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Article

Detection of Ylide Formation between an Alkylidenecarbene and Acetonitrile by Femtosecond Transient Absorption Spectroscopy

Sujan K. Sarkar, Minji Ko, Xueqin Bai, Lili Du, Dasan M. Thamattoor,* and David Lee Phillips*

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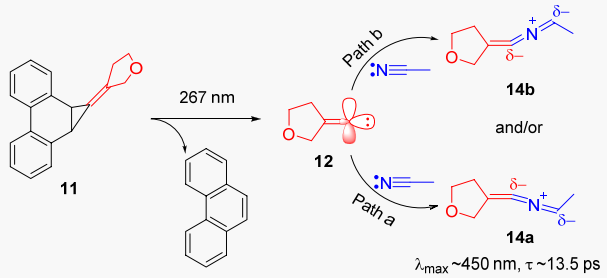
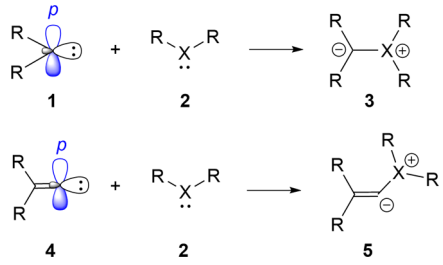
ABSTRACT: Femtosecond laser flash photolysis of 3-(1*a*,9*b*-dihydro-1*H*-cyclopropa[*l*]phenanthren-1-ylidene)tetrahydrofuran produces singlet 3-oxacyclopentylidenecarbene which reacts with acetonitrile solvent to form an ylide. This is the first direct detection of ylide formation by an alkylidenecarbene. This new type of ylide was observed to have a broad absorption band in the visible region with λ_{max} ∼450 nm and a lifetime of ∼13.5 ps. As with other "conventional" carbenes (the divalent carbon atom is separately bound to two substituents), this ylide formation method could be also useful for detecting alkylidenecarbenes, especially those that do not absorb at wavelengths suitable for direct observation. Furthermore, the mechanisms by which 3-oxacyclopentylidenecarbene forms the ylide and the overall favorability of ylide formation, vis-à-vis ring expansion of the carbene to strained 3-oxacyclohexyne, were supported by results from density functional theory calculations.



INTRODUCTION

"Saturated" electrophilic singlet carbenes (**1**), endowed with an empty p-orbital on the formally sp^2-hybridized divalent and neutral carbon atom, are known to accept an electron pair from heteroatom-containing moieties (e.g., **2**) to form the corresponding ylides (**3**) (Scheme 1).[1−14] These carbene-derived ylides have proven to be of considerable synthesis value,[15−27] and in many instances, they have been directly observed and spectroscopically characterized.[28−39] The structurally different "unsaturated" alkylidenecarbenes (**4**), which feature an sp-hybridized carbon atom attached to only one substituent by a double bond, prefer singlet ground states and are electrophilic in nature (Scheme 1).[40−42] As expected, carbenes such as **4** also form ylides **5** by accepting an electron pair in their vacant p-orbital from appropriate nucleophilic donors (**2**) (Scheme 1).[4,40,43−48]

Scheme 1. Ylide Formation in "Saturated" and "Unsaturated" Carbenes



Remarkably, however, to the best of our knowledge, neither the direct observation of ylide formation between alkylidenecarbenes **4** and heteroatom donors nor the spectroscopic characterization of the resulting ylide has been reported to date. Perhaps this void in the literature may be attributed to the paucity of suitable photochemical precursors of **4**. For instance, although carbenes such as **1** may be routinely produced from diazo compounds[49,50] and diazirines,[51] equivalent precursors are not as synthetically accessible for the generation of **4**. In this regard, we have previously reported that phenanthrene-based methylenecyclopropanes **6a**,[52] **6b**,[53,54] and **6c**[55] are viable photochemical sources of corresponding alkylidenecarbenes **7a−c** (Scheme 2). We also demonstrated that related precursors **8a,b** may be used to produce alkylidenecarbenes **9a,b** bearing cyclic substituents, that subsequently rearrange to cycloalkynes (**10a,b**) via ring expansion (Scheme 2).[56] In an analogous manner, we demonstrated the extension of this strategy to access a strained heterocyclic alkyne by photolyzing **11** to form 3-oxacyclopentylidenecarbene **12**, which then rearranges to 3-oxacyclohexyne (**13**) (Scheme 2).[57]

Herein, we report the use of femtosecond time-resolved absorption (fs-TA) spectroscopy to directly observe, for the

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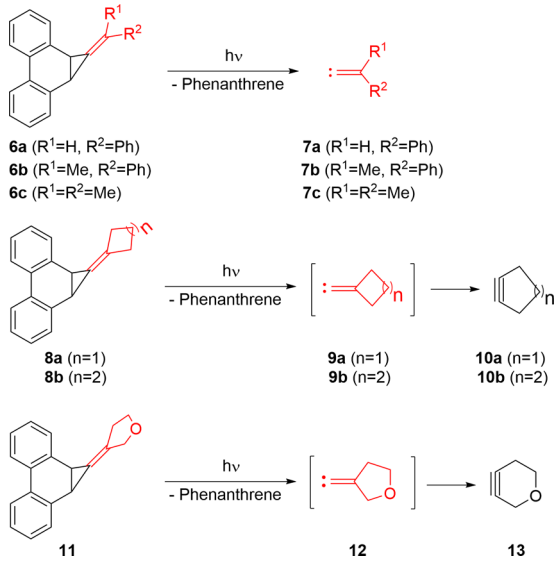
Scheme 2. Formation and Reactivity of Several Alkylidenecarbenes



first time, the ylide formed by the interaction of an alkylidenecarbene (**12**) with acetonitrile and measure its lifetime. The experimental outcome is consistent with results from density functional theory (DFT) calculations which indicate that ylide formation between **12** and acetonitrile is a significantly more favorable process compared to the ring expansion in **12**.

RESULTS AND DISCUSSION

fs-TA Spectroscopy. Time-resolved absorption measurements were carried out in the femtosecond time scale to obtain information about the intermediates formed during photolysis of precursor **11** (UV−vis spectrum: Figure S1), which was excited using a 267 nm laser. A laser flash photolysis (LFP) study of a 0.05 mM solution (~30 mL, flowing sample experiment) of **11** in acetonitrile showed broad absorption spectra with λ_{max} at ~450 nm (Figure 1). The transient absorption was assigned to ylide **14a** and/or **14b** (depicted in Scheme 3a) after comparison of the experimental spectra to those calculated with time-dependent DFT (TD-DFT)[58,59] method at the B3LYP/6-311+G(2d,p)[60−62] level of theory. These calculations located electronic transitions above 325 nm

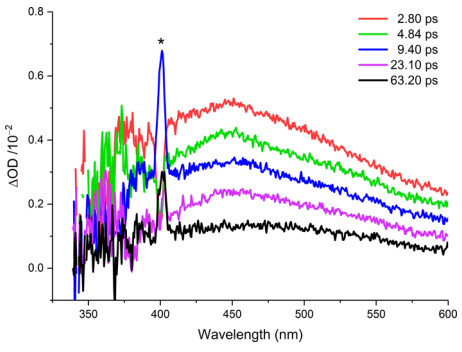
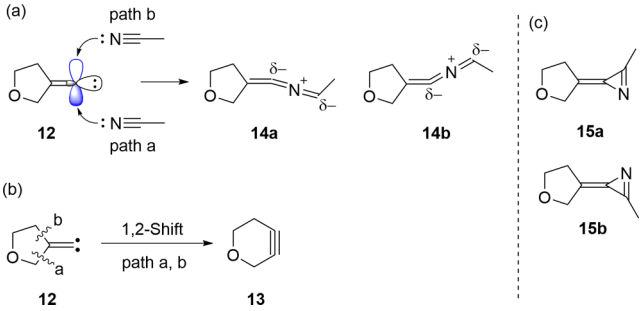


Figure 1. Time-resolved absorption spectra of 0.05 mM solution of **11** in acetonitrile after excitation using a 267 nm laser in fs-TA measurement. Asterisk (*) marks the region affected by subtracted scattered light at 400 nm.

Scheme 3. Reactivity and Mechanism of Cycloalkylidenecarbene 12



for **14a** at 437.4 nm (oscillator strength (f) = 0.0025) and for **14b** at 437.1 nm (f = 0.0024) (Figure 2). Due to the

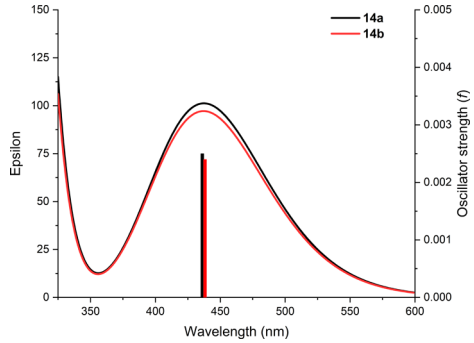


Figure 2. TD-DFT calculations of **14a** and **14b** at the B3LYP/6-311+G(2d,p) level of theory. The left *Y*-axis is showing calculated epsilon value (line) and the right *Y*-axis is showing calculated oscillator strength (vertical bar).

asymmetric nature of cycloalkylidenecarbene **12**, it can possibly result in two stereoisomers of the ylide (**14a** and **14b**). The ylides are presumably generated via interception of **12** by acetonitrile solvent from either side of **12** (Scheme 3a: paths a and b). The TD-DFT calculations of both **14a** and **14b** produced similar spectra (Figure 2); thus, it is difficult to conclude if any one or both the ylide isomers is/are formed. The decay kinetics observed at 450 nm was fitted using a monoexponential equation which gave a lifetime (τ) of ~13.5 ps (k = 7.4 × 10^{10} s^{-1}) for ylide species **14** (Figure 3).

A similar possibility of approach of the electron pair from either side of the carbene carbon has been discussed in the literature, and the stereoselectivity was supposed to be based

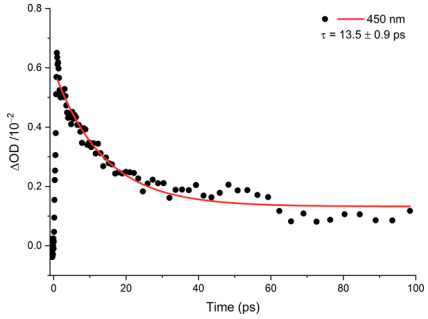


Figure 3. Kinetics observed at 450 nm of 0.05 mM solution of **11** in acetonitrile using a 267 nm laser and the fitting was done using a monoexponential decay equation.

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on the steric effect of the substituents at the α-position.[47] However, in carbene **12**, the difference in the steric hindrance of the two sites of approach is presumed to be negligible; thus, the nucleophile may approach from either side. It is noteworthy that in the nanosecond time-resolved absorption (ns-TA) measurements we did not observe the ylide **14**; instead, we observed peaks with λ_{max} at ∼450 and ∼480 nm (Figure S2), which were assigned to the triplet−triplet absorption of phenanthrene,[63] formed as a counterpart of **12** during photolysis of **11**. A comparable precursor also showed similar peaks in the nanosecond time scale due to the formation of phenanthrene byproduct.[12]

Photolysis of precursor **11** is expected to form **12** initially; therefore, we also obtained the TD-DFT calculated spectra of **12**. The predicted band of **12** above 325 nm at 343.3 nm (f = 0.0072) (Figure S3) did not match with the experimentally observed peak at ∼450 nm. Alkylidenecarbenes like **12**, which do not have a useful absorption in the accessible region of the experiment and/or preferably in the visible region, are difficult to detect directly. The clear and distinct peak in the visible region at ∼450 nm for ylide **14** enabled detection of such carbene **12** using the "ylide formation" method.

Similar to several other alkylidenecarbenes, **12** can also undergo a rearrangement process via a 1,2-shift to form **13** (Scheme 3b). The TD-DFT calculated peak of **13** (Figure S4) was found to be blue-shifted by ∼120 nm from those of ylides **14a** and **14b** and did not match the experimentally observed band at ∼450 nm. Notably, alongside the formation of **14** via intermolecular process, we cannot completely exclude the pathway to form **13** via intramolecular rearrangement, because due to the limitation of the instrument we could not verify the presence of **13**. Furthermore, we looked into the possibility of azirines[32] **15a** and **15b** (Scheme 3c), which could be formed via intramolecular reaction in the ylides **14a** and **14b**, but again their TD-DFT calculated spectra (Figure S5) did not match with the experimental peak at ∼450 nm.

Quantum Chemical Calculations. We carried out computational investigations using DFT calculations at the B3LYP/6-311+G(2d,p)[60−62] level of theory to get a better insight about the reactivity and mechanisms of the photochemical processes. Optimization of precursor **11** and its singlet- and triplet-excited states (S_1 and T_1, respectively) showed that the main changes occurred on the C−C bond lengths of the biphenyl and cyclopropane ring systems (Figure 4). During photolysis of **11**, cleavage of two C−C bonds of the cyclopropane ring system seems to be responsible for the generation of the corresponding carbene **12** and phenanthrene. The two relevant C−C bonds of the cyclopropane ring became elongated in S_1 of **11** (1.53 Å) compared to those in S_0 of **11** (1.47 Å) (Figure 4A,B), whereas these two bond lengths are more or less the same in S_0 of **11** (1.47 Å) and T_1 of **11** (1.48 Å) (Figure 4A,C). Therefore, it is presumed that the photocleavage of the two relevant C−C bonds occur on the singlet excited surface of **11** (S_1) to result in **12** and phenanthrene.

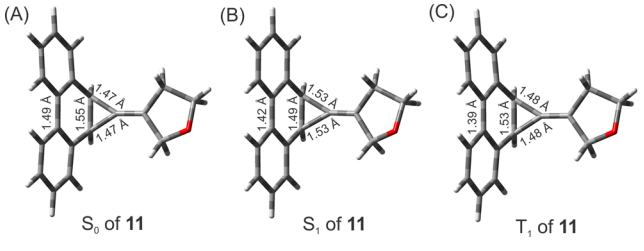


Figure 4. Optimized structures of S_0 (A), S_1 (B), and T_1 (C) of **11** at the B3LYP/6-311+G(2d,p) level of theory.

We found noteworthy differences between the structures of the singlet and triplet states of **12** (S-**12** and T-**12**, respectively), and the main one is the alkenic bond length, which is much shorter in S-**12** (1.29 Å) compared to that in T-**12** (1.40 Å) (Figure 5A,B). Our calculations demonstrated that

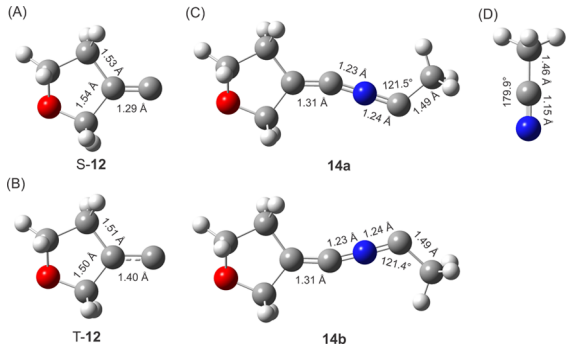
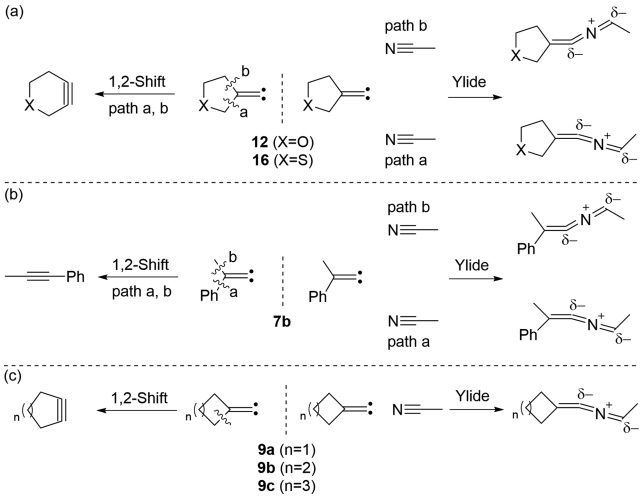


Figure 5. Optimization of S-**12** (A), T-**12** (B), **14a** and **14b** (C), and acetonitrile (D) at the B3LYP/6-311+G(2d,p) level of theory.

this cycloalkylidene carbene **12** has a singlet ground state with S-**12** at 43.1 kcal mol^{-1} ($\Delta E_{ST} = E_T - E_S$) lower in energy than T-**12**. This is comparable to the ΔE_{ST} of ∼41 kcal mol^{-1} that we previously reported (B3LYP/6-31+G*).[57] We also reported similar energy gaps (ΔE_{ST}) of 39.6 and 40.3 kcal mol^{-1} for cyclobutylidene (**9a**) and cyclopentylidene (**9b**), respectively, at the B3LYP/6-31+G* level of theory (Scheme 4c).[56]

Scheme 4. Intermolecular (Ylide Formation) and Intramolecular (1,2-Shift) Processes in Several Alkylidenecarbenes



Moreover, alkylidenecarbenes are generally known to have singlet ground states.[40,64] Due to the presence of the O heteroatom in **12**, acetonitrile can possibly approach from two sides of the carbene (Scheme 3a: paths a and b) and form corresponding ylide isomers **14a** and **14b**, although the energy difference between the ylides is only ∼0.1 kcal mol^{-1}. The C(CH_3)−N bond lengths (1.24 Å) in both **14a** and **14b** were

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found to be longer compared to that in free acetonitrile (1.15 Å), suggesting a decrease in its bond order in the ylides (Figure 5C,D). Although, simple concept of hybridization angle might have indicated a linear geometry for the C═C═N moiety, the C═C═N bond angles were observed to be 163.9 and 164.9° in **14a** and **14b**, respectively. In this context, it is notable that in a cumulene system capped with O atom the interaction between the nonbonding orbital of O atom and adjacent antibonding orbital results in deviation from linearity.[65]

The calculated transition state energy barriers for formation of both ylides **14a** and **14b** were found to be low, 3.1 (imaginary frequency (ν_i) = −142.78 cm^{-1}) and 4.2 (ν_i = −145.51 cm^{-1}) kcal mol^{-1} for paths a and b, respectively (Scheme 3a, Figure 6A,B). The parent acyclic alkylidenecarbene (H_2C═C:) undergoes a rapid Fritsch−Buttenberg−Wiechell (FBW)[66−68] type rearrangement to form acetylene.[69−71] Cycloalkylidenecarbenes are also known for yielding cycloalkynes[56,57,72,73] via a 1,2-shift, a common rearrangement process for such systems.[73−77] Therefore, we computationally compared the intramolecular 1,2-shift process in **12**, which can result in the formation of the strained oxacyclohexyne **13** (Scheme 3b), to ylide(s) formation. Due to the lack of symmetry in **12**, the 1,2-migration can occur via paths a and b, but irrespective of the path, it would yield **13** (Scheme 3b). The calculated transition state energy barriers for the 1,2-shift were found to be 9.9 (ν_i = −359.44 cm^{-1}) and 13.9 (ν_i = −413.46 cm^{-1}) kcal mol^{-1} for paths a and b, respectively. The electron pair of the O atom in **12** facilitates the bond breaking via path a and plays an important role to lower the transition state energy barrier in path a compared to path b.[78] Moreover, the O atom assists in stabilization of 1,2-shift product **13**.[79,80]

The transition state energy barriers for both of the 1,2-shift pathways in **12** (9.9 and 13.9 kcal mol^{-1}; Figure 6) are much higher compared to that in any of the ylide formation pathways (3.1 or 4.2 kcal mol^{-1}; Figure 6). Therefore, we can conclude that for cycloalkylidenecarbene **12** the intermolecular adduct formation is considerably faster than the intramolecular rearrangement process. Previous calculation of the ring expansion in **12** at a different level of theory (CCSD(T)/cc-pVTZ//B3LYP/6-31+G*) showed similar transition state energy barrier of 8.9 and 12.8 kcal mol^{-1} for paths a and b, respectively.[57] It is noteworthy that symmetric cyclopentylidenecarbene **9b** (Scheme 4c) has only one path to form cyclohexyne and previously, we found the transition state energy barrier to be 9.1 kcal mol^{-1} (CCSD(T)/cc-pVTZ//B3LYP/6-31+G*).[56]

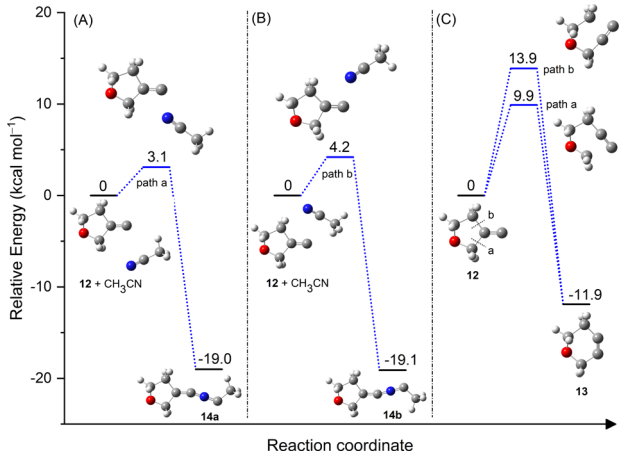

Figure 6. Calculated relative energy (kcal mol^{-1}) diagram of the species involved in the inter- and intramolecular reactivity of cycloalkylidenecarbene **12** at the B3LYP/6-311+G(2d,p) level of theory.

To further understand the selectivity of the intermolecular (ylide formation) versus the intramolecular (1,2-shift) processes, we carried out computations on several other alkylidenecarbenes and compared the relevant transition state energy barriers for the two processes (Scheme 4 and Table 1).

Table 1. Comparison of Transition State Energy Barriers for Intermolecular (Ylide Formation) and Intramolecular (1,2-Shift) Processes in Several Alkylidenecarbenes Depicted in Scheme 4 at the B3LYP/6-311+G(2d,p) Level of Theory[a]

	12	16	7b	9a	9b	9c
ylide	3.1,[b] 4.2[c]	2.9,[b] 3.8[c]	5.7,[b] 5.0[c]	4.0	4.9	4.8
1,2-shift	9.9,[b] 13.9[c]	11.4,[b] 12.9[c]	3.1,[b] 10.8[c]	3.5	10.0	11.4

[a]All the energies are in kcal mol^{-1}. [b]Path a. [c]Path b.

Previously, using time-resolved spectroscopy, we observed that even in the presence of acetonitrile, acyclic alkylidenecarbene **7b** (Scheme 4b) prefers the 1,2-shift process, rather than ylide formation.[53,54] Therefore, to understand the reactivity of **7b**, we calculated the related transition state energy barriers for this system and found that the barriers for ylide formation (paths a and b) are higher compared to that of the 1,2-shift process via path a (Scheme 4b, Table 1). Cycloalkylidenecarbene **16** (Scheme 4a), the S heteroatom substituted analogue of **12**, also showed a similar preference for either of the ylide formation pathways compared to the 1,2-shift process (Table 1). Cycloalkylidenecarbenes **9b** and **9c** (Scheme 4c), without any heteroatom substituents, also showed a similar trend of preference of ylide formation (Table 1). However, cycloalkylidenecarbene **9a** (Scheme 4c), which contains a smaller ring, demonstrated very similar transition state energy barriers for both the processes; thus, it would be interesting to study this experimentally in future to know its preferred pathway (Table 1).

CONCLUSION

We demonstrated, for the first time, that a cycloalkylidenecarbene (**12**) can be intercepted by acetonitrile to form an ylide, which has an easily detectable broad absorption in the visible region (~450 nm) and a lifetime in the picosecond range (~13.5 ps). Therefore, similar to "saturated" carbenes, an "ylide formation" method can be used effectively in the future to detect alkylidenecarbenes, especially the ones which have inaccessible/inadequate chromophore absorption. Moreover, ylides are important species in organic synthesis and further studies on similar adduct formation of both cycloalkylidenecarbenes and acyclic alkylidenecarbenes will provide more information on this new type of ylide and help to understand the general trend of their structures, reactivities, mechanisms, and other properties. Indeed, other nucleophiles such as pyridine, acetone, benzonitrile, and so on are expected to generate similar ylides and future work will be directed to study them to observe any distinct changes in their lifetimes and absorptions induced by the nucleophile.

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EXPERIMENTAL SECTION

fs-TA Experiment. A detailed description of the experiment setup of fs-TA measurement has been provided in previous publications.[81,82]

Quantum Chemical Calculation. Gaussian16[83] was used to perform the density functional theory (DFT) calculations at the B3LYP/6-311+G(2d,p)[60−62] level of theory. All the transition states were confirmed to have one imaginary vibrational frequency and intrinsic reaction coordinate (IRC) calculations were carried out which showed correlation of the transition state with the reactant and product.[84,85]

Synthesis. Precursor **11** was prepared using the method that we have described previously.[57]

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.1c07074.

Experimental and computational supporting figures, and Cartesian coordinates of the relevant optimized structures and transition states (PDF)

AUTHOR INFORMATION

Corresponding Authors

David Lee Phillips − *Department of Chemistry, The University of Hong Kong, Hong Kong S.A.R.*; Email: phillips@hku.hk

Dasan M. Thamattoor − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*; orcid.org/0000-0002-6619-4392; Email: dmthamat@colby.edu

Authors

Sujan K. Sarkar − *Department of Chemistry, The University of Hong Kong, Hong Kong S.A.R.*; orcid.org/0000-0002-8471-6297

Minji Ko − *Department of Chemistry, Colby College, Waterville, Maine 04901, United States*

Xueqin Bai − *Department of Chemistry, The University of Hong Kong, Hong Kong S.A.R.*

Lili Du − *Department of Chemistry, The University of Hong Kong, Hong Kong S.A.R.; School of Life Science, Jiangsu University, Zhenjiang 212013, PR China*; orcid.org/0000-0002-9712-3925

Complete contact information is available at: https://pubs.acs.org/10.1021/jacs.1c07074

Notes

The authors declare no competing financial interest.

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