


22.1: The Colors of Rubies and Emeralds

Rubies are deep red and emeralds are brilliant green, yet the color of both gemstones is caused by the same ion, Cr^{3+} . The difference lies in the crystal that hosts the ion. Rubies are crystals of aluminum oxide (Al_2O_3) in which about 1% of the Al^{3+} ions are replaced by Cr^{3+} ions. Emeralds, by contrast, are crystals of beryllium aluminum silicate [$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$] in which a similar percentage of the Al^{3+} ions is replaced by Cr^{3+} . The embedded Cr^{3+} ion is red in the aluminum oxide crystal but green in the beryllium aluminum silicate crystal. Why?

The answer to this question lies in the effect that the host crystal has on the energies of the atomic orbitals in Cr^{3+} . Atoms in the crystal create a field around the ion—sometimes called the *crystal field*—that splits the five normally degenerate *d* orbitals into two or more levels. The color of the gemstone is caused by electron transitions between these levels. In rubies, the crystal field is stronger (and the corresponding splitting of the *d* orbitals greater) than it is in emeralds. Recall from Chapter 2  that the color of a substance depends on the colors *absorbed* by that substance, which in turn depends on the energy differences between the orbitals involved in the absorption. The greater splitting in ruby results in a greater energy difference between the *d* orbitals of Cr^{3+} and, consequently, the absorption of a different color of light than in emerald. Here we see the theme of this book repeated yet again—the structure that surrounds the Cr^{3+} ion determines its color.



Ruby and Emerald The Cr^{3+} ion is responsible for both the red color of ruby and the green color of emerald.

The splitting of the *d* orbitals in transition metal ions embedded within host crystals also is responsible for the colors of several other gemstones. For example, the red in garnet, which has $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$ as a host crystal, and the yellow-green of peridot, which has Mg_2SiO_4 as a host crystal, are both caused by electron transitions between *d* orbitals in Fe^{2+} . Similarly, the blue in turquoise, which has $[\text{Al}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}]^{2-}$ as a host crystal, is caused by transitions between the *d* orbitals in Cu^{2+} .



Garnet, Peridot, and Turquoise The red in garnet and the yellow-green of peridot are both caused by Fe^{2+} . The blue of turquoise is caused by Cu^{2+} .

In this chapter, we examine the properties of the transition metals and their ions more closely. We also examine the properties of coordination compounds in some detail. We first discussed this common type of transition metal compound in [Chapter 17](#) (see [Section 17.7](#)). In a coordination compound, bonds to a central metal ion split the d orbitals much as they are split in the crystals of gemstones. The theory that explains these splittings and the corresponding colors is crystal field theory, which we also explore in this chapter.

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