

## Origin of the Preference for the Orbital Symmetry Forbidden Stereochemistry of the 1,5-Sigmatropic Shift of Substituted Norcaradienes

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The [1,5]-sigmatropic carbon shift is a classic example of a Woodward–Hoffmann pericyclic process, potentially involving a six-electron aromatic transition state (Figure 1). If concerted, the alkyl shift is predicted to occur with retention of configuration at the migrating carbon.<sup>1</sup> The [1,5]-sigmatropic shift of norcaradiene is an example of a “walk rearrangement”, in which a substituted methylene “walks” around the perimeter of an aromatic ring. It came as a major surprise when Klärner reported a series of elegant studies establishing that this reaction occurs mostly with inversion of configuration at the migrating carbon atom.<sup>2</sup> Several examples are summarized in Figure 2. Compounds bearing substituents on the cyclopropane ring (C-7) of the norcaradiene exhibit inversion with stereoselectivities of 92 to ≥99%.<sup>2</sup>

Schoeller reported semiempirical calculations and proposed that inversion was favored over retention at the migrating carbon center by 1.4 kcal/mol, due to the distorted geometry necessary to maintain overlap in the [1r,5s] rearrangement.<sup>3</sup> Recently, Carpenter proposed that inertial dynamic effects in diradical intermediates can explain the stereoselectivity of [1,3]-sigmatropic carbon shifts.<sup>4</sup> Dynamics should also favor the inversion pathway observed in the cycloheptatriene walk rearrangement. For the analogous vinylcyclopropane–cyclopentene rearrangement and the 1,3-shift of bicyclo[3.2.0]hept-2-ene, the potential energy surfaces alone can explain qualitatively the reaction stereochemistry.<sup>5</sup> The walk rearrangement in bicyclo[2.1.0]pent-2-ene has been studied by Morokuma et al.<sup>5d</sup> We report theoretical investigations which provide an explanation of the unexpected stereochemistry in the 1,5-shift of norcaradiene.

Ab initio calculations were performed with GAUSSIAN 94.<sup>6</sup> Geometries were fully optimized at the UB3LYP/6-31G\* level and, in some cases, the CASSCF(6,6)/6-31G\* level. Energetics were also evaluated with CASPT2N/6-31G\* calculations using MOLCAS 4.<sup>7</sup> Weinhold's natural bond order<sup>8</sup> method was used to analyze the transition states.

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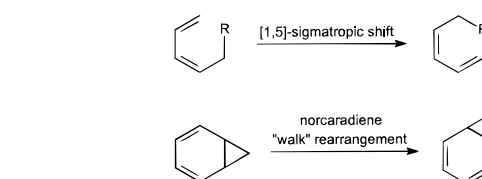


Figure 1. The [1,5]-sigmatropic and the norcaradiene walk rearrangements.

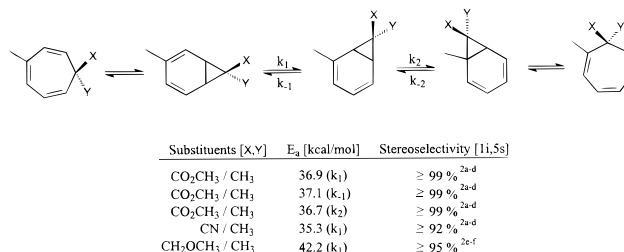


Figure 2. Experimental results with various substituents.

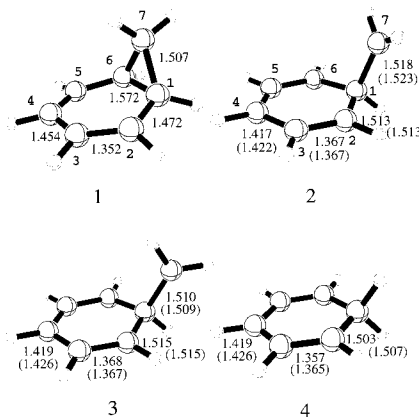


Figure 3. UB3LYP/6-31G\* (CASSCF(6,6)/6-31G\*) stationary points on the norcaradiene rearrangement pathways: norcaradiene (1), retention TS (2), inversion TS (3), and the cyclohexadienyl radical (4).

Norcaradiene rearranges via one of two possible transition structures shown in Figure 3. Both transition structure 2 for the [1r,5s] process and transition structure 3 for the [1i,5s] are diradicals, with cyclohexadienyl radical substructures essentially identical to the cyclohexadienyl radical 4. The B3LYP transition vector for 2 ( $\nu = 196 \text{ i cm}^{-1}$ ) involves a rotation about the C1–C7 bond, while the [1i,5s] transition structure 3 ( $\nu = 182 \text{ i cm}^{-1}$ ) involves motion of C7 toward C6 or C2. The distances from the radical center, C7, to the pentadienyl radical termini, C2 and C6, are 2.450 Å (2.449 Å by CASSCF) and 2.478 Å (2.480 Å by CASSCF) in transition structures 2 and 3, respectively. In neither case is there any significant bonding between C7 and either C2 or C6. The NBOs of forming and breaking bonds are 0.107 in 2 and 0.114 in 3. These distances and NBOs are similar to those in the transition structure for the analogous 1,3-shifts of vinylcyclopropane<sup>5a,b</sup> and bicyclo[3.2.0]hept-2-ene.<sup>5c</sup> The forbidden [1i,5s] transition structure 3 is computed to be 0.9 kcal/mol more stable than the [1r,5s] by UB3LYP and 0.3 kcal/mol by CASSCF, but 0.5 kcal/mol less stable by CASPT2N/CASSCF calculations (Table 1). The large spin contamination in structures 2 ( $\langle S^2 \rangle = 0.95$ ) and 3 ( $\langle S^2 \rangle = 1.05$ ) is a signature of the biradical nature of

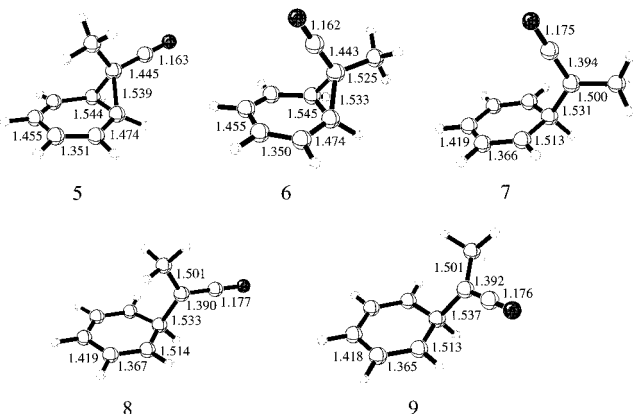
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**Table 1.** Relative Energies for the [1r,5s] and [1i,5s] Shifts of Norcaradienes

structure	CASSCF-(6,6)/6-31G*	CASSCF-(8,8)/6-31G* <sup>a</sup>	CASSCF-(10,10)/6-31G* <sup>a</sup>	CASPT2N/6-31G*	UB3LYP/6-31G* + ZPE
1				0 <sup>b</sup>	0
2	0.3			44.3 <sup>b</sup>	30.1
3	0			44.8 <sup>b</sup>	37.2
5				1.6 <sup>a,c</sup>	0
6				0 <sup>a,c</sup>	0.4
7		0.7	0.4	35.5 <sup>a,c</sup>	25.8
8		0	0	34.4 <sup>a,c</sup>	24.8
9		3.1	3.0	37.3 <sup>a,c</sup>	27.3

<sup>a</sup> Geometries are UB3LYP/6-31G\* optimized. <sup>b</sup> CASPT2N(6,6). <sup>c</sup> CASPT2N(8,8).

**Figure 4.** Stationary points on the *cis*- and *trans*-7-cyano-7-methyl-norcaradiene rearrangement pathway (UB3LYP/6-31G\*): norcaradienes (**5** and **6**), inversion TS (**7** and **8**), and retention TS (**9**).

both transition states; the wavefunctions are essentially 50% singlet and 50% triplet. The CASPT2N computed triplet state lies 1.0 kcal/mol lower than the singlet for transition state **3**, but 1.4 kcal/mol higher than the singlet for transition state **2**. We conclude that **2** and **3** are both diradicals, essentially equal in energy. Intrinsic reaction coordinates (IRC) at the UB3LYP/3-21G level indicate that there are no intermediates.

For comparison, we also calculated the transition structures for the [1i,3s] and [1r,3s] sigmatropic shifts of bicyclo[2.1.0]pent-2-ene at the CASSCF(4,4)/6-31G\* level, earlier studied by Morokuma with UMP2/3-21G geometry optimizations.<sup>5d</sup> In this case, the Woodward–Hoffmann rules predict the inversion process; CASSCF calculations predict it to be favored by 8.1 kcal/mol. This large energy difference arises from the better overlap which results in significant covalent bonding in the inversion transition state. The overlap in the transition state for the retention pathway is absent for symmetry reasons, and a pure diradical results.

The 7-cyano-7-methyl-substituted norcaradiene was explored for a direct comparison with experimental results. Compounds **5** and **6** are interconnected by the [1r,5s] pathway via transition structure **9**, while the [1i,5s] route connects **5** to a second molecule of **5** via transition structure **8**. The inversion transition structure **7**, converts **6** to a second molecule of **6**. Figure 4 shows **5**, **6**, and the three transition structures **7–9**.<sup>9</sup> The reaction pathway starting from the ground-state species **5** via the [1i,5s] transition structure

**8** is preferred by 2.5–3.1 kcal/mol relative to the pathway through the [1r,5s] transition structure **9**. For rearrangement of **6**, the [1i,5s] reaction pathway via transition structure **7** is preferred over the pathway via [1r,5s] structure **9** by 1.5–2.9 kcal/mol. On the basis of the UB3LYP free energies at 453 K, a 97:3 ratio of inversion to retention is predicted, which is in reasonable agreement with the 92:8 ratio found experimentally. As in the unsubstituted case, the NBO analysis of the transition states **7**, **8**, and **9** revealed that all three are diradicals; this is confirmed by the CASSCF wavefunctions. The occupation numbers are 1.00 for the two nonbonding natural orbitals in the transition structures **7** and **8**, while the wavefunction of **9** shows a very small covalent contribution (occupation numbers of  $\psi_{25} = 1.03$  and  $\psi_{26} = 0.97$ ). The activation energy for the disubstituted case is about 10 kcal/mol lower than for the parent: the full radical-stabilizing effects of Me and CN are felt in the diradical transition state.

To evaluate the role of steric effects, analogous geometries of the 1-cyano-1,2-dimethylpropyl radical were optimized using UB3LYP/6-31G\*. These results confirm that the conformation corresponding to **9** is highest in energy because of steric interactions. In the transition structure **9**, the shortest H–H (Mering H) distance is 2.49 Å, substantially shorter than in **7** (2.61 Å) and **8** (2.86 Å); **9** is sterically destabilized. The origin of the experimentally observed stereochemistry is therefore steric, not electronic, in nature.

The 1,5-shifts of norcaradienes are diradical processes but do not involve any diradical minima on the potential energy surface. The strain required to achieve bonding in the [1r,5s] process is too large for this allowed process to be favored. For the parent system, no significant preference of one path over the other is predicted; this would be an ideal case to test the role of dynamics on stereochemistry.<sup>4</sup> However, substituents can introduce significant steric effects which cause the inversion pathway to be favored substantially. Singlet diradicals, like radical pairs,<sup>10</sup> have no inherent enthalpy barrier to bond formation between the radical centers. There may be barriers to bond formation resulting from conformational or strain effects which must be overcome in order to bring two radical centers into proximity for 1,4-bond formation. On the other hand, stabilized diradicals may have barriers to bond cleavage and can exist as minima for conformations where bond formation cannot occur until conformational barriers are overcome. For the diradicals, **2**, **3**, and **7–9**, the two radical centers can always combine to form a bond without distortion or conformational change.

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**Supporting Information Available:** Cartesian coordinates, energies (UB3LYP, CASSCF, CASPT2N), and thermodynamic data (UB3LYP) of all reported structures (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(9) The imaginary frequencies for the transition states indicate that the surface is very flat: **7** (39  $i$  cm<sup>-1</sup>), **8** (52  $i$  cm<sup>-1</sup>), **9** (34  $i$  cm<sup>-1</sup>).

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