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Exploring and Analyzing the Causes of Color in the Earth

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Abstract: Color is an essential element of human visual perception, which exists in all aspects of our daily lives and plays a key role in scientific research and technological applications. Color is produced by various mechanisms, including absorption and reflection of chemical pigments, complex formation of transition metal ions, and micro- and nanostructural modulation of structural colors. This paper aims to comprehensively explore the scientific principles of color generation and its applications in different fields. The article first describes how transition metal ions exhibit colors by forming complexes and explains in detail the coordination process of copper ions in an aqueous solution and its resulting d-orbital splitting, which in turn absorbs light of specific wavelengths and exhibits complementary colors. Secondly, the article explores the mechanism of color expression of natural pigments in plants, significantly how pigment molecules containing conjugated double bonds, such as β-carotene, can absorb specific wavelengths of light and exhibit vivid colors through electron delocalization and energy level jumps. Finally, the article illustrates the principles of structural color and its potential for industrial applications, including using micro- and nanostructures, such as photonic crystals, to modulate the scattering and absorption of light, thus enabling dynamic changes in color and environmental protection. The in-depth exploration of the mechanism of color generation enhances our understanding of the basic principles of color science. It provides theoretical support for technological innovation and practical applications in related fields.

Keywords: Color, transition metal, plant, structure, mechanism.

1. Introduction

Color is a fascinating topic in the incredible journey of exploring nature and science. Colors give the world a rich visual dimension and are an essential communication medium between nature and human society. From gorgeous flowers to blue skies, from deep oceans to variegated feathers and colors, their unique charms attract us to learn more about the mysteries behind them.

Since ancient times, humanity has never stopped exploring colors. From primitive paintings to modern dyeing technology to modern color science, research and application of color have been carried out throughout the history of human civilization. In contemporary society, color is even more ubiquitous and widely used in art, design, medicine, biology, and other fields [1]. It affects people's visual perception and invisibly shapes our aesthetic concepts and lifestyles.

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The significance of the study of color is that it can help people better understand the laws of nature and promote the development and innovation of related disciplines. In materials science, an in-depth study of color can give people new ideas for material preparation to develop new materials with specific colors and properties [2]. In biology, studying natural pigments in plants can reveal the mystery of biological evolution and provide new inspiration for biomedical engineering [3]. In addition, studying structural colors has brought new research directions and application prospects in optics and photonics [4].

The study of color not only has theoretical value but also has a wide range of practical value. With the continuous progress of science and technology and people's continuous pursuit of quality of life, the application of color will become more and more extensive and in-depth. Therefore, people must conduct in-depth research and discussion on the generation mechanism of color and its application to contribute more wisdom and strength to the progress and development of humanity.

2. Color of metal

Firstly, there is a wide range of colorful metal compounds and ions within natural life. Compounds formed by transition metals have color-like complex ions of central metal ions surrounded by ligands. A ligand is a molecule or ion that uses lone pairs to bind to a metal, such as ethylenediamine. Transition metals form colored solutions and compounds because these elements have unfilled d orbitals. The metal ions aren't colored independently because the d orbitals are degenerate. In other words, they all have the same energy corresponding to the same spectral signal. Transition metal ions form complexes and compounds with other molecules and become colored. A complex form occurs when a transition metal bonds to one or more neutral or negatively charged ligands. The complex ions will absorb light with the same visible color and the same wavelength [5]. Therefore, other colored light will pass through, and eventually, the complementary light of absorbed light will be expressed, which can be optically seen.

Octahedral complexes have six simple ligands arranged around a central metal ion. The argument is not any different if you have multidentate ligands. When the ligands bond with the transition metal ion, there is repulsion between the electrons in the ligands and the electrons in the d orbitals of the metal ion. That raises the energy of the d orbitals. However, how the d orbitals are arranged in space only raises some of their energies by the same amount. Instead, it splits them into two groups. Figure 1 shows the arrangement of the d electrons in a Cu^{2+} ion before and after six water molecules bond with it.

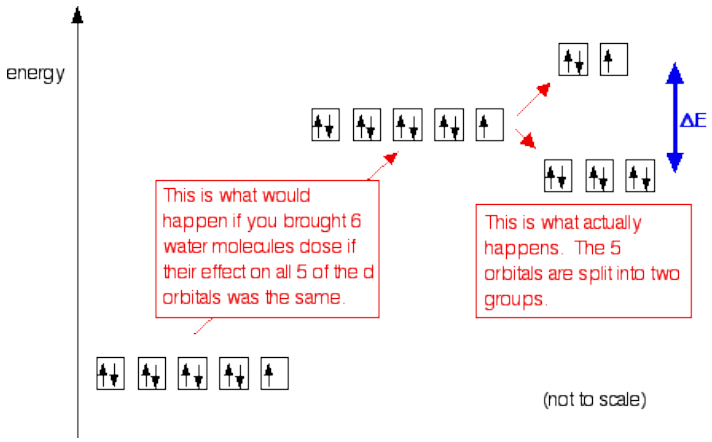


Figure 1: Arrangement of the d electrons in a Cu^{2+} before and after six water molecules bond with it.

Whenever six ligands are arranged around a transition metal ion, the d orbitals are split into two groups in this way - 2 with a higher energy than the other 3. The size of the energy gap between them

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varies with the nature of the transition metal ion, its oxidation state (whether it is 3+ or 2+, for example), and the nature of the ligands. When white light is passed through a solution of this ion, some of the energy in the light is used to promote an electron from the lower set of orbitals into a space in the upper set [5].

Each wavelength of light has a particular energy associated with it. Red light has the lowest energy in the visible region. Violet light has the most incredible energy. Suppose that the energy gap in the d orbitals of the complex ion corresponded to the energy of yellow light. Yellow light would be absorbed because its energy would be used to promote electrons. That leaves the other colors. Your eye would see the light passing through as a dark blue because blue is the complementary color of yellow. For example, in Copper Sulfate ($CuSO_4$), If white light (ordinary sunlight, for example) passes through copper(II) sulfate solution, some wavelengths in the light are absorbed by the solution. Copper(II) ions in solution absorb light in the red region of the spectrum. The light that passes through the solution and out the other side will have all the colors except red.

It can be concluded that a relative correlation needs to be established between the observed color (for the eye) and the wavelength of light absorbed. Based on the complementary color wheel, the following relationships can be obtained (arranged from the highest to the lowest energy absorbed):

400-nm Violet light absorbed → Green-yellow observed

430-nm Blue light absorbed → Orange observed

450-nm Blue light absorbed → Yellow observed

490-nm Blue-green light absorbed → Red observed

570-nm Yellow-green light absorbed → Violet observed

580-nm Yellow light absorbed → Dark blue observed

600-nm Orange light absorbed → Blue observed

650-nm Red light absorbed → Green observed

What about the non-transition metals and the complex ions? The reason is that non-transition metals do not have partly filled d orbitals. Visible light is only absorbed if some energy from the light is used to promote an electron over precisely the proper energy gap. Non-transition metals do not have any electron transitions which can absorb wavelengths from visible light. For example, although scandium is a member of the d block, its ion (Sc^{3+}) has yet to get any d electrons left to move around. This is no different from an ion based on Mg^{2+} or Al^{3+}. Scandium(III) complexes are colorless because no visible light is absorbed. In the zinc case, the 3d level is completely whole - there are no gaps to promote an electron. Zinc complexes are also colorless [6,7].

3. Color in plants

There are various mechanisms for colors in plants, while the primary mechanism would be explained using β-Carotene and anthocyanin.

β-Carotene is an important orange pigment commonly found in plants and used widely in food, medical, and cosmetic industries. Its usage includes as a colorant due to its color, as a nutrient due to its ability to transfer into vitamin A, and as an antioxidant due to its properties. β-Carotene has a molecular formula of $C_{40}H_{56}$ and a molecular mass 537; its structure is shown in Figure 2.

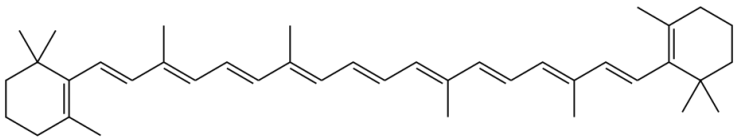


Figure 2: Structure of β-Carotene.

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The skeletal formula shows that β-Carotene consists of a chain of intersecting C-C and C=C, which makes up a sizeable conjugated system. A conjugated system separates the conjugated double bonds by one single bond. Because the π bonds are so close to each other, the p orbitals of the π bonds would overlap with the ones of the conjugated π bonds, forming a system where electrons of the p orbitals could be delocalized and freely move across. Figure 3 shows the conjugated system in benzene, where the electrons are delocalized throughout the system.

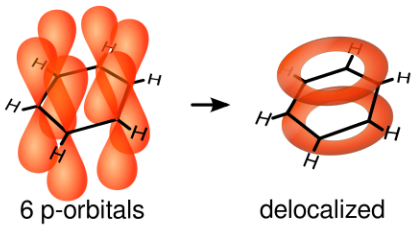


Figure 3: Conjugated systems in benzene.

The molecule of β-Carotene has a chain of 11 continuous conjugated double bonds. Therefore, all the p orbitals of the π bonds could overlap, forming a sizeable conjugated system that allows electrons to be delocalized and move across almost the entire molecule, as shown in Figure 4.

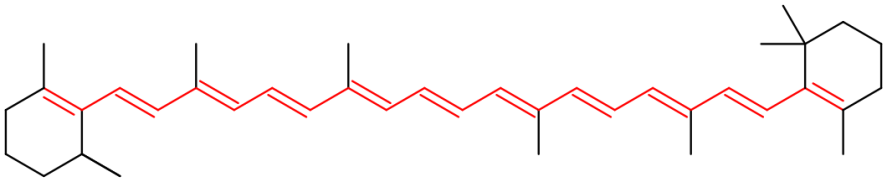


Figure 4: Continuous conjugated double bonds in the beta-carotene molecule.

The delocalized π electrons in this conjugated system can accept the energy of a photon of specific wavelength according to the gap energy and move from the ground state when the electron is in π orbital with the lowest energy to an exited state when the electron is in π* orbital with higher power. An example of the movement of electrons in butadiene is shown in Figure 5.

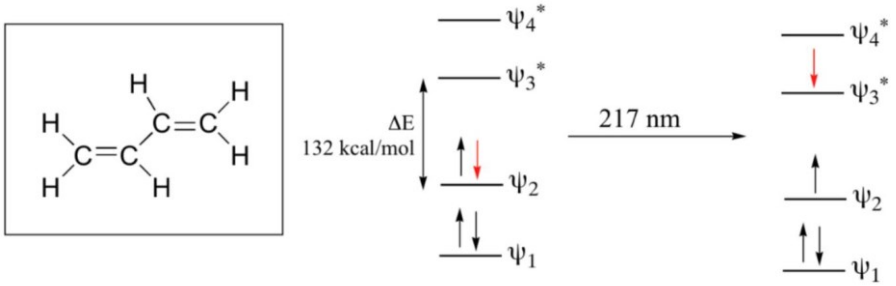


Figure 5: Movement of an electron in butadiene.

The lowest gap energy is when the π electron moves from the highest unoccupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). The lowest gap energy could be calculated using the formula below [8].

$$E_{n+1} - E_n = \frac{(n+1)^2 h^2}{8mL^2} - \frac{n^2 h^2}{8mL^2} = (2n+1)\frac{h^2}{8mL^2}$$

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This formula is calculated in quantum mechanics so that it wouldn't be shown here. In this formula, n is the number of continuous conjugated C=C, h is the Planck constant, m is the mass of one electron, and L is the length of the molecular box, which would be approximately linear with n. This would cause the wavelength of the photon absorbed by the electrons to increase as n increases. For example, butadiene, hexatriene, and octatetraene would absorb photons with wavelengths of 217nm, 252nm, and 304nm, respectively. In the case of β-Carotene, according to its structure, n would be 11, and L would be 0.294nm. Also, m would be $9.110*10^{-31}$kg, and h would be $6.626*10^{-34}$Js as constants. The calculation could then be taken as below.

$$\Delta E = \Delta E_{12} - \Delta E_{11} = (2 \times 11 + 1)\frac{\left(6.626 \times 10^{-34} Js\right)^2}{8 \times \left(9.220 \times 10^{-31} kg\right) \times \left(2.94 \times 10^{-10} m\right)^2} = 1.60 \times 10^{-19} J$$

Next, the formula ΔE = h * v where h is the Planck constant and v is the frequency could be used to calculate the frequency of the photon absorbed as below.

$$V = \frac{\Delta E}{h} = \frac{1.60 \times 10^{-19} J}{6.626 \times 10^{-34} Js} = 2.41 \times 10^{14} s^{-1}$$

The measured experimental value for the frequency is $6.03*10^{14}$, and using the formula c = v * λ, the wavelength of the photon absorbed could then be calculated to be 497nm. This means that the light of wavelength 497nm, the color of cyan, would be absorbed for the electrons to move from HOMO to LUMO. Therefore, with the color of cyan absorbed, the light of the opposite color, orange, would be reflected and expressed by β-Carotene, which is how it obtains an orange color.

In β-Carotene, the chromophores are the conjugated C=C, which could absorb photons and express colors. Another pigment that uses conjugated C=C as chromophores, like β-Carotene, is named Lycopene with the structure shown in Figure 6. Lycopene has 11 continuous conjugated double bonds like β-Carotene. Therefore, it expresses a similar red color. This uses a similar coloring principle: the absorption of photons of a specific wavelength to move electrons from π orbital to π* orbital of a higher energy. Some other pigments, such as anthocyanidin, with similar coloring principles might have other chromophores, including conjugated systems from C=O, N=N, and even aromatic systems.

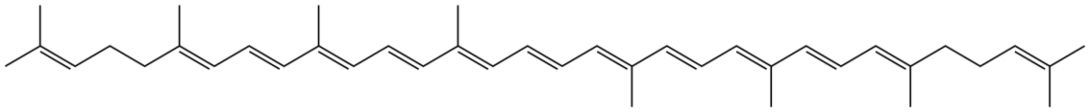


Figure 6: Structure of Lycopene.

Anthocyanin is a water-soluble vacuolar pigment belonging to flavonoids present in many different types of plants, such as purple cabbages. It was found that the color expressed by anthocyanin could change under various pH conditions.

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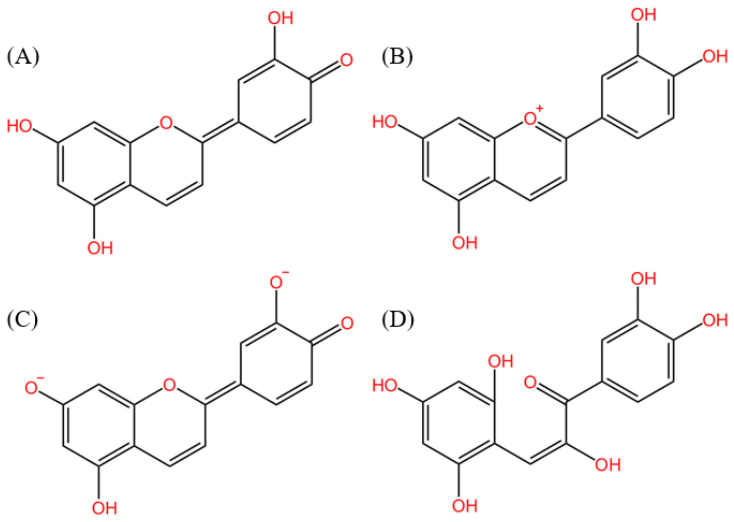


Figure 7: Structure of anthocyanin at (A) pH 6-7; (B) Ph < 3; (C)pH 7-8; and (D) pH > 12.

The anthocyanin molecule contains a benzene ring and other alternating C=C, thus forming a conjugated system. The conjugated system can absorb photons of specific wavelengths depending on the size of the conjugated system, emitting light of the opposite color. The larger the conjugated system, the longer the wavelength of light absorbed and the shorter the wavelength of light emitted. At pH 6-7, the structure of an anthocyanin is named the quinone group, as shown in Figure 7-A. C=C connects the benzene ring on the right to the rest of the molecule in a sizeable conjugated system. As a result, long-wavelength photons from yellow to orange are absorbed. As a result, anthocyanins appear blue-violet in a neutral environment. In an acidic environment, when the pH drops below 3, the structure of the anthocyanin transforms into a Flavylium cation, as shown in Figure 7-B. The benzene ring on the right is not connected to the rest of the molecule in a conjugated system. As a result, the conjugated system is much smaller and will absorb shorter wavelengths of light, i.e., the color green. As a result, anthocyanins appear red at pH values below 3. In an alkaline environment with a pH of 7-8, the structure of anthocyanins transforms into an anionic quinone group, as shown in Figure 7-C. The entire molecule forms an extensive conjugated system. In this environment, anthocyanins absorb long-wavelength orange photons and thus exhibit a blue-to-green color. As the pH rises above 12, the anthocyanin structure changes to Chalcone, as shown in Figure 7-D. The molecules are separated by C=O, making the conjugated system smaller. As a result, the minor conjugated system absorbs violet light, and the anthocyanin takes on a yellow color [9].

4. Structural color

Compared with pigment colors, which are produced by the absorption or reflection of light by a single substance, structural colors rely on the periodic micro-nano structure of substances to control light. It has the advantages of chemical stability, environmental protection, and high resolution. Moreover, structural color has strong wavelength selectivity and can achieve the presentation of specific colors by controlling the surface structure of the substance. High-purity colors can be scattered to achieve accurate colors, making the presentation more vivid and full. Unlike the characteristics of chemical dyes, structural colors can change with the surrounding environment, as chameleons, squid, octopus, etc., have dynamic structural colors. Structural colors can also cope with harsh environments such as intense light exposure, acid and alkali corrosion, etc. Their production process vastly reduces the harmful effects of chemical dyes and paints on the environment and the human body [10].

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The production of structured colors is closely related to photonic crystals. A photonic crystal is a regular optical structure with a periodic media arrangement with different reflectivity. This is because it can control the propagation of photons in the same way as a semiconductor does for electrons. It is an ordered structure consisting of several basic units arranged according to a specific periodic law, just like a crystal. Photonic crystals are classified as one-dimensional, two-dimensional, and three-dimensional. A one-dimensional photonic crystal is a structure in which the dielectric constants are periodically arranged in one direction only and uniformly distributed in the other direction. For example, Brazil has a butterfly called the 'blue saucer' because of its bright blue wings. Scientists have tried to extract blue pigment from the wings of the blue saucer with an organic solvent, but the wings are green in the organic solvent and dark brown when viewed against the sun, which indicates that the blue saucer does not have a blue component in its wings. Zooming in on the microstructure of its wings reveals some ridged surfaces like a Christmas tree, and this repeating nanostructured unit enhances the reflection of blue light. As another example, the beetle's wing sheaths reflect green and dark purple light, and its abdomen reflects orange light. This structural color originates from a multilayer membrane structure consisting of alternating layers of chitin and melanin. Chameleons can change color in response to the external environment, a typical example of dynamic structural color [8]. The chameleon's skin contains many nanoparticles arranged in a regular dot matrix. When light hits the surface of the chameleon's skin, these nanoparticles will diffract, thus reflecting light of different colors. When the chameleon is stimulated, the spacing of the nanoparticles will become more extensive, and the wavelength of the reflected light will increase. Then, the reflected blue light will gradually turn into yellow, orange, and red light [11].



Figure 8: Silicon dioxide structural color crystal thin film [12].

Figure 8 shows a basic experiment on the preparation of photonic crystal structures. In this experiment, sub-micron uniform silica nanoparticles were prepared, and the silica was deposited to form photonic crystals (presented as structured colored films of different colors from red to blue) [12]. These silica crystals must be uniformly aligned to form effective photonic crystal thin film samples. The solvent control method used in this experiment effectively regulates the particle size of the nanoparticles by fixing the other reaction conditions and only varying the solvent volume to ensure uniformity of the particles. This is very important for making photonic crystal thin film samples.

In addition, structural colors play an essential role in industry. For example, scientists have discovered various methods to prepare fabrics with structural colors, such as inkjet printing and vertical deposition. However, in addition to these conventional methods, we can prepare structural color fibers first and then make structural color fabrics from the structural color fibers using knitting and weaving methods. That is, the 'particle-fibre-fabric' two-step method. Compared with other methods, the 'two-step method' of preparing structural color fabrics is complicated and challenging. Still, its structural color is firm, and it is gradually receiving more and more attention [13].

However, there are still many problems in applying structural color, such as the poor mechanical strength of structural color fabrics and the ease of fade. Secondly, the ordered photonic crystal structure generally has a high angle dependence, limiting its application. If these problems can be overcome, this research result is believed to go further.

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5. Conclusion

This paper provides a comprehensive discussion of the multiple mechanisms of color production and their applications in different fields, mainly including the principles of color production by transition metal compounds, the color expression of natural pigments in plants, and the properties and preparation of structural colors. Transition metals can form complex ions with ligands due to their unfilled d-orbitals, and these ions exhibit color when absorbing light at specific wavelengths. This is due to the color expression mechanism of natural pigments in plants, especially pigment molecules containing conjugated double bonds such as β-carotene and carotenoids. These molecules exhibit vibrant colors by absorbing light at specific wavelengths through electron delocalization and energy level jumps in conjugated systems. Structural colors differ from those produced by chemical dyes, which rely on the periodic micro-nano-structure of substances to control light propagation. They have attracted much attention due to their chemical stability, environmental friendliness, and high resolution. However, their poor mechanical strength, susceptibility to color fading, and angle dependence still need to be addressed.

Despite the progress made in this paper regarding color generation mechanisms and applications, some things could still be improved. Firstly, for the color generation principle of transition metal compounds, the article only covers the basic complex formation process and needs to explore the more complex coordination chemistry and spectral properties in depth. Secondly, in the section on phytochromes, the article needs to address the biosynthetic pathways and regulatory mechanisms of pigments, which are essential for understanding the functions and roles of pigments in plants. Finally, in the section on structural colors, the article provides limited information on the preparation methods and application areas of photonic crystals, which must fully reflect the current research progress and challenges.

Future research can further expand the depth and breadth of color science. In transition metal compounds, the influence of coordination chemistry on color can be studied in depth, and new structures and properties of complexes can be explored. Regarding phytochromes, attention can be paid to the biosynthetic pathways and regulatory mechanisms of pigments and their functions in plant stress resistance and photosynthesis. In structural colors, research on the preparation technology and application of photonic crystals can be strengthened to solve the problems of their poor mechanical strength and susceptibility to fading and to explore more innovative application areas. In addition, intelligent research and application of color science can be carried out by combining technical means, such as computer science and artificial intelligence, to support technological innovation and industrial upgrading in related fields.

Authors Contribution

All the authors contributed equally, and their names were listed alphabetically.

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