

Calculating Kinetic Isotope Effects

i) Running Quiver

As a starting point, you need a checkpoint file which includes a frequency job. You need to convert this to a formatted checkpoint file – do this with the command

```
formchk filename.chk
```

This generates a file filename.fchk.

To set up the input deck to quiver (the program that generates the final data), you now need to use the program qcrunch. Type:

```
qcrunch filename.fchk
```

qcrunch will then prompt you for the details of the isotopic substitution patterns that you are interested in. It first asks for the number of additional isotopomers that you wish to calculate. This is the number in addition to the 'normal' isotopomer which will be assumed to be the first and reference isotopomer. Next you will be asked to enter the masses for each atom of each isotopomer. Each isotopomer must be specified as a string of integers (accurate masses are inserted by quiver) separated by commas. You must enter the masses for each atom, not just those which change. Next you are asked how many temperatures you wish to calculate at and then for these temperatures.

qcrunch will then generate a file:

```
filename.qinput
```

This is the input file for quiver. To process this, type:

```
quiver
```

You will then be asked for the input filename and the output filename. You are then asked whether you want short (0) or long (1) output. Enter 1 for long output which includes the frequency data you will need for KIE calculation. The short output simply includes the different zero-point energies as well as the Bigeleisen Mayer analysis but not the full frequency analysis. Finally, you are asked for a scaling factor. This is a frequency scaling factor. Suggested values of these have been published but here are a few from two papers on the subject:

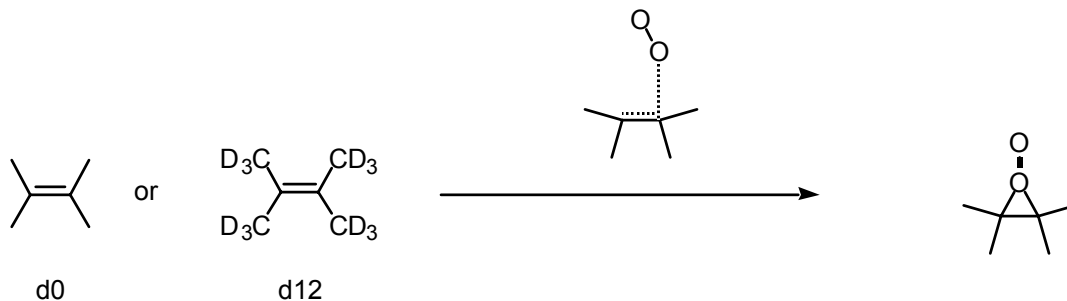
Level	Scaling Factor	Reference
B3LYP/6-31G*	0.9613	1
MP2/6-31G*	0.9427	1
SVWN/6-31G*	0.9833	1
BLYP/6-31G*	0.9940	1
BVWN/6-31G*	0.9820	1
B3P86/6-31G*	0.9559	1
AM1	0.9532	2
PM3	0.9761	2
HF/3-21G	0.9085	2
HF/6-31G*	0.8953	2
HF/6-31+G*	0.8970	2
HF/6-31G**	0.8992	2
HF/6-311G**	0.9051	2
HF/6-311G(df,p)	0.9054	2
QCISD(frozen core)/6-31G*	0.9538	2
BLYP/6-311G(df,p)	0.9986	2
BP86/6-31G*	0.9914	2
B3PW91/6-31G*	0.9573	2

Quiver will then generate an output file with the name you specified. This includes a frequency, normal co-ordinate and zero point energy analysis for each isotopomer beginning with the 'normal' or 'original' one. The modified isotopomers specified by you will then be treated as isotopomer 1, isotopomer 2, etc. At the end of the file, is the Bigeleisen Mayer data for each isotopomer at each temperature. To make life complicated, it renumbers the isotopomers – what was the 'original' isotopomer, is now isotopomer #1, what was #1 in the first part of the file is now #2 etc. The information you need for each isotopomer from this file is the imaginary frequency (if a transition state) and the Bigeleisen Mayer functions (S2/S1)^f. These are derived from consideration of the ratio of partition functions for the modified isotopomer to the original isotopomer.

ii) Processing the output

How this data is processed will depend on the type of isotope effect you are calculating, to illustrate, the example of the ene reaction of singlet oxygen with tetramethylethylene is used and inter- and intra-molecular isotope effects are calculated. Hopefully, this will serve as a useful general template.

Intermolecular Isotope Effects



In this case, we are comparing the rates of reaction of the d12 compound with the d0 compound. The rate is calculated by:

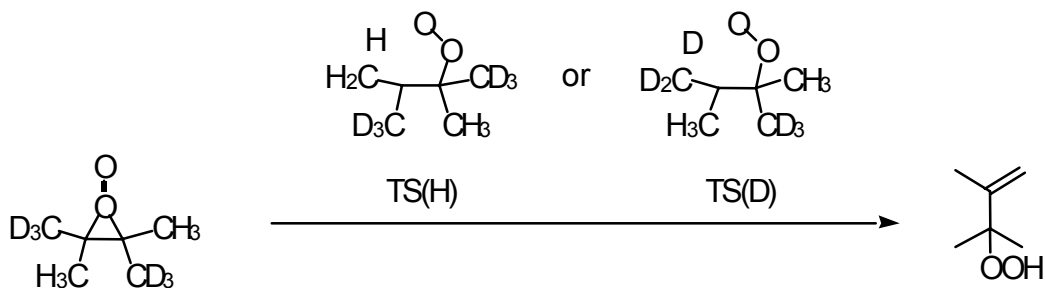
$$\frac{k_H}{k_D} = \frac{k_{d0}}{k_{d12}} = \frac{v_{d0TS}^\ddagger}{v_{d12TS}^\ddagger} \cdot \frac{\left[\left(\frac{S2}{S1} \right) f \right]_{TS}}{\left[\left(\frac{S2}{S1} \right) f \right]_{GS}}$$

Where v_{d0TS}^\ddagger is the imaginary frequency in the non-deuterated transition state (the imaginary frequency for the “original” isotopomer). v_{d12TS}^\ddagger is the corresponding value for the d12 isotopomer. These two frequencies are found in the first part of the quiver output file.

$\left[\left(\frac{S2}{S1} \right) f \right]_{TS}$ is the Bigeleisen Mayer function for the d12 transition state. This is a ratio of partition functions between this transition state and the “original”, i.e. the d0, transition state. $\left[\left(\frac{S2}{S1} \right) f \right]_{GS}$ is the corresponding value for the reactant.

Technically, this should be the product of these B. M. functions for each of the reactants but in this case, the isotopic constitution of the singlet oxygen is always the same and so its value is 1. Therefore, this is the Bigeleisen Mayer function for d12 TME (which is a ratio of partition functions for d12 TME to d0 TME).

Intramolecular Isotope Effects



In this instance, an irreversibly formed intermediate can choose between a reaction abstracting deuterium or one abstracting hydrogen. In this case, the KIE is calculated by:

$$\frac{k_H}{k_D} = \frac{v_{TS(H)}^\ddagger}{v_{TS(D)}^\ddagger} \cdot \frac{\left[\left(\frac{S_2}{S_1} \right) f \right]_{TS(H)}}{\left[\left(\frac{S_2}{S_1} \right) f \right]_{TS(D)}}$$

Where $v_{TS(H)}^\ddagger$ is the imaginary frequency in the H abstracting transition state TS(H) and $v_{TS(D)}^\ddagger$ the corresponding frequency in the D abstracting transition state. The ratio of these two is multiplied by the ratio of the Bigeleisen Mayer functions for the two transition states (each of which is a ratio of the partition function for the particular d6 species, TS(H) or TS(D), to that for the same d0 species).

Tunneling Corrections

There are two tunneling corrections frequently applied. Both are very unreliable for transition structures involving H abstraction. The simplest (and worst) is the Wigner correction.³ This involves multiplying the k_H/k_D calculated using the formulae above by a factor of $(1+u_H^2/24)/(1+u_D^2/24)$. Where, for instance, u_H is obtained from the imaginary frequency in the "original" (intermolecular) or protio (intramolecular) transition state by:

$$u_H = \frac{h\nu_H^\ddagger}{kT}$$

The frequency must first be converted to hertz. Therefore, this can be simplified to:

$$u_H = -1.43877 \times \frac{\nu_H^\ddagger}{T}$$

Where the frequency is now in wavenumbers. The value of u_D is calculated in an analogous fashion for the alternative transition state.

A more accurate correction to the predicted KIEs is made using the infinite parabolic model of Bell.³ This uses the same u values discussed above for the Wigner correction. This model multiplies the crude predicted KIEs by a factor of B where:

$$B = \frac{u_H}{\sin\left(\frac{u_H}{2}\right)} \cdot \frac{\sin\left(\frac{u_D}{2}\right)}{u_D}$$

iii) Literature Citations

Bigeleisen Mayer theory for predicting KIEs is presented in:

Bigeleisen, J.; Mayer, M. G. *J. Chem. Phys.* **1947**, *15*, 261.

Further discussion and examples can be found in:

Wolfsberg, M. *Acc. Chem. Res.* **1972**, *5*, 225.

Quiver was introduced in:

Saunders, M.; Laidig, K. E.; Wolfsberg, M. *J. Am. Chem. Soc.* **1989**, *111*, 8989.

iv) References

1) Wong, M. W. *Chem. Phys. Lett.* **1996**, *256*, 391-399.

2) Scott, A. P.; Radom, L. *J. Phys. Chem.* **1996**, *100*, 16502-16513.

3) (a) Bell, R. P. *The Tunnel Effect in Chemistry*; Chapman and Hall: London, 1980; pp60-63. (b) Bell, R. P. *Chem. Soc. Rev.* **1974**, *3*, 513-544.

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