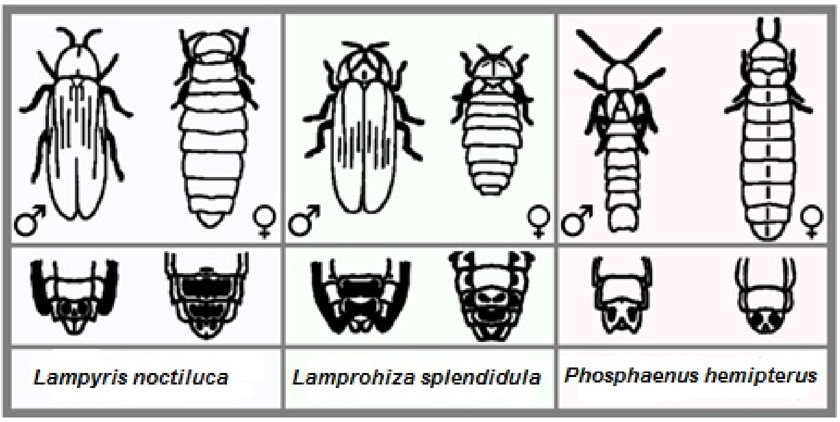
Background information

Bioluminescence: combining biology, chemistry, and bionics

Lampyridae in Europe

With only three species in central Europe, Lampyridae are one of the smallest families of beetles.[1] Larvae of the Lampyridae hatch from eggs in the ground and prey on snails and slugs.[2] Adults do not eat and die shortly after copulation/egg deposition.[3]

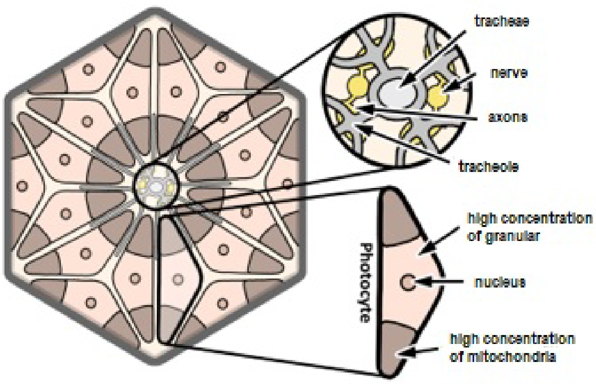
The light signal individuals emit is specific to each species and serves to attract a mating partner.[4] There are two forms of communication for central European species. The stationary *Lampyris noctiluca* female emits light to find a mating partner between June and September. With its brownish colour and lack of wings, it almost appears larva-like. Its primary light organs are located beneath the sixth to eighth abdominal segments.[2] Male and female *Lamprohiza splendidula* create species-specific light signals for mating between June and July. Males let their sixth and seventh abdominal segments emit light in a specific pattern, which is taken up by a receptive female willing to copulate. Females live on the ground. They cannot fly and appear larva-like due to their yellow–brownish colour.[2] The last species, *Phosphaenus hemipterus*, only has weakly developed light-emitting organs. Males and females cannot fly and only glow slightly as adults. Attracting and finding a partner for mating is achieved through sexual pheromones.[5]



Schematic overview of three species of Lampyridae living in central Europe (based on Ref. [6]). Image courtesy of Marcel Hammann

The photophore

The photophore can be found on the bottom of the last abdominal segment of Lampyridae. Its visible part consists of so-called photocytes. A non-transparent layer of cells, which serves as a reflector, is located right behind the layer of photocytes. Photocytes are cylindrically arranged around the tracheal network. Granules located in the middle of each photocyte store luciferase and luciferin.[2] Light emission can be regulated through nerve impulses and is dependent on oxygen levels inside the photocyte. Mitochondria in photocytes are located near the tracheal network, which carries oxygen. Thus, mitochondria normally use almost all oxygen that would be needed to initiate light-emitting reactions through luciferin stored in the granules in the centre of the photocyte. Through a nerve impulse, nitrogen monoxide is emitted, which, in turn, reduces oxygen uptake by mitochondria. This way, the level of oxygen rises and initiates the enzymatically catalysed oxidation of luciferin in the granules.[2]

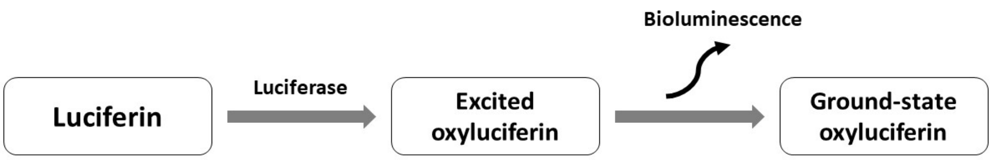


Schematic illustration of photophore with photocytes arranged around tracheal network Image courtesy of Marcel Hammann

Luminescence

In luminescence, energy is emitted in the visible-wavelength range of light through the oxidation of a luminophore.[7] In simplified terms, one of the products does not directly reach the final energy level of the reaction. Luciferin is oxidized to oxyluciferin, which is temporarily in an excited state and emits light when decaying to its ground state. Unlike in fluorescence or phosphorescence, which receive energy from light, the excitation energy in luminescence is chemical energy. Bioluminescence is a specific type of chemiluminescence, in which processes are enzymatically catalysed in living organisms.

In the case of luciferin – the luminophore that can be found in many photophores of light-emitting beetles – luciferase catalyses its oxidation through stabilizing the reactive luciferin–adenosine monophosphate (AMP) complex.[8] Through oxidation, a carbon dioxide molecule is released and the resulting oxyluciferin molecule reaches a high-energy state. Through emitting a photon, the luminophore then reaches the energetic ground state of its oxidized form.



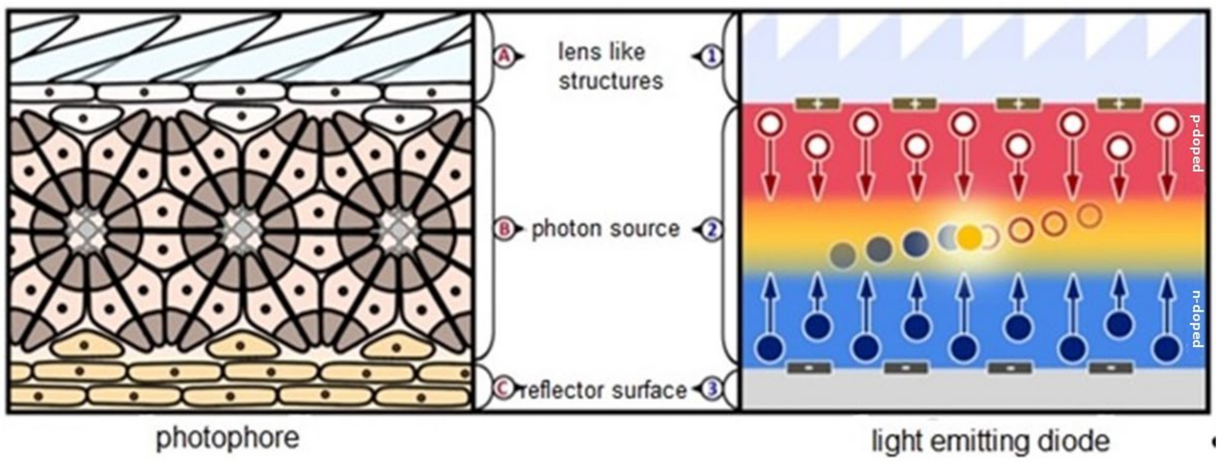
Simplified light-emitting reaction of luciferin at the molecular level (based on Ref. [8]) Image courtesy of Carolin Zehne

Photophores of Lampyridae and LEDs

Light created in the photophores has to pass through the cuticula to be radiated into the surrounding environment. Whenever light is emitted, it needs to pass through an optically dense medium (cuticula) to a less dense medium (air). The speed with which light travels through an optically denser medium differs from the speed in a less dense medium. Due to the difference of speed with which light travels through these two media, light refraction and reflection occur near the interface of the two media. Thus, only part of the light actually passes through to the new medium. The other part is reflected back into the source medium. If light hits the interface at a certain angle of incidence, almost all of it is reflected. For the cuticula of the photophore of Lampyridae, this angle is 40°.

A closer examination of the cuticula reveals its uneven structure: the photophore's surface is covered in scales, which are slightly inclined and have sharp ends. Due to their inclination, the surface structure is similar to that of a prism. This way, the angle at which light hits the cuticula is changed. Through the sharp ends of the scales, more light is scattered, thus leading to additional light transmission, increasing light emission by 45%.

When comparing the structure of the photophore to that of a LED, certain similarities become apparent. Both have a light-generating layer covered with a transparent layer. In the case of an LED, the light-generating layer is formed of doped semiconductors, which generate light through electroluminescence. Stacking p- and n-doped materials enables spatially limited electron transmission to take place, and thus, leads to a balance of charge carriers at the interface. An LED consists of an anode and cathode. The semiconductor is embedded in a reflective cavity and part of the anvil. A wire bond connects it to the post. The post and anvil form the lead frame, which is covered with a glass or plastic case for protection. By applying a voltage, the continuous recombination of charge carriers at the interface of the layers can be induced, which leads to photon emission.[9]



Comparison of structural properties of a schematic photophore of Lampyridae (left) and a LED (right) Image courtesy of Marcel Hammann

Similar to reflection occurring at the photophore surface, part of light emitted by an LED is reflected at the interface between glass and air, thus lowering the luminous efficiency. To increase efficiency, the scaly structure of the cuticula was transferred to the surface of LEDs following a typical three-step bionics procedure:

I. Exploring a biological phenomenon
II. Abstracting results obtained
III. Abstracted results serve as a solution to technical issues

References

[1] Harde KW, Severa F (2006) *Der Kosmos Käferführer: Die Käfer Mitteleuropas [The Kosmos Beetle Guide: Beetles in Central Europe*] p 37. Kosmos. ISBN: 978-3440139325

[2] Dettner K (2010) Biolumineszenz [Bioluminescence]. In Dettner K, Peters W (eds), *Lehrbuch der Entomologie* [*Textbook Etymology]* pp 601–611. Spektrum. ISBN: 978-3-8274-2617-8

[3] Klausnitzer B, Förster M (2002) *Wunderwelt der Käfer* [*The Magic World of Beetles*] p 121. Spektrum. ISBN: 978-3662586969

[4] Klausnitzer B, Förster M (2002) *Wunderwelt der Käfer* [*The Magic World of Beetles*] p 177. Spektrum. ISBN: 978-3662586969

[5] DeCock R (2000) Rare, or simply overlooked? Practical notes for survey and monitoring of the small glow-worm *Phosphaenus hemipterus* (Coleoptera: Lampyridae). *Belgian Journal of Zoology*, **130**: 93–101.

[6] DeCock R (2012) Three central European glow-worm species: how to recognise central European glow-worm species. Retrieved from http://www.glowworms.org.uk/ident.html.

[7] Hofmann P (2013) *Einführung in die Festkörperphysik. Lehrbuch Physik* [*Introduction to Solid-State Physics. Textbook Physics*]. p 98. Wiley. ISBN: 978-3-527-41226-6

[8] Girotti S, Ferri EN, Bolelli L, Sermasi G (2001) Applications of bioluminescence in analytical chemistry. In García-Campaña AM, Baeyens WRG (eds) *Chemiluminescence in Analytical Chemistry* pp 247–284. Marcel Dekker. ISBN: 0-8247-0464-9

[9] Hofmann P (2013) *Einführung in die Festkörperphysik. Lehrbuch Physik* [*Introduction to Solid-State Physics. Textbook Physics*]. p 140. Wiley. ISBN: 978-3-527-41226-6