

# Week 14

## Exotic Reactivity

### 14.1 Kinetic Resolution and Related Asymmetric Processes

12/3:

- Announcements.
  - Today: Last Tuesday's lecture.
    - Next time: Electron Transfer.
  - Exam 2 tomorrow.
    - Format like the practice exam.
    - Administered remotely.
    - Work alone, and closed note (honor code).
    - Available for 48 hours: Start of Wednesday til end of Thursday.
  - Do the teaching evaluations for both Alex and Masha!!
- Today: Kinetic selectivities.
- Consider a starting material (SM) that can evolve to a product A or B.

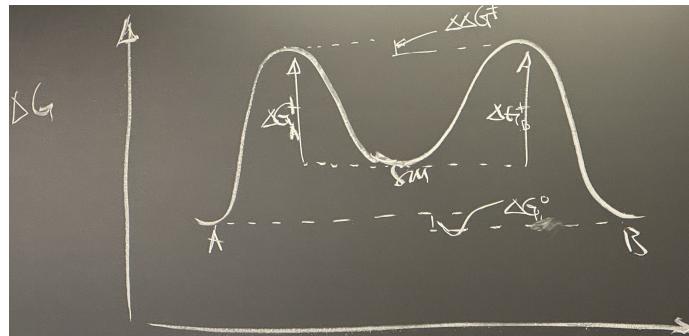


Figure 14.1: Thermodynamic vs. kinetic selectivity energy diagram.

- We can map this reaction onto a potential energy surface.
- If A and B are free to reversibly interconvert, then we can explain the product distribution in terms of the  $\Delta G^\circ$  between A and B.
  - In particular,  $\Delta G = -RT \ln K_{\text{eq}}$  where  $K_{\text{eq}} = [\text{A}]/[\text{B}]$ .

- Today, we'll consider the case in which A and B do *not* reversibly interconvert.
- In this case, what's important is the  $\Delta\Delta G^\ddagger$  between the transition states.
- Here, the selectivity is given as the ratio of the rate constants:

$$\text{selectivity} = \frac{[A]}{[B]} = \frac{k_A}{k_B} = \frac{e^{-\Delta G_A^\ddagger/RT}}{e^{-\Delta G_B^\ddagger/RT}} = e^{-\Delta\Delta G^\ddagger/RT}$$

- Note that  $k_A/k_B = k_{\text{rel}}$ . This quantity is important for determining dr's, er's, etc.
- A case in which kinetic selectivity is important: Catalytic kinetic resolution.

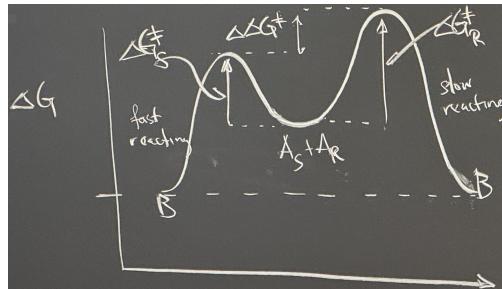


Figure 14.2: Catalytic kinetic resolution energy diagram.

- A is our starting material, a chiral racemic compound.
  - Thus, we can denote the starting materials as  $A_S + A_R$ .
  - As enantiomers,  $A_R$  and  $A_S$  have identical free energies.
- $\text{cat}^*$  is a **homochiral** catalyst.
  - Then resolution to a product B can happen two different ways: Through a transition state that consumes the (*S*)-enantiomer, and through a transition state that consumes the (*R*)-enantiomer.
  - When a homochiral catalyst acts on two enantiomers, it forms two different, diastereomeric adducts:  $A_S \cdot \text{cat}^*$  and  $A_R \cdot \text{cat}^*$ .
    - Unlike enantiomers, diastereomers *are* different compounds that may have two different energies.
  - What we've indicated in Figure 14.2 is that the (*S*)-enantiomer is converted faster than the (*R*)-enantiomer.
  - Thus,
 
$$k_{\text{rel}} = \frac{k_{\text{fast}}}{k_{\text{slow}}} = e^{-\Delta\Delta G^\ddagger/RT}$$
    - In the literature,  $k_{\text{rel}}$  is sometimes referred to as an **S-factor** (for “selectivity factor”).
    - Reference: Sheldon (2001).
- **Homochiral** (catalyst): A chiral catalyst of which we're using only a single enantiomer.
- There are many catalytic kinetic resolutions in the literature.
  - Radosevich developed one in grad school, when he was roughly our age!

- Example catalytic kinetic resolution.

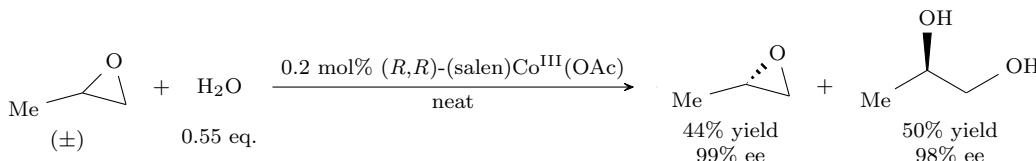


Figure 14.3: Hydrolytic kinetic resolution.

- Take propylene oxide (racemic) and 0.55 eq. of water.
  - React them, neat, in the presence of a small amount of homochiral catalyst.
    - The structure of this complex is totally irrelevant to our aims, but we can look it up in the reference if we're curious.
    - This is our homochiral catalyst that will act on the two relatively inexpensive starting materials.
  - We run this reaction neat, and recover one enantiomer of our starting material in nearly quantitative yield with near perfect ee.
  - We also obtain a ring-opened *vic*-diol in nearly quantitative yield with near perfect ee.
  - $k_{\text{rel}} \approx 500$  here!
  - Reference: Tokunaga et al. (1997).
  - This is a **hydrolytic kinetic resolution**.
    - This is a very useful reaction for the resolution of terminal epoxides — and access to terminal 1,2-diols — because there exists no method to synthetically prefer a single enantiomer.
    - Propylene is so small that even the best chiral epoxidation catalysts aren't very selective here, so it's better to do a racemic epoxidation and then this.
  - Great atom economy.
- In a kinetic resolution like the above, the percent ee of both starting material and product is subject to change over time.
  - To see this, let's build a theoretical model for a catalytic kinetic resolution.



- The net transformation involves the above two chemical reactions.
- We can write differential rate laws for each enantiomer

$$\frac{d[\text{A}_S]}{dt} = -k_{\text{fast}}[\text{A}_S][\text{cat}^*]$$

$$\frac{d[\text{A}_R]}{dt} = -k_{\text{slow}}[\text{A}_R][\text{cat}^*]$$

- The consumption of the fast-reaction enantiomer will deplete [A].
- Assuming  $[\text{cat}^*]$  is approximately constant throughout the reaction, each of these differential rate laws can be independently integrated to

$$\ln\left(\frac{[\text{A}_S]}{[\text{A}_S]_0}\right) = -k_{\text{fast}}[\text{cat}^*]t$$

$$\ln\left(\frac{[\text{A}_R]}{[\text{A}_R]_0}\right) = -k_{\text{slow}}[\text{cat}^*]t$$

- Then, the key thing to note here is that for a racemic mixture,  $[\text{A}_S]_0 = [\text{A}_R]_0$ .
- Thus, we can make this substitution and divide the above two integrated rate laws to get

$$k_{\text{rel}} = \frac{k_{\text{fast}}}{k_{\text{slow}}} = \frac{\ln([\text{A}_S]/[\text{A}_S]_0)}{\ln([\text{A}_R]/[\text{A}_S]_0)}$$

- This is a useful result, but we can make it even better. We'll start with a couple of definitions.
- **Conversion:** The ratio of how much of a reactant has reacted. *Denoted by  $c$ . Given by*

$$c := 1 - \frac{[A_S] + [A_R]}{[A_S]_0 + [A_R]_0} = 1 - \frac{[A_S] + [A_R]}{2[A_S]_0}$$

- **Enantiomeric excess:** A measurement of the degree to which a sample contains one enantiomer in greater amounts than the other. *Denoted by  $ee$ . Given by*

$$ee := \frac{[A_S] - [A_R]}{[A_S] + [A_R]}$$

- We can now do some algebra.
  - Indeed, it follows from the above definitions that

$$1 - ee = \frac{2[A_R]}{[A_S] + [A_R]} \quad 1 + ee = \frac{2[A_S]}{[A_S] + [A_R]}$$

- Then we can derive the following interesting relationships.
  - We can now know the extent to which a reaction has evolved to consume one enantiomer or the other as a function of observables!
  - Thus, we may define  $S = k_{\text{rel}}$  as a function of conversion and ee.
  - For recovered starting material,

$$S = \frac{\ln[(1 - c)(1 - ee)]}{\ln[(1 - c)(1 + ee)]}$$

- For the product,
- These relations allow us to relate conversion to ee for a catalyst of a given, set selectivity  $S$ . Specifically, we can parametrically plot ee as a function of conversion.
- Let's first do this for the percent ee in the recovered starting material.

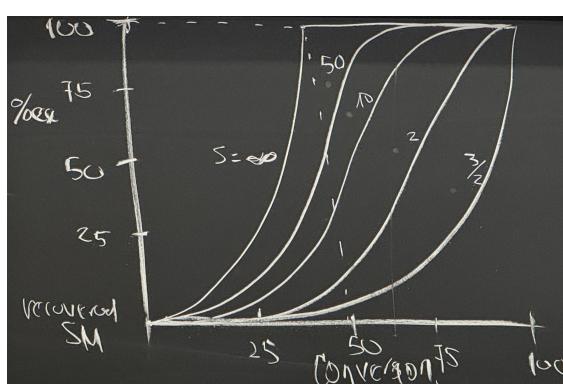


Figure 14.4: Starting material ee vs. conversion in a catalytic kinetic resolution.

- Consider first what happens in the limit that our selectivity factor is very large, i.e., that  $\Delta\Delta G^\ddagger = \text{large}$ .
- If  $S = \infty$ , then 50% conversion will get us all we need.
  - This is because at this point, the enantiomer we don't want to recover will have been fully consumed.
- As the S-factor drops, we need higher conversions to get better ee's in the recovered starting material.
- What's cool about this is we can still get high ee's with bad catalysts... at the expense of conversion.
  - Essentially, with bad catalysts, we'll recover *less* enantiopure starting material (because some of it will have been consumed at higher conversions), but we *can* still recover essentially enantiopure starting material.
- For the product.

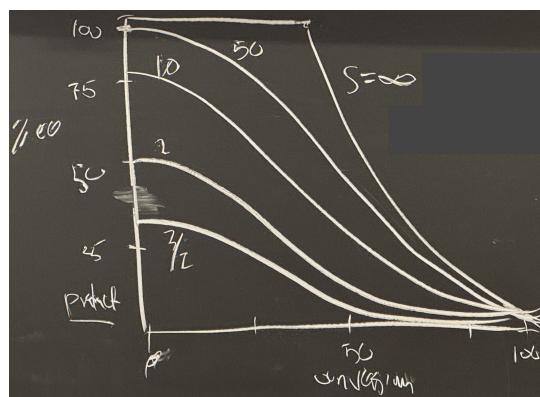


Figure 14.5: Product ee vs. conversion in a catalytic kinetic resolution.

- If  $S = \infty$ , the product will be enantiopure up until we begin converting some of the other enantiomer.
- If  $S = 50$ , we start at near-optimal purity, and then our bias will erode.
- What this implies is that for the purpose of kinetic resolution of the product, we need very good catalysts.
- That's what's remarkable about the Jacobsen catalyst: It's extremely selective for both the starting material *and* product.
- Let's now enter into some more complex kinetic regimes.

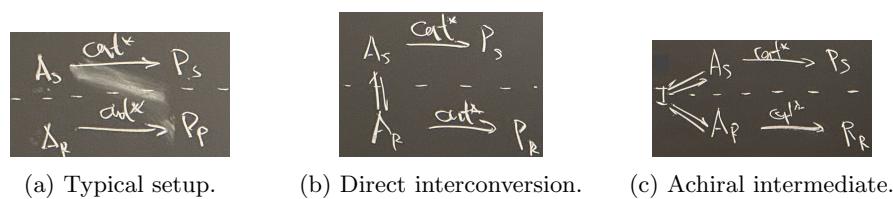


Figure 14.6: Dynamic kinetic resolution models.

- As we've depicted it in Figure 14.2, our starting materials are equal in energy and not interconverting.
  - We can conceptualize this scenario as having a mirror plane between our starting materials and products that we *never* cross (Figure 14.6a).
- But what about when the starting materials do interconvert?
  - There are two ways in which this can happen: We can cross the mirror plane directly (Figure 14.6b), or through an achiral intermediate (Figure 14.6c).
- The 50% mass balance limit that is otherwise imposed is now lifted!
- Now our catalyst can sample both enantiomers via the epimerization.
- $A_S$  interconverts with  $A_R$ , subject to a kinetically selective catalyst.
- Enantiomers under fast equilibrium are still under kinetic control, but with 100% theoretical yield.

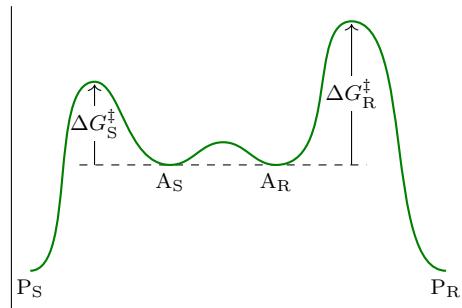


Figure 14.7: Dynamic kinetic resolution energy diagram.

- This is known as a **dynamic kinetic resolution**.
- Example dynamic kinetic resolution: Interconversion of chiral  $\beta$ -ketoesters prior to asymmetric hydrogenation.

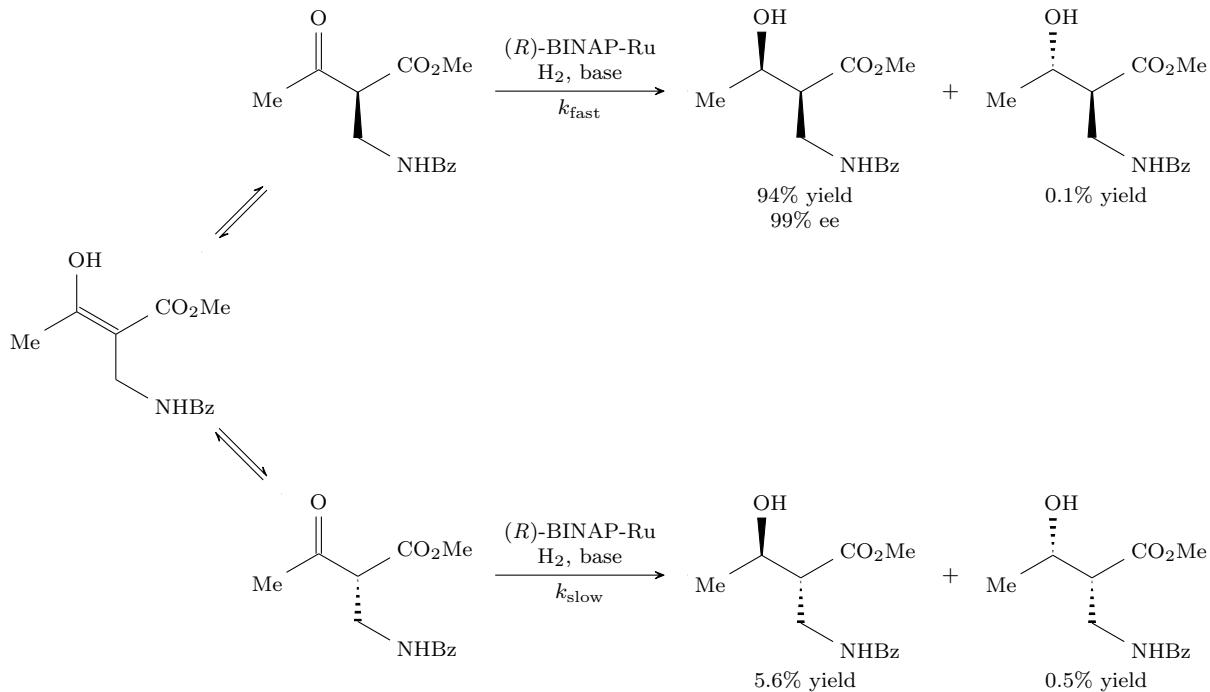


Figure 14.8: Noyori asymmetric hydrogenation.

- Consider a racemic sample of  $\alpha$ -alkylated  $\beta$ -ketoester.
- Subject it to hydrogenation under **Noyori conditions**.
  - Both enantiomeric starting materials may become a *syn* or *anti* diastereomers.
  - Thus, in principle, you'd get a mess.
- Our mess is slightly alleviated by the fact that  $k_{\text{fast}}/k_{\text{slow}} = 15$  for the ruthenium-BINAP catalyst.
  - This is about 2 kcal/mol of difference.
  - However, per Figure 14.5, this S-factor is not great.
- Our saving grace is the dynamic nature of this reaction.
  - When we actually run the experiment, we get fast enolization and interconversion through an achiral intermediate because of the base<sup>[1]</sup> in solution and the acidic  $\alpha$ -proton.
  - Indeed, if the rate of enolization/racemation is denoted by  $k_{\text{rac}}$ , we have  $k_{\text{rac}}/k_{\text{fast}} \approx 100!$
- Thus, we get 94% yield of one stereoisomer in 99% ee.
- Reference: Noyori et al. (1995).
  - See Table 3, Figure 19, and the associated discussions.
  - The whole paper is a good review of this chemistry, though.
- **Noyori asymmetric hydrogenation:** The asymmetric hydrogenation of a ketone using a homochiral ruthenium-BINAP catalyst, hydrogen gas, and a base.
- A related kinetic selectivity: Curtin-Hammett kinetics.

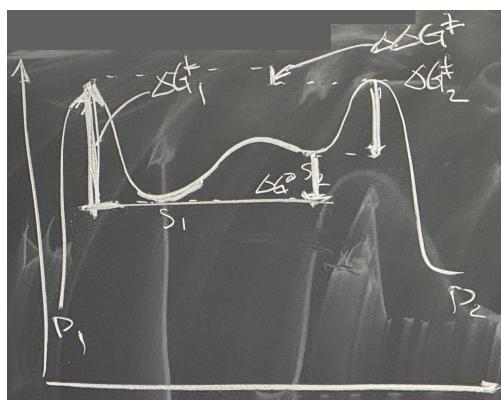


Figure 14.9: Curtin-Hammett selectivity derivation.

- Instead of (*R*)- and (*S*)-enantiomers, which rigorously have the same energy, we can consider other interconverting species with different energies.
- We can quantitate — with rate laws — the formation of the products.

$$\frac{d[P_1]}{dt} = k_1[S_1] \quad \frac{d[P_2]}{dt} = k_2[S_2]$$

- Then taking a ratio gives

$$\frac{d[P_1]}{d[P_2]} = \frac{k_1[S_1]}{k_2[S_2]}$$

- Note that

$$\frac{[S_1]}{[S_2]} = K_{\text{eq}}$$

so

$$\frac{d[P_1]}{d[P_2]} = \frac{k_1}{k_2} K_{\text{eq}}$$

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<sup>1</sup>It appears from the paper that there may not be a base; this may just be keto-enol tautomerization.

- Thus, with Arrhenius,

$$\frac{d[P_1]}{d[P_2]} = \frac{e^{-\Delta G_2^\ddagger/RT}}{e^{-\Delta G_1^\ddagger/RT}} e^{-\Delta G^\circ/RT} = e^{(\Delta G_1^\ddagger - \Delta G_2^\ddagger - \Delta G^\circ)/RT}$$

- And then referencing Figure 14.9, we can see pictorially that

$$\Delta G_1^\ddagger - \Delta G_2^\ddagger - \Delta G^\circ = \Delta \Delta G^\ddagger$$

- Thus,

$$\frac{d[P_1]}{d[P_2]} = e^{\Delta \Delta G^\ddagger/RT}$$

if we have a fast equilibrium  $S_1 \rightleftharpoons S_2$  (10 times faster than  $P_1$  or  $P_2$  formation).

- Essentially, if we have this fast starting equilibrium, then the product ratio is under kinetic control.

- Now suppose we drop  $S_2$  down in free energy and leave the rest of the diagram unperturbed.
    - This change in one variable is compensated for by a change in the other variable, and we remain under kinetic control.
  - Alex briefly discusses kinetic quench.
  - Curtin-Hammett example 1 (Figure 6.4a).
    - $P_1$  is kinetically favored.
    - $[S_1] > [S_2]$ .
    - Here, the  $S_1/S_2$  ratio is irrelevant to product formation. This is “invisible” C/H kinetics. Mathematically,
- $$\frac{[S_1]}{[S_2]} \neq \frac{[P_1]}{[P_2]}$$
- Curtin-Hammett example 2 (Figure 6.4b).
    - $P_1$  is kinetically favored.
    - $[S_1] < [S_2]$ .
    - This is “classic” C/H kinetics.
    - Great example of this in Landis and Halpern (1987).
    - This scenario is actually pretty common.
  - Curtin-Hammett example 3 (Figure 6.4c).
    - Here,  $\Delta G_1^\ddagger = \Delta G_2^\ddagger$ .
    - This scenario is pretty uncommon, but it is possible.
    - In this case, the equilibrium ratio *does* reflect the product ratio.
  - Takeaway: It is far more likely that your equilibrium ratio of intermediates has no bearing on your ratio of products.

## 14.2 Exam 2 Review Sheet

- 12/4:
- Noncovalent interactions.
    - Quadrupoles preferentially bind hard, positively charged ions.
    - The strongest hydrogen bonds have short bond lengths and are nearly linear; vice versa for weak.
    - There is an energetic penalty to mixing polar and nonpolar solvents. The penalty is mostly entropic, because putting a hydrophobic link in the water disrupts the water's ability to randomly hydrogen bond to itself. Less H-bonding means more ordered, less entropic water.
  - Transition states are first-order saddle points on a hypersurface defined by vibrational DOFs.
    - $\Delta G = -RT \ln K_{\text{eq}}$ .
    - $\Delta G^\ddagger = -RT \ln k$ .
    - $\Delta \Delta G^\ddagger = -RT \ln(k_A/k_B)$
  - **van't Hoff analysis:** Experimental determination of  $\Delta H^\circ$  and  $\Delta S^\circ$ .

$$\begin{aligned} -RT \ln K_{\text{eq}} &= \Delta H^\circ - T\Delta S^\circ \\ R \ln K_{\text{eq}} &= -\Delta H^\circ \left( \frac{1}{T} \right) + \Delta S^\circ \end{aligned}$$

- Fragmentations give 9 kcal/mol, or 30 e.u. at 300 K.
- Transition state theory.
  - General form.
  - Postulates.
    1. Activated complex is in quasi-equilibrium with starting material.
    2. Any molecule that makes its way to the transition state will then proceed onto the product barrierlessly ( $\kappa = 1$ ).
  - The number of times a starting material appears in the TS is it's order in the rate law.
  - Eyring equation:

$$k = \kappa \left( \frac{k_B T}{h} \right) e^{-\Delta G^\ddagger / RT}$$

■ Linearization (for experimental determination of  $\Delta H^\ddagger$  and  $\Delta S^\ddagger$ ):

$$\ln \left( \frac{kh}{\kappa k_B T} \right) = -\frac{\Delta H^\ddagger}{R} \left( \frac{1}{T} \right) + \frac{\Delta S^\ddagger}{R}$$

- Hammond postulate.
- Isotope effects.
  - QMech foundation:

$$E_n = h\nu \left( n + \frac{1}{2} \right) \quad \nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}}$$

- C–D lower by 1.5 kcal/mol.
- Equilibrium isotope effect:

$$\frac{K_H}{K_D}$$

- C–D bonds hold onto their electrons more tightly.

- Kinetic isotope effect.

$$\text{KIE} = \frac{k_{\text{H}}}{k_{\text{D}}}$$

- Asymmetric stretch is the reaction coordinate.

- Symmetric stretch is the important orthogonal vector.

- Under thermoneutral conditions with identical atoms on either side, KIE = max because the symmetric stretch has no isotopic sensitivity.

- Bent transition states have more contributions from bending mode isotopic sensitivities, but smaller overall sensitivities (1.5-3.5).

- Quantum tunnelling can give anomalously large KIEs.

- Secondary isotope effects at the  $\alpha$ -position largely governed by out-of-plane bending modes.

- Going to a slacker potential: Normal  $2^\circ$  KIE.

- Going to a stiffer potential: Inverse  $2^\circ$  KIE.

- Secondary isotope effects at the  $\beta$ -position governed by hyperconjugation, or actually primary because involved (e.g., E<sub>2</sub>).

- Experimental determination.

- Independent absolute rate measurement.

- Intramolecular competition experiment.

➢ Correction: If

$$C := \frac{[\text{P}_{\text{H}}]}{[\text{SM}_{\text{H}}]_0} \quad R := \left( \frac{[\text{SM}_{\text{D}}]}{[\text{SM}_{\text{H}}]} \right)_t \quad R_0 := \left( \frac{[\text{SM}_{\text{D}}]}{[\text{SM}_{\text{H}}]} \right)_0$$

then

$$\text{KIE} = \frac{k_{\text{H}}}{k_{\text{D}}} = \frac{\ln(1 - C)}{\ln \left[ (1 - C) \cdot \frac{R}{R_0} \right]}$$

- Intramolecular competition can probe post-rate-determining steps.

➢ Extract KIE from the product ratio at *any* conversion.

- Heavy-atom KIEs.

- Extracted at high conversions.

- Choose a reference atom, take NMRs at high conversion, plug into conversion formula to get KIEs.

- Can tell you what sites are involved in the RDS!

- Conversion-*dependent* isotopic enrichment is affiliated with the RDS.

- Conversion-*independent* isotopic enrichment is affiliated with post-RDS steps.

- Rate laws.

- Zeroeth-order, first-order, and second-order integrated rate laws.

- $k_{\text{obs}}$  vs. swamping concentrations to determine  $k$ .

- SSA.

- If A is more stable than B, the SSA is valid.

- If I is depleted faster than it is formed, the SSA is valid.

- QEA.

- Only valid when  $k_{-1} > k_2$ .

- Limiting cases.

- The saturation regime.
- Defining the total concentration of the catalyst is often useful.
- Michaelis-Menten kinetics.
- Blackmond's work.
  - Same-excess experiment and visual overlay.
  - Different excess experiment.
- Kinetic resolution.
  - Relations between conversion and ee.
  - Dynamic kinetic resolution: Going through an intermediate or other interconversion.
  - Curtin-Hammett kinetics.

### 14.3 Electron Transfer

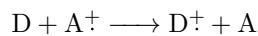
12/5:

- Through the end of the semester, we'll look at classes of reactions we haven't yet discussed.
  - Thus far, we've looked at pairwise movements of electrons; we'll now get into single-electron transfer.
  - Broadly, this is **open shell chemistry**.
- Today: The fundamentals of electron transfer processes.
- Three types of electron transfer.

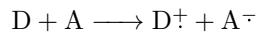
1. Electron transfer: A radical anion (donor) transfers to a neutral acceptor.



2. Hole transfer: A donor transfers to an electron-deficient radical cation.



- We can also think of this as a hole transfer from the acceptor to the donor.
- 3. Charge transfer: The donor and acceptor are both neutral, but are induced into a radical cation/anion pair.



- How do we know when any of these electron transfers are spontaneous?
- To answer this question, we need to know something about the free energy of an electron transfer.
- Said free energy is related as follows.

$$\Delta G^\circ = -nF\Delta E^\circ = -nF(\Delta E_D^\circ - \Delta E_A^\circ)$$

- $n$  is the number of electrons transferred.  $n = 1$  in each of the above 3 examples.
- $F = 96\,485\text{ C/mol}$  is Faraday's constant.
- $\Delta E^\circ$  is the standard reduction potential for the given species.
- Double check this equation — not sure it's right or what sign convention we're using??
- But how do we determine standard reduction potentials?
- Standard reduction potentials are determined using electrochemistry, most commonly cyclic voltammetry (CV).

- Cyclic voltammetry overview.

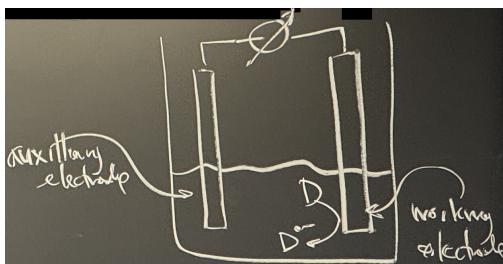


Figure 14.10: Cyclic voltammetry setup.

- Take your analyte of interest (D), dissolve it in a medium of interest, and to make your medium sufficiently conductive, also dissolve in an electrolyte.
- In a 2-electrode system (which stands in contrast to some modern 3-electrode systems), bathe in the **working electrode** and **auxiliary electrode**.
- Connect the two electrodes with a system that will allow us to continuously vary the voltage across those electrodes.
- Modify the voltage until such a time as we close the circuit by donating an electron to D, making it  $D^-$ .
- Imagine your electrode as a metal that has a continuum of states up to a point.

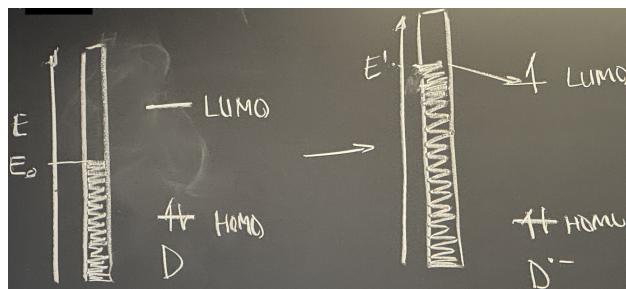


Figure 14.11: Cyclic voltammetry electron transfer.

- That point is denoted  $E_0$ .
- The donor molecule will have some filled orbitals and empty orbitals. One of the filled orbitals is a HOMO, and the other is a LUMO.
- By varying the potential, we can alter the electrochemical potential up, to the point that the electrode can spontaneously populate the donor's LUMO.
- Sergei: Why is only one electron transferred to the LUMO if more than one is available?
  - The Fermi level will probably be equal to the LUMO.
  - You can keep pumping electrons in if you apply a higher voltage.

- What does a cyclic voltammogram look like?

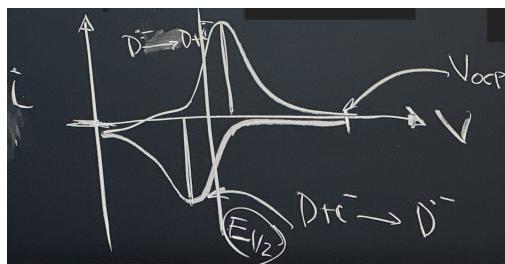
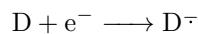
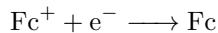


Figure 14.12: Cyclic voltammogram.

- We plot current against voltage, starting at an open circuit potential  $V_{OCP} := 0$ .
- As we decrease the voltage, we will essentially reach a point at which current begins being delivered (reduction) and subsequently slows (because of diffusion control).
  - The shape rigorously depends on diffusion and more complex math that Alex won't go into.
- Then as we scan back forward, we get oxidation.
- $E_{1/2}$  is the midpoint of the two peaks, and is the reduction potential for the reaction



- We also need a reference. Most frequently, we reference to the ferrocene/ferrocenium redox couple.



- Note that  $Fc \equiv Cp_2Fe^{II}$ .
- Kinetics of electron transfer.

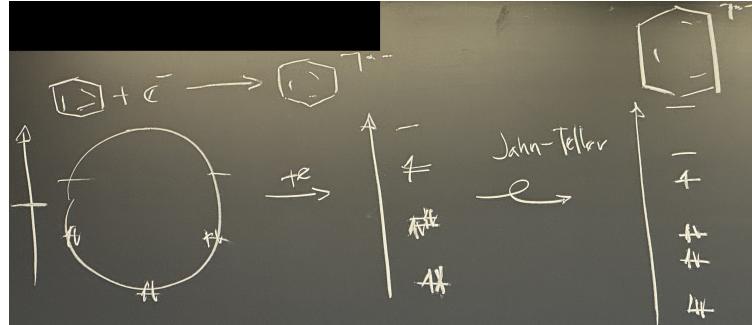
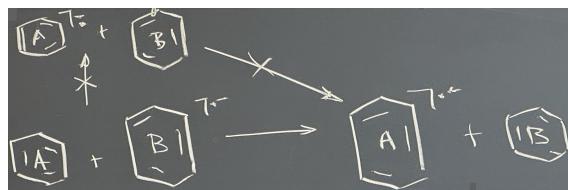


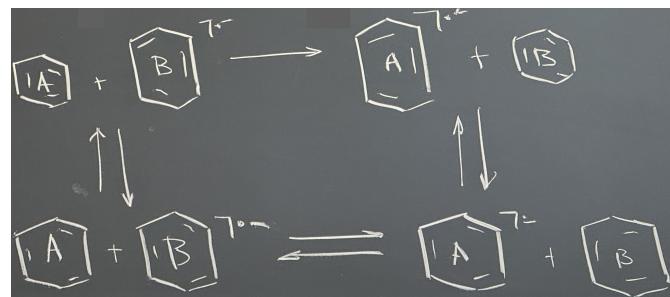
Figure 14.13: Electron transfer can induce geometric distortion.

- In this example, we'll consider benzene and its reduction to the corresponding radical anion.
- Recall that the frontier orbitals of benzene are given by Hückel theory (see Figure 2.10).
- Thus, in this reaction, we will drop an electron into a doubly degenerate frontier orbitals.
  - The system will then distort to relieve that degeneracy and lower the energy of the overall system; this is called a **Jahn-Teller distortion**.
  - This also implies that the benzene radical anion will distort from perfect six-fold symmetry.
- It could be a C-C bond elongation, but the true distortion's nature is somewhat under debate.
  - The actual distortion is likely a slight out of plane ruffling in a fedora/sombrero-type shape.

- Let's now take a look at the self-exchange electron transfer reaction.



(a) Possible mechanism.



(b) Actual mechanism.

Figure 14.14: Self-exchange electron transfer.

- Mix benzene (A) and the distorted benzene radical anion (B).
- If this does an electron transfer without any nuclear motion, it will then be followed by thermodynamically downhill nuclear reorganization, but this is in contrast with the law of conservation of energy, so it must not be this mechanism (Figure 14.14a).
  - Notice that the forward and reverse reactions also have different mechanisms here, so we are *not* obeying microscopic reversibility.
- Real mechanism: A elongates and B shrinks until we can have an energetically degenerate electron transfer (Figure 14.14b).
  - This is a closed thermodynamic square that is net neutral in free energy.
  - It also obeys the principle of microscopic reversibility!
- Self-exchange electron transfer on a free energy surface.

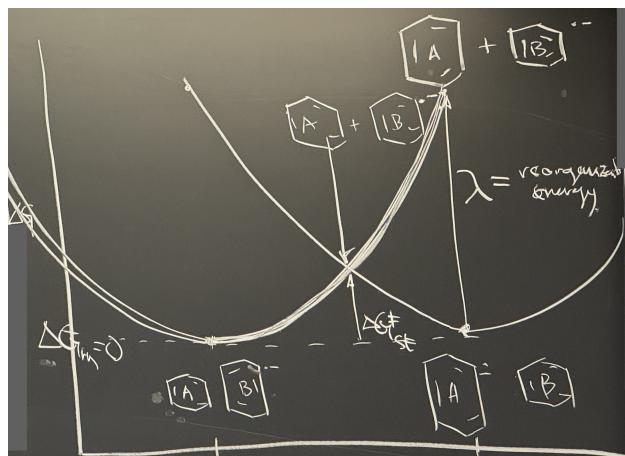


Figure 14.15: Self-exchange electron transfer energy diagram.

- Parabolic shape comes from the Morse potential and its harmonicity near the bottom.
- Where the curves cross corresponds to the transition states where electron transfer happens.
- This is a thermoneutral, degenerate reaction with  $\Delta G_{rxn} = 0$ .
- However, we can quantify the barrier  $\Delta G^\ddagger$  to self exchange.
- A Franck-Condon electron transfer with no nuclear motion is denoted by  $\lambda$  and called the **reorganization energy**.
- What about when electron transfer is nondegenerate?

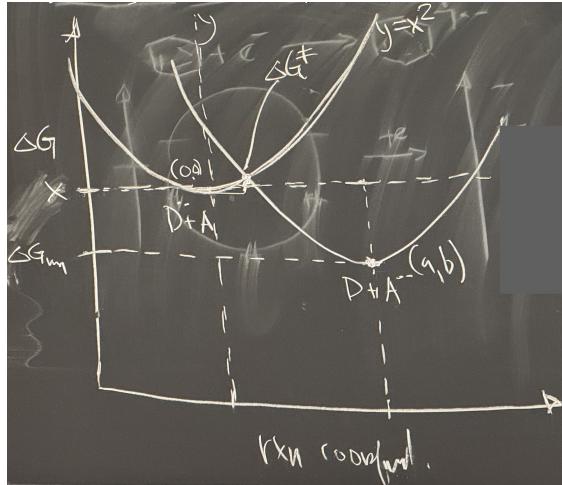


Figure 14.16: Nondegenerate electron transfer energy diagram.

- Apply the same formalism, but modify it: Simply shift the product parabola down.
- To understand the kinetics, we still need to understand  $\Delta G^\ddagger$ .
- We can do this as follows.
- Consider the parabolas existing in a Cartesian plane, with the origin at the vertex of the starting material parabola (see Figure 14.16).
  - Then the product parabola has vertex at  $(a, b)$ .
  - It follows from a bit of algebra that

$$\begin{aligned} x^2 &= (x - a)^2 + b \\ x &= \frac{b + a^2}{2a} \end{aligned}$$

so the parabolic curve crossing happens at

$$\left( \frac{b + a^2}{2a}, \frac{(b + a^2)^2}{4a^2} \right)$$

- Additionally,  $b$  is the  $\Delta G$  of the reaction, and  $a^2$  is the reorganization energy  $\lambda$ .
- Thus,

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

- This is the **Marcus relationship**.

- Example cases of electron transfer with varied driving force.

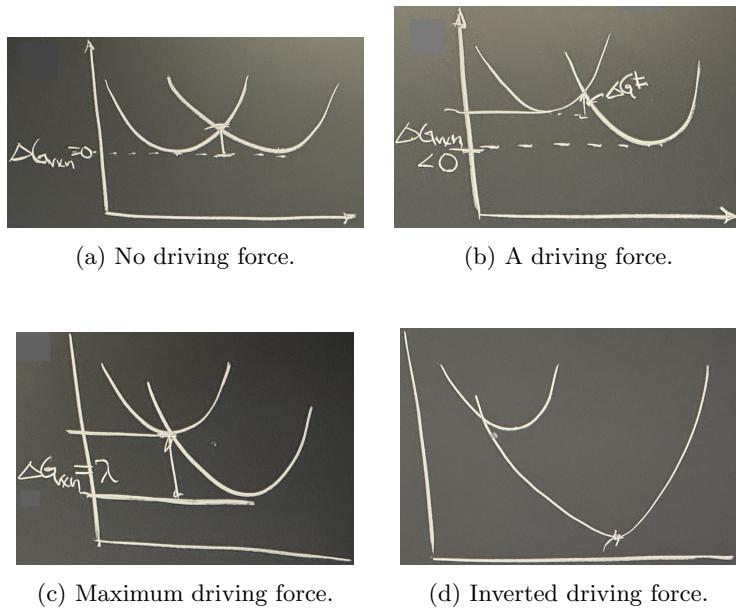


Figure 14.17: Electron transfer with different driving forces.

1. We could have no driving force.
  2. We could have a driving force.
  3. We could have a driving force so great that the transfer is barrierless.
  4. We could have a driving force so great that we begin to get a barrier again!
- Electron transfer driving forces induce varying rates.

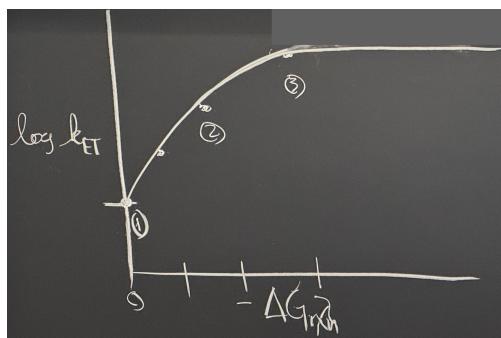


Figure 14.18: Electron transfer rate with different driving forces.

- As we increase the driving force, we would decrease the barrier  $\Delta G^\ddagger$ .
- Thus, the rate should increase with increasing driving force.
- The rate should increase until  $\Delta G_{rxn} = \lambda$ , where the product parabola intersects the starting material vertex.
- If we try to go faster than this, we have a driving force so profound that we build back in a barrier to the electron transfer.
- However, practically, we reach the diffusional limit in rate.

- Discovering the Marcus inverted region.

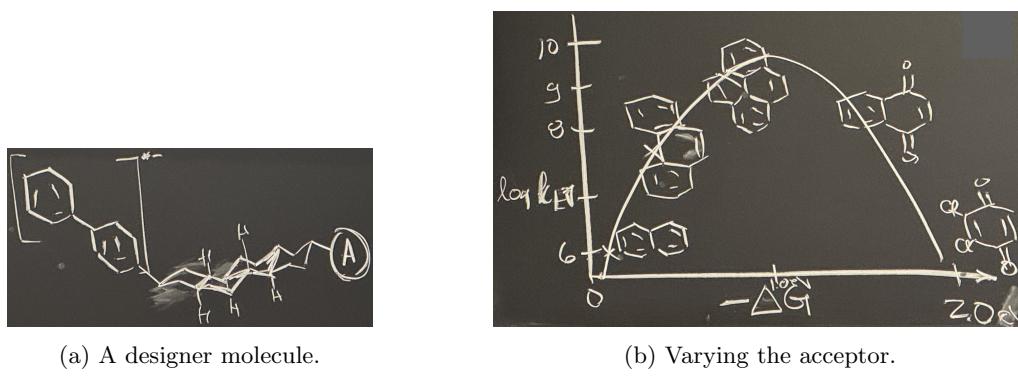


Figure 14.19: Experimental design of Marcus inverted electron transfer.

- Rudy Marcus made this theoretical prediction 50-60 years ago.
- People tried to prove it by mixing very strong reductants and oxidants, but there was a flaw in this experimental setup: Diffusion control, aka the diffusional limit for bimolecular electron transfer.
- Indeed, we needed to eliminate diffusion control, which we did by looking at unimolecular processes.
- We took a biphenyl species, loaded it with an electron (as in Figure 14.14), and then studied it with pulse radiolysis (where we attach an electron onto the biphenyl with high-energy pulsed electrons).
- The biphenyl was attached onto a rigid, steroidal hydrocarbon. This hydrocarbon is a linker of defined length, and then we appended an acceptor to the other end.
- The acceptor was varied to change the driving force over about 40 kcal/mol (which is about 2 eV).
  - Naphthalene is a weak acceptor, then anthracene is a bit better, then pyrene.
  - Then quinones, and halogenated quinones could finally get us to the Marcus inverted region.
  - This is a landmark paper in electron transfer theory: Miller et al. (1984).
  - These donors and acceptors had likely all been explicitly studied in an intermolecular sense.
    - Diffusion limit might have slowed reactions before the scenario in Figure 14.17c.
    - A lot of pulse radiolysis is done cryogenically, so diffusion was likely entirely taken out of consideration.
- Next class: Photophysics, the photochemistry of excited states, etc.