengths. The classical theory predicted that the shorter the concerned wavelength, the stronger the intensity of light emitted from the blackbody. However, in reality, the intensity of light reaches a maximum at a certain wavelength, and as the wavelength gets shorter, the intensity decreases and finally reaches zero in the limit of zero wavelength.

In 1900, Max Planck came up with an empirical formula that happened to perfectly match the blackbody radiation spectrum. Then, the next year he mathematically derived the empirical law for which he later received a Nobel Prize. In the derivation, he had to use a new relation which is now called "Planck relation." It is stated as follows:

$$E = hf \tag{1}$$

where E is the energy of individual photon (i.e. a light particle), f is the frequency of the photon, and h is what is now called "Planck constant." As mentioned in the last article, frequency is a property of wave or oscillation, which tells you how many times it oscillates per a second. In case of wave, frequency is equal to the speed of wave divided by its wavelength, as we have shown. In our later article "Planck's law of blackbody radiation," we will actually derive the blackbody radiation spectrum from Planck's relation, albeit in a different manner than Planck's original derivation.

Let me discuss the significance of this relation. Those who have studied some chemistry know what atoms are; we cannot divide matter into infinitely smaller pieces. The smallest units of which matter is made are called "atoms." Similarly, light has the smallest unit called "photons." Therefore, a light beam with frequency f cannot take any value as its energy, but only integer multiples of hf as its value. For example, it cannot have $2.6hf$ as energy, since there are no such things as 2.6 photons. It should be either 2 photons or 3 photons. From this new consideration, Planck could derive the blackbody radiation spectrum.

In 1905, Albert Einstein used the Planck relation to explain some of the properties of the photoelectric effect for which he later received a Nobel Prize. If you shoot a light beam to a metal, the beam kicks off the electrons in the metal, and the electrons are emitted from the metal. This is the photoelectric effect.

The puzzle is that no electrons are emitted from the metal if the frequency of the light is smaller than a certain value, no matter how intense the beam is, contrary to what the old theory based on assumption that light is a wave predicted. Einstein solved this puzzle. There is a certain amount of energy that an electron needs to escape from a metal. As it is virtually impossible for an electron to be knocked off by two or more photons at the same time, no matter how intense the beam may be (i.e. no matter how many photons were thrown), if the energy of a single photon (i.e. the minimal unit of light particle) thrown to the metal is less than this energy, no electron will get enough energy from the photon to escape from the metal.

Furthermore, he explained another puzzle: When higher intensities of beams with the same frequency were shot to a metal, each individual emitted electron didn't have higher kinetic energy; only the number of emitted electrons increased in such a case. A higher intensity of beam means a greater numbers of photons. Again, as a single electron can be knocked out only by a single photon, increasing the number of photons should only result in more numbers of electrons knocked off, rather than higher kinetic energy for each individual electron.

Thus, Einstein proposed the following formula.

$$K = hf - \phi \tag{2}$$

K is the maximum energy an emitted electron can have when it is exposed to a light beam with frequency f. ϕ called "work function" is the minimum energy the electron needs to escape from the metal. In other words, a photon with energy hf uses energy of at least ϕ to make an electron escape from the metal. Then, the electron obtains the rest of the energy. This formula was experimentally verified in 1914. Different metals have different ϕ. (By 1905, the puzzles of photoelectric effect were known only qualitatively rather than quantitatively.) In the next article, we will also see how the Planck relation was used to explain the Rydberg formula, which was crucial to our understanding of orbits of electrons in atoms.

So, did Planck and Einstein prove that light is actually particles instead of waves? No. A century earlier, Young's experiments showed that light is waves. As there is no chance that Young's experiments were misinterpreted, physicists couldn't help but accepting that light is particles and waves at the same time. This may not sound that strange, if you do not know enough physics to understand the difference between particles and waves, but they are indeed strange. You will be able to understand that it is strange, if you read our later article "De Broglie's matter waves" after learning Young's experiments. Furthermore, de Broglie showed that not only photons, but also every particle is a wave at the same time! This fact is crucial to quantum mechanics. This is the reason why the Danish physicist Niels Bohr said, "anyone who is not shocked by quantum theory has not understood it," and the American physicist Richard Feynman said, "I think I can safely say that nobody understands quantum mechanics."

Final comments. In the late 19th century, many physicists thought that physics was near completion; they could already explain many phenomena and they believed they could explain others if they applied the known laws correctly. They believed that the only phenomenon that they couldn't explain was the blackbody radiation spectrum.

Before I entered Harvard in September 2001, I attended the Korea Advanced Institute of Science and Technology (KAIST) for a semester, because I graduated high school in February 2001. I took a quantum mechanics class at KAIST, and the professor teaching it said that physics was almost complete and the only unsolved problem was the quantization of gravity. I told this story to Dr. Sangmin Lee, who became my advisor ten years later. Then, he told me about the situation of physics in the late 19th century. I believe he was correct. Nobody knows. History repeats itself. We are not at the last period of physics.

Problem 1. Ultraviolet light has a shorter wavelength than visible light. Why is ultraviolet light harmful to skin, while visible light isn't? This is a big problem these days, because the ozone layer, which blocks ultraviolet light from the Sun, is getting destroyed by chemicals made by human beings, such as the ones used for air-conditioning. (Hint: frequency is inversely proportional to wavelength, and the higher frequency the more energy it has.)

Problem 2. Can a beam of visible light have more energy than a beam of ultraviolet light?

Problem 3. The work function of lead is 6.81×10^{-19} J, and the Planck constant is 6.626×10^{-34} J·s. What is the minimum frequency required for light, if it has to be shot toward lead and emit electrons? ("Joule" is a unit of energy, and often abbreviated as "J." "s" is an abbreviation of second.)

Problem 4. The speed of light is 299792458 m/s. If a bunch of light beam with wavelength 350 nm is shot toward lead, will it be able to emit electrons? Explain your reasoning.

(Hint[1])

Summary

- The Planck relation is given by
$$E = hf$$
where E is the energy of individual photon, f is the frequency of the photon, and h is Planck constant.

- A light beam with frequency f cannot take any value as its energy, but only integer multiples of hf as its value, because the number of photons must be an integer.

- Planck derived the blackbody radiation spectrum from the Planck relation.

- If you shoot a light beam to a metal, the beam kicks off the electrons in the metal, and the electrons are emitted from the metal. This is the photoelectric effect.

- Einstein used the Planck relation to explain some of the properties of the photoelectric effect:

- No electrons are emitted from the metal if the frequency of the light is smaller than a certain value, no matter how intense the beam is.

- When higher intensities of beams with the same frequency were shot to a metal, each individual emitted electron didn't have higher kinetic energy; only the number of emitted electrons increased in such a case.

- Einstein proposed the following formula.
$$K = hf - \phi$$
K is the maximum energy an emitted electron can have when it is exposed to a light beam with frequency f. ϕ is the minimum energy the electron must have to escape from the metal.

[1] First calculate what is the frequency of light with wavelength 350 nm. You need to use one of the formulas you learned in "Light as waves."