

Effect of phenyl substitution on the lifetime and product distribution of cyclobutylidene: preference change in the rearrangements via 1,2-carbon shift and 1,2-hydrogen shift

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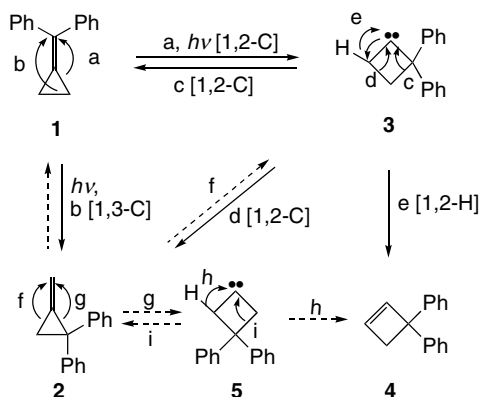
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Abstract—Steady state and laser flash photolytic experiments with precursors **6** and **11** revealed that diphenyl substitution affects the lifetime and reaction mode of cyclobutylidene. 2,2-Diphenylcyclobutylidene **3** ($\tau < 0.1$ ns) produces methylenecyclopropane **1** via 1,2-carbon in significant preference to the positional isomer **2** or cyclobutene **4**. On the other hand, 3,3-diphenylcyclobutylidene **5** ($\tau = \text{ca. } 4$ ns) gives 1,2-hydrogen shift product **4** more favorably than 1,2-carbon shift product **2** together with formal carbene dimer **14**. MRMP2//MP2 calculations afford useful results to understand the interrelationship among substitution, structure, and reactivity.

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Our recent studies¹ on the photochemistry of methylenecyclopropane **1** suggested a mechanism involving 1,2-carbon shift (Scheme 1, arrow a) for transformation from **1** to isomer **2** and cyclobutene **4** in competition with ordinary 1,3-carbon shift (Scheme 1, arrow b). The 1,2-carbon shift process leading to generation of cyclobutylidene **3** is shown to be important because the intervention of **3** rationally explains the formation of both methylenecyclopropane **2** and cyclobutene **4** (Scheme 1, arrows d and e). In relation to this is that not only cyclobutylidene **3**, but also isomer **5** can be generated (Scheme 1, arrows f and g) and postulated to play a role in the photoreversal from isomer **2** to the starting methylenecyclopropane **1** and the formation of cyclobutene **4**. Although intermediacy of these isomeric cyclobutylidenes **3** and **5** has been our current issue, previous experiments designed to trap these carbenes have remained unsuccessful presumably because of their short lifetimes and low quantum yields for generation.

It is fairly common that substituents directly combined to a carbene carbon play a decisive role in determining



Scheme 1.

the reactivity.³ On the other hand, it is much less obvious in the three-center type of rearrangements of singlet carbenes such as **3** and **5** whether substituents on the α - or β -position to a carbene carbon play a significant role in determination of the product distribution and lifetime. Thus, we sought to generate carbenes **3** and **5**

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independently by photolysis of the appropriate precursors. Oxadiazolines^{4,5} were chosen because of their synthetic easiness and their general photochemical behavior as straightforward carbene precursors. In fact, parent singlet cyclobutylidene^{6,7} can be generated from the corresponding oxadiazoline.⁵ Accordingly, oxadiazolines **6** and **11** were synthesized and their steady-state photochemistry and laser flash photochemical behavior were investigated in order to gain insight into the reactivity of carbenes **3** and **5**. Also carried out were computational investigations concerning the effects of phenyl groups on the rearrangement pathways of **3** and **4**.

Table 1 summarizes the results from steady-state photolyses with oxadiazoline **6**.⁸ One can find that methylenecyclopropane **1** is formed as a major rearrangement product in significant preference to the positional isomer **2** or cyclobutene **4**. Also produced were cyclobutanone **8**, diphenylethylene **9**, and azine **10**. Formation of diphenylethylene **9** can be explained in terms of photochemical [2+2]cycloreversion of oxadiazoline **6**. Azine **10** is most likely due to a bimolecular reaction of diazocyclobutane **7** as is often the case in photoreaction of diazoalkanes. In fact, lowering the concentration of oxadiazoline **6** resulted in significant suppression in the yield of azine **10** and led to almost exclusive formation of **1**.

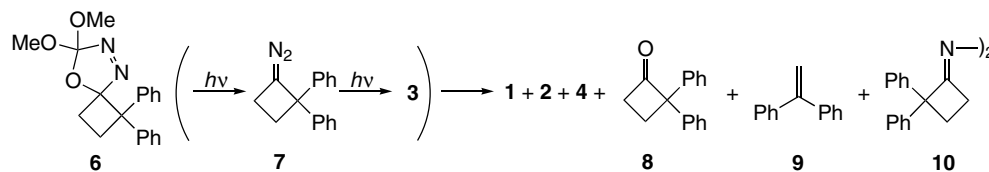
Photolysis of isomeric oxadiazoline **11** in solution proceeded more slowly compared to **6** and afforded a mixture of **2** and **4** in reversed distribution ratio, cyclobutene **4** being formed in preference to **2** (entry 1). Also interesting in this case is that formal carbene dimer **14** was obtained⁹ in 43% yield together with azine **15** (36%) and a trace amount of cyclobutanone **13**. Photolysis of precursor **11** at somewhat lower concentration in benzene resulted in a similar product distribution, but no practical suppression was observed in the formation of **14** or **15** (entry 2). In acetonitrile, the photolysis proceeded more efficiently to give higher yield of dimer **14** but hydrocarbons **2** and **4** were formed in somewhat lower yields (entry 3). It was found that irradiation at 254 nm afforded cyclobutene **4** (30%) in much higher yield and in preference to **2** (2%), with the total material balance being reduced to some extent (entry 4).¹¹

In order to gain insight and evidence for the intervention of cyclobutylidenes **3** and **5**, nano-second laser flash photolysis (LFP, XeCl, 308 nm) of oxadiazoline precursors **6** and **11** was examined. Since cyclobutylidenes **3** and **5** are expected to be spectroscopically invisible, a probe technique¹² with pyridine¹³ was used. Many alkyl carbenes are known to form ylides with pyridine^{13d,e} in competition with their uni- and bimolecular reactions and the resulting ylide absorptions appear in UV–vis region (typically between 300 and 400 nm).¹⁴ Cyclobutylidenes **3** and **5** may also be trapped with pyridine if they have trappable lifetime. Despite our effort, LFP of a solution of oxadiazoline **6** in cyclohexane or acetonitrile containing pyridine (1.2–10 M) resulted in no transient absorptions ascribable to pyridine ylide. It is likely that the lifetime of carbene **3** is too short. If we assume a rate constant for pyridine ylide formation to be $1 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$, 10 M pyridine could easily trap the carbene with its lifetime of ca. 0.1 ns.¹⁵

In contrast, LFP of oxadiazoline **11** in cyclohexane containing pyridine (1.2 M) resulted in transient absorptions as shown in **Figure 1**. Fairly intense absorption with λ_{max} 380 nm can be ascribed to pyridine ylide because it was not observed in the absence of pyridine. Broad and weaker absorption around 470 nm is due to at least two species: one is triplet excited state of **11** ($\lambda_{\text{max}} \sim 450 \text{ nm}$) and the other is much longer-lived diazocyclobutane **12** (λ_{max} 510 nm). These assignments are based on their kinetic behavior and quenching experiments.¹⁶

It is desirable to directly measure the growth rate (k_{obs}) for pyridine ylide absorption so that the bimolecular rate constant for pyridine ylide formation (k_{pyr}) and the lifetime of carbene **5** ($\tau = 1/k_0$) can be determined from the slope and the intercept of a plot of k_{obs} versus concentration of pyridine according to the equation: $k_{\text{obs}} = k_0 + k_{\text{pyr}} [\text{pyridine}]$.¹³ Unfortunately, k_{obs} in this case turned out to be too fast to measure directly with our instruments, presumably because the lifetime of cyclobutylidene **5** is very short. In such a case, Stern–Volmer type analysis is useful.¹³ Indeed, a double reciprocal plot of ylide absorbance (A_{ylide}) versus concentration of pyridine gives a straight line as shown in the inset

Table 1. Steady-state photolysis of oxadiazoline **6**



Entry	Solvent	[6] (mM)	Time (h)	Products (yield (%))
1	<i>c</i> -Hexane	67.0	8	1 (34), 2 (2), 4 (1), 8 (<1), 9 (6), 10 (23)
2	<i>c</i> -Hexane	6.70	2	1 (70), 2 (4), 4 (1), 8 (<1), 9 (17), 10 (8)
3	MeCN	67.0	8	1 (25), 2 (2), 4 (1), 8 (<1), 9 (12), 10 (29)
4	MeCN	6.70	2	1 (72), 2 (3), 4 (1), 8 (<1), 9 (14), 10 (7)

A nitrogen-saturated solution of **6** (0.20 mmol) was irradiated by a 300 W medium pressure mercury lamp ($\lambda > 300$) and the reaction mixture was analyzed by ¹H NMR (300 MHz).

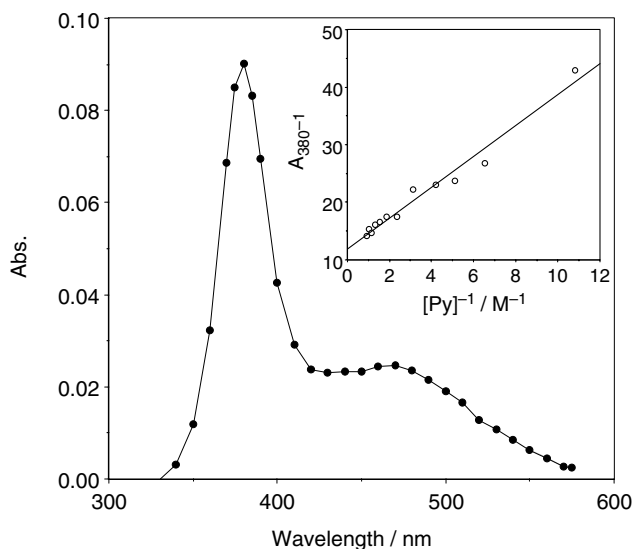


Figure 1. Transient absorption spectrum observed 200 ns after LFP (XeCl, 308 nm) of a cyclohexane solution containing oxadiazoline **11** (2×10^{-2} M) and pyridine (1.2 M). Inset shows a double reciprocal plot for ylide absorbance at 380 nm and the concentration of pyridine, which affords the intercept/slope ratio of 4.4.

of **Figure 1** and the intercept/slope ratio is obtained to be 4.4 M^{-1} , which corresponds to $k_{\text{pyr}} \cdot \tau$. If we assume that $k_{\text{pyr}} = 1 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$, then the lifetime (τ) would be ca. 4 ns.¹⁵ This corresponds to a shorter limit of the estimated lifetime of parent cyclobutylidene (4–20 ns in cyclohexane).⁵

Product analyses in the steady-state photolytic experiments and the results of LFP experiments suggest that the phenyl groups on C2 of cyclobutylidene ring would lead to particular acceleration in the rate of rearrangements from **3** to **1**. Indeed, MRMP2//MP2 based theoretical calculations¹⁷ support this view. As shown in

Figure 2, cyclobutylidene **3** is calculated to have distorted bicyclobutane-like structure with substantial bonding between C1 and C3. The type of non-classical structure was already reported for parent singlet cyclobutylidene.⁷ In the present case, the C1–C3 bond length (1.677 Å) is even shorter than that of parent cyclobutylidene (1.715 Å) calculated by the present method.²¹ Notably, the energy difference between cyclobutylidene **3** and transition state **TS**₃₋₁ leading to **1** by 1,2-C shift is only $0.9 \text{ kcal mol}^{-1}$ (**Fig. 2**), which is much lower than the corresponding energy difference of $8.4 \text{ kcal mol}^{-1}$ between parent cyclobutylidene and its transition state to methylenecyclopropane.^{17,21} Phenyl groups on C2 play an important role in stabilization of **TS**₃₋₁ by electronic delocalization. It is noteworthy that two phenyl groups also lower the energy level of transition state for the other mode of 1,2-C shift (**TS**₃₋₂, $5.7 \text{ kcal mol}^{-1}$). On the other hand, little effect is found for 1,2-H shift (**TS**₃₋₄) since the energy barrier of $10.1 \text{ kcal mol}^{-1}$ is virtually the same as calculated for 1,2-H shift for parent cyclobutylidene ($10.9 \text{ kcal mol}^{-1}$). These results are in line with the observations that formation of **1** is much more favored than the formation of **2** or **4** and that 2,2-diphenylcyclobutylidene **3** has eluded both trapping and spectroscopic observations.

In contrast to **3**, isomeric cyclobutylidene **5** is calculated to be destabilized by $6.3 \text{ kcal mol}^{-1}$ relative to **3** (**Fig. 2**). A major difference between their structures is the C1–C3 bond length: 1.836 Å (**5**) versus 1.667 Å (**3**). It is evident that diphenyl substitution on C3-position of a cyclobutylidene ring would result in considerable congestion around C3, because C3 is a pentacoordinate carbon. Thus, elongation of the C1–C3 bond is an obvious structural consequence to diminish the steric energy. On the other hand, calculations for parent cyclobutylidene predict that departure from the optimum C1–C3 bond length of 1.715 Å results in significant molecular destabilization.^{17,21} Eventually, cyclobutylidene **5** adjusts

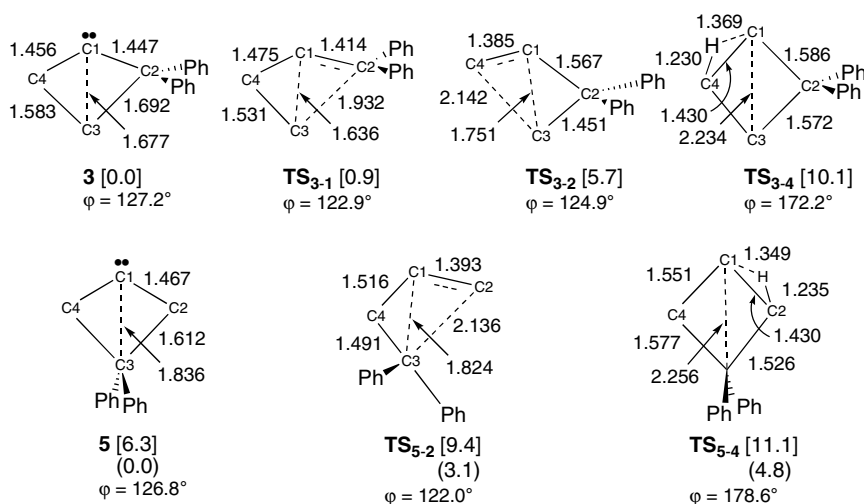
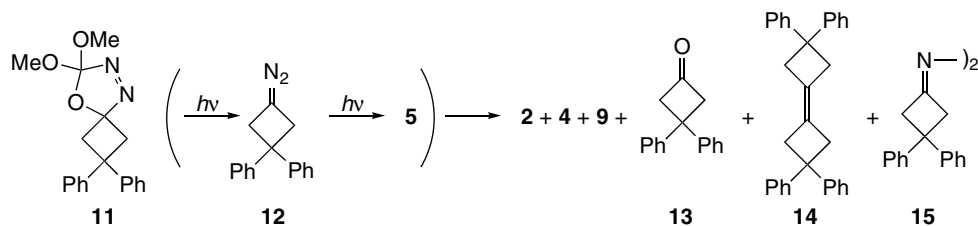


Figure 2. Illustrative structures of singlet cyclobutylidenes (**3** and **5**) and the transition states for the corresponding 1,2-C shifts (**TS**₃₋₁, **TS**₃₋₂, and **TS**₅₋₂) and 1,2-H shifts (**TS**₃₋₄ and **TS**₅₋₄), respectively. Bond lengths are in Å. Numbers in square brackets are energies (kcal mol^{-1}) relative to **3**. Numbers in parentheses are energies relative to **5**. ϕ represents dihedral angle C2–C1–C3–C4.

Table 2. Steady-state photolysis of **11**

Entry	Solvent	[11] (mM)	Time (h)	Products (yield %)
1	Benzene	6.70	13	2 (4), 4 (10), 9 (2), 13 (<1), 14 (43), 15 (36)
2	Benzene	3.35	13	2 (5), 4 (11), 9 (2), 13 (2), 14 (39), 15 (38)
3	MeCN	6.70	8	2 (1), 4 (8), 9 (0), 13 (1), 14 (52), 15 (9)
4 ^a	MeCN	6.70	13	2 (2), 4 (30), 9 (5), 13 (1), 14 (5), 15 (1)

A nitrogen-saturated solution of **11** (0.20 mmol) was irradiated by a 300 W medium pressure mercury lamp ($\lambda > 300$) and the reaction mixture was analyzed by ¹H NMR (300 MHz).

^a Irradiated by four low pressure mercury lamps (254 nm, Toshiba GL-20, 15 W).

itself to have the optimum C1–C3 bond length of 1.836 Å, maintaining the C1–C3 bonding and avoiding overelongation.

Two transition states, **TS**₅₋₂ and **TS**₅₋₄ for 1,2-C and 1,2-H shift of **5**, respectively, also have longer C1–C3 distances and thereby are not stabilized compared to **TS**₃₋₂ or **TS**₃₋₄. However, energy barriers for both 1,2-C and 1,2-H shifts leading to **2** and **4**, respectively, become somewhat low (3.1 and 4.8 kcal mol⁻¹) because the energy level of the starting structure **5** is already high. While these lower energy barriers of 3.1 and 4.8 kcal mol⁻¹ (relative to **5**) appear to be in line with the LFP results showing that the lifetime of **5** is comparable to or a little shorter than that of parent cyclobutylidene, the predicted preference based on the calculated barrier heights disagrees with the observation that 1,2-H migration is more feasible to give **4** than 1,2-C migration to give **2**. However, it is important to note that the energy difference between the barrier heights is fairly small (only 1.7 kcal mol⁻¹) and that such a small difference in calculated energies can be upset in solution eventually by enthalpic factors like solvation and/or entropic factors. In fact, **4/2** ratios observed in the steady-state photolyses of oxadiazoline **11** appear to depend on solvent polarity (Table 2). The values are almost one order of magnitude higher in polar acetonitrile than those in non-polar benzene. These observations are reminiscent of a LFP study of 1-phenyldiazoethane,²² which demonstrated that the transition state of the 1,2-H shift in 1-phenylethylidene is polar and the rate can be accelerated by more than a factor of 30 in polar acetonitrile.

Additional experimental and theoretical studies are under way to understand the interrelationship among substitution, structure, and reactivity of other types of carbenes.

Acknowledgments

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- carbene **5** itself. See Ref. 10 for alkene formation by the reaction of carbene with diazocompounds. Reaction of **5** with precursor **11** or involvement of the triplet state of **5** for the formation of dimer **14** is also a possibility, for which no evidence has been obtained yet.
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 - Absorption of pyridine ylide of parent cyclobutylidene appears at 350–360 nm.⁵
 - The assumed rate constant for pyridine ylide formation may be an upper limit because cyclobutylidenes **3** and **5** are sterically hindered by two phenyl groups.
 - T–T absorption due to ³**11*** decayed with rate constant of $8 \times 10^5 \text{ s}^{-1}$. It can be quenched by typical triplet quenchers like oxygen ($k_q = 3 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$) or ferrocene ($k_q = 2.5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$). After complete decay of ³**11***, much weaker absorption due to **12** persisted for a few seconds.
 - All calculations were carried out by using the GAMESS suite of program codes.¹⁸ Multi-reference second-order Møller–Plesset perturbation calculations (MRMP2)¹⁹ on the molecules were performed at geometries optimized by using single-reference Møller–Plesset perturbation (MP2) method, where the 6-31G(d) basis set was employed.²⁰ Since rearrangements of carbenes are known to proceed through the singlet state, our calculations were limited to the singlet surfaces.
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 - Our results for parent cyclobutylidene are in line with the previous report by Sulzbach et al.^{7a} and Stracener et al.^{7b} They already investigated the structure, bonding, rearrangements,^{7a} and singlet–triplet energy gap^{7b} of parent cyclobutylidene using reliable computational methods. They also reported that singlet cyclobutylidene is predicted to have a non-classical bicyclobutane-like structure with the C1–C3 bond lengths between 1.72 and 1.85 Å.
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