

Unit 2

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2.1 Lecture 4: Substitution Reactions

4/5:

- Association/dissociation reactions.
- Fairly related to organic S_N2 and S_N1 reactions, respectively.
- General form:



- We investigate the position of the equilibrium with the three main characteristics that determine reactivity.

1. Sterics.

- Related to the metal coordination number.
 - C.N. > 6 is typically disfavored.
 - C.N. < 6 is possible.
- The size of L' is also important: If L' = PPh₃ for example, this is hard to get to C.N. > 4.

2. Ligand character.

- In nonpolar media, dissociation of charged groups (e.g., Cl[−]) will be disfavored. However, the opposite is true in polar media.
 - This is because of the issue of making charge/ionizing.
- The match between M and L (e.g., hard/soft, electron rich/poor) is also important.
 - For example, Fe⁰ will bind CO strongly since Fe⁰ is electron rich and CO is a π acceptor.
 - However, Fe^{IV} will not (as a hard, electron-poor metal center).

3. Electronic structure of the metal center (whether or not the metal is electronically saturated [has 18 electrons]).

- 18 e[−]: it will not want to coordinate an additional L'.
- 20 e[−]: it will want to dissociate.
- 16 e[−]: it *can* associate.
 - However, it may not want to given that 16 e[−] square-planar complexes are fairly stable.
 - The associated state may be a transition state in a square-planar ligand substitution or otherwise not a ground state.

- Ligand substitution reactions terms: **Kinetic** and **thermodynamic**.
- **Kinetic** (considerations): Elements are inert (slow) or labile (fast).
- **Thermodynamic** (considerations): Which side of an equilibrium will be favored. Elements are stable or reactive.

- In ligand substitution reactions, there are two limiting regimes:

1. Associative substitution.

- See the related discussion in Labalme (2021).
- This is the most general reaction type, even for coordinatively saturated complexes.
- Rate law:

$$\frac{d[\text{ML}_5\text{L}']}{dt} = k_{\text{obs}}[\text{ML}_6][\text{L}']$$

2. Dissociative mechanism.

- See the related discussion in Labalme (2021).
- There are many things that look dissociative that are associative (e.g., instead of forming a 5-coordinate species, you could just have a molecule of the solvent displace a ligand).
- This mechanism is rare and hard to prove.
- Rate law:

$$\frac{d[\text{ML}_5\text{L}']}{dt} = \frac{k_2 k_1 [\text{ML}_6][\text{L}]}{k_{-1}[\text{L}] + k_2[\text{L}]}$$

- Experimentally, we swamp the reaction with L' so that [L'] >>> than all other reagents. This makes it so that the rate is just $k_{\text{obs}}[\text{ML}_6]$, i.e., pseudo-first order conditions.

- Unfortunately, much like in orgo, very few cases are at these extremes and we can have hybrids called. . .

3. Interchange mechanisms.

- See the related discussion in Labalme (2021).
- Within this category, we can have I_a (associative interchange) and I_d (dissociative interchange).
- In the transition state, we have L' coming in and L leaving at the same time.

- Kinetics and rates of these mechanisms.

- Several categories (measure with water exchange rates; see Labalme (2021)):

- I) Very fast.

- Alkali metals (species that primarily engage in ionic bonding; little covalent character).
- 10^8 s^{-1} ; close to the diffusion limit.

- II) Fast.

- Higher valent ions; often M^{3+} such as Al^{3+} .
 - Higher charge \Rightarrow higher ligand affinity \Rightarrow slightly slower but still pretty fast.
- 10^3 - 10^8 s^{-1} .

- III) Slower.

- Getting into the transition metals: Fe^{3+} , V^{3+} , Ti^{3+} .
 - d -orbital splitting + covalency \Rightarrow stronger bonding \Rightarrow slower exchange rate.
- 10^1 - 10^4 s^{-1} .

- IV) Inert.

- Co^{3+} , Cr^{3+} , Pt^{2+} , and $\text{Fe}^{2+}(\text{L.S.})$.
- 10^{-8} - 10^{-4} s^{-1} .

- The overlap between the rates reflects the fact that there is no hard and fast cut off between categories.

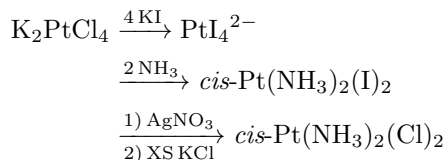
- The identity of L' also influences rates.

- Reaction rates increase with the ligand field strength of L'^[1].

¹Goes over Table IX.1 from Labalme (2021).

- Characteristics of the metal that control the observed rates.
 - Ranking L.S. metal centers (slowest to fastest): $\text{Co}^{\text{III}} < \text{Cr}^{\text{III}} < \text{Mn}^{\text{III}} < \text{Fe}^{\text{III}} < \text{Ti}^{\text{III}} < \text{V}^{\text{III}}$.
 - Considering the d counts, we have $d^6 < d^3 < d^4 < d^5 < d^1 < d^2$.
 - Now think of this in terms of the d -orbitals splitting diagram (Figure 1.7b).
 - As the antibonding orbitals get filled, σ bonds will weaken, promoting a faster exchange.
 - Full and half-full t_{2g} also provides stability.
- Thus, we list the following configurations as inert and labile (see the related discussion in Labalme (2021)):
 - Inert: d^3 , L.S. $d^{4,5,6}$, and square planar d^8 .
 - Labile: d^0 , d^1 , d^2 , H.S. $d^{4,5,6}$, d^7 , d^9 , d^{10} .
- Other important kinetic factors:
 1. Oxidation state.
 - As oxidation state increases, exchange rate decreases (becomes more inert).
 2. Size.
 - Smaller ions are more inert.
 - However, first row ions are almost always labile (because they more readily populate higher spin states).
 3. Chelate effect.
 - Reviews some info from Labalme (2021).
 - Chelating ligands form a ring or a **metallacycle** (this is why 4,5-membered ligands are stable; because 5,6-membered rings are favorable).
 - Binding of a chelating ligand is typically favored, primarily due to entropic reasons (effective concentration is secondary).
 - Example: Gives actual $\Delta G = \Delta H - T\Delta S$ thermodynamic data for the formation reaction of $\text{Cu}(\text{MeNH}_2)_4^{2+}$ vs. $\text{Cu}(\text{en})_2^{2+}$ to emphasize the importance of entropy (see the related discussion in the notes on Chapter 10 in Labalme (2021)).
 - EDTA is a hexadentate ligand that is commonly used in biology to pull all metal centers out of solution.
 - For Fe^{3+} for example, $K_f = 10^{25} \text{ mol}^{-1}$. What is mol^{-1} and why is it here?
 - Siderophores and euteroactin are biology's own chelators ($K_f = 10^{52} \text{ mol}^{-1}$).
 - These chelators involved because if bacteria are going to invade a host, they need to scavenge iron, but iron is pretty tightly regulated. Thus, there has been an arms race of molecules that can scavenge iron or prevent iron from being scavenged.
 - Chelation therapy: If exposed to a heavy metal, you will be given chelating agents that will bind to metal ions and cause them to be excreted from the body.
 4. Trans effect.
 - Reviews some info from Labalme (2021).
 - Helps predict the **regiochemistry** of where a given ligand will substitute.
 - Cis-platin reaction mechanism: $\text{cis-Pt}(\text{NH}_3)_2(\text{Cl})_2 \longrightarrow \text{cis-Pt}(\text{NH}_3)_2(\text{H}_2\text{O})_2$ in the body, which binds to DNA on the *cis*-water side, causing a kink, stopping transcription, and initiating apoptosis.
 - Cis-platin is quite toxic (people are trying to develop formulations that are less so), but highly effective at stopping cancer.
 - Can't have *trans* because it doesn't have the *cis*-water side. Thus, this synthesis mechanism doesn't work: $[\text{PtCl}_4]^{2-} \xrightarrow{2\text{NH}_3} \text{trans-Pt}(\text{NH}_3)_2\text{Cl}_2$.

- Therefore, we synthesize it as follows.

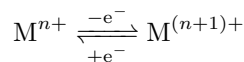


- Note that we start from tetrachloroplatinate because it is the most common form of platinum.
- Also note that XS stands for “excess.”
- Trans-effect order listed.
- The trans-effect is kinetic; concerned with rates of exchange.
 - Stronger *trans*-directors **labelize** the ligands opposite them.
- The trans influence is thermodynamic.
 - It influences the ground state structure, causing lengthening of bonds *trans* to a strong-field ligand (think of this in terms of competition for electrons on the central atom; a strong-field ligand will attract more of these, making the other bond weaker).
- Note that intramolecular reactions (such as a second binding of a bidentate chelating ligand) are highly favored.

2.2 Lecture 5: Electron Transfer Reactions

- 4/7:
- More unique to inorganic chemistry since metal atoms have access to many more electrons than common organic atoms.

- General form:



- The forward reaction is known as **oxidation** (metal oxidation state increases), while the reverse is known as **reduction** (metal oxidation state decreases).
- This is different than the oxidation/reduction reactions of organic chemistry, which involve removing or adding, respectively, a hydrogen.
- This redox chemistry is important because many transition metals have access to multiple oxidation states.
- Two Nobel prizes in this area:
 - Henry Taube (1983): Electron transfer in metals.
 - Rudy Marcus (1992): Marcus theory of electron transfer.
- 2 general flavors of electron transfer reactions: **inner sphere** and **outer sphere**.
- **Inner sphere**: Bonds are formed.
- **Outer sphere**: No bonds are formed.
- Example:
 - Consider the reaction $\text{Fe}(\text{CN})_6^{4-} + \text{Mo}(\text{CN})_8^{3-} \longrightarrow \text{Fe}(\text{CN})_6^{3-} + \text{Mo}(\text{CN})_8^{4-}$ (electron transfer from iron to molybdenum).
 - The energies at play: $\text{A}^{(n+1)} + \text{B}^n \longrightarrow [\text{A}^{(n+1)} + \text{B}^n] \longrightarrow [\text{A}^n + \text{B}^{(n+1)}]^* \longrightarrow \text{A}^n + \text{B}^{(n+1)}$.
 - Reactants \rightarrow encounter complex \rightarrow electron transfer state (an excited state) \rightarrow products.

- Energies:



Figure 2.1: Electron transfer reaction energies.

1. Thermodynamic:

- The difference in the potentials of A^{n+1} and A^n , and B^{n+1} and B^n .
 - These can be measured electrochemically.
 - We can measure the electrochemical driving force for these processes (i.e., the change in free energy during the reaction) with cyclic voltammetry.
- In a cyclic voltammetry experiment...
 - As we increase the potential to the point where the redox reaction will occur, we will see an increase as oxidation occurs.
 - Then as we decrease the potential again to where the redox reaction will occur in the reverse direction, we will see a decrease as reduction occurs.
- The midpoint $E_{1/2}$ is the thermodynamic potential (where redox is at equilibrium and you have equal amounts of both species). Is this ΔG ? What is going on here? Why are the equilibria misaligned?

2. Kinetics:

- $\Delta G = E_{1/2A} - E_{1/2B}$ where $E_{1/2X}$ is the thermodynamic potential of substance X.
 - ΔG is the thermodynamic contribution.
- ΔG^\ddagger is the kinetic barrier, or activation energy.

- The role of ΔG^\ddagger in an electron transfer.

- Electrons move very quickly and are highly delocalized with respect to the nuclei, so what dictates kinetics in these processes is nuclear motion (recall reorganization energy).
- In a simplistic sense, the key is the $[A^n + B^{(n+1)}]^*$ encounter complex.
- Electron transfer changes bond length.
 - There is a kinetic barrier to the electron transfer because the thermodynamic energy is based on minimizing the energy in the reduced and oxidized forms.
- Bond lengths change upon redox, so the solvent and counterions have to reorganize.
- This **reorganization energy** leads to a kinetic barrier (i.e., ΔG^\ddagger).
- You can see evidence of the reorganization energy in Figure 2.1a.
 - You must go past the thermodynamic potential to observe the maximum/minimum current and attain complete oxidation/reduction.

- Measuring the reorganization energy.
 - We do a self-exchange reaction with radiolabeled metal centers (see Labalme (2021)).
 - Think of the energy scale on Figure IX.1 in Labalme (2021)) as discrete. To get over ΔG^\ddagger , we must change vibrational states.
 - Indeed, the short- and long-bond iron complexes have two vibrational states, but their combined transition state with medium bonds has a new vibrational state.
 - With electronic coupling, the two parabolas split into an upper loop and a lower loop with a bump.
 - To treat this, we use the equation $\Delta G^\ddagger = \Delta G_t^\ddagger + \Delta G_v^\ddagger + \Delta G_0^\ddagger$.
 - ΔG_t^\ddagger is the translational energy, which is moving the two species together.
 - ΔG_v^\ddagger is vibrational, which is concerned with the bond lengths of the irons' matching structures.
 - ΔG_0^\ddagger is the solvent, dipole, counterion, etc. This can be large (so one of the greatest contributors is the environment in which the system lies).
- Example:
 - $\text{Co}(\text{NH}_3)_6^{2+} / \text{Co}(\text{NH}_3)_6^{3+}$ is H.S. d^7 / L.S. d^6 .
 - Self-exchange is slow because nuclear reorganization is large (0.2 Å difference in bond length, which is significant).
 - Note that this arises from the different electronic configurations.
 - The ion is getting smaller *and* going low-spin during reorganization.
- Another example:
 - $\text{Ru}(\text{NH}_3)_6^{2+} / \text{Ru}(\text{NH}_3)_6^{3+}$.
 - k_{exch} is eight orders of magnitude faster than the previous example.
 - This is because ruthenium is low-spin throughout ($\Delta(\text{Ru}-\text{N}) \approx 0.04 \text{ \AA}$ which is much smaller, so there is a smaller reorganization energy).
- Key take aways:
 - Electrons move fast, so what actually induces a kinetic barrier is the movement of the nuclei which have to reorganize in order to accommodate the electron popping between the two atoms.
 - Can be accelerated by electron coupling, as in inner sphere mechanisms.
- Inner sphere electron transfer: Some bonds are involved in the electron transfer.
 - Accelerated by electron coupling, but hindered by greater nuclear reorganization energy (a bridging bond must be formed).
- Example:
 - Consider the reaction

$$\text{Co}(\text{NH}_3)_5\text{Cl}^{2+} + \text{Cr}(\text{H}_2\text{O})_5^{2+} \longrightarrow \text{Co}(\text{NH}_3)_5^{2+} + \text{Cr}(\text{H}_2\text{O})_5\text{Cl}^{2+}$$

$$\xrightarrow{\text{H}_2\text{O}} \text{Co}(\text{H}_2\text{O})_6^{2+} + \text{Cr}(\text{H}_2\text{O})_5\text{Cl}^{2+}$$
 - The intermediates are $[(\text{H}_3\text{N})_5\text{Co}^{\text{III}}-\text{Cl}-\text{Cr}^{\text{II}}(\text{OH}_2)_5]^{4+} \longrightarrow [(\text{H}_3\text{N})_5\text{Co}^{\text{II}}-\text{Cl}-\text{Cr}^{\text{III}}(\text{OH}_2)_5]^{4+}$.
 - The rate is reasonably fast ($6 \times 10^5 \text{ mol}^{-1} \text{ s}^{-1}$).
 - How does this vary as a function of X^- ?
 - As ligand size (more diffuse; better at bridging) and charge (more electrostatic influences) increase, so does rate ($\text{Br}^- > \text{Cl}^- > \text{F}^- > \text{H}_2\text{O} > \text{NH}_3$).

- Inner-sphere electron transfer: Mixed valency.
- Consider the Creutz-Taube ion.



Figure 2.2: The Creutz-Taube ion.

- The bridging ligand is a pyrazole.
- The electron transfer is very fast; thus, the oxidation state is approximately $\text{Ru}_2^{2.5}$.
- Such electron transfers are measured with Near-IR spectroscopy, which can see inter-valence charge transfer bands (IVCT), which include bonds.
 - This very low energy form of spectroscopy observes the energy that it takes to excite an electron between the two ruthenium centers.
- Robin-Day classification:
 - Completely localized.
 - Regardless of the spectroscopic technique used, a difference between Ru^{II} and Ru^{III} can be observed.
 - Evidence of some delocalization.
 - Most common.
 - Completely delocalized.
- If you go fast enough (ultrafast spectroscopy; femtosecond lasers), almost any system looks localized.
- Marcus theory:
 - Built off of the Bell-Evans-Polanyi Relationship.
 - See Figure IX.2 and the related discussion in Labalme (2021).
 - Two big insights:
 - When $\Delta G = -\lambda$, $\Delta G^\ddagger = 0$.
 - When $\Delta G < -\lambda$, $\Delta G^\ddagger > 0$.
 - The case where $\Delta G^\circ < -\lambda$ is called the **Marcus inverted region**.
 - **Marcus equation:**

$$k_{\text{ET}} = \nu_N k_e e^{-\Delta G^\ddagger / RT}$$

where ν_N is the nuclear frequency (how accessible vibrational excited states are; related to the width of the parabolas in Figure IX.2 of Labalme (2021)) and k_e is the electronic factor (related to overlap, probability of transfer, etc.; usually set to 1).

- More importantly, Marcus discovered that

$$\Delta G^\ddagger = \frac{(\lambda + \Delta G)^2}{4\lambda}$$

which implies that as $\lambda \rightarrow -\Delta G$, $\Delta G^\ddagger \rightarrow 0$. Furthermore, as λ passes $-\Delta G$, ΔG^\ddagger increases.

- This has important implications in biology, catalysis, etc. For example, if you want to slow down an undesirable side reaction and speed up your main reaction, provide more driving force. This accelerates your main reaction and moves your side reaction into the inverted region.