

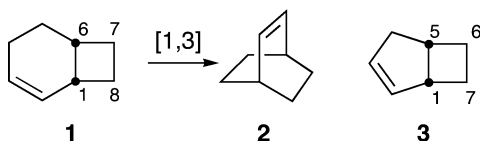
## Thermal Reactions of 7-*d*- and 8-*d*-Bicyclo[4.2.0]oct-2-enes

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Detailed studies of the thermal chemistry of bicyclic vinylcyclobutanes have provided telling insights on the stereochemical course of [1,3] carbon shifts and other kinetically competitive reactions.<sup>1</sup> This communication reports the first study of the thermal conversions of bicyclo[4.2.0]oct-2-ene (**1**) to bicyclo[2.2.2]oct-2-ene (**2**) and to the fragmentation products 1,3-cyclohexadiene and ethylene. The chemistry exhibited by **1** stands in sharp contrast to the pattern of transformations found for the extensively investigated bicyclo[3.2.0]hept-2-ene reactant (**3**).<sup>2</sup>

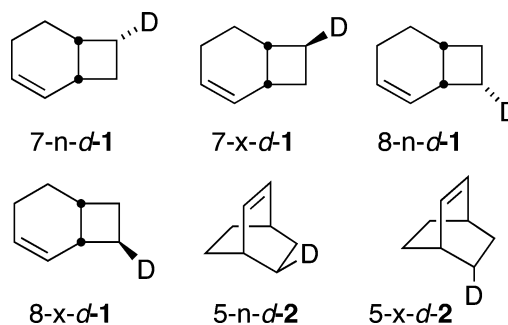


The [1,3] carbon shifts converting **3** to norbornene take place with a noteworthy preference for inversion of configuration: work with deuterium-labeled analogues has been used to determine  $k_{si}/k_{sr}$  ratios of  $\sim 3$  at 276 °C and  $\sim 8$  at 312 °C.<sup>2b,c</sup> One interpretation of this stereochemical outcome has posited competition between a favored orbital-symmetry-controlled sigmatropic shift with inversion and a minor stereochemically randomizing diradical-mediated path. Were this model correct, one would expect that [1,3] shifts from **1** would favor migration with inversion more dominantly, for the larger homologue has more conformational flexibility than the [3.2.0] system and could facilitate a concerted process with inversion by providing access to a less geometrically demanding transition structure.<sup>3</sup>

For a diradical-mediated [1,3] shift, however, the increased distance between the migrating carbon and the migration terminus might favor a diminished  $k_{si}/k_{sr}$  ratio and more kinetically prominent roles for stereomutation at C8 and fragmentation to 1,3-cyclohexadiene and ethylene.<sup>3</sup>

To prepare for securing the required kinetic and stereochemical data, the well-known compounds **1** and **2** and the deuterium-labeled analogues 7-*n-d-1*, 7-*x-d-1*, 8-*n-d-1*, 8-*x-d-1*, 5-*n-d-2*, and 5-*x-d-2* were prepared and characterized.

Selective reductions of 7-*d*- and 8-*d*-bicyclo[4.2.0]octa-2,7-dienes<sup>4</sup> with diimide generated in situ by treatment of hydrazine with 30% hydrogen peroxide at  $-20$  °C<sup>2h,5</sup> gave the 7-*d*- and 8-*d*-bicyclo[4.2.0]oct-2-enes, which were isolated and purified by preparative GC. The diastereomeric ratios determined by <sup>2</sup>H NMR at 92.124 MHz reflected a preferential reduction from the exo face of the C7–C8 double bond: 7-*n-d-1* ( $\delta$  1.77):7-*x-d-1* ( $\delta$  1.91) = 4.8:1 and 8-*n-d-1* ( $\delta$  1.63):8-*x-d-1* ( $\delta$  2.23) = 5.9:1. These chemical shift assignments were based on NOE experiments with unlabeled **1**.



Gas phase kinetic runs at 300 °C with cyclooctane as an internal standard and N<sub>2</sub> as the bath gas gave rate constants for decay of **1** ( $k_o = 1.39 \times 10^{-5} \text{ s}^{-1}$ ), formation of **2** from **1** ( $k_{13} = 4.26 \times 10^{-6} \text{ s}^{-1}$ ), and of 1,3-cyclohexadiene and ethylene from **1** ( $k_f = 9.60 \times 10^{-6} \text{ s}^{-1}$ ). No isomerization to 1,3(Z),7-octatriene was observed.

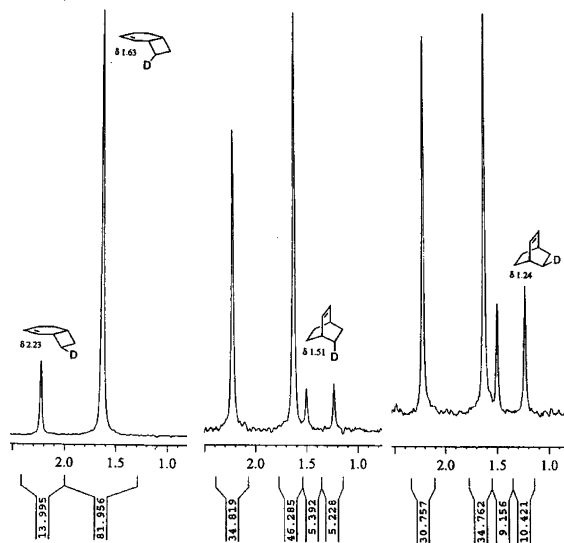
Samples of both 7-*d-1* and 8-*d-1* rich in the endo isomers were heated at 300 °C for various times up to 30 h. Analyses of thermal product mixtures by <sup>2</sup>H NMR provided measures of equilibration between exo and endo *d*-labeled versions of **1** and ratios of 5-*n-d-2* and 5-*x-d-2* products. Interconversions between 7-*n-d-1* and 7-*x-d-1* were too slow to be detected: the 7-*n-d-1* component in the mixture of epimers remained  $82.7 \pm 2.5\%$  over six kinetic runs, while the 5-*x-d-2* isomer in the mixture of product epimers was  $83.9 \pm 2.3\%$ . As a percentage of the two epimers, after 29.5 h at 300 °C, there was 85.4% of 7-*n-d-1* and 84.8% of 5-*x-d-2* in the thermal reaction mixture.

The absence of a structural isomerization of **1** to 1,3(Z),7-octatriene and of a detectable two-centered ring-inverting stereoisomerization interconverting 7-*n-d-1* with 7-*x-d-1* implies that C1–C6 bond cleavage to form a diradical intermediate is not kinetically competitive. That the thermal profile of **3** includes both an isomerization to a linear triene and a C1–C5 two-centered epimerization reaction is undoubtedly dependent on a common diradical intermediate formed by C1–C5 bond cleavage. The absence of both types of reaction from **1** suggests that it has more to overcome thermodynamically to cleave its C1–C6 bond than **3** has to break its C1–C5 bond.

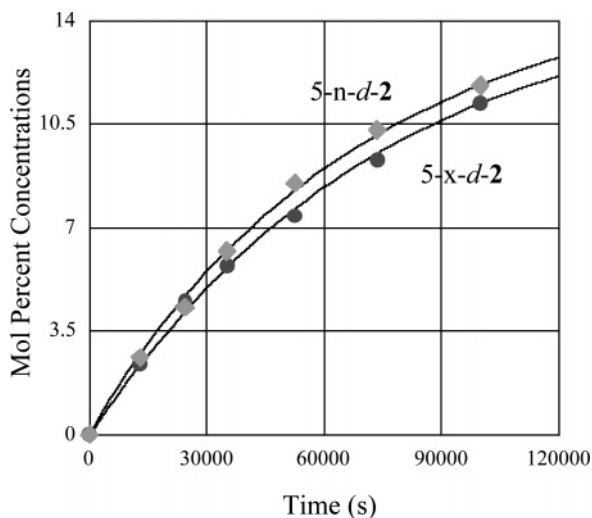
When 8-*d-1* was followed kinetically, the endo–exo equilibration proved kinetically dominant (Figure 1). The simple exponential function for approach to 8-*n-d-1*:8-*x-d-1* equilibrium characterized by rate constant  $k_{eq} = 6.11 \times 10^{-5} \text{ s}^{-1} = 2k_{8e}$  was some 14 times larger than  $k_{13} = (k_{si} + k_{sr})$  for the isomerization of **1** to **2**. A very modest kinetically controlled stereochemical preference for  $k_{si}$  over  $k_{sr}$  ( $k_{si} = 2.46 \times 10^{-6} \text{ s}^{-1}$ ;  $k_{sr} = 1.80 \times 10^{-6} \text{ s}^{-1}$ ;  $k_{si}/k_{sr} \approx 1.4$ ) was deduced from <sup>2</sup>H NMR spectral data obtained for thermal rearrangement samples and calculations based on integrated rate expressions (Figure 2). The substantial amount of C8 epimerization coupled with little kinetically controlled stereoselectivity for the

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**Figure 1.**  $^2\text{H}$  NMR spectra of 8-*d*-1 and 5-*d*-2 isomers from 300 °C thermal reaction mixtures:  $t = 0$  (left), 7 h, and 14.5 h (right).

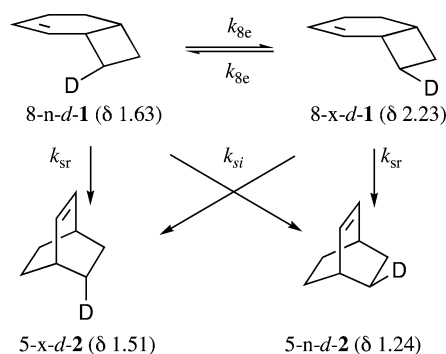


**Figure 2.** Observed mol % concentrations of 5-*x-d-2* and 5-*n-d-2* (with the sum of both 8-*d-1* epimers at  $t = 0$  defining 100%) as functions of time in thermal reaction mixtures. The integrated rate equations appropriate to Scheme 1 and a best-fit calculation using a single variable gave ( $k_{\text{si}} - k_{\text{sr}} = 0.67 \times 10^{-6} \text{ s}^{-1}$  (rms error = 0.19%).

[1,3] migration is consistent with homolytic cleavage of the C1–C8 bond to generate a diradical intermediate having a relatively long lifetime. Although the initial trajectory of the C7–C8 bond rotation may propel the migrating carbon C8 toward the [1,3] migration terminus C3, the low  $k_{\text{si}}/k_{\text{sr}}$  ratio and the relatively fast epimerization at C8 suggest that the diradical has ample time to explore substantial regions of configurational space before re-forming the C1–C8 bond or fragmenting or giving a [1,3] shift product.

The thermal reactions of **3** (and deuterium-labeled analogues) are characterized by rate constants ( $k_{\text{si}} + k_{\text{sr}}$ ) > fragmentation > epimerization at C7  $\gg$  two-centered stereomutation at C1,C5; the  $2k_{7e}/(k_{\text{si}} + k_{\text{sr}})$  ratio is 0.2.<sup>2d,h</sup> For **1**, the progression of rate constants in order of importance is epimerization at C8 > fragmentation > ( $k_{\text{si}} + k_{\text{sr}}$ ), and  $2k_{8e}/(k_{\text{si}} + k_{\text{sr}})$  is 14. The prediction<sup>3</sup> of more

### Scheme 1. Thermal Isomerizations of 8-*d*-1 Isomers



significant one-centered stereomutations at C8 and fragmentation relative to [1,3] shifts was thus fully confirmed. The homologues **1** and **3** behave quite differently, which would have not been anticipated only a short time ago.

The kinetic and stereochemical characteristics of thermal reactions shown by bicyclo[4.2.0]oct-2-ene (**1**) and deuterium-labeled analogues underscore the significant role small variations in geometrical constraints may have on reactions taking place through conformationally flexible diradical intermediates. Such intermediates are presented with multiple options among exit channels leading from a relatively flat high-energy region of a potential energy surface, or caldera,<sup>6</sup> and small conformational factors can strongly influence product distributions.

Appropriate computational efforts will no doubt shed further light on the mechanisms and dynamics of thermal reactions of bicyclo[4.2.0]oct-2-enes, as will further experimental work on closely related stereochemically constrained vinylcyclobutanes.

**Acknowledgment.** The authors acknowledge the Donors of the American Chemical Society Petroleum Research Fund for support of this research at Franklin & Marshall College. We thank the National Science Foundation for support at Syracuse University through CHE-0211120 and CHE-0514376, and Anuradha S. Raghavan and David J. Kiemle for their invaluable assistance.

**Supporting Information Available:** Outlines of synthetic schemes, selected  $^1\text{H}$ ,  $^2\text{H}$ , and  $^{13}\text{C}$  NMR spectra, tables of kinetic data, and kinetic plots. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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JA0636035