The physics of Protaetia cuprea's Special STRUCTURAL disappearing Colors

Author: Shira Hadass

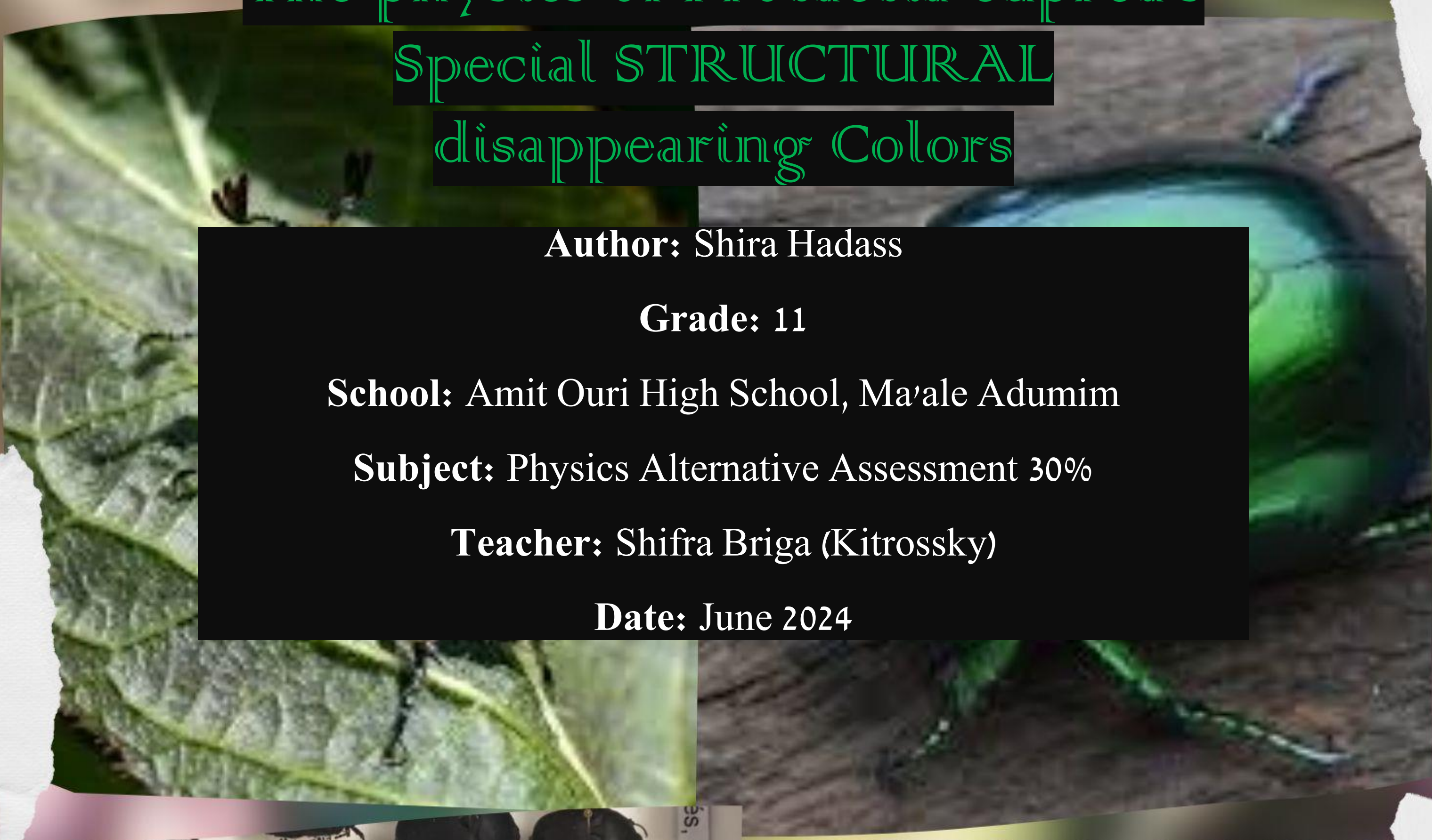
Grade: 11

School: Amit Ouri High School, Ma'ale Adumim

Subject: Physics Alternative Assessment 30%

Teacher: Shifra Briga (Kitrossky)

Date: June 2024



Contents

Background:

Protaetia Cuprea, also known as the Copper Chafer, belongs to the Chafer species of the Scarabaeidae family. It has metallic bright green and copper colors. When one observes the beetle through a right-handed circular polarizer its colors disappear and its looks turn to a colorless brown hue. On the other hand, if one observes the beetle through a left - handed polarizer its color become brighter and more vivid. In 1911, Albert Abraham Michelson discovered that the light reflected from the golden scarab beetle is circularly polarized. Even back then he understood that the metallic color is achieved due to a helix shaped structure. This article is explaining the mechanism and the physics of this splendid phenomenon.

In order to understand the mechanism of the beetle's colors, we'll discuss several subjects:

1) Characteristics of electromagnetic waves.
2) Polarization of light.
3) How the metallic color of the beetle is created.
4) How and why using a polarizer, the color of the beetle disappears.

<u>Light: electromagnetic wave</u>

First of all, what is light?

Visible light is electromagnetic radiation that can be perceived by the human eye. The visible light is comprised of the colors of the rainbow and represents only a very small portion of the electromagnetic spectrum. Light is (also) waves.

Electromagnetic waves are composed of two waves that are linked together - one is a changing magnetic field and the other is a changing electric field. These two waves oscillate in time and space perpendicular to each other. In simpler terms, imagine two ropes tied together at one end and being shaken up and down and side to side at the same time. This creates a wave-like motion that moves through the space.

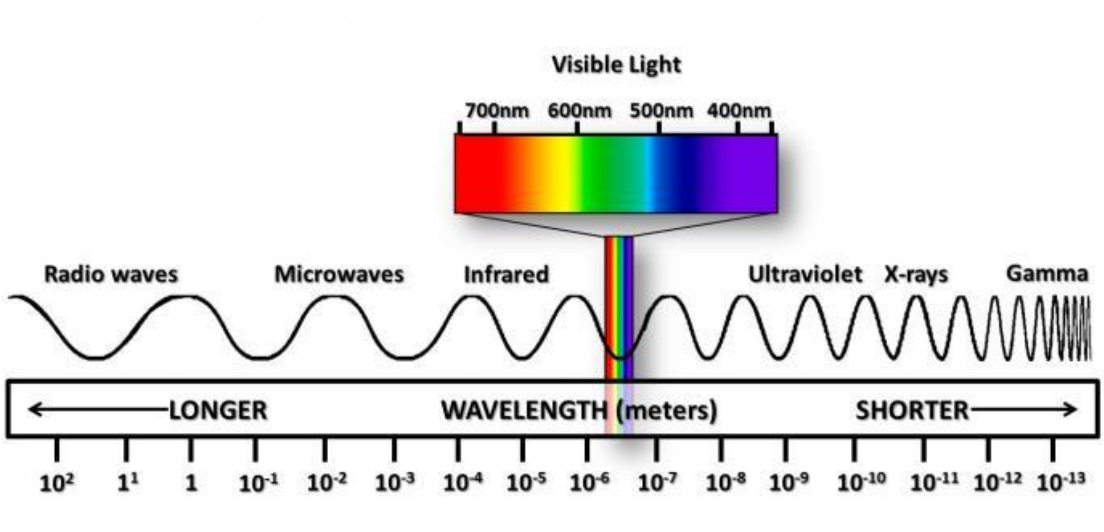


Figure 1: A dipiction of the electromagnetic spectrum

Wavelength is the distance between the two successive crests or troughs of the light wave. The distance between either one crest or trough of one wave and the next wave is known as the wavelength. The longer the wavelength, the redder the color and the shorter the wavelength, the bluer the color.

Frequency is the number of full wavelengths that pass by a given point in space every second. The shorter the wavelength, the higher the frequency, and vice versa.

Amplitude is the distance between the equilibrium position and the maximum displacement of the wave's electric/magnetic field value . It's associated with the brightness of the light, or intensity of the wave.

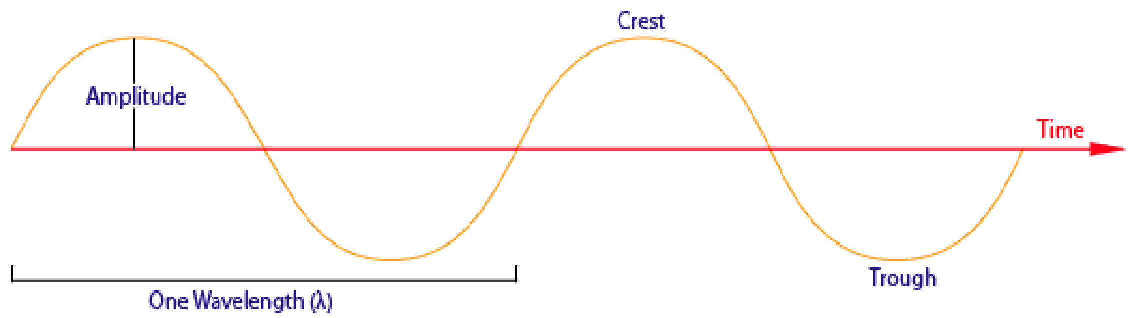


Figure 2: A harmonic wave and it's characteristics

Polarization of light:

Polarization is linked to the plane the wave oscillates in.

Light waves are transverse, meaning that the vibrating electric field vector associated with each wave is perpendicular to the direction of propagation. The direction of the polarization is the direction of the electric field vector motion.

The electric field is a fundamental concept in electromagnetism that represents the force experienced by charged particles in the presence of other charges. It has two key components:

1. Magnitude: The magnitude of the electric field describes the strength or intensity of the field at a particular location. It is measured in Volts per meter (V/ m) and indicates how strong the force exerted on charged particles will be in that region.
2. Direction: The electric field has a specific direction at each point in space. the electric field points in a direction perpendicular to the direction in which the wave is propagating.

Linear polarization is a property of the electromagnetic radiation where the electric field vectors oscillates in a single plane as the light wave travels through space. It is created by filtering out light waves vibrating in unwanted directions, resulting in light waves with their electric field aligned and oscillating in the same direction.

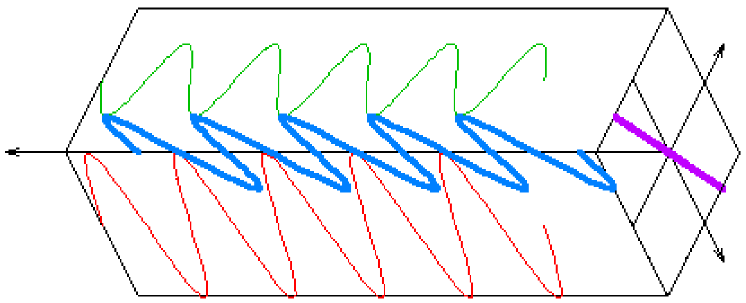


Figure 3: Diagram of the electric field of a light wave (**blue**), linear-polarized along a plane (**purple line**), and consisting of two orthogonal, in-phase components (**red** and **green** waves).

In the case of light waves, the electric field oscillates back and forth as the wave travels. For linearly polarized light, the electric field vector oscillates in a single plane called the polarization plane. This means that the electric field's direction remains fixed within that plane as the wave progresses.

Circular polarization:

Circularly polarized light refers to a type of electromagnetic radiation where the electric field vector of the light wave rotates in a circular motion as it propagates through space. In circularly polarized light, the orientation of the electric field vector traces out a helix. It can be either right-handed or left-handed, depending on the direction of rotation.

There are two linear components in the electric field of light that are perpendicular to each other such that their amplitudes are equal, but the phase difference is $\pi/2$ (quarter wave period). The propagation of the occurring electric field will be in a circular motion. The phase difference between the two electric fields determines the handedness of the rotation. A clockwise rotation corresponds to a right-hand circular polarization state and a phase shift of $-\pi/2$, while a counterclockwise rotation refers to left-hand circular polarization state and a phase shift of $+\pi/2$.

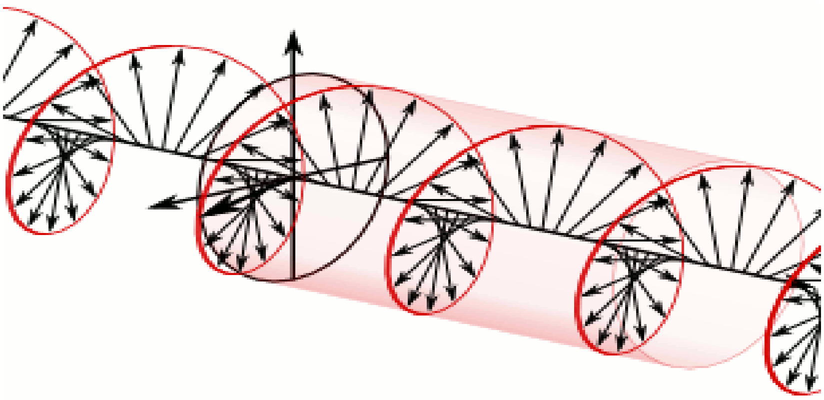


Figure 4: the electric field vector rotates and "draws" a circle. This is left handed are counterclockwise circular polarization.

Representation of light emitted from the sun:

Light emitted by the sun, by a lamp or by a candle flame are examples for unpolarized light that we encounter daily. That is because light arriving from these natural sources comes in many different polarizations.

Linear polarizer: A linear polarizer is an optical device that selectively transmits light waves vibrating in a particular direction while blocking or reducing the intensity of light waves vibrating in other directions.

Circular polarizer**:** A circular polarizer works by combining a linear polarizer and a quarter-wave plate. The linear polarizer selectively allows light waves with electric field vibrating in a specific direction to pass through. The quarter-wave plate introduces a $\pi/2$ phase shift to the electric field of the linearly polarized light, converting the wave it into circularly polarized light. This circularly polarized light has an electric field vector that rotates in a circular motion as it propagates.

The mechanism that creates the metallic color of the beetle

Now that we possess background knowledge, we can move on to understanding how the color of the beetle is created.

The coloration of the beetle is not due to pigments, but it is caused by microscopic structured surfaces in the beetle's exoskeleton's cuticula which is called Bouligand structures.

The Bouligand structure is a unique arrangement of Chitin fibers found in the exoskeleton of certain beetles. This structure plays a crucial role in producing the vibrant and iridescent colors observed in these beetles. The Bouligand structure is a structure that enhances the mechanical properties of materials - it can be distorted more easily under pressure and its especially known for its fracture resistance.

The helix pitch effects on color

The Bouligand structure has a characteristic that is the helix pitch.

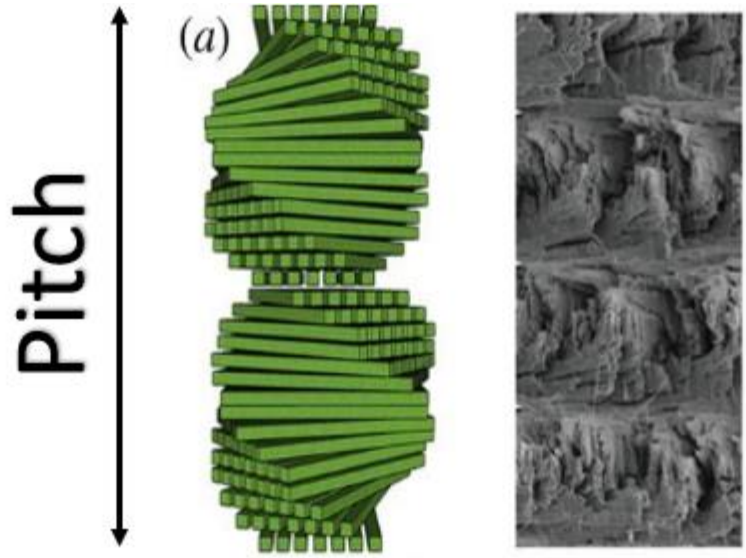


Figure 5: Bouligand structure model and SEM image of structure as found in dactyl club of the mantis shrimp.

Every layer is rotated a bit more than the previous one until a helix is formed. The length of the helix (until it resets on the same rotation as the start the second time) is called a **pitch**. The precise arrangement and dimensions of the Bouligand structure determines the specific colors that can be observed in beetles. The pitch of the helix, the spacing between the Chitin fibers, and the overall thickness of the layers all influence the wavelengths of light that are selectively amplified and reflected.

The mechanism- what happens to a singular light wave that's entering the helix:

Birefringence refers to the property of certain materials that have two different refractive indices, resulting in the splitting or polarization of light.

In the Bouligand structure, the chitin fibers exhibit birefringence. As the light wave enters the structure, it encounters these fibers, which have different refractive indices for light polarized parallel or perpendicular to their long axis. This leads to the separation of the incident light into two polarization components, each experiencing a different refractive index.

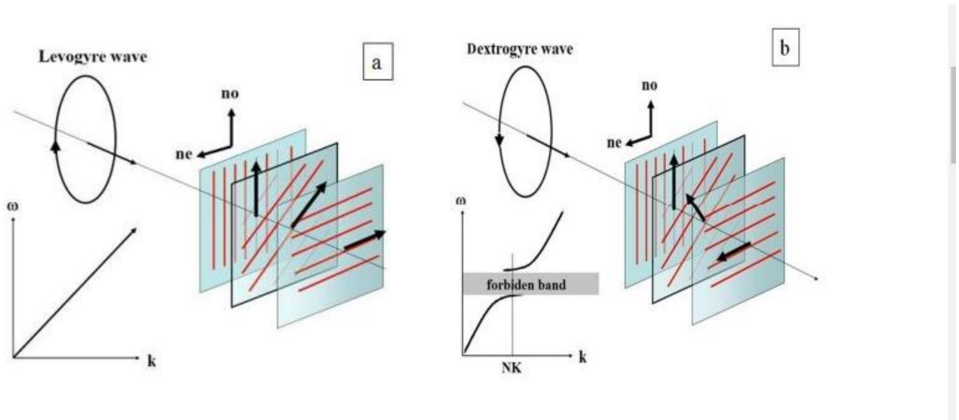


Figure 6: The light passes through the Bouligand structure. a – the light wave is synchronized with the helix. b - the light wave is unsynchronized with the helix

When circularly polarized light that is in the same orientation as the helix enters the structure and if its wave length is matching the helix, then as it travels from one Chitin fiber layer to the next, it moves so that the direction of the polarization is always in in the same orientation as the Chitin fibers. Because of this, the light wave doesn't experience any change in the refractive index and isn't refracted and returned between each layer, and thus continues to pass in its full intensity until the end of the structure. (figure 7a)

On the other hand, in any orientation that's opposite to the direction of the helix in each layer, the orientation of the electric field in relation to the Chitin fibers changes and as a result, it is transitioning from one medium to the other between the layers. In any such transition, a portion of the light-wave is reflected and so the light wave will not pass the structure. Meaning, only a light wave with an identical orientation as the helix and with a wave length that's synchronized with the helix' pitch will be reflected back from the beetle. (figure 7b)

Mathematical approach

The equation of the helix:

$$\boldsymbol{\lambda} = \boldsymbol{n} \cdot \boldsymbol{\rho}$$

$\boldsymbol{n}$ is the light refractive index.

$\boldsymbol{\rho}$ is the structure's length so that it goes back to its original orientation.

$\boldsymbol{\lambda}$ **is** the wavelength of the light that reflected from the beetle (the color of the beetle).

How, while using a polarizer, the color of the beetle disappears:

Figure 7: left and right circular polarizer sunglasses, the beetle. and a mirror.

When viewed through a right circular polarizer, the beetle appears to be colorless. This happens because it allows only right circular polarized wave to pass through, while the light reflected from the beetle is left – handed circularly polarized.

Figure 8: this picture was photographed through right handed circular polarizer. The beetle looks colorless brown. Through the mirror it has colors again.

If we look at the beetle through a left circular polarizer, it will enhance the beetle's colors.

Figure 9: this picture was photographed through left - handed circular polarizer. The color of the Beetle is bright and vivid. Through the mirror it has colorless.

We can see that in both pictures, the beetle image in the mirror is "opposite" (meaning colored/colorless) to the actual beetle. This happens because the mirror reflects light in the opposite direction, left circularly polarized light returns as right circularly polarized light and vice versa.

Suggestions as to why the beetle has these properties:

The Copper Chafer might have these properties for several reasons:

1. Iridescence is an effective form of camouflage: British biologists conducted a study in which they tested whether predators are better at finding iridescent or non-iridescent targets. They took the wing cases of iridescent and non-iridescent beetles and baited them with a tasty mealworm. They put out more than 800 targets like this in a wooded area.
   Birds found and ate 85 percent of the non-iridescent targets, but only 60 percent of the iridescent ones. Humans also found the iridescent targets harder to find. The iridescent targets were especially hard to find on glossy leaves.
2. The Scarab beetles have exoskeletons that provide protection from the environment, mechanical load support, and body structure. The outer layer, called the epicuticle, is thin and waxy and is the main waterproofing barrier. Below is the procuticle, which is designed as the main structural element to the body. The procuticle is made of two sections, the exocuticle on the outer part, and the endocuticle on the inner part. The exocuticle is denser than the endocuticle; the endocuticle makes up about 90% volume of the exoskeleton. Both the exocuticle and endocuticle are made of Bouligand structures. Maybe the fact that the light that reflected from the beetle is circular polarized is only a biproduct.

How can we execute it into science?

- The main issue with 3D printing is the introduction of microstructural heterogeneities within layers of deposited material. These defects, including porosity and unique interfaces, result in anisotropy of the mechanical response of the workpiece, which is undesirable. To combat this anisotropic mechanical response, a Bouligand-inspired tool path is used to deposit the material in a twisted Bouligand structure.

- Crab shells which already have the Bouligand structure can be used as templates for nanostructured battery electrodes.
- The 3D printed concrete is laid in a helicoidal, twisting pattern rather than parallel lines, similar to the design of the lobster shell. This methodology better integrates the layers of concrete as it sets. Additionally, the concrete mixture is reinforced with steel fibers that reduce defects and porosity, allowing the concrete to harden more consistently to create a better base for the layers above.

References:

- https://www.researchgate.net/publication/363729059_Additive_Manufacturing_An_Emerging_Tool_to_Fabricate_Bioinspired_Structures

- https://asknature.org/strategy/amazonian-fish-has-tough-scales-to-protect-from-predators/ - need to write.

- concrete Bouligand structure. need citation. All of them.

- Lenau, Torben & Aggerbeck, Martin & Nielsen, Steffen. (2009). Approaches to mimic the metallic sheen in beetles. Proc SPIE. 7401. 10.1117/12.826227.

- Vivek Sharma, Matija Crne, Jung Ok Park, Mohan Srinivasarao, Bouligand Structures Underlie Circularly Polarized Iridescence of Scarab Beetles: A Closer View, Materials Today: Proceedings, Volume 1, Supplement, 2014, Pages 161-171, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2014.09.019 (https://www.sciencedirect.com/science/article/pii/S2214785314000200)

- I. E. Carter, K. Weir, M. W. McCall, and A. R. Parker, "Variation in the circularly polarized light reflection of Lomaptera (Scarabaeidae) beetles," Journal of The Royal Society Interface, vol. 13, no. 120, Jul. 2016.