Effects of Geminal Methyl Groups on the Tunnelling Rates in the Ring Opening of Cyclopropylcarbiny1 Radical at Cryogenic Temperature†,#

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CVT + SCT calculations on the rate of tunnelling at 20 K in the ring opening of cyclopropylcarbiny1 radical, substituted with geminal methyl groups at a ring carbon (1b), have been performed. The calculations predict that, contrary to expectations based on the effect of mass on the rate of tunnelling, the geminal methyl substituents in 1b should make the rate of ring opening to 1,1-dimethyl-3-butenyl radical (2b) $10^4$ times faster than the rate of ring opening of unsubstituted cyclopropylcarbiny1 radical (1a) to 3-butenyl radical (2a) and almost $10^5$ times faster than the rate of ring opening of 1b to 2,2-dimethyl-3-butenyl radical (2c). The reasons for these unexpected findings are discussed.

The ring opening of cyclopropylcabinyl radical (1a) to 3-butenyl radical (2a), shown in Scheme 1, has been extensively investigated. The extreme rapidity of this reaction has resulted in its widespread use as a “radical clock” for timing the rates of other free radical reactions.

Professor Athel Beckwith made many important contributions to the study of this ring opening reaction, including measuring the effects of substituents on it. For example, in 1989 Newcomb and Beckwith published back-to-back papers on the ring opening of 2,2-dimethylcyclopropylcarbiny1 radical (1b). Although the tertiary radical center in 2b makes it by far the thermodynamically preferred product, ring opening of 1b to 2b is only favored kinetically over ring opening to 2c by a factor of about 6.5 at both 25° and 60°. The temperature dependence of the ratio of 2b/2c is nearly square, and 1 kcal/mol probably is an upper limit on the difference between the Ea values for these two reactions. The results of several different types of ab initio calculations, performed by Schlegel and Newcomb, also give values of slightly less than 1 kcal/mol for the difference between the barrier heights for ring opening of 1b to 2b and 2c.

Scheme 1

The rate constants for the ring opening of the unsubstituted radical (1a) have been measured at temperatures as low as 128 K and as high as 395 K. An Arrhenius plot over this very wide temperature range is reasonably linear and gives $E_a = 7.05$ kcal/mol and $\log A = 13.15$ s$^{-1}$. The linear Arrhenius plot and the high A factor both suggest that, at least at the high end of this temperature range, the ring opening of 1a to 2a proceeds largely by passage over the reaction barrier, rather than by tunnelling through it.

We have been interested in the possibility that, at cryogenic temperatures, 1a might undergo rapid ring opening by tunnelling, despite the fact that a CH$_2$ group, rather than a hydrogen atom, would have to tunnel in this reaction. Although not common, there are now several reactions in which experiments have shown that tunnelling by carbon can occur and occur rapidly.

The two requirements for tunnelling by carbon to be rapid are a reaction barrier that is both low and narrow. These requirements are met in the ring opening of 1a. Indeed our previous calculations have predicted that, at temperatures up to 20 K, the ring opening of 1a to 2a should occur exclusively by temperature-independent tunnelling from the lowest vibrational level of 1a, with $k = 2.22 \times 10^5$ s$^{-1}$. Although the rate of ring opening of 1a has not yet been measured at cryogenic temperatures, the intramolecular $^{13}$C kinetic isotope effects (KIEs) on this reaction have been determined in solution between 173 – 253 K by Gonzalez-James and Singleton. The KIEs that they measured support the hypothesis that tunnelling plays an increasingly important role in the ring opening of 1a as the temperature is lowered. The experimental KIEs are fit much better by KIEs, computed with inclusion of small-curvature tunnelling (SCT) corrections, than by KIEs, computed without inclusion of tunnelling. In addition, an Arrhenius plot of the experimental $^{13}$C/$^{12}$C KIEs is curved. The curvature provides purely experimental evidence, independent of comparisons between computed and measured rate constants, for a prominent role for tunnelling in the ring opening of 1a.

In the ring opening of 1a, $^{13}$C tends to become concentrated at C2 of 2a, because C1 undergoes much more motion than C2 in the ring opening reaction; and the probability of tunnelling is higher for the lighter isotope of carbon ($^{12}$C). For the same reason, our SCT calculations predicted that, at 20 K, with geminal deuteria, attached to a ring carbon of 1e, the deuteria will tend to wind up at C2 (as in 2e), rather than at C1 (as in 2d). Therefore, it is easy to guess that the regiochemistry of the ring opening of 1b, found around room temperature by Newcomb and Beckwith, will be reversed at 20K by tunnelling and that 2c, not 2b, will be the major product.

We have tested this prediction by carrying out tunnelling calculations on the ring opening of 1b at 20 K. Our results show that this naive prediction is completely wrong. Our calculations on the ring opening of 1b, by tunnelling from the lowest vibrational level, actually give a ratio of 2b/2c that is computed to be many orders of magnitude larger at 20 K than the ratio of ca. 6.5, found by the experiments of Newcomb and Beckwith around room temperature.
In carrying out tunnelling calculations on the ring opening of 1b, we employed computational methodology similar to that we used in performing tunnelling calculations on the ring opening of 1a.11,12,13 Unrestricted electronic structure calculations were carried out with the B3LYP functional and the 6-31+G(d,p) basis set.13 Canonical variational transition state theory (CUT)16 was used to locate the transition structure (TS) for the ring opening of 1 to 2. Quantum effects on the reaction dynamics were computed semiclassically, using the small-curvature tunnelling (SCT) approximation.17 The direct dynamics calculations were carried out with GAUSSRATE18 as the interface between Gaussian 0319 and POLYRATE.20 The UB3LYP/6-31+G(d,p) and the experimental activation energies for the ring opening of unsubstituted cyclopropylcarbinyl radical (1a) and the 2,2-dimethyl derivative (1b) are given in Table 1. The UB3LYP activation energies are in reasonable agreement with the experimental values, except that the calculated $E_a$ for ring opening of 1b to 2b appears to be ca. 1 kcal/mol too low. Therefore, since the calculated difference in $E_a$ values for formation of 2b and 2c is a little too high, the calculated product ratio of 2b to 2c of 25.4 at 300 K is about a factor of four larger than the observed value.4,5

**Table 1.** Enthalpy differences$^a$ at 300 K, computed by B3LYP/6-31+G(d,p) for the ring opening of cyclopropylcarbinyl radicals 1a and 1b and the $E_a$ values that have been measured.

<table>
<thead>
<tr>
<th></th>
<th>1a $\rightarrow$ 2a</th>
<th>1b $\rightarrow$ 2b</th>
<th>1b $\rightarrow$ 2c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta H^{act}$</td>
<td>-3.4</td>
<td>-7.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>$E_a$</td>
<td>7.3$^b$</td>
<td>5.0</td>
<td>6.7</td>
</tr>
<tr>
<td>$E_a$</td>
<td>7.05$^b$</td>
<td>6.1$^d$</td>
<td>7.2$^d$</td>
</tr>
</tbody>
</table>

$^a$Values in kcal/mol.$^b$6 kcal/mol with the 6-31G* basis set (ref. 11). $^c$Ref. 9. $^d$Ref. 6.

The results of our CUT + SCT calculations, comparing the rates of ring opening of 1a and 1b at 20 K, are given in Table 2. Tunnelling rates are expected to decrease exponentially with the square root of the effective tunnelling mass.21 Therefore, at first glance, it is not surprising that the geminal methyl groups in 1b are computed to slow the rate of formation of ring-opened product 2c, in Scheme 1 by a factor of 39.1, relative to the rate of formation of 2a from 1a.

**Table 2.** CUT+SCT rate ratios$^a$ calculated for ring opening of 1a-e to 2a-e at 20 K.

<table>
<thead>
<tr>
<th>Substituted C in product 2</th>
<th>$k (1a)/2 (1b)$</th>
<th>$k (1a)/2 (1c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$^1$</td>
<td>5.04 E-05$^b$</td>
<td>6.47$^b$</td>
</tr>
<tr>
<td>C$^2$</td>
<td>39.1</td>
<td>0.85$^b$</td>
</tr>
<tr>
<td>Ratio C$^1$/C$^2$</td>
<td>7.76 E+05$^c$</td>
<td>0.13$^{bd}$</td>
</tr>
</tbody>
</table>

$^a$The calculated rates for ring opening of 1a have been divided by 2, in order to eliminate the statistical factor that arises from the presence of two equivalent CH$_2$ groups in 1a.13 $^b$Ref. 13. $^c$Predicted ratio of methyl groups at C$^1$ (2b) to methyl groups at C$^2$ (2e) in the ring opening of 1b. $^d$Predicted ratio of D$_2$ at C$^1$ (2d) to D$_2$ at C$^2$ (2e) in the ring opening of 1c.

Also given in Table 2 are the H/D KIEs that we previously calculated for the ring opening of 1c.15 It should be noted that the geminal deuteria in 1c are not calculated to retard the rate of ring opening to 2c; in fact, they are actually predicted to accelerate it by a factor of 1/0.85 = 1.2, relative to the rate of ring opening of 1a to 2a. Thus, the question arises, if geminal deuteria make the rate of ring opening of 1c to 2c slightly faster than the rate of ring opening of 1a to 2a, why do geminal methyl groups retard the rate of ring opening of 1b to 2c by a factor of 39.1, relative to the rate of ring opening of 1a to 2a?

Table 2 also shows that geminal deuteria are calculated to make the rate of ring opening of 1e to 2d a factor of 6.47 slower than the rate of ring opening of 1a to 2a. However, in stark contrast, the geminal methyl groups in 1b are actually predicted to accelerate the rate of ring opening to 2b by a factor of 1/(2 x 5.04 x 10$^{-3}$) = 10,000.

The explanation of both of these unexpected predictions about the ring opening of 1b to 2b and 2c must be that more than just the mass of the methyl groups affects the rate of tunnelling in the ring opening of 1b. For example, as shown in Table 1 the geminal methyl groups make the calculated exothermicity of the ring opening of 1b to 2b larger than that of 1a to 2a by 3.6 kcal/mol. Probably as a direct result of this increased exothermicity, the methyl groups make the calculated barrier for 1b $\rightarrow$ 2b 2.3 kcal/mol lower than that for 1a $\rightarrow$ 2a. The methyl groups at C1 of 2b obviously stabilize the radical center at this carbon; and, to a lesser extent, they stabilize the incipient radical center at this carbon in the transition structure for ring opening of 1b.

The lower barrier to ring opening of 1b to 2b, compared to that for ring opening of 1a to 2a, makes tunnelling through the former barrier more probable than tunnelling through the latter.21 Therefore, the effect of the methyl groups on reducing the barrier height for ring opening of 1b to 2b will, in contrast to the effect of the greater mass of the methyl groups, tend to increase the rate of tunnelling.

In addition, because the ring opening of 1b to 2b is more exothermic than the ring opening of 1a to 2a, according to Hammond's postulate,22 1b $\rightarrow$ 2b is likely to have an earlier transition structure than 1a $\rightarrow$ 2a. An earlier transition structure for 1b $\rightarrow$ 2b implies that this ring opening reaction should have a narrower barrier than 1a $\rightarrow$ 2a.23 In fact, as shown in Figure 1, our POLYRATE calculations find that the barrier width in the ring opening of 1b to 2b is 0.54 Å, which is 21% smaller than the barrier width of 0.68 Å in the ring opening of 1a to 2a.

The probability of tunnelling increases exponentially as the reaction barrier width and height are decreased.21,24 Therefore, the 21% narrower barrier width and the 32% lower barrier height for 1b $\rightarrow$ 2b than for 1a $\rightarrow$ 2a both tend to make ring opening of 1b to 2b much faster than the ring opening of 1a to 2a. According to the results in Table 2, the acceleration of the rate of tunnelling, due to the lower and thinner barrier for 1b $\rightarrow$ 2b than for 1a $\rightarrow$ 2a, more than overcomes the larger effective tunnelling mass in the ring opening of 1b to 2b.

Do barrier height and/or barrier width also play a role in retarding the rate of tunnelling in the ring opening of 1b to 2c? As already noted, the geminal deuteria in 1c are calculated actually to accelerate the rate of ring opening to 2c,15 so it is hard to see why the mass of the methyl groups should serve to retard the rate of ring opening of 1b to 2c. Moreover, as shown in Table 1, the barrier for ring opening of 1b to 2c is actually calculated to be 0.6 kcal/mol lower than that for ring opening of 1a to 2a. Therefore, a higher barrier cannot be the cause of the finding that 1b $\rightarrow$ 2c is calculated to be 39.1 times slower than 1a $\rightarrow$ 2a. Consequently, by process of elimination, the factor that is responsible for the slower rate of ring opening of 1b to 2c, relative to 1a $\rightarrow$ 2a, must be a wider barrier for the former reaction.

As noted above, Hammond's postulate leads to the expectation that the less exothermic of two closely related reactions should have the wider barrier.22 As shown in Table 1, the ring opening of 1b to 2c is approximately thermoneutral; whereas, the ring opening of 1a to 2a is exothermic by 3.4 kcal/mol. Therefore, 1b $\rightarrow$ 2c is likely to have a wider barrier than 1a $\rightarrow$ 2a. In fact, as shown in Figure 1, our POLYRATE calculations find that the width of the barrier for ring opening of 1b to 2c is 0.83 Å, which
is 0.15 Å wider than the barrier in the ring opening of 1a to 2a. The wider the barrier, the lower the rate of tunnelling; so the wider barrier to ring opening in 1b → 2c does, indeed, appear to be the reason that the geminal methyl groups retard the rate of this reaction, relative to the ring opening of 1a → 2a.

Table 1 shows that our B3LYP/6-31+G(d,p) calculations overestimate the difference between the barrier heights for formation of 2b and 2c from 1b, but by less than 1 kcal/mol. Therefore, the calculated ratio of \( \approx 10^6 \), favoring formation of 2b over 2c by tunnelling at 20 K, is large enough to lead us to be confident in making the following prediction: Experiments performed at 20 K would, in fact, find the ratio of 2b to 2c to be many orders of magnitude larger than the ratio of 6.5, measured at much higher temperatures by Newcomb and by Beckwith.

**Notes and references**

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3 Electronic Supplementary Information (ESI) available: [The optimized B3LYP/6-31+G(d,p) geometries, energies, thermal corrections, and harmonic frequencies for 1a, 1b and 2a, 2b, 2c and the transition structures connecting them, and the CVT and CVT + SCT rate constants for these reactions. (10 pages)]. See DOI: 10.1039/b000000x/
4 This Communication is dedicated to the memory of Professor Athel Beckwith.

14 (a) A. D. Becke, J. Chem. Phys. 1993, 98, 5648. (b) C. Lee, W. Yang, and R. G. Parr, Phys Rev. B 1988, 37, 78. (c) B. Mieghlich, A. Savin, H. Stoll, and H. Preuss, Chem. Phys. Lett. 1989, 157, 200. (d) Of the many functionals that we tried, B3LYP gave \( E_b \) values for the ring opening of 1a to 2a and 1b to 2b + 2c that provided the best agreement with the experimental values given in Table 1.
18 J. C. Corchado, Y.-Y. Chuang, E. L Coitino, B. A. Ellingson, and D. G. Truhlar, GAUSSRATE–version 9.5; University of Minnesota: Minneapolis, MN.


22 (a) G. S. Hammond, J. Am. Chem. Soc. 1955, 77, 334. (b) The corollary to Hammond's postulate, that the more exothermic of two reactions should have the narrower barrier, is irrelevant for reactions that occur by passage over energy barriers. However, this corollary is of critical importance for reactions that occur by tunnelling through energy barriers, especially by tunnelling from the lowest vibrational levels of the reactants.

23 The barrier width of 0.68 Å, calculated with the 6-31+G(d,p) basis set, is 0.04 Å narrower than the barrier width computed in ref. 11, with the 6-31G(d) basis set.

24 The negative logarithm of the tunnelling probability depends on a product of terms, which involve the square roots of the barrier height and effective tunnelling mass; but the product is linear in the barrier width. Therefore, a factor of two decrease in barrier width increases exponentially the probability of tunnelling by the same amount as a factor of four decrease in barrier height or in effective tunnelling mass.