Quantum Color Theory

Elie W'ishe Sorongane

Physics Department, University of Kinshasa, Kinshasa, Democratic Republic of the Congo
Email: wisheselie@gmail.com

Abstract

The color of an object is defined as the color of the light it reflects. The color is therefore not a characteristic of the object but rather a characteristic of the light that illuminates it, thus objects are quite simply "color thieves". However, the reflected light is subject to the Snell-Descartes law of reflection: the angle of incidence is equal to the angle of reflection. This law implies that the color of the object can only be seen by observers occupying specific positions. But we all know that this is not the case, the color of the object is seen by any observer regardless of position. In this work, we then introduce a new way to define the color of an object based on spectroscopic principles: The atoms of the object absorb the white light of the sun and subsequently they emit radiation of which frequency corresponds only to the color of the object.

Keywords

Color, Light, Reflection, Absorption, Emission

1. Introduction

Classical color theory (CCT) laid down the fundamental principle that defines the origin of the color of an object: the color of an object is not a characteristic of the object but rather a characteristic of the light which illuminates it, thus the objects are quite simply "color thieves". The objects absorb all or part of the colored rays of the light which reach them and according to the rays returned towards the eye, these objects appear to us in one color or another. The color of an object is the color of the light it reflects back to our eye [1]. It is the part of sunlight that it does not absorb.

White objects fully reflect all seven colors of the solar spectrum; black objects totally absorb all colors and reflect nothing [2].

Thus, a red sweater appears red to us when illuminated by white light, because it absorbs all the colors of the solar spectrum except for the red light which is re-

flected back to our eye.

This CCT, which we have just briefly described above, explains a certain number of the physical phenomena of white light. However, it still has some shortcomings such as:

- Why does a wet black garment (*i.e.* which absorbs all white light) dry less quickly in the sun than a white garment (*i.e.* which reflects all seven colors of the solar spectrum)?
- How does a chameleon manage to take on any color while keeping the same skin?
- One of our problems, of a rather cosmological nature, is that of Olbers' paradox, for which since the 16th century, scientists have been trying to find an adequate explanation: in an infinite and homogeneous universe, any line of sight must end at the surface of a star so why is the sky dark at night?
- Why do Gold nanoparticles change color as their size decreases (from red to purple)?

It was to answer such questions that we realized that the color of an object could not be entirely described by the simple phenomenon of absorption—a reflection of light.

It must be produced by a much more complex phenomenon.

The quantum color theory (QCT) that we are going to build throughout this work can be summarized in three small points:

- Absorption of light by the atoms of the system;
- Excitation of system atoms;
- De-excitation of system atoms.

2. The Theory

2.1. Principle

We begin by introducing a paradox that highlights the limits of classical color theory.

1) The paradox of the dark room

Several observers are placed in a dark room, *i.e.* a room plunged into total darkness. One of the observers' projects, thanks to a laser beam torch which he holds at eye level, a monochromatic beam on the wall is just in front of him. Since the various rays that make up the beam are all parallel to the direction orthogonal to the wall, the Snell-Descartes law on reflection (the angle of incidence is equal to the angle of reflection as shown in Figure 1 allowing us to affirm that only the observer holding the torch will be able to see the image projected onto the wall. However, it is noted that the image is seen by any observer in the room and regardless of the position he occupies in the room. How is it possible?

2) States

The principle of the QCT is simple, and it can be stated as follows:

a) The atoms of the system absorb all the white light coming from the sun.

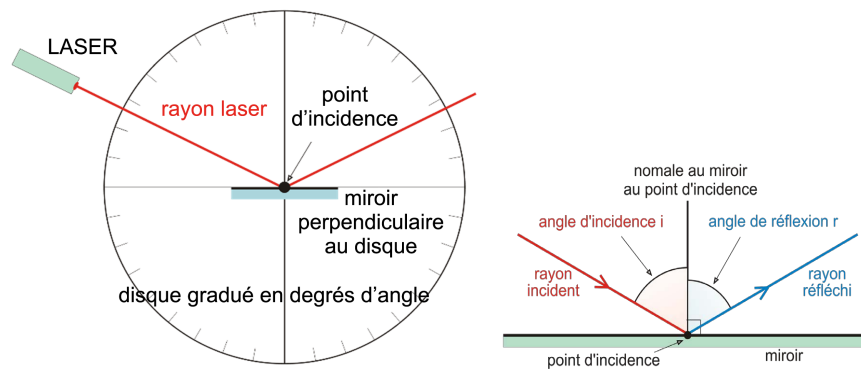They then pass from the fundamental level to an exciting level.

Figure 1. Snell-descartes law on reflection (the angle of incidence *i* is equal to the angle of reflection *r*).

b) The atoms of the system now occupy an excited (unstable) level, then de-excite to a lower level by emitting radiation whose wavelength (or frequency) matches the color of the object.

c) The rest of the energy absorbed by the atom is transferred to the other atoms in the system by collision. This allows the atom to return to the ground state, thus increasing the temperature (thermal agitation) of the system.

2.2. Mathematical Formalism [3]

We know thanks to the trichromy, that we can obtain any color by adding only the 3 primary colors in suitable proportions.

So for the sake of simplicity, we consider a white light composed of only the 3 primary colors: red, green and blue. Moreover, the human eye is only sensitive to these three colors. We will then have the following processes (see **Figure 2**):

- Before the absorption of photons by the atom, it is in the ground state with energy E_0. By convention, we will take $E_0 = 0$ to say zero photons absorbed.
- The atom then absorbs three photons (red, green and blue), it then passes from the fundamental level to the exciting level of energy

$$E_{R,V,B} = h(v_R + v_V + v_B).$$

- Then the atom de-excites by emitting a photon of frequency v_B; here we have considered an object of blue color.

It then passes from the exciting level of energy $E_{R,V,B}$, at a lower energy level $E_{R,V} = h(v_R + v_V).$

- Finally, the atom transfers this energy $E_{R,V}$ to the other atoms of the system by collision to return to the fundamental level of energy E_0. And the system heats up.

The problem is therefore simply to determine the coefficients of Einstein corresponding to the different processes.

1) Absorption

Line profile: A monochromatic ray can be considered as a plane wave. The different monochromatic or polychromatic beams are then wave packets, *i.e.* superpositions of plane waves given by the Fourier transform. The profile of the
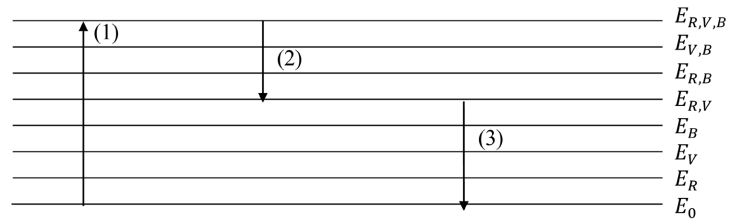
Figure 2. Different levels accessible to the system and the corresponding processes. (1): Absorption; (2): Radiative de-excitation (or emission); (3): Non-radiative (or collision) de-excitation.

line, in first approximation, can then be considered as homogeneous, it is a Lorentzian. The mid-height width of the spectrum is therefore given by:

$$\Delta v = \frac{1}{2\pi}\Gamma \tag{1}$$

Here we have neglected two effects that can be observed in the system, namely:

- The displacement of the levels due to the interactions between the system and its environment.
- The Doppler effect due to the movements of the observer relative to the atoms of the system.

These two effects can be ignored if we consider the following two hypotheses:

- The system is completely isolated from its external environment.
- The observer is static or at rest relative to the system (the object).

For our case, during absorption, we will therefore have:

$$\Delta v = v_R + v_V + v_B = \frac{1}{2\pi}\Gamma_{R,V,B}$$

$$\Rightarrow \Gamma_{R,V,B} = 2\pi\left(v_R + v_V + v_B\right) \tag{2}$$

The Einstein coefficient in absorption is given by:

$$B_{R,V,B} = C\int_{v_R}^{v_B} \frac{\Omega_{R,V,B}\left(v\right)}{hv}\mathrm{d}v \tag{3}$$

We know that:

$$\Gamma_{R,V,B} = N_{ph} \times \Omega_{R,V,B} \times C$$

$$\Leftrightarrow \Omega_{R,V,B} = \Gamma_{R,V,B} \cdot \frac{1}{N_{ph}\cdot C}$$

$$\Leftrightarrow \Omega_{R,V,B} = \frac{2\pi\left(v_R + v_V + v_B\right)}{N_{ph}\cdot C} \tag{4}$$

Then

$$B_{R,V,B} = C\int_{v_R}^{v_B} \frac{2\pi\left(v_R + v_V + v_B\right)}{N_{ph}\cdot C\cdot hv}\mathrm{d}v$$

$$= \frac{2\pi\left(v_R + v_V + v_B\right)}{N_{ph}\cdot h}\int_{v_R}^{v_B}\frac{\mathrm{d}v}{v} \tag{5}$$

$$= \frac{v_R + v_V + v_B}{\hbar\cdot N_{ph}}\left(l_n v_B - l_n v_R\right)$$

with $\hbar = \dfrac{h}{2\pi}$.

2) Radiative de-excitation

Here again, the profile of the line is a Lorentz curve, with width at mid-height given by:

$$\Delta v = \left(v_R + v_V + v_B\right) - \left(v_R + v_V\right) = v_B = \frac{1}{2\pi}\Gamma_B \Rightarrow \Gamma_B = 2\pi v_B$$

The Einstein coefficient of spontaneous emission is given by:

$$A_B = \Gamma_B = 2\pi v_B \tag{6}$$

3) Non-radiative de-excitation

Here the atom is at the exciting level $E_{R,V}$. It must then transfer this energy to the other atoms of the system by collision. This phenomenon can be considered as a stimulated emission during which the atom emits a photon of energy $E_{R,V}$. However, this photon remains trapped inside the system and is therefore always absorbed by another atom in the system. The system therefore behaves like a black body which emits radiation of spectral density $u\left(v_R + v_V\right)$ while increasing its temperature until it reaches the equilibrium temperature T.

Planck's law specifies that the spectral density of radiation at temperature T is given by the expression:

$$u(v) = \frac{8\pi h v^3}{C^3} \cdot \frac{1}{\mathrm{e}^{\frac{hv}{k_B T}} - 1}$$

$$\Rightarrow u\left(v_R + v_B\right) = \frac{8\pi h \left(v_R + v_B\right)^3}{C^3} \cdot \frac{1}{\mathrm{e}^{\frac{h\left(v_R + v_B\right)}{k_B T}} - 1} \tag{7}$$

with k_B: Boltzmann's constant.

We can also consider the absorption of photons by the atoms of the system as a phenomenon of absorption of radiation of spectral density $u\left(v_R + v_V + v_B\right)$ by a black body. The temperature then rises until it reaches equilibrium at temperature T.

We will have:

$$u\left(v_R + v_V + v_B\right) = \frac{8\pi h \left(v_R + v_V + v_B\right)^3}{C^3} \cdot \frac{1}{\mathrm{e}^{\frac{h\left(v_R + v_V + v_B\right)}{k_B T}} - 1} \tag{8}$$

Under these conditions, the kinetic equations describing the evolution of populations N_0; $N_{R,V}$ and $N_{R,V,B}$, in interaction with the radiation and taking into account all the processes of absorption, spontaneous and simulated emission are written:

$$\frac{\mathrm{d}N_0}{\mathrm{d}t} = -B_{R,V,B}\, u\left(v_R + v_V + v_B\right)N_0 + A_B N_{R,V,B} + B_{R,V}\, u\left(v_R + v_V\right)N_{R,V}$$

$$\frac{\mathrm{d}N_{R,V,B}}{\mathrm{d}t} = B_{R,V,B}\, u\left(v_R + v_V + v_B\right)N_0 - A_B N_{R,V,B} - B_{R,V}\, u\left(v_R + v_V\right)N_{R,V}$$

At equilibrium at temperature T, we will have:

1) $N_{R,V,B} = N_{R,V}$

2) $\dfrac{N_{R,V,B}}{N_0} = \dfrac{g_{R,V,B}}{g_0} e^{\frac{-h(v_R + v_V + v_B)}{kBT}}$

Newton showed that a monochromatic beam could not be broken down into other colors. So we have $g_{R,V,B} = g_0 = 1$ because the levels are nondegenerate.

We then have:

$$B_{R,V,B} u(v_R + v_V + v_B) N_0 - A_B N_{R,V,B} - B_{R,V} u(v_R + v_V) N_{R,V,B} = 0 \qquad (9)$$

Divide this equation by N_0, we have:

$$B_{R,V,B} u(v_R + v_V + v_B) - \frac{A_B N_{R,V,B}}{N_0} - B_{R,V} u(v_R + v_V) \frac{N_{R,V,B}}{N_0} = 0 \qquad (10)$$

Replacing $\dfrac{N_{R,V,B}}{N_0}$ by its value, the equation becomes:

$$B_{R,V,B} u(v_R + v_V + v_B) - A_B \cdot e^{\frac{-h(v_R+v_V+v_B)}{k_B T}} - B_{R,V} \cdot u(v_R + v_V) \cdot e^{\frac{-h(v_R+v_V+v_B)}{k_B T}} = 0$$

$$\Leftrightarrow B_{R,V} = B_{R,V,B} \frac{u(v_R + v_V + v_B)}{u(v_R + v_V)} \cdot e^{\frac{-h(v_R+v_V+v_B)}{k_B T}} - \frac{A_B}{u(v_R + v_V)} \qquad (11)$$

with: $\ast\ B_{R,V,B} = \dfrac{v_R + v_V + v_B}{\hbar \cdot N_{ph}} \left(l_n v_B - l_n v_R \right)$

$\ast\ A_B = 2\pi v_B$

$\ast\ u(v_R + v_V + v_B) = \dfrac{8\pi h (v_R + v_V + v_B)^3}{C^3} \cdot \dfrac{1}{e^{\frac{h(v_R+v_V+v_B)}{kBT}} - 1}$

$\ast\ u(v_R + v_v) = \dfrac{8\pi h (v_R + v_v)^3}{C^3} \cdot \dfrac{1}{e^{\frac{h(v_R+v_v)}{K_B T}} - 1}$

2.3. Discussion

- The color of the object alone defines a kind of selection rule which makes it possible to distinguish between allowed transitions and transitions prohibited.

  Here, for example, our object being of blue color, only the radiative transitions which are such that $\Delta E = h v_B$, are allowed, and any other radiative transition is forbidden.

- We can describe the kinetics of the levels of a system having any color by following the same basic diagram and a mathematical formalism analogous to that presented above. The Einstein coefficient of absorption will always be the same for any color, only the Einstein coefficients of spontaneous emission and stimulated emission will vary according to the color of the object.

- A completely transparent (like pure water) or completely reflective (perfect mirror) system will be defined by a crosssection of absorption of zero. This implies radiative and non-radiative de-excitation rates to be also zero. We

then conclude that an object will be totally transparent or completely reflective if the Einstein coefficients corresponding to the different processes are all zero. The system is said to be colorless.

- In this work, for simplicity, we considered a white light composed only of the three primary colors. A much more rigorous and complete formalism will have to take into account the fact that the white light of the sun is rather composed of the seven fundamental colors (the colors of the rainbow), infrared radiation and ultraviolet radiation.

- The spectrum of white light is continuous. In practice, the average value corresponding to the frequency distribution of a specific color will therefore be taken each time. We will have for example, the red color:

$$v_{\min} = 4 \times 10^{14} \text{ Hz}, v_{\max} = 4.8 \times 10^{14} \text{ Hz};$$

$$v_R = \frac{v_{\min} + v_{\max}}{2} = 4.4 \times 10^{14} \text{ Hz}.$$

3. Applications of the Quantum Color Theory

1) Black garment and white garment

At the very beginning of this work, we asked ourselves the question of how to explain the fact that a black garment dried less quickly in the sun than a white garment. Thanks to the QCT, we notice that an object can be black in two different ways:

- The object absorbs all the white light coming from the sun and emits nothing at all by radiative de-excitation.

- The object absorbs all the white light from the sun and then emits infrared and ultra-violet radiation which is imperceptible to the human eye.

Similarly, an object will be colored white in two different ways:

- The object absorbs all the white light of the sun and emits all of this radiation by radiative de-excitation.

- The object absorbs all the white light of the sun and then emits all the absorbed radiation except radiation in the infrared range and ultraviolet.

Thus, a white garment that only emits radiation in the visible spectrum heats up faster than a black garment that only emits radiation in the invisible spectrum (infrared and ultraviolet).

This is explained by the fact that the rate of de-excitation by collision corresponding to the white garment will be higher than that corresponding to the black garment.

2) Black skin and white skin

Referring to the description of the black and white colors given in the previous point, a black skin which does not emit any radiation by radiative de-excitation will have to heat up more quickly than white skin.

This difference in temperature variations is the reason why black skin and white skin have different biological compositions. Indeed, black skin contains more melanin than white skin. If, this was not the case, in other words, if black

skin contained the same amount of melanins as white skin, the black man would literally burn in the sun.

3) Olbers' paradox

Olbers' paradox is stated as follows: "in an infinite and homogeneous universe, all lines of sight must end at the surface of a star, so why is the sky black at night?"

Two solutions to this paradox have been proposed by scientists [4]. And one like the other does not seem to convince in its entirety, the entire scientific community.

Indeed, we manage to find each time contradictory elements which create a reasonable doubt on the veracity of the said "solutions".

The first explanation for the black color of the sky at night is given by the expansion of the universe. The universe being in perpetual expansion, the different stars that make up our galaxy, and even the neighboring galaxies, are continually moving away from the terrestrial observer. This produces a Doppler effect, more precisely a shift towards the red so that the visible spectrum emitted by the star is transformed into an invisible spectrum (infrared) for a terrestrial observer.

Such a shift supposes an expansion of the universe at a very high speed, which is false (in first approximation, the Doppler effect is given by: $\delta v = v - v_0 = v_0 \dfrac{v}{c}$; with v_0, the frequency emitted by the source; v, the frequency perceived by the observer; v, the speed of the source relative to the observer and c is the speed of light in a vacuum).

Hubble has calculated an expansion rate of the universe H_0 (a speed divided by a distance) which is called the Hubble constant. H_0 is currently estimated at 71 ± 4 Km/s/Mpc, which means that a galaxy located 1 Mp from the observer moves away at a speed of 71 Km/s (1 parsec = 3.261 light-years).

A second solution to Olbers' paradox was given by Kelvin. Indeed, when we look out into space, we are also looking back in time. The darkness we see between the distant stars is the primordial darkness that existed before the stars were born. Modern estimates of the distance from a possible luminous starry background (the limit of visibility) give a value of 10^{23} light-years, which means that we would only see stars in any direction if they had been shining for at least 10^{23} years. But the lifetime of an average star such as the sun is only 10^{10} years. So when asked where most of the starlight has gone, Kelvin replies that it simply hasn't reached us.

This answer from Kelvin assumes that the majority of the stars that our galaxy and neighboring galaxies are made of are located more than 10^{23} light-years from the earth. What is once again completely false and moreover, the age of the universe is estimated today at some 15 billion years.

The QCT allows us to introduce here a solution to Olbers' paradox, which will be less ambiguous and more convincing.

We have shown that, thanks to this theory, an illuminated body which emits radiative de-excitation radiations in the field of the invisible will be of black

color.

Using Newton's laws of gravity, physicists have been able to demonstrate that the visible matter that we observe in the universe constitutes only 5% of all the mass contained in the universe. In other words, the universe is made up largely, or 95%, of invisible matter [5]. The physicist called this dark matter, claiming that it was of an unknown form and therefore not baryonic. We say no!

The QCT allows us to affirm in fact that dark matter is not of unknown form. It is the only baryonic matter which absorbs all the radiation coming from the various stars but then only emits radiation in the invisible domain. Relevant proof of the QCT is the existence of the cosmic radiation at 2.7 K observed in the universe in all directions. The cosmic microwave background is nothing but the radiation, in the microwave range, emitted by the dark matter that contains the entire universe.

Thus, we can say that when we look in any direction in the universe, we always come across dark matter and that is why the sky is black at night.

4) The color of the chameleon [6]

The chameleon is able to take on any color. An explanation for this phenomenon was given by French researchers during the 25th Physics Olympiad 2017-2018. They claimed then that the skin of the chameleon being composed of crystals of guanine, the different colors of the chameleon would therefore simply result from the phenomena of diffraction of sunlight on the crystals of guanine. However, diffraction is only a phenomenon of reflection on the reticular planes of the crystal as shown in Figure 3. And as we showed when we introduced the dark room paradox, the color of the chameleon should not be seen by any observer, regardless of their position. Exactly the same effect occurs for the rainbow which also results from the phenomena of diffraction of the white light of the sun on drops of water.

The QCT gives us a simple explanation for the color change of the chameleon. In fact, the chameleon is able to vary the temperature of its skin at will. This allows him to make a rigorous and meticulous selection of the waves emitted by radiative de-excitation after absorption. He can then take any color.
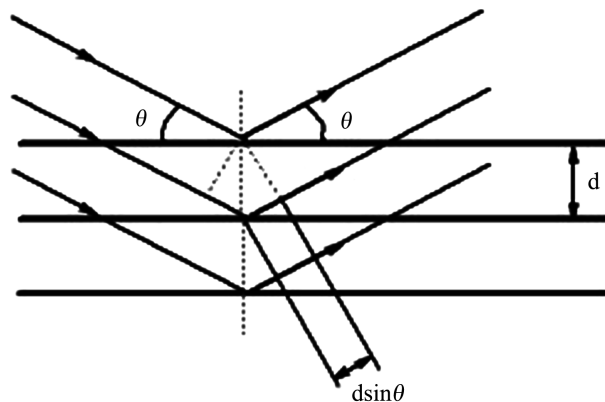

Figure 3. Diffraction of the light or reflection on the reticular planes of the crystal.

5) Gold nanoparticles

Gold nanoparticles are smaller than 10 nanometers (1 nm = 10^{-9} m). Gold then has extremely interesting optical properties, because the nanoparticles change color from red to purple depending on their size. This property cannot be explained by classical color theory because the nanoparticles considered here all have the same shape, usually a spherical shape. Thus, they should all reflect light in the same way regardless of their size. However, quantum color theory gives a more adequate explanation for this phenomenon. Indeed, the more the size of the nanoparticle decreases, the more the number of atoms in the system also decreases. There will therefore be less and less energy transferred between atoms by collision. Thus, the color of the nanoparticles will change from red to purple as their size decreases.

4. Conclusions

In this work, we have shown the shortcomings of the classical color description. The quantum color theory that we have introduced here is the one that best describes the different colors that we observe on a daily basis. In addition, it allows us to explain many physical phenomena which are still poorly understood today, I quote:

- A wet white garment dries much faster in the sun than a wet black garment because its white color corresponds to the emission of waves whose frequencies are associated only with the seven fundamental colors and not with infrared or ultraviolet. While the black garment only emits ultraviolet and infrared. This causes wet white clothing to heat up much faster in the sun than wet black clothing.
- Black skin and white skin have different biological characteristics associated with their respective colors. When exposed to the sun, black skin heats up much faster than white skin because it emits no radiation while white skin emits all of the absorbed solar radiation.
- The sky is dark at night (Olbers' paradox) because our Universe is made up mostly of dark matter (95% of all matter that makes up the Universe). Indeed, dark matter absorbs the light emitted by various stars and only emits radiation corresponding to a temperature of 2.7 K in the microwave range: cosmic radiation, which is invisible to the naked eye.
- The chameleon manages to change the color of its skin by varying its temperature. At each temperature, the skin of the chameleon emits radiation whose frequency corresponds to a specific color.
- Gold nanoparticles change color as their size decreases (from red to purple) because as they decrease in size, the number of atoms of which the nanoparticle is made also decreases. Thus, the frequency of the emitted radiation will increase as the size decreases.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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