Transition metal complexes which undergo rapid substitution of one ligand for another are **labile**, whereas complexes in which substitution proceed slowly or not at all are **inert**. For an inert complex, it is a large activation energy which prevents ligand substitution. Inert complexes are therefore **kinetically stable** compounds. As a classic example, the substitution reaction:

\[
[[\text{Co(NH}_3)_6]^{3+}]_{(aq)} + 6\text{H}_3\text{O}^+_{(aq)} \rightarrow [[\text{Co(H}_2\text{O})_6]^{3+}]_{(aq)} + 6\text{NH}_4^+_{(aq)} \quad \text{Label[Eq1]}
\]

has an equilibrium constant of \(10^{64}\). The large equilibrium constant suggests that the complex ion \([[\text{Co(NH}_3)_6]^{3+}]\) is **thermodynamically unstable**. This reaction is highly thermodynamically favored, yet the inert \([[\text{Co(NH}_3)_6]^{3+}]\) complex ion lasts for weeks in acidic solutions because the rate of the reaction is very slow. Thus, the large activation energy acts as an efficient barrier for ligand substitution rendering the \([[\text{Co(NH}_3)_6]^{3+}]\) ion **thermodynamically metastable**.

The allotropes of carbon

Although diamond is thermodynamically less stable than graphite, diamonds last a long time (~100 million years) since the conversion of diamond into graphite occurs extremely slowly.

Here is an example of a **labile** complex (notice difference in oxidation state for \([\text{Co}]\) in Equation \(\text{ref[Eq1]}\)):

\[
[[\text{Co(NH}_3)_6]^{2+}]_{(aq)} + 6\text{H}_3\text{O}^+_{(aq)} \rightarrow [[\text{Co(H}_2\text{O})_6]^{2+}]_{(aq)} + 6\text{NH}_4^+_{(aq)}
\]

This reaction is virtually complete in a few seconds. The \([[\text{Co(NH}_3)_6]^{2+}]\) complex is thermodynamically unstable and also labile. Notice that the only difference between the two ammine cobalt complexes shown in the examples above is the oxidation number of the cobalt atom. The inert complex has Co(III) while the labile one has Co(II). Both ammine complexes are octahedral and in the case of Co(III), a d\(^6\) species, the t\(_{2g}\) levels are filled. Co(II), on the other hand, has partially filled e\(_g\) orbitals. It is straightforward to demonstrate lability since changes will occur and ligand substitution in complexes is normally accompanied by a color change. Inertness, however, is somewhat dull since nothing happens. In this experiment the inertness of ligand substitution by chromium (III) ions is compared with other reactions that do proceed at reasonably fast rates.

---

**How to Predict if a Complex is Labile or Inert**

Henry Taube (Nobel Prize, 1983) tried to understand lability by comparing the factors that govern bond strengths in ionic complexes to observations about the rates of reaction of coordination complexes. He saw some things that were unsurprising. Taube observed that many M\(^{+1}\) ions (M = metal) are more labile than many M\(^{+3}\) ions, in general. That is not too surprising, since metal ions function Lewis acids and ligands function Lewis bases in forming coordination complexes. In other words, metals with higher charges ought to be stronger Lewis acids, and so they should bind ligands more tightly. However, there were exceptions to that general rule. For example, Taube also observed that Mo(V) compounds are more labile than Mo(III) compounds. That means there is more going on here than just charge effects. Another factor that governs ionic bond strengths is the size of the ion. Typically, ions with smaller atomic radii form stronger bonds than ions with larger radii. Taube observed that Al\(^{3+}\), V\(^{3+}\), Fe\(^{3+}\) and Ga\(^{3+}\) ions are all about the same size. All these ions exchange ligands at about the same rate. However, other factors are in play that are outside the
Labile and Inert octahedral Complexes 1. [https://www.youtube.com/watch?v=g4fJSM_cE-s](https://www.youtube.com/watch?v=g4fJSM_cE-s)

Example \(\PageIndex{1}\)

In which compound from each pair would you expect the strongest ionic bonds? Why?

a. LiF vs KBr
b. CaCl₂ vs. KCl

Contributors and Attributions

- Angel C. de Dios (Georgetown University)