## Workshop 10

In class, we talked about secondary kinetic isotope effects (2° KIEs) that occur when hybridization changes at an atom attached to the isotope. In that case, differences in vibrational frequencies between the starting material and the (rate-determining) transition state resulted in $k_H/k_D \neq 1$. Similar differences can be observed, however, when the isotope is not directly attached to the reaction center. For example, the S_N1 solvolysis of *t*-butyl chloride shows a substantial isotope effect due to isotopic substitution at β-carbons:

$$\frac{k_H}{k_D} = 1.35$$
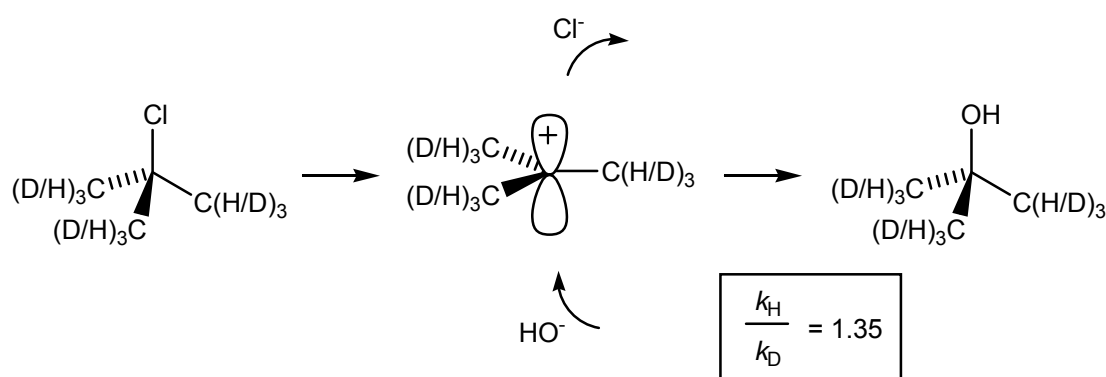
This 2° KIE has been attributed to the way that C-H vibrational modes change on the way from the starting material to the intermediate cation (see values at right).[1,2]

a. It has been argued that vibrational frequencies are lower in the cation because bonding electrons in the C-H bond delocalize, causing the bond to become "floppier". In terms of molecular orbitals, what is the basis for this delocalization?

b. Which of the two changes at right will be more important to the isotope effect? On the potential energy diagram on the next page, draw vibrational wells in the 3rd dimension that describe the effect of the more important change in vibration.

$\nu_{stretch} = 2985\ cm^{-1}$ $\nu_{stretch} = 2840\ cm^{-1}$

$\nu_{wag} = 1300\ cm^{-1}$ $\nu_{wag} = 1060\ cm^{-1}$
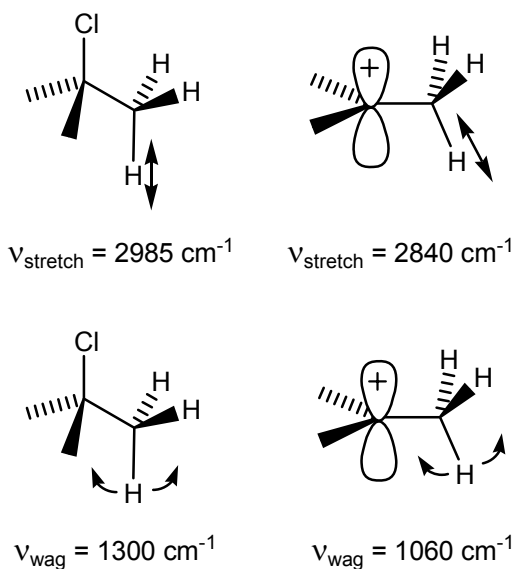
[1] Sieber, S.; Buzek, P.; Schleyer, P. v. R.; Koch, W.; Cameiro, J. W. de M. *J. Am. Chem. Soc.* **1993**, *115*, 259-270.
[2] Olah, G. A.; Prakash, G. K. S.; Sommer, J. *Superacids*; Wiley-Interscience: New York, 1985; Chapter 3.
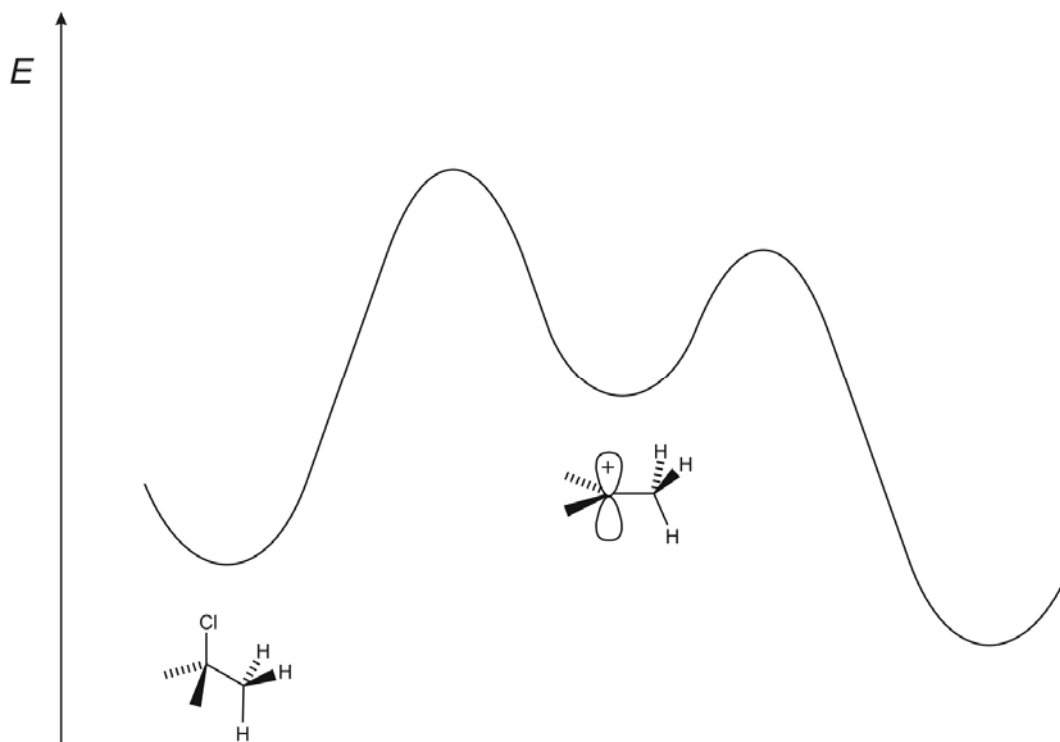
c. What is the absolute maximum kinetic isotope effect that you would calculate for a single H→D substitution at room temperature, assuming that all of the change in vibrational frequency between starting material and intermediate is felt in the transition state?

  i. Start by expressing k_H/k_D in terms of Eyring equations.

  ii. Next, convert this expression containing $\Delta G^{\ddagger}$ terms to an expression containing $\Delta ZPE_{TS} = ZPE(C\text{-}H)_{TS} - ZPE(C\text{-}D)_{TS}$ and $\Delta ZPE_{SM} = ZPE(C\text{-}H)_{SM} - ZPE(C\text{-}D)_{SM}$. (It might help to label your diagram with ΔZPE_{TS} and ΔZPE_{SM}.)

iii. What are ΔZPE_{TS} and ΔZPE_{SM}? You will want to keep in mind that

$$\frac{\nu_{CD}}{\nu_{CH}} = \frac{\frac{1}{2\pi}\sqrt{\frac{k}{\mu_{CD}}}}{\frac{1}{2\pi}\sqrt{\frac{k}{\mu_{CH}}}} = \sqrt{\frac{\mu_{CH}}{\mu_{CD}}} = \sqrt{\frac{\left(\frac{m_C m_H}{m_C + m_H}\right)}{\left(\frac{m_C m_D}{m_C + m_D}\right)}}$$
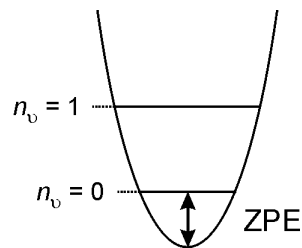
and that

$$ZPE(\text{any vibration}) = \frac{1}{2}h(c)\nu$$

$$= \frac{1}{2}(6.626 \times 10^{-34}\ \text{J sec})(3.00 \times 10^8\ \text{m/sec})(100\ \text{cm/m})$$

$$\times (6.022 \times 10^{23}\ /\text{mol})(\nu\ \text{in cm}^{-1})$$

$$= (5.99\ \text{J cm/mol})(\nu\ \text{in cm}^{-1}).$$

iv. Using the answers from (ii) and (iii) above, calculate the maximum kinetic isotope effect.

d. The assumption you made on the previous page wasn't realistic; not all of the change in vibrational frequency between starting material and intermediate would be experienced by the transition state. How much would be—more than half? Less than half?

e. The number you calculated is for one H→D substitution only, but the k_H/k_D value given on the first page is for all nine hydrogens substituted with deuteriums. If the effect of n substitutions is additive, one can expect that

$$\frac{k_{H \times n}}{k_{D \times n}} = \left(\frac{k_{H,single}}{k_{D,single}} \right)^n$$

How well does this match the experimentally measured isotope effect?

f. The diagram on the previous page shows that the first step in the reaction is the rate-determining step. What do you expect the 2° KIE would be if the second step were rate-determining? What energy differences would determine this KIE?