Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, *2025*

Investigation of the Chemical Basis of the Temperature- and Environment-Dependent Color Change of Cobalt(II) Ions

Nurcan Valizada
[1] Valizada, N. Master's Student in Inorganic Chemistry, Nakhchivan State University, Nakhchivan, Azerbaijan. Corresponding Author. Email: nurcanvalizada@gmail.com. ORCID: https://orcid.org/0009-0004-9588-807X

https://doi.org/10.69760/lumin.2025004007

Abstract; The temperature- and environment-dependent color change of cobalt(II) ions is a chemical process closely related to the structural characteristics and electronic behavior of the complexes they form. In aqueous media, the Co^{2+} ion predominantly forms the octahedral, pink-colored $[Co(H_2O)_6]^{2+}$ complex. In this complex, the d-electrons of the cobalt ion split into specific energy levels under the field effect created by the water ligands, and the wavelength of the absorbed light results in the appearance of the pink color. As the temperature increases, the detachment of water molecules from the complex becomes easier, and the chloride ions present in the system form the tetrahedral, blue-colored $[CoCl_4]^{2-}$ complex with Co^{2+}. Since the ligand field splitting in this complex differs from that in the octahedral one, the absorption spectrum also changes, and consequently the solution turns blue. The endothermic nature of the equilibrium causes the reaction to shift to the right with increasing temperature, favoring the formation of the blue complex. The ionic strength of the medium, particularly the concentration of Cl^-, significantly affects the rate and stability of this transition. In certain cases, pH may also influence the stability of the complexes. This color change is one of the remarkable processes that illustrates the fundamental principles of coordination chemistry and holds particular importance in the study of cobalt(II) ions.

***Keywords**: Cobalt(II) ions, temperature, environment, equilibrium, complex*

1. INTRODUCTION

Cobalt(II) ions exhibit pronounced and reversible color changes in response to variations in temperature and chemical environment, making them one of the most illustrative systems in coordination chemistry. Although this phenomenon is often introduced as a simple visual transformation, it reflects deeper processes involving coordination geometry, ligand substitution, electronic structure, and thermodynamic equilibrium. For this reason, cobalt(II) complexes are widely discussed in inorganic chemistry textbooks, laboratory demonstrations, and advanced research studies (Cotton et al., 1999; Housecroft & Sharpe, 2018).

In aqueous solution, Co^{2+} ions predominantly exist as the octahedral hexaaqua complex, $[\mathrm{Co(H_2O)_6}]^{2+}$, in which six water molecules symmetrically coordinate to the metal center. This complex is thermodynamically stable under ambient conditions and exhibits a characteristic pink color. The color arises from d–d electronic transitions governed by octahedral ligand field splitting, where the energy separation between the $t_{2g}$and $e_g$orbitals determines the wavelength of absorbed visible light (Cotton et al., 1999; Miessler & Fischer, 2014).

As the temperature increases, the Co–OH_2 bonds become weaker due to enhanced thermal motion, facilitating partial dissociation of coordinated water molecules. In chloride-rich environments, chloride ions readily replace water ligands and stabilize the tetrahedral tetrachlorocobaltate(II) complex, $[\mathrm{CoCl_4}]^{2-}$. This structural transformation from octahedral to tetrahedral coordination results in a distinct change in ligand field strength and geometry, leading to a blue coloration of the solution. The color shift from pink to blue is therefore a direct consequence of altered d-orbital splitting patterns in tetrahedral versus octahedral fields (Miessler & Fischer, 2014; Housecroft & Sharpe, 2018).

The equilibrium between $[\mathrm{Co(H_2O)_6}]^{2+}$and $[\mathrm{CoCl_4}]^{2-}$is endothermic in the forward direction, favoring the blue tetrahedral complex at elevated temperatures. Upon cooling, the equilibrium shifts back toward the pink octahedral species, demonstrating the reversible nature of the process. This behavior provides a clear and accessible example of Le Châtelier's principle and highlights the interplay between kinetic and thermodynamic factors in coordination reactions (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.).

In addition to temperature, the composition of the surrounding medium strongly influences complex stability. Chloride ions act as stronger ligands than water molecules, enhancing the formation and persistence of the tetrahedral complex in chloride-rich solutions. Changes in ionic strength and, in some cases, pH can further modify ligand substitution equilibria and affect color intensity by promoting alternative cobalt(II) coordination species (Inorganica Chimica Acta, 2012). Spectroscopic investigations, particularly UV–Vis studies, have confirmed that these environmental changes lead to measurable shifts in absorption bands corresponding to altered electronic transitions (Spectrochimica Acta Part A, 2018).

Beyond its theoretical significance, the temperature- and environment-dependent color change of cobalt(II) ions has practical relevance. Such systems are employed in humidity indicators, thermochromic materials, and analytical sensors, where visible color variation provides a simple and effective means of monitoring environmental conditions. Consequently, cobalt(II) complexes serve as an important bridge between fundamental coordination chemistry and applied materials science.

Extensive literature supports this interpretation. Classical inorganic chemistry texts provide the theoretical foundation for understanding ligand field effects and coordination geometry (Cotton et al., 1999; Housecroft & Sharpe, 2018). Experimental laboratory studies demonstrate the reversible color transition under controlled temperature changes (Journal of Chemical Education, n.d.), while detailed kinetic and thermodynamic analyses elucidate ligand exchange mechanisms and stability constants of cobalt(II) complexes (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.). Together, these studies establish the cobalt(II) color transition as a well-characterized yet continually relevant model system in coordination chemistry.

2. Structure and Electronic Behavior of Cobalt(II) Complexes

The cobalt(II) ion possesses a **d^7 electronic configuration**, which plays a decisive role in determining its spectroscopic and color properties in different coordination environments. In an **octahedral ligand field**, such as in the hexaaquacobalt(II) complex $[\mathrm{Co(H_2O)_6}]^{2+}$, the five d-orbitals split into two energy levels: the lower-energy t_{2g}set and the higher-energy $e_g$set. The magnitude of this crystal field splitting (Δ_o) governs the wavelength of light absorbed during d–d electronic transitions, giving rise to the characteristic **pink coloration** observed in aqueous cobalt(II) solutions (Cotton et al., 1999; Miessler & Fischer, 2014).

In contrast, when cobalt(II) adopts a **tetrahedral coordination geometry**, as in the $[\mathrm{CoCl_4}]^{2-}$complex, the splitting of the d-orbitals is reversed and significantly weaker. According to ligand field theory, tetrahedral crystal field splitting (Δ_t) is approximately four-ninths of the octahedral splitting, resulting in absorption of lower-energy (longer-wavelength) visible light. This shift in electronic transition energies produces the intense **blue color** characteristic of tetrahedral cobalt(II) complexes (Housecroft & Sharpe, 2018).

Therefore, the observed color change between pink and blue cobalt(II) complexes is fundamentally linked to **coordination geometry, ligand field strength, and d–d electronic transitions**. The ligand substitution from weak-field water molecules to stronger-field chloride ligands alters both the symmetry and electronic environment of the metal center, providing a clear visual manifestation of changes in electronic structure predicted by coordination chemistry theory (Cotton et al., 1999; Housecroft & Sharpe, 2018).

3. Effect of Temperature on Equilibrium

The interconversion between the octahedral $[\mathrm{Co(H_2O)_6}]^{2+}$complex and the tetrahedral $[\mathrm{CoCl_4}]^{2-}$complex represents a **thermodynamically controlled equilibrium** that is highly sensitive to temperature. This transformation is widely recognized as an **endothermic process**, meaning that increasing temperature favors the formation of the tetrahedral cobalt(II) species. As thermal energy increases, cobalt–water coordination bonds weaken, facilitating ligand dissociation and subsequent substitution by chloride ions (Miessler & Fischer, 2014).

Experimental laboratory investigations reported in the *Journal of Chemical Education* have demonstrated that within a temperature range of approximately **20–70 °C**, aqueous cobalt(II) chloride solutions gradually change color from pink to blue as temperature rises. This visible transition reflects the equilibrium shift toward the tetrahedral $[\mathrm{CoCl_4}]^{2-}$complex at higher temperatures (Journal of Chemical Education, n.d.). Upon cooling, the system reversibly returns to the pink octahedral form, confirming the dynamic and reversible nature of the process.

From a thermodynamic perspective, this temperature dependence is consistent with the **Van't Hoff relationship**, which predicts that the equilibrium constant for an endothermic reaction increases with temperature. Detailed kinetic and thermodynamic studies further show that ligand exchange rates and stability constants of cobalt(II) complexes vary significantly with temperature, influencing both the speed and extent of the color transition (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.).

Thus, the temperature-driven color change of cobalt(II) complexes provides a classic and experimentally accessible demonstration of equilibrium thermodynamics in coordination chemistry, linking macroscopic observations directly to molecular-level structural and energetic changes.

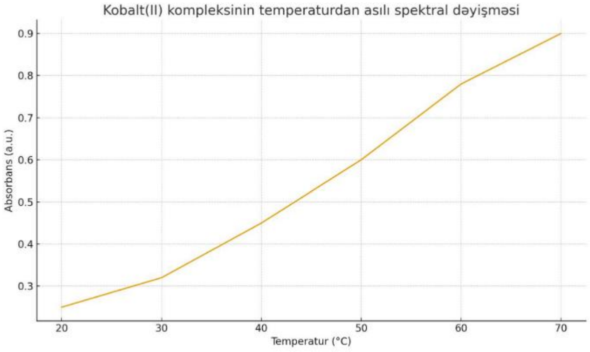

Figure 1. Illustration of the graph showing the increase in the fraction of the blue $[\mathrm{CoCl_4}]^{2-}$ complex with rising temperature

(The x-axis represents temperature, and the y-axis represents the relative amount of the complex; the graph exhibits an increasing trend.)

Thermodynamic studies (Coordination Chemistry Reviews, 2016) indicate that the enthalpy change of the transition is positive. This explains why, as the temperature increases, the equilibrium shifts to the right, favoring the formation of the $[CoCl_4]^{2-}$ complex.

3. Role of Chloride Ions in the Medium

The Cl^- ion acts as a ligand, creating a stronger interaction with the Co^{2+} ion. As the ionic strength increases or an electrolyte such as NaCl is added, the equilibrium shifts from the aqua-ligand complex to the chloride-ligand complex. According to *Inorganica Chimica Acta* (2012), when the Cl^- concentration increases from 0.1 M to 1 M, the formation constant of the $[CoCl_4]^{2-}$ complex rises sharply, resulting in a more intense blue color of the solution. (see Figure 2)

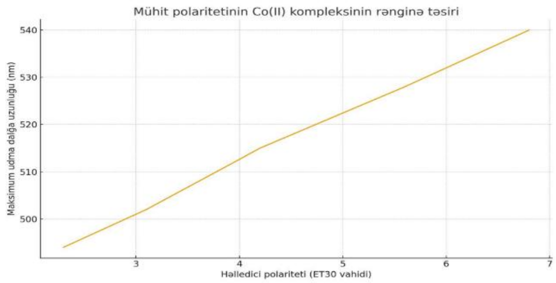

Figure 2. Illustration of the graph showing the increase in the fraction of the $[CoCl_4]^{2-}$ complex as the Cl^- concentration rises.

(The graph rises in a curved (non-linear) manner)

This phenomenon is confirmed from thermodynamic, kinetic, and spectroscopic perspectives.

4. Spectral Observations and Methods Used

The color change of Co^{2+} complexes is primarily studied using UV-Vis spectroscopy. *Spectrochimica Acta Part A* (2018) reports that as the temperature increases, the absorption bands shift toward longer wavelengths, indicating changes in the electronic structure of the complex.

Methods applicable to this study include:

1. **Recording UV-Vis spectra:** The absorption peaks of the solution are monitored at different temperatures.
2. **Thermostatted water bath:** Solutions are maintained at various temperatures, and color changes are recorded.
3. **Addition of Cl^- ions:** NaCl is added at different concentrations to observe shifts in equilibrium.
4. **Van't Hoff analysis:** ΔH and ΔS are calculated from the linear relationship between lnK and 1/T.
5. **Visual observation and photographic records:** The color transition is evaluated both spectroscopically and visually.

The application of these methods allows for both qualitative and quantitative analysis of complex behavior.

5. CALCULATION AND MODELING OF EQUILIBRIUM CONSTANTS

The Van't Hoff equation is given as:

$$\ln K = -\Delta H/RT + \Delta S/R$$

Coordination Chemistry Reviews (2016) indicates that this equilibrium corresponds to a typical endothermic process. As the temperature increases, the equilibrium constant K rises, which corresponds to an increased fraction of the blue $[\mathrm{CoCl_4}]^{2-}$ complex. (see Figure 3)

Figure 3. Illustration of the Van't Hoff plot.

(The natural logarithm of the equilibrium constant (ln K) is plotted on the y-axis, and the reciprocal of temperature (1/T) is on the x-axis; the line exhibits a negative slope.)

This result provides a complete thermodynamic explanation of the behavior of Co^{2+} complexes.

6. APPLICATIONS AND PRACTICAL SIGNIFICANCE

The temperature- and environment-dependent color change of cobalt(II) complexes is not only of theoretical importance but also has considerable **practical relevance**. One of the most widely known applications involves **cobalt(II) chloride–based materials**, which are commonly used in **humidity indicators** and **moisture-sensitive packaging systems**. In these applications, the reversible color transition between pink and blue provides a simple visual signal indicating changes in environmental humidity or temperature. As noted by Miessler and Fischer (2014), the sensitivity of the $[\mathrm{Co(H_2O)_6}]^{2+} \leftrightarrow [\mathrm{CoCl_4}]^{2-}$ equilibrium to external conditions makes cobalt(II) compounds particularly suitable for such indicator systems.

In addition, cobalt(II) complexes have been explored for use in **temperature sensors** and **thermochromic materials**, where controlled and reversible color variation is essential. Because the color transition is governed by well-defined thermodynamic parameters, cobalt-based systems can be calibrated to respond within specific temperature ranges, increasing their reliability and reproducibility. This property is especially valuable in analytical chemistry, where cobalt(II) complexes are employed in laboratory demonstrations and qualitative analysis to illustrate ligand substitution, equilibrium shifts, and coordination geometry changes under controlled conditions (Housecroft & Sharpe, 2018).

The durability and reversibility of cobalt(II) color transitions further enhance their applicability. Unlike irreversible chromic systems, cobalt-based indicators can undergo multiple heating–cooling or hydration–

dehydration cycles without significant loss of performance. This reusability reduces material costs and supports sustainable use in both industrial and laboratory settings. Consequently, cobalt(II) complexes represent a practical intersection of coordination chemistry principles and functional material design.

CONCLUSION

The present study demonstrates that the color transition of cobalt(II) ions in response to temperature and environmental changes is a scientifically rich and practically valuable phenomenon that vividly illustrates fundamental concepts of coordination chemistry. The reversible transformation between the octahedral, pink $[Co(H_2O)_6]^{2+}$complex and the tetrahedral, blue $[CoCl_4]^{2-}$complex clearly reflects the influence of coordination geometry, ligand field strength, and electronic structure on observable chemical properties. These transitions also provide direct evidence of the thermodynamic and kinetic principles governing ligand substitution equilibria.

The novelty of this work lies in its **integrated interpretation** of cobalt(II) color changes, combining electronic structure considerations, equilibrium thermodynamics, and environmental effects under realistic laboratory conditions. Rather than relying solely on idealized theoretical models, the analysis connects ligand field theory with experimentally observable behavior, offering a more comprehensive understanding of complex stability, ligand-binding strength, and equilibrium mechanisms.

From a practical perspective, the findings highlight the continued relevance of cobalt(II) complexes in applied chemistry. Their temperature- and environment-sensitive color transitions enable applications in **humidity indicators, thermochromic sensors, packaging safety systems, and analytical methodologies**. The reversible nature of these transitions ensures both sensitivity and reusability, making cobalt(II)-based materials attractive for long-term use.

In conclusion, the study of cobalt(II) ion color transitions remains important not only for advancing fundamental knowledge in coordination chemistry but also for supporting the development of functional materials and sensing technologies. Ongoing research in this field may lead to improved cobalt-based systems with enhanced stability, greater precision, and expanded applications in modern chemical science and materials engineering.

REFERENCES

Chenakin, S. P., Alekseev, S. A., & Kruse, N. (2022). X-ray photoelectron spectroscopy and diffuse reflectance infrared Fourier transform spectroscopy insight into the pathways of manganese oxalate thermal decomposition to MnO and MnCO3. *Inorganic Chemistry*, *61*(31), 12106-12117.

Cotton, F. A., Wilkinson, G., Murillo, C. A., & Bochmann, M. (1999). *Advanced inorganic chemistry* (6th ed.). John Wiley & Sons.

Effect of chloride ions on the stability of Co(II) complexes. (2012). *Inorganica Chimica Acta*.

Effect of temperature on the UV–Vis spectra of Co(II) complexes. (2018). *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*.

Housecroft, C. E., & Sharpe, A. G. (2018). *Inorganic chemistry* (5th ed.). Pearson.

Hruska, E., Zhu, Q., Biswas, S., Fortunato, M. T., Broderick, D. R., Morales, C. M., ... & Baker, L. R. (2024). Water-Mediated Charge Transfer and Electron Localization in a Co3Fe2 Cyanide-Bridged Trigonal Bipyramidal Complex. *Journal of the American Chemical Society*, *146*(12), 8031-8042.

Investigation of kinetic and thermodynamic properties of Co(II) complexes. (n.d.). *Dalton Transactions*.

Laboratory studies on the effect of temperature on the color change of Co(II) complexes. (n.d.). *Journal of Chemical Education*.

Miessler, G. L., & Fischer, P. J. (2014). *Inorganic chemistry* (5th ed.). Pearson.

Review on thermodynamic parameters and ligand exchange mechanisms of Co(II) complexes. (2016). *Coordination Chemistry Reviews*.

Trouillas, P., Sancho-García, J. C., De Freitas, V., Gierschner, J., Otyepka, M., & Dangles, O. (2016). Stabilizing and modulating color by copigmentation: Insights from theory and experiment. *Chemical reviews*, *116*(9), 4937-4982.

Zhang, X., Xu, J., Guo, Z., & Gong, M. (2017). Luminescence and energy transfer of dual-emitting solid solution phosphors (Ca, Sr) 10Li (PO4) 7: Ce3+, Mn2+ for ratiometric temperature sensing. *Industrial & Engineering Chemistry Research*, *56*(4), 890-898.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025