Luminescence in Nature and in the Education

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Abstract

Luminescence is an attractive phenomenon that is present in our artificial environment as well as in nature. This interdisciplinary topic involves physical, chemical, and biological aspects. Luminescence can be easily demonstrated in classrooms, which is an efficient way to motivate students and to turn their interest toward science. Students develop a specific knowledge by learning about luminescence that helps them to see nature as a complete and complex system. Luminescence has numerous occurrences in nature offering spectacular images to demonstrate this phenomenon.

Introduction

Multiple reasons prove the usefulness of teaching luminescence in high schools. We are going to list some of them here.

Luminescence is a phenomenon that is more common than one would think. It is present in our everyday life, such as on the face of watches and clocks, light switches, security marks on bank notes, in tonic water, light sticks, and glow-in-the-dark ornaments. Besides these, it occurs at more exotic places, such as in deep-sea animals.

Unfortunately students know very little or even nothing about luminescence although they learn about atomic physics that builds up the fundamentals. Teaching atomic energy-levels, absorption, and emission becomes more interesting for students by connecting them with luminescence.

Luminescence is an interdisciplinary topic. Areas of physics, chemistry, and biology have to be covered to answer a question like “How do fireflies emit light?”. Physics and chemistry are necessary to understand the process of light emission. Biology helps to discover the importance of this skill in animals during the evolution. By learning about luminescence, students develop a specific knowledge in this topic that helps them to see nature as a whole and complex system. This topic also provides a good opportunity to assign projects for students.

Students find themselves easily excited about this topic by searching for the presence of luminescence and by recognizing it where they would not expect it. Students gain motivation and start to develop a strong interest in science by learning about luminescence.

Luminescence is still a hot topic for researchers and provides new discoveries even today, e.g., in 2008, the Nobel-prize in chemistry was given to a scientist doing research on cancer treatment based on luminescence research results.

The phenomenon of luminescence

Luminescence is a light emission caused by an excitation effect. It is important to note that this emission is not the result of heating, i.e., the emitted light is not from a thermal radiation.

According to the source of excitation, the main types of luminescence are the photoluminescence (the excitation source is an incident light), the chemiluminescence (chemical reaction causes the excitation), the bioluminescence (photoluminescence or chemiluminescence in a living organism), the electroluminescence (electrical interaction is the root cause) and the triboluminescence (luminescence of a crystal after mechanical stress).

This article focuses on photoluminescence, chemiluminescence, and bioluminescence because these types are the most motivating and easy to understand for students.

Photoluminescence

Photoluminescence is a light emission caused by light excitation, i.e., the incident UV light excites electrons from ground state to a high energy-level. The energy difference is emitted as a visible light, as the electrons return to the ground state. According to Stokes-law, the wavelength of the emitted light is longer than the incident light, so some energy deficit is observed. Fluorescence and phosphorescence are distinguished by the light emission process that is discussed below.

In fluorescence, the emission is short. It lasts as long as the excitation. The emitted energy of the light is lower and the wavelength is longer than the incident light. Fluorescence can be easily demonstrated in classrooms. Only a UV-lamp, and either a banknote, or washing powder (or a white cloth washed by this washing powder), a fluorescent lamp bulb or tonic water are necessary. The fluorescence appears immediately as any of these are illuminated.

In phosphorescence, the emission is present even after the end of the excitation. It can last as long as several hours. Phosphorescence can be demonstrated in classrooms by UV illumination of clock faces, light switches, toys, or glow-in-the-dark ornaments.

The difference between the phenomena of phosphorescence and fluorescence is shown in Fig. 1 by the Jablonski-diagrams. Figure 1(a) shows the energy level-changes of an electron in the case of fluorescence. The excited molecules exert an impact on each other. Their electrons, losing some energy, fall down to a low vibration energy level and to the ground state in one step. Figure 1(b) explains the energy change of an electron in the case of phosphorescence. The electrons also step down to a low vibration energy level like in fluorescence, but in two steps. First, the electrons step to an intermediate energy level in a fast process, and then they fall down to the ground state in a slow process. The second transition of the electron is slow because it is limited by the quantum mechanical selection rules. These rules state that only those transitions are allowed in which the quantum numbers are changed with the stated values. Therefore, electron transition occurs rarely and stretched in time, but light emission lasts even after the illumination is removed.

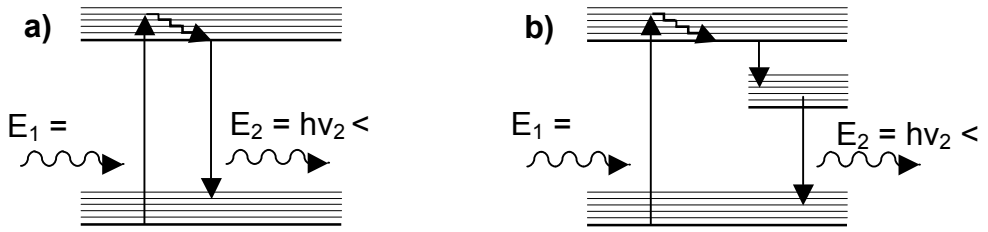

Figure 1. The Jablonski-diagram of fluorescence (a) and phosphorescence (b).

Chemiluminescence

Chemiluminescence is based on a chemical reaction, in which one of the products in excited state emits light while relaxing to the ground state. This reaction is followed by a minimal heat emission as most of the energy is emitted as light. Enzymes can raise the efficiency of the reaction. Party light sticks, fishing lures and the luminol-test in criminal investigation are a few examples of chemiluminescence.

Light sticks and fishing lures are commercially available; therefore experiments in classrooms can be easily performed. These sticks are constructed from two cylinders, the inner one has a fragile wall and contains hydrogen-peroxide, whereas the outer one is flexible made from plastic and contains phenyl-oxalate-ester (DNPO or TCPO, Fig 2.) and fluorescent dye.

To demonstrate chemiluminescence, the stick needs to be bent so that the inner cylinder is broken, allowing the chemicals to mix. During the reaction, DNPO/TCPO is

oxidized by the hydrogen-peroxide, and the resulting energy excites the fluorescent dye, which emits visible light.

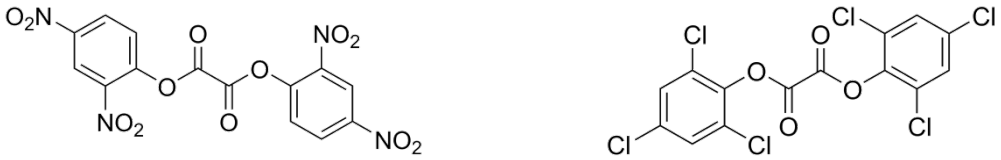

Figure 2. The skeletal formula of DNPO (left) and TCPO (right).

Chemiluminescence is used in criminal investigation that definitely increases the interest of the students. The so-called 'luminol-test' detects old, dried blood stains. During the investigation, luminol (Fig. 3) and hydrogen-peroxide are sprayed to the fabric, and the iron of hemoglobin catalyzes the chemical reaction of these two compounds. As the chemical reaction of chemiluminescence starts and the light is emitted, the available 30 seconds can be used to photograph the blood stain. This experiment is possible to work in classrooms with luminol, hydrogen-peroxide, sodium-hydroxide and potassium-carbonate. By mixing these materials in a dark room blue light is emitted.

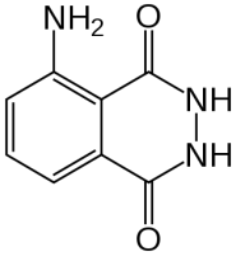

Figure 3. The skeletal formula of luminol.

Bioluminescence

Bioluminescence is a light emission by fluorescence or chemiluminescence in a living organism. Since incident light is required for fluorescence, it is rare in nature. Therefore, chemiluminescence is more common and mostly used by deep-sea animals due to the lack of light.

Although the occurrences of bioluminescence in species are numerous, the same type of chemical reaction provides the light. In this chemical reaction, the so-called luciferin reacts with oxygen in presence of luciferase enzyme, magnesium-ions and adenosine-triphosphate (ATP). Light is emitted as the excited luciferin resumes to the ground state. The efficiency of this reaction is 100 %, meaning that the whole relaxation energy is emitted as light without any heat dissipation. Therefore, the emitted light is often called "cold light".

The only difference between the various species is the specific compound that is used as luciferin and as luciferase. Figure 4 shows a specific luciferin of the firefly.

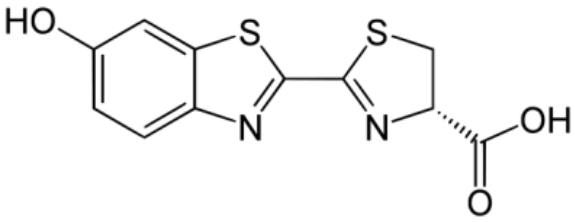

Figure 4. The skeletal formula of the luciferin of the firefly.

Animals known for their ability to emit light are the mushrooms, unicellular, bacteria, worms, sponges, jellyfishes, squids, crabs, shells, snails, and insects. Luminescence does not exist in vertebrates as it is missing from the list above as well. Among several explanations, one is mentioned here below. At the beginning of the life on earth, the atmosphere had a different gas content than today, it had a reducing effect. The oxygen was present in a small amount, being toxic for anaerobe animals. These animals had to eliminate oxygen; therefore they developed a chemical reaction that could not include any heat release although every oxidation reaction is exothermic. As a solution, luminescence was used that allows energy release as light emission. As the atmosphere became oxygenated by time, the skill of emitting light remained, although, the function changed. The glow is used in these animals for reproduction, for prey inveiglement, for deterring, and for escape. The vertebrates appeared on Earth after the atmosphere became rich in oxygen, therefore having no need to develop such a skill.

In the following paragraph, some light emitting species are listed. Amazing pictures are available on the internet that can be shown in classrooms or used as homework assignments.

Mushrooms

Among mushrooms, there are more than sixty species that use luminescence. The Jack-o'-lantern mushroom (*Omphalotus olearius*) is one example. The 'ghost fungus' (*Omphalotus nidiformis*), which lives in southern-Australia, was used by soldiers as a torch on their guns.

Bacteria

Bacteria often live in symbiosis with other animals e.g. the flashlight fish (*Photoblepharon*). It has bacteria under the eyes helping the fish to navigate under the sea. Another example of symbiosis is the humpback anglerfish (*Melanocetus johnsonii*) that has bacteria in its hook to attract prey close to its mouth.

Some luminescent bacteria are present on specific meat surfaces that were common at markets before the age of refrigerators. A French scientist, Raphael Dubois was the first who examined luminescence in the 19th century and showed that bacterial cultures filled in a 25-liter bottle can illuminate a room on the World Expo, Paris, 1900.

Worms

The female fireworm (*Odontosyllis enopla*) hovers on the surface of the seabed and emits green light that attracts males. The railroadworm (*Phrixothrix hirtus*) shows an interesting behavior by emitting two different light colors. Only two red dots illuminate its head when the animal is calm. In stress, eleven pairs of spots start to emit green light and the worm seems like a train in the darkness.

Jellyfishes

Crystal jelly (*Aequorea victoria*) uses fluorescence with a special protein, the green fluorescent protein (GFP). For the discovery of this protein and its application in cancer therapy, a Nobel-prize was given in 2008. GFP bounds to cancerous cells and emits green light at UV illumination. During the surgery, this allows the doctor to see the real tumor size along with the boundary between cancerous and healthy tissues.

Shells

The first animal which was studied in terms of luminescence was a shell, *Pholas dactylus,* that uses luminescence for escaping.

Crabs

As an example among the crabs, krill can emit light. The reason of light emitting might be hiding. During the World War II, Japanese soldiers used krill to illuminate their maps in the darkness.

Insects

Several insects are able to emit light with luminescence. Only the fireflies have two thousand species. Fireflies like the *Pteroptyx tener* can control the time and the duration of light emission. Therefore, they can perform synchronized light emission giving the impression of a Christmas tree in the dark.

Summary

Teaching of the phenomenon of luminescence involves several disciplines, which makes it challenging. The physical, chemical, and biological background is hard to understand for high school students, but the relatively easy experiments and interesting pictures from nature provide a strong motivation. This topic helps students to gain an interdisciplinary picture of nature.

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