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The Rearrangement of Fluorenylideneallene Oxide. A DFT Study

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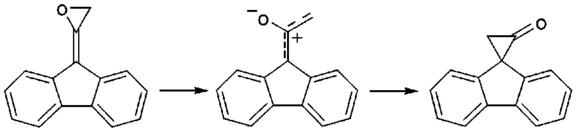
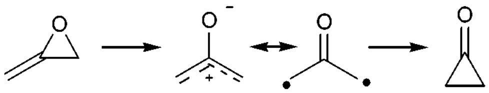
ABSTRACT



Density functional calculations indicate that the rearrangement of fluorenyl allene oxide to the spiro fluorenyl cyclopropanone proceeds through the reactive intermediate fluorenyl oxyallyl. The calculated energetics of this conversion are in agreement with that observed experimentally. The spiro fluorenyl cyclopropanone was calculated to have a low activation energy for its conversion to fluorene and carbon monoxide.

Allene oxides and oxyallyls are thought to play a key role as reactive intermediates in the biosynthesis of prostaglandins.[1−6] However, they have remained elusive intermediates that have been very difficult to isolate and characterize. Only one allene oxide has been isolated, 1,3-di-*tert*-butylallene oxide, and it was found to undergo isomerization at 100 °C to *trans*-2,3-di-*tert*-butylcyclopropanone.[7] Allene oxides have also been observed in the gas phase.[8] The rearrangement of allene oxides to cyclopropanones is thought to involve oxyallyl as an intermediate (Scheme 1). Greene and co-workers showed that enantiomerically enriched *trans*-2,3-di-*tert*-butylcyclopropanone undergoes a thermal racemization and proposed that this reaction occurs via an oxyallyl intermediate.[9] Subsequently Sorensen and Sun reported *cis*-di-*tert*-butylcyclopropanone undergoes isomerization to the *trans* diastereomer, which lent further support to the existence of oxyallyl as a reactive intermediate.[10]

Scheme 1



1 **2** **3**

In 1998 we reported that both CASSCF and DFT calculations confirmed that the parent allene oxide (**1**) should rearrange first to another reactive intermediate, oxyallyl (**2**), which should subsequently very quickly close to give cyclopropanone (**3**) (Figure 1).[11] Given the very low barrier to ring closure it appears very unlikely that the parent oxyallyl can be observed even at low temperature.

Very recently Clay, Durber, and Schepp reported spectral evidence for the existence of fluorenylideneallene oxide (**6**) and a kinetic study for its first-order rearrangement to fluorenylidenecyclopropanone (**8**).[12] They suggested that an

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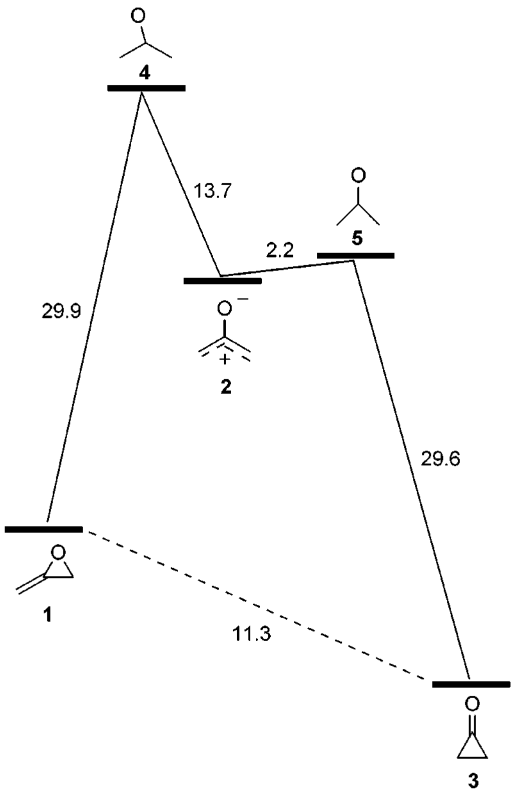
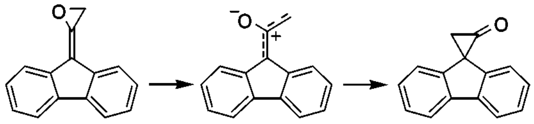


Figure 1. The DFT reaction pathway for the isomerization of allene oxide (**1**) to cyclopropanone (**3**) via the intermediate oxyallyl (**2**). Energies are in kcal/mol.

oxyallyl (**7**) was a likely intermediate in this isomerization shown in Scheme 2. The existence of **6** suggests the

Scheme 2



6 **7** **8**

intriguing possibility that incorporation of oxyallyl into a larger system might stabilize it to the point where it would be observable since the fluorenyl radical is known to be relatively stable.[13]

Therefore it was decided to undertake density functional calculations on structures **6**−**8** as well as on the transition states that link them.[14]

The DFT calculations were performed with the Gaussian 98W computational package[15] using Becke's three-parameter functional,[16] B3LYP or UB3LYP, with the Lee−Yang−Parr correlation function[17] and the 6-31G* basis set.[18] Zero point energies were calculated with unscaled (U)B3LYP/6-31G* frequencies. All stationary points (minima and transition structures) were characterized by computation of their second derivatives.

The allene oxide **6** was found to have all of its atoms in a plane except for the two hydrogens attached to the epoxide ring (C_s symmetry). Comparison of the calculated DFT geometry[19] of the allene oxide in **6** to that of allene oxide (**1**) shows them to be very similar with the exception of the carbon−carbon double bond of the allene oxide, which is predicted to be 0.014 Å longer in **6**. On the other hand oxyallyl **7** has a geometry significantly different from that of its parent system (**2**) (see Figure 2). First of all the oxyallyl system is not planer in **7**, since it was found to have significant twisting about the C−C bond that has one carbon as a part of the five-membered ring. The three carbons of the oxyallyl and the two carbons in the five-membered ring have dihedral angles of 29.6° and −147.7°. Furthermore the C−CH_2 is significantly longer in **7** than in **2**, and the other C−C bond of the oxyallyl is significantly shorter (1.478 and 1.438 vs 1.453 Å in **2** (see further the discussion below about this point). This longer C−C bond in **7** is suggestive that there might be significant delocalization of one of the unpaired electrons into the fluorenyl system. The nonplanar

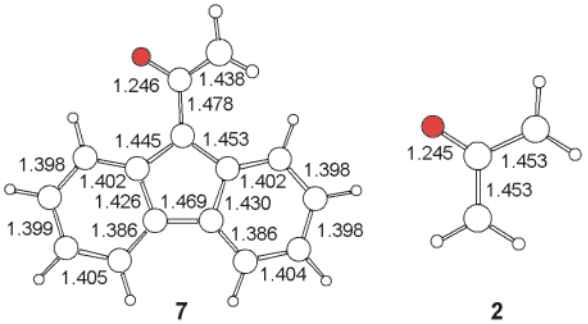


Figure 2. DFT bond distances (in Å) of oxyallyl **7** and oxyallyl **2**.

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[12] Clay, M.; Durber, J.; Schepp, N. P. *Org. Lett.* **2001**, *3*, 3883.

[13] The bond dissociation energy of the CH−H hydrogen in fluorene has recently been determined to be 81 kcal/mol: Römer, B.; Janaway, G. A.; Brauman, J. I. *J. Am. Chem. Soc.* **1997**, *119*, 2249.

[14] The structures studied here are of such a size that a CASSCF calculation is not feasible, but the good agreement between the CASSCF and DFT calculations for allene oxide (ref 8) provide some confidence in the DFT results presented here.

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[19] See Supporting Information for details of the calculational results.

geometry of **7** is most likely caused by steric interactions between the oxygen and one of the methylene hydrogens of the allene oxide and two hydrogens on the benzene rings. Since **7** is nonplanar, the question arises as to what degree this nonplanarity affects the electronic structure of **7**.[20] In connection with another study on allene oxides, the rearrangement of cyclopentadienylideneallene oxide was examined.[21] In this case the corresponding oxyallyl is planar (there is no steric effect). Also, not only are the C−C bond distances of the two oxyallyls very similar, but the overall energy profiles of the reactions of the two allene oxides are almost identical. This suggests that steric effects do not play a major role in the energetics of the rearrangement of **6**.

The geometry of cyclopropanone **8** is unremarkable (C_s symmetry). The two transition structures, **TS67** and **TS78**, which link their respective minima as shown in Figure 3, were located on the potential surface. The transition structure **TS67** for the ring opening of the epoxide in **6** is quite similar to transition structure **4** for the ring opening in allene oxide. **TS67** has a C−C−O angle of 97.7°, and that of **4** is 98.5°. On the other hand the transition structure (**TS78**) for the ring closure of the oxyallyl in **7** to cyclopropanone **8** is further along the reaction pathway than in **5**. The closing C−C−C bond angle in **TS78** is 99.7°, whereas it is 104.8° in **5**.

Although the geometries of the minima and transition structures for the two allene oxide rearrangements to cyclopropanones are quite similar, there is a noticeable difference in the energetics of the reaction pathway. Most notable is the significant stabilization of the oxyallyl **7** compared to oxyallyl **2**. The former lies only 5.7 kcal/mol above the allene oxide **6**, while the parent oxyallyl is 16.2 kcal/mol higher in energy than allene oxide (and of course the steric strain in **7** mentioned above would presumably destabilize **7**). It is therefore apparent that the oxyallyl in **7** is stabilized by the fluorenyl system. This stabilization is also suggestive that the structure of oxyallyl is more diradical than zwitterionic in character, since the fluorenyl radical is quite stable[13] and the fluorenyl cation is not.[22−25]

Although the oxyallyl **7** is significantly stabilized by the fluorenyl group, the transition structure leading from the allene oxide **6** to **7** is only slightly more stabilized relative the parent system (E_a for **1** to **2** = 29.9 kcal/mol; E_a for **6** to **7** = 24.9). This relatively large activation energy for the rearrangement of fluorenylideneallene oxide to oxyallyl **7** is in apparent agreement with the results of Schepp, since he was able to observe the allene oxide spectroscopically as well as study the kinetics of its rearrangement and reaction with nucleophiles. While the oxyallyl in **7** appears to be significantly stabilized by the fluorenyl system, the transition structure (**TS78**) for its conversion to cyclopropanone **8** lies only 4.3 kcal/mol above **7**, which makes it unlikely that the oxyallyl **7** will be observable. However, this stabilization of **7** suggests that isolable derivatives of oxyallyl with an even better stabilizing substituent might be found.

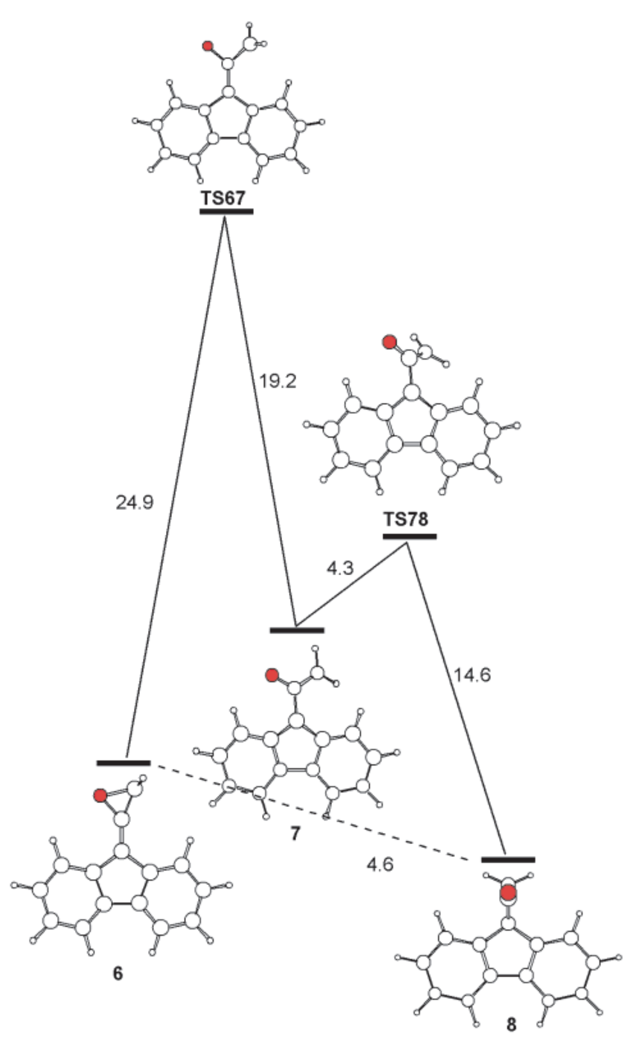
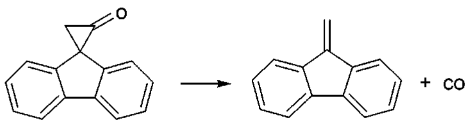


Figure 3. The DFT reaction pathway for the isomerization of fluorenylideneallene oxide (**6**) to fluorenylidenecyclopropanone (**8**). Energies are in kcal/mol.

Finally, Schepp finds among the products from rearrangement of **6** methylenefluorene (**9**), which he proposes arises from the loss of carbon monoxide from the cyclopropanone **8**. We have also examined this reaction and located the transition structure (**TS89**) for the loss of CO. These results are summarized in Figure 4. It is not surprising that this reaction was found to occur by Schepp given its low activation energy (18.7 kcal/mol). The intrinsic reaction coordinate pathway[26] leading from **8** to **9** via **TS89** was followed. Points along the pathway are displayed in Figure



8 **9**

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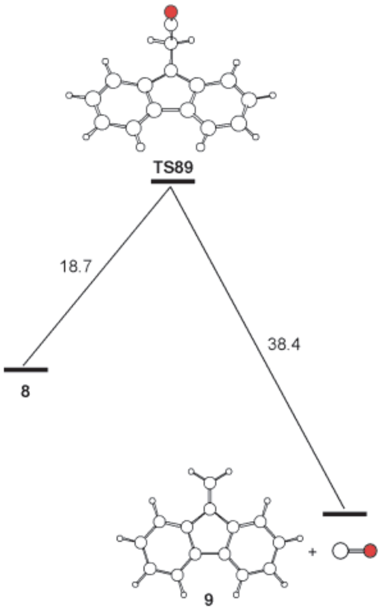

Figure 4. The DFT reaction pathway for the loss of carbon monoxide from fluorenylidenecyclopropanone (**8**). Energies are in kcal/mol.

5, and it is seen that C_s symmetry is maintained throughout the reaction. There is a smooth opening of the three-membered ring leading to **TS89** followed by loss of CO with the expected geometry reorganization taking place leading to methylenefluorene (**9**). While this suggests this is the likely mechanism for the loss of CO, it does not rule out other possible mechanisms. It is interesting to note the pivoting of C−O during the course of its expulsion from the cyclopropanone ring.

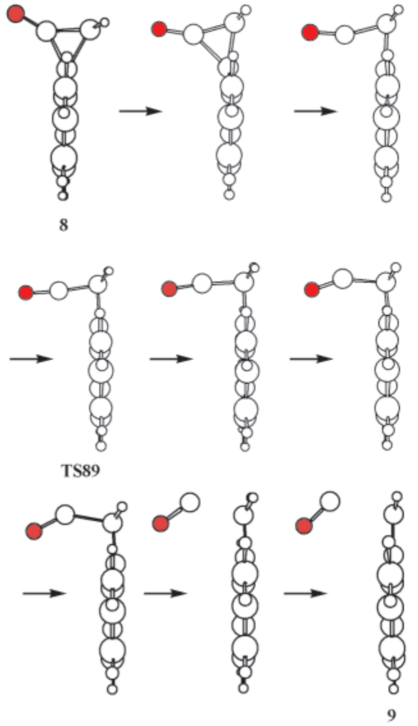

Figure 5. The DFT intrinsic reaction coordinate pathway for the loss of carbon monoxide from fluorenylidenecyclopropanone (**8**) via **TS89**. Energies are in kcal/mol.

In summary, the computational results presented here are in good agreement with the experimental observations reported by Schepp for the fluorenyl allene oxide. It was found that oxyallyl **7** is significantly stabilized by the presence of the fluorenyl system.

Supporting Information Available: Cartesian coordinates, total energies, vibrational frequencies, and zero point energies of **6**−**9**, **TS67**, **TS78** and **TS89**. This material is available free of charge via the Internet at http://pubs.acs.org.

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