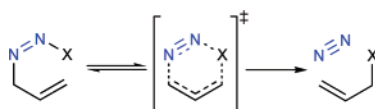


Transition States of the Retro-Ene  
Reactions of Allylic DiazenesArash Jabbari,<sup>†</sup> Erik J. Sorensen,<sup>‡</sup> and K. N. Houk<sup>\*†</sup>Department of Chemistry and Biochemistry, University of California, Los Angeles,  
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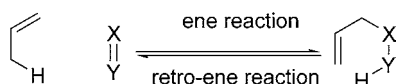
## ABSTRACT



Density functional theory studies of intramolecular retro-ene reactions of allyldiazenes show that the reaction is a concerted process involving a six-center cyclic transition state. The activation barriers for deazetization for X = H, Me, F, Cl, and Br (3a–e) are 2.4, 40.2, 22.3, 9.3, and 8.8 kcal/mol, respectively.

The Alder ene reaction<sup>1</sup> is a versatile synthetic method. The reaction (Scheme 1) involves the addition of an alkene

Scheme 1. The Ene and Retro-ene Reaction



bearing an allylic hydrogen (ene) to an unsaturated compound X = Y (enophile), usually electron deficient. Formally, this reaction is a concerted [ $\pi 2_s + \pi 2_s + \sigma 2_s$ ] process in Woodward–Hoffmann notation.<sup>2</sup> The retro-ene reaction, the reverse of the above process, is frequently observed at elevated temperatures (Scheme 1). The retro-ene reaction involves a 1,5 shift of hydrogen,<sup>3</sup> and its mechanism and synthetic utility have been extensively documented.<sup>4</sup> The retro-ene reaction is a method for accessing unsaturated, often reactive molecules, and parallels the retro-Diels–Alder reaction.<sup>5</sup>

Both experimental data<sup>6</sup> and theoretical calculations<sup>7</sup> indicate that the reaction occurs through a concerted mech-

anism. However, in some cases, stepwise mechanisms may be involved.<sup>8</sup>

The elimination of nitrogen from diazenes takes place easily and has found interesting applications.<sup>9,10</sup> Recently, one of our groups synthesized substituted 1-hydrazinodienes that were employed in Diels–Alder reactions to obtain cyclohexenes, **1** (Scheme 2). Upon hydrolysis, intermediate monoalkyl diazenes, **2**, are obtained and undergo a nitrogen extrusion reaction with alkene transposition.<sup>11</sup>

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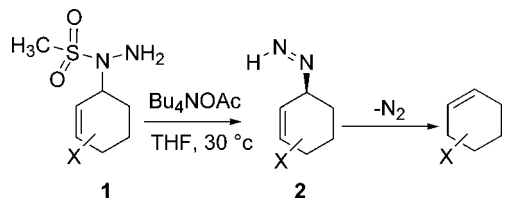
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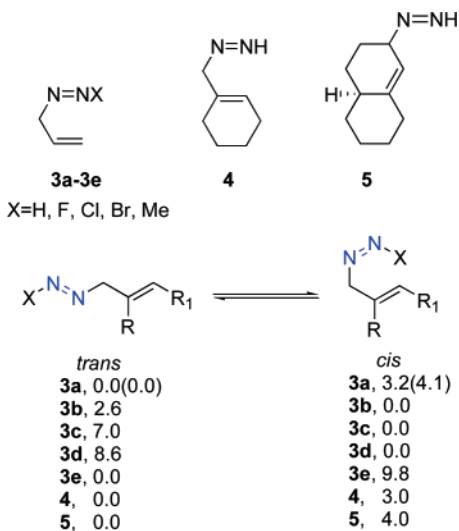
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**Scheme 2.** Synthesis of Allylic Diazenes and the Retro-Ene Deazetization Reaction



We have established, through DFT calculations, the mechanism and the character of the transition states for these retro-ene reactions. We also assessed the likelihood that groups other than H could be transferred in analogous reactions. DFT calculations were performed with the B3LYP method and the 6-31G(d) basis set, and for small systems the energetics were evaluated with the high accuracy CBS-QB3 method.<sup>12</sup>

The *cis* and *trans* allyldiazenes can interconvert by rotation around the double bond or by nitrogen inversion. Nitrogen inversion is predicted to be favored over double bond rotation. The calculations show that the *anti* form of allyldiazene (*trans-3a*) is the most stable, but for the reaction to occur it is necessary that this form be converted to *cis-3a*. The latter isomer is 4.1 kcal/mol higher in energy than *trans-3a* (CBS-QB3) (Figure 1). The retro-ene reaction of

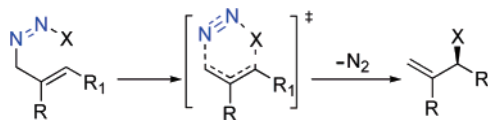


**Figure 1.** The B3LYP/6-31G(d) enthalpies of *trans* and *cis* isomers of **3a–e** to **5** (kcal/mol). CBS-QB3 values are given in parentheses.

**3a** proceeds through a six-center cyclic transition state (Figure 2) with a 4.5 kcal/mol activation energy (CBS-QB3).

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**Figure 2.** The mechanism of the retro-ene reaction.

The transition states for reactions of **3a**, **4**, and **5** are shown in Figure 3, and the energetics are summarized in Table 1.

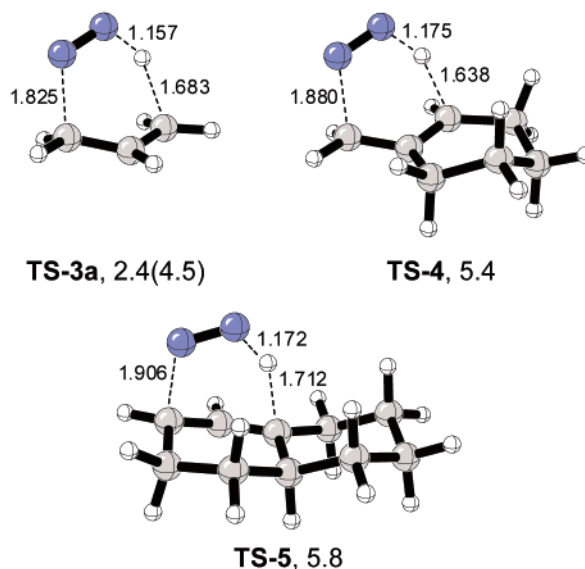
**Table 1.** Calculated Activation and Reaction Enthalpies (kcal/mol) of the Retro-Ene Reaction of *Cis* Isomers of **3a–e**, **4**, and **5**<sup>a</sup>

Isomer	$\Delta H^\ddagger$	$\Delta H_r$
<i>cis-3a</i>	2.4 (4.5)	−57.5 (−60.8)
<i>cis-3b</i>	22.3	−65.2
<i>cis-3c</i>	9.3	−52.6
<i>cis-3d</i>	8.8	−47.9
<i>cis-3e</i>	40.2	−60.5
<i>cis-4</i>	5.4	−51.2
<i>cis-5</i>	5.8	−53.6

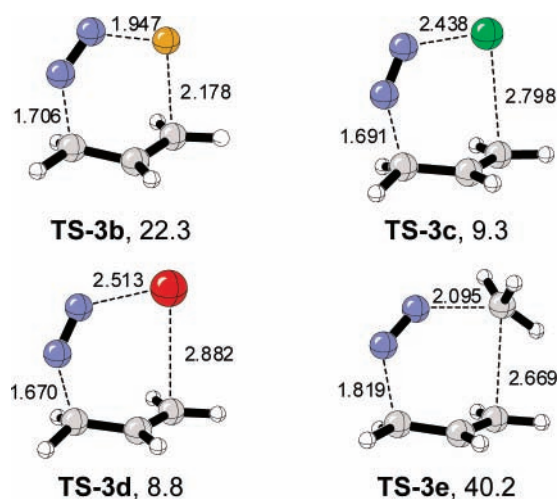
<sup>a</sup> The values in parentheses are CBS-QB3 results.

The elimination of nitrogen is highly exothermic by 61 kcal/mol. For comparison, the retro-ene reaction of 1-pentene has a calculated activation energy of 50 kcal/mol. This reaction is endothermic by 29 kcal/mol.<sup>7b</sup>

The transition state **TS-3a** is half-chair, with all of the atoms arranged in the same plane except C2. The energetics



**Figure 3.** Geometries of the transition states for retro-ene reactions of **3a–5**. Activation barriers are given in kcal/mol. Bond lengths are given in Å. The value in parentheses is a CBS-QB3 result.



**Figure 4.** TSs for the retro-ene reaction of *cis*-fluoro, -chloro, -bromo, and -methyl diazenes **3b–e**. B3LYP enthalpies are given in kcal/mol. Bond lengths are given in Å.

with B3LYP are similar to those with CBS-QB3. The charge distribution in **TS-3a** shows that the nitrogens and carbons have the partial negative charge and the transferring hydrogen is partially positive.

A stepwise reaction involving homolytic cleavage of the C3–N4 bond to form two monoradicals was also investigated. The activation enthalpy for cleavage is 50.5 kcal/mol,

which is in good agreement with an extensive study of deazetization.<sup>13</sup>

The concerted reaction is highly favored. The retro-ene reaction of **4** has an activation energy of 5.4 kcal/mol (Figure 3). The *trans* form of **5** is 4.0 kcal/mol lower in energy than the *cis* form. The activation barrier for elimination of nitrogen from the *cis* isomer is 5.8 kcal/mol. All these reactions are highly exothermic.

The hydrogen transfer is extraordinarily facile, raising the possibility that the transfer of other groups might be feasible. Similar calculations were carried out on hypothetical methyl and halodiazenes **3b–e**. Halodiazenes **3b–d** are more stable as *cis* isomers (Figure 1). The transition states for nitrogen loss are depicted in Figure 4.

The activation barrier and exothermicity decreases with increasing halogen size. While the barriers for F and Me transfer are quite high, the calculations suggest the feasibility of Cl or Br transfer in a retro-ene type process. These activation barriers are ~9 kcal/mol, and these reactions should be very facile.

**Supporting Information Available:** Full citation of ref 12, Cartesian coordinates, electronic energies, zero-point vibrational energies, and enthalpies of optimized structures of ground states and transition states. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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