What makes color? – Chemistry in language of physics

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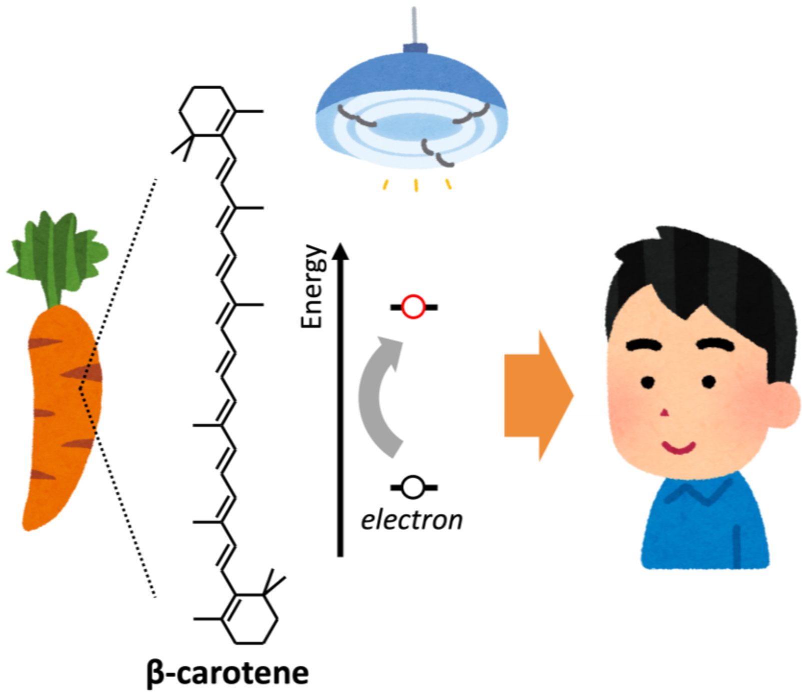

Most of you must love to see chemistry experiments. Your favorite experiments may include beautiful color changes and mysterious light emissions, or perhaps, spectacular destruction of objects cooled in liquid nitrogen and dynamic explosion. Physical chemistry thoroughly pursues the reason why these chemical phenomena happen.

Physical chemistry describes chemical phenomena, literally, using the concept of physics. Daily objects you see every day are chemical substances whether natural or artificial, which consist of very tiny molecules, or even smaller units, atoms. Atoms are assemblies of electrons and nuclei, and two or more atoms stick together to form molecules while the electrons play roles as glue. For example, β-carotene ($C_{40}H_{56}$, see the image), a well-known reddish-orange dye contained in a carrot or a squash, consists of a large number of carbon atoms (C) and hydrogen atoms (H) [1]. Appearance of color of dyes is a chemical phenomenon. Chemistry deals with such phenomena on a molecular or atomic level, focusing on the characteristics of the substances. On the other hand, physics deals with universal properties which substances can exhibit. In the case of dyes, physicists are interested in what in general makes dyes colored, not in the dyes themselves. Physical chemistry is a fused discipline of physics and chemistry: it aims to understand the physical principles of chemical phenomena based on the characteristics of the substances.

In fact, I was rather attracted by how interesting physical chemistry is than how useful it is and decided to do my research in this field. The starting point was when I learned the principle of color as a high school student. I think that many people do not even come up with the question of what makes a difference of color, which we distinguish unconsciously every day. Consider you want to burst a balloon by gathering sunlight on it using a lens. In that situation, a black balloon more easily bursts than a white one does. This fact suggests that the darker the color of the dye becomes, the more vigorously the dye on the surface of the balloon absorbs light to be transformed into heat, leading to the destruction of the plastic film. In other words, the appearance of color and the absorption of light can be seen as two sides of the same coin. This fact can be understood more tangibly using the concept of wavelength of light. Light has a property of wave with a certain length of a repetitive unit, which is called wavelength, and the energy of light is correlated to its wavelength. For instance, blue light has generally larger energy than red light. When natural light such as sunlight comprising of light with many different wavelengths is irradiated on a dye, the electrons of the dye molecules try to absorb the energy of each component of the light with a specific wavelength. The electrons can absorb only specific components of the light depending on the molecule because, surprisingly, the electrons in the molecules can take specific values of energy (see the image). If they can absorb the energy, which is called optical excitation, the absorbed component of the light disappears, and the remaining components enter our eyes to be recognized in the form of color. This is why the appearance of color and the absorption of light are two sides of the same coin. I was personally very impressed by the way that the appearance of color was connected with the concept of wavelength which I learned in physics class. I remember the world I had ever seen with my eyes suddenly changed into the visual image created by the enormous number of dye molecules in my mind. I believe that it is one of the interesting aspects of physical chemistry to focus on quite fundamental phenomena and to find the relation of it with physics in this way.

Eventually, how does physical chemistry improve our society? Let us exemplify dyes again. When you want to create dyes with new colors, you need to understand what makes the colors of known dyes first. This is one of the representative questions tackled by physical chemistry: "Why does a dye exhibit that color?" For example, in a specific class of organic dyes including β-carotene, physical chemistry has provided us with a general relationship between the structure of a molecule and the wavelength it absorbs: the larger the size of the spatial range where the electrons can move around becomes, the longer the absorbed wavelength becomes. This relationship stems from the physical rule that the electrons need less energy to be excited within a larger box. In this way, physical chemistry aims to clarify, from the perspective of physics, how the colors of dyes come from their molecular structures. Once the cause of the appearance of color is characterized, you can conversely design new dyes by changing the causal factors, such as elongating the chain of β-carotene to expand the spatial range of electrons in the design of more reddish dyes. Therefore, the insight from physical chemistry presents us with a guideline for designing new dyes, which will be useful for chemists of other disciplines such as organic or inorganic chemists to synthesize the new dyes. Physical chemistry cooperates with other fields of chemistry to effectively develop novel functional materials such as dyes for our daily lives.

References

[1] Muranaka A., *Kagaku to Kyoiku* **2017**, 65, 246.

Grammarly was used to check grammatical mistakes (https://www.grammarly.com/grammar-check).

Several free images were used (https://www.irasutoya.com).