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The Missing C_1-C_5 Cycloaromatization Reaction: Triplet State Antiaromaticity Relief and Self-terminating Photorelease of Formaldehyde for Synthesis of Fulvenes from Enynes

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ABSTRACT: The last missing example of the four archetypical cycloaromatizations of enediynes and enynes was discovered by combining a twisted alkene excited state with a new self-terminating path for intramolecular conversion of diradicals into closed-shell products. Photoexcitation of aromatic enynes to a twisted alkene triplet state creates a unique stereoelectronic situation which is facilitated by the relief of excited state antiaromaticity of the benzene ring. This enables the usually unfavorable 5-endo-trig cyclization and merges it with 5-exo-dig closure. The 1,4-diradical product of the C_1-C_5 cyclization undergoes internal H-atom transfer that is coupled with the fragmentation of an exocyclic C-C bond. This sequence provides efficient access to benzofulvenes from enynes and expands the utility of self-terminating aromatizing enyne cascades to photochemical reactions. The key feature of this self-terminating reaction is that, despite the involvement of radical species in the key cyclization step, no external radical sources or quenchers are needed to provide the products. In these cascades, both radical centers are formed transiently and converted to the closed-shell products via intramolecular H-transfer and C-C bond fragmentation. Furthermore, incorporating C-C bond cleavage into the photochemical self-terminating cyclizations of enynes opens a new way for the use of alkenes as alkyne equivalents in organic synthesis.

INTRODUCTION

Cycloaromatization reactions defy common chemical logic by creating diradical species from closed shell reactants without external radical initiators. In these unusual but very useful[1] processes, one chemical bond is always created at the expense of *two* chemical bonds that are sacrificed. The unavoidable decrease in the number of chemical bonds along the reaction path distinguishes cycloaromatization reactions from their cousins: concerted pericyclic reactions and simple cyclizations.[2] Furthermore, this feature always leads to the formation of *two radical centers* (or a zwitter-ion[3]) and imposes an intrinsic thermodynamic penalty. Out of the four reactions shown in Figure 1, only the C_1-C_6 cyclization of enediynes (the Bergman cyclization)[4,5] is assisted by aromaticity. The other members of this reaction family do not receive such a generous thermodynamic bailout and have to rely, instead, on alternative sources of electronic stabilization. For example, C_1-C_5 cyclizations[6] can be facilitated by conjugating the exocyclic π-radical centers with a terminal substituent R.[7] Because such effects are generally weaker than aromatic stabilization, rational design of such intrinsically challenging uphill processes span a number of innovative approaches.[8] For example, the alleviation of transient antiaromaticity was used to drive radical anionic cyclization of the benzannelated enediynes, enabling efficient C_1-C_5 "cyclorearomatization" at room temperature.[9]

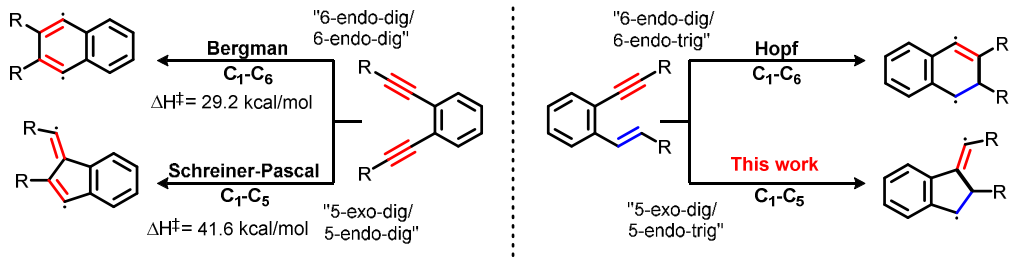


Figure 1. The possible cycloaromatization modes for enediynes (left) and enynes (right). BCCD(T)/cc-pVDZ values obtained from ref. 6a.

Considering the broad interest in cycloaromatization reactions, it is remarkable that, in contrast to the Hopf cyclization of enynes,[10] an efficient C_1-C_5 counterpart remains unknown. What are the possible reasons that the last member of the cycloaromatization reaction family had remained so elusive?

Can thermodynamic factors provide an explanation? Unlike enediyne cyclizations, where the preference for C_1-C_6 over C_1-C_5 closure is biased by the aromatic stabilization gained in the p-benzyne product, neither cyclization mode for enynes is thermodynamically assisted by aromaticity. Hence, the situation is more evenly balanced for enynes.

Can it be stereoelectronics? The stereoelectronic rules for cyclizations[11] suggest a kinetic preference for exo-ring closures at alkynes that should favor C_1-C_5 closure (which can be classified as a "5-exo-dig/5-endo-trig" ring closure by expanding Baldwin's classification for cyclization reactions[12]) over C_1-C_6 ("6-endo-dig/6-endo-trig") closure of enynes. However, at the same time, C_1-C_5 closure of enynes involves a 5-endo-trig closure at the alkene, an unfavorable process according to the Baldwin rules.[13] Hence, the stereoelectronic predictions are mixed.

Can the problem lie in one of the subsequent cascade steps? This question is justified because the ring closure itself is not the only challenge in the design of cycloaromatization processes. Because two radical centers are created in each cycloaromatization reaction, their subsequent fate is an integral part of the overall transformation. In fact, the cyclization step is quite often *not* the rate-limiting step in reaction cascades where an open shell diradical is generated from a closed shell precursor. Even in the Bergman cyclization, the most favorable of the four archetypal cycloaromatizations, the first H-transfer step can still be the greatest kinetic hurdle, even if this step is intramolecular.[14] Not surprisingly, Schreiner and Hopf have shown that intramolecular termination is rate-limiting for the C_1-C_6 cyclization of enynes (the Hopf cyclization).[15] In this process, aromatization after C_1-C_6 closure occurs via two consecutive high barrier 1,2 H-shifts (highest $\Delta H^{\ddagger} = 44.1$ kcal/mol), shown in Figure 2. The same problem should apply to the so far unknown C_1-C_5 closure of enynes. Once the diradical is generated, it needs to undergo consecutive 1,2 H-shifts or other high energy intramolecular reactions in order to be converted to the fulvene product without the assistance of aromatization.[16]

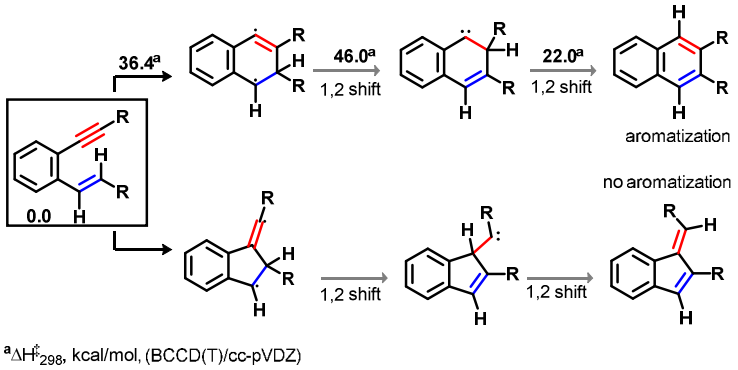


Figure 2. Termination for C_1-C_6 and C_1-C_5 enyne closures could occur via high barrier consecutive intramolecular 1,2-H-shifts.

In order to overcome the possible problems associated with trapping the diradical product of the elusive C_1-C_5 cyclization of enynes, we have envisaged an innovative solution based on self-terminating[17] radical cyclizations. In this recently reported class of organic transformations, the cyclization is terminated by a stereoelectronically promoted and thermodynamically favorable C-C bond fragmentation driven by aromatization and the formation of two-center/three-electron bonds.[18] This idea can be implemented for terminating the C_1-C_5 cyclization of enynes in the two ways shown in Figure 3. In the first design, introduction of a CH_2OMe group at the alkene terminus can facilitate the C-C fragmentation, but a facile intramolecular path for the final H-abstraction at the exocyclic vinyl radical is not offered. In the more ambitious scenario, the C-C fragmentation is coupled with an intramolecular H-abstraction made possible by the introduction of a CH_2OH moiety in an unprecedented reaction that converts the diradical directly into a closed-shell species via a single concerted step.

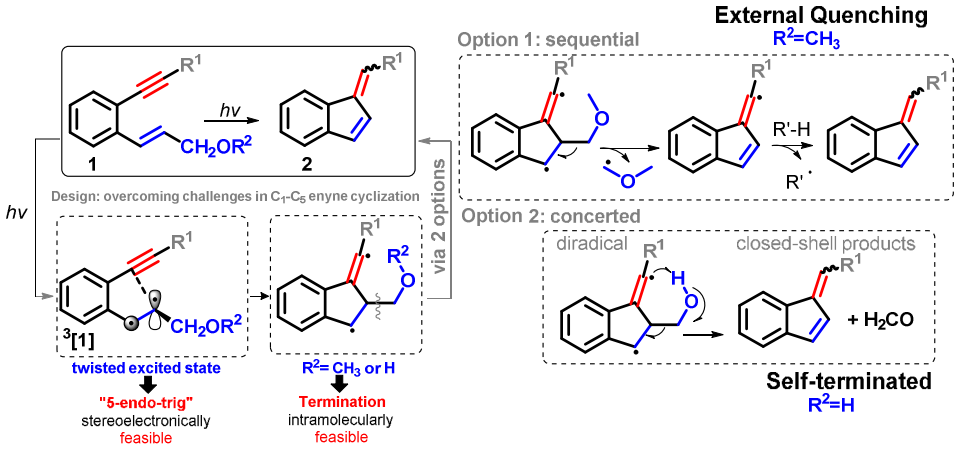


Figure 3. Overcoming restrictions for C_1-C_5 cyclization via twisted excited state and electrocyclic termination to produce fulvenes.

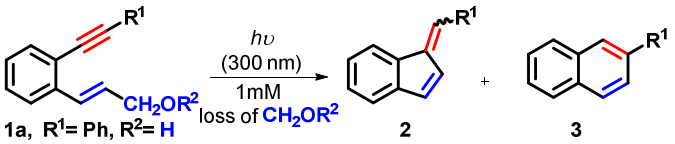
In this work, we combine experimental and computational techniques to test a new concept for overcome restrictions for C_1-C_5 closure. We apply the high energy of photochemical excitation followed by alleviation of the destabilizing excited state antiaromatic character of the benzene moiety[19-21] as the driving force for an intrinsically unfavorable pair of transformations. Furthermore, the photoexcitation can uncouple the alkene π-electrons to form an orthogonal diradical species that would remove the stereoelectronic constraints for 5-endo-trig closure, as shown in the Figure 3.[22]

COMPUTATIONAL METHODS

All DFT calculations were performed with Gaussian09, revision D.01[23], the M06-2X functional of Truhlar and co-workers,[24] and the 6-311+G(d,p) basis set of Pople and co-workers.[25] We chose the M06-2X functional for its well-documented accuracy for thermochemistry.[26] Optimizations and frequency calculations employed the SMD solvation model[27] with dichloromethane solvent, as implemented in Gaussian09. It has previously been shown that this is a satisfactory method for obtaining solution free energies.[28] All stationary points were confirmed by frequency calculations and IRC calculations were used to confirm the identity of the transition states. For the singlet surface, unrestricted DFT was used and the initial guesses were obtained with the 'guess=mix' keyword. All Kohn-Sham solutions were checked for instabilities with the 'stable' keyword. HOMA (Harmonic Oscillator Model of Aromaticity)[29] values were used as a structural criterion of aromaticity. Values close to 1 correspond to aromaticity whereas lower values indicate approach to non-aromaticity. The ACID method of Herges and co-workers is a general method to visualize conjugation, aromatic and antiaromatic ring-currents. [30] Clockwise ring currents correspond to aromaticity, counter-clockwise ring currents correspond to antiaromaticity and the absence of ring currents correspond to non-aromaticity. ACID plots were generated by AICD 2.0.0 at 0.050 isosurface value at the M06-2X/6-311+G(d,p)/SMD(dichloromethane) level using the CSGT method.[31]

RESULTS AND DISCUSSION

Cyclization. Enyne **1a** was synthesized using previously reported procedures[18] and irradiated at 300 nm using a low pressure mercury lamp in 1 mM solutions of Et_2O, hexane, DCM, cyclohexane, and benzene. In all of the solvents, cyclization with concomitant fragmentation (loss of CH_2OH) into the naphthalene product **3** was observed at room temperature, albeit in low yields. Naphthalene formation from enynes is consistent with previous work.[32] Interestingly, in DCM and benzene, we observed product signals for the more intriguing benzofulvene product **2**, derived from an alternative C_1-C_5 cyclization (Table 1). The presence of the allylic alcohol group in **1a** proved critical for the formation of benzofulvene product **2** since irradiation of enyne **1b** (R^2=CH_3) only produced naphthalene **3** in all five solvents.



Solvent	DCM	Benzene	Et_2O	Hexane	Cyclohexane
% Conversion (1a)	68[a]	56[a]	35[b]	25[b]	40[b]
% Conversion (1b)	23[b]	20[b]	2.5[b]	10[b]	20[b]

[a] a mixture of fulvene **2** and naphthalene **3** is observed
[b] only naphthalene **3** is observed

Table 1. Initial trials of the photochemical cyclization/fragmentation of enynes **1a-b**.

Scope: C_1-C_5 vs C_1-C_6. As shown in Table 2, a library of enynes, with varied alkynyl substituents (R_1), was synthesized and irradiated to test the generality of the C_1-C_5 cyclization mode. To our delight, we found that formation of benzofulvenes is the preferred path for the photocyclization with 100% conversion of starting material observed for enynes **1g-p**. In most cases, the photocyclization/fragmentation was completed in 4-6 hours to cleanly provide benzofulvenes, as the only isolable products, in 83-95% yields. Only with enynes **1b-f** where the alkynyl substituent R = Ph, tolyl, pyridine and *p*-fluorophenyl was the photocyclization/fragmentation inefficient and produced a mixture of naphthalene and benzofulvene products (**3b-f** and **2b-f**). Fluoro-substituted enyne **1f** was the slowest to react (12h). The clean formation of mono-fulvene from dienyne **1p** indicated that transformation of the intermediate fulvene diradical into closed-shell fulvene via Hydrogen Atom Abstraction (HAA) and C-C fragmentation proceeded faster than trapping via 5-endo-trig radical cyclization with the additional vinyl group.[33]

Quantum yields for the reactions were determined by comparing the conversion rate of 50 μM solution of enyne with the benzophenone-benzohydrol actinometer system (φ=0.57).[34] The results are summarized in the SI (Figure S1) along with UV/Vis absorption spectra of selected benzofulvenes in DCM (Figure S2).

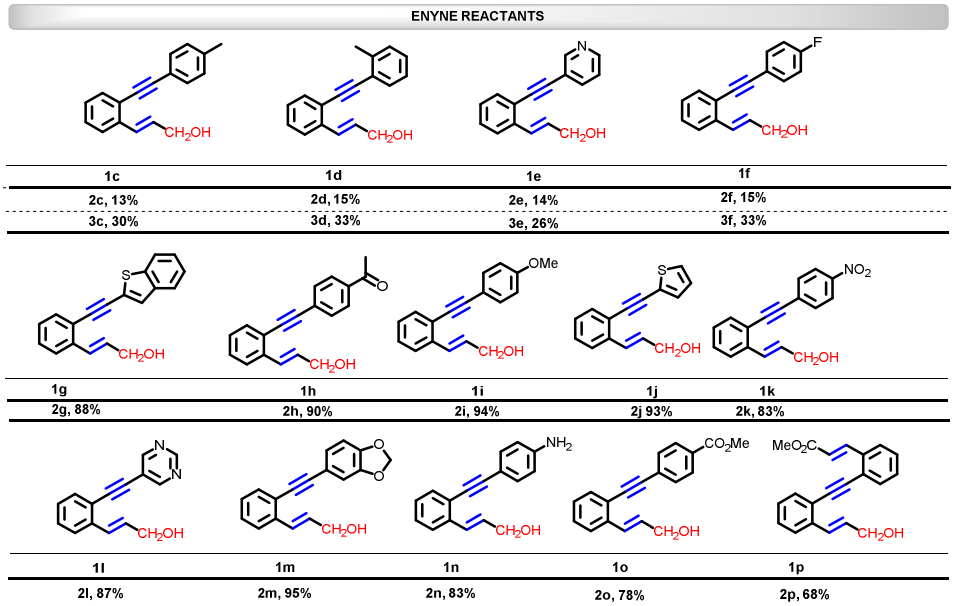


Table 2. Photocyclization of enynes to benzofulvenes **2** and naphthalenes **3**. Isolated yields of products are given below the reactant structures.

Sensitization. In order to gain insight into the nature of the excited state responsible for the observed photoreactivity, the photocyclization/fragmentation was carried out in the presence of benzophenone, a known triplet sensitizer (E_T = 68 kcal/mol).[35] The addition of benzophenone to the reaction mixture of enynes **1b-f** successfully suppressed naphthalene formation and promoted exclusively the formation of fulvene products **2b-f**, as shown in Figure 4. These results strongly suggest that fulvene formation proceeds from the triplet manifold.

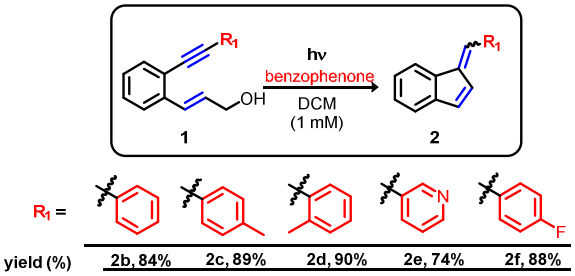


Figure 4. Triplet sensitization promotes fulvene formation.

Computational analysis of the mechanism. Various mechanistic possibilities which account for the loss of the alkene CH_2OH substituent during the formation of fulvenes and naphthalenes are shown in Figure 3 and Scheme 3. Without triplet sensitization, the observed phototransformation likely involves excitation of enyne **1** to a singlet state that undergoes intersystem crossing (ISC) to form a reactive triplet diradical species ^{3}**[1].** The latter can then undergo rapid 5-exo-dig/5-endo-trig C_1-C_5 cyclization to form a cyclic diradical intermediate. This diradical is too reactive to be intercepted via an intermolecular reaction and undergoes rapid

fragmentation into the final fulvene product via two mechanistic pathways. Since there is no efficient external H atom donor present in the reaction mixture (D_o^{298K} (expt.) = 95.6 ± 0.6 kcal/mol for H-$CHCl_2$)[36], fragmentation to the fulvene monoradical could initially occur and the H atom subsequently abstracted from the expelled radical fragment. The O-H bond dissociation energy in the CH_2OH radical has been estimated to be only 30 kcal/mol.[37] However, the most efficient way to convert the diradical into a closed shell stable product is to couple the fragmentation and HAA in a novel concerted process, as shown in Figure 3 ("option 2").

The (U)M06-2X/6-311+G(d,p)/SMD(DCM) potential energy surfaces for the possible cyclization sequences to naphthalene and fulvene formation were calculated for the singlet (S_0) and triplet (T_1) states, shown respectively in Figure 5. Calculated energies for C_1-C_6 and C_1-C_5 closures indicate that both cyclization modes are difficult to accomplish in the ground state. The barriers for ring closure are very high (both above 40 kcal/mol!) and both processes are ~30 kcal/mol endergonic. Interestingly, the thermal C_1-C_5 closure has a lower barrier than the Hopf cyclization indicating that C_1-C_5 is not an intrinsically unfavorable process. Considering that additional substituents at the ring closure points increase the activation energy compared to the parent system, the high activation energy of the C_1-C_6 path is consistent with earlier analysis of Schreiner, Hopf and coworkers who reported a 36.4 kcal/mol BCCD(T) barrier for the parent benzannelated enyne (Figure 2)[6a]. The high endergonicity of the diradical products is not surprising – in both of them two π-bonds are broken to form a single σ-bond.[2]

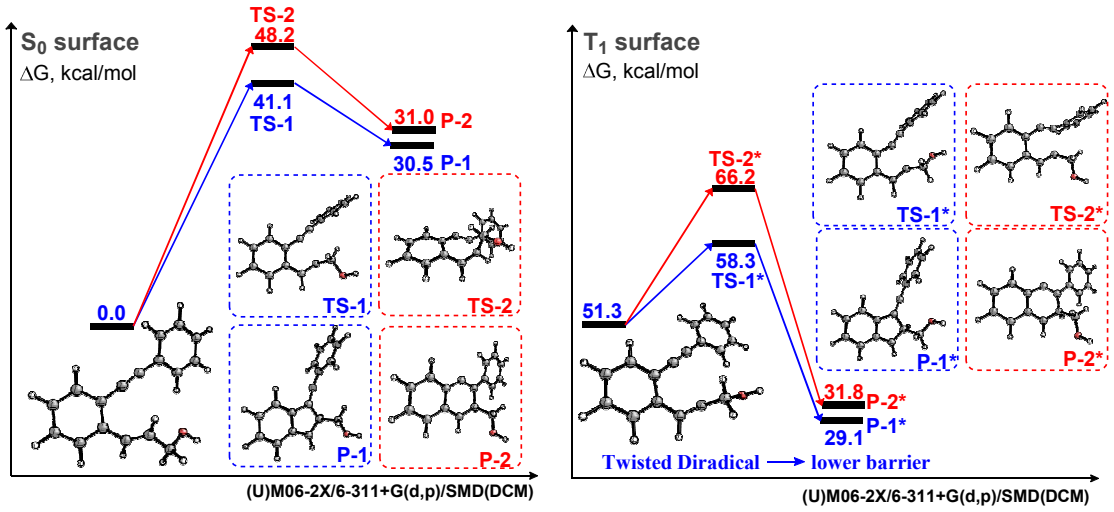


Figure 5. Singlet and triplet surface of the cyclization step of **1a** explored computationally using (U)M06-2X/6-311+G(d,p)/SMD(DCM).

On the triplet manifold, the barrier to C_1-C_5 cyclization from the twisted excited state geometry is much lower (only 7 kcal/mol) but the selectivity is not affected. As on the singlet surface, the C_1-C_5 cyclization barrier is much lower than the 14.9 kcal/mol C_1-C_6 barrier to naphthalene formation. The dramatic decrease in the calculated activation barrier for the triplet state reaction in comparison to its ground state counterpart illustrates the power of photochemical activation.[38] Furthermore, both triplet cyclizations are exergonic.

The role of alkene twisting for cyclizations: Photochemical alkene twisting directly accounts for the efficiency and low barrier for five-membered ring formation in the present system. The cyclization reaction benefits from a highly favorable combination of two factors: a) the twisted alkene π-bond projects a radical orbital toward the alkyne and b) the alkyne has two orthogonal π-systems,[39] so it can accept the incoming radical without breaking its conjugation with the benzene π-system (Figure 6). This combination of factors leads to a surprisingly facile 5-endo-trig closure that bypasses the usual stereoelectronic limitations for this process, which, in the ground state, requires significant distortion to reach the favorable Bürgi-Dunitz trajectory.[40,41] Furthermore, the relaxation from the vertically excited structure to the T_1 minimum with the twisted alkene bond releases 24.8 kcal/mol when the purely electronic energy is considered.

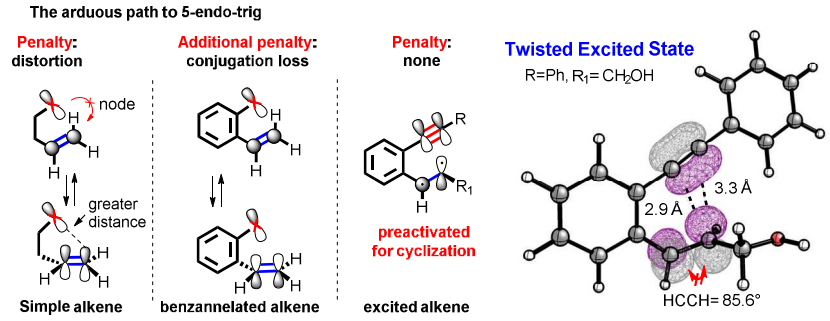
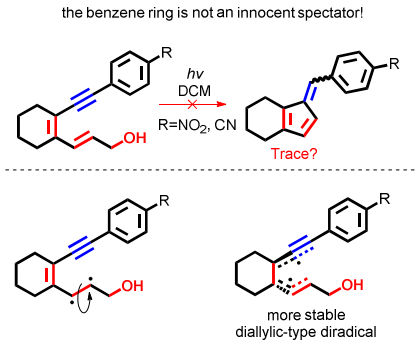


Figure 6. Left: The penalties inherent in 5-endo-trig cyclizations of simple and benzannelated alkenes. Right: The twisted conformation of the alkene activates the enyne toward 5-exo-dig/5-endo-trig cyclization in T_1. NBO orbitals for the twisted alkene diradical and the in plane π-bond of the alkyne are shown to illustrate the favorable alignment of reacting orbitals.

However, what is the role of the central benzene ring for the twisting of the alkene? To determine the importance of this structural unit for the outcome of the reaction we also studied the cyclization/fragmentation sequence with two non-benzannelated enynes shown in Scheme 1. It was clear that the efficiency of the reaction suffered. At best, only trace amounts of products were indicated by the NMR spectra of reaction mixtures. The isolation of any fulvene products was unsuccessful for both substrates. Photolysis in the presence of triplet sensitizers was equally inefficient.



Scheme 1. Photochemical cyclization of non-benzannelated enynes is inefficient.

Computational analysis of a non-benzannelated enyne showed that the lack of reactivity is likely due to a competition between twisting of the central and the terminal bond of the enyne (Scheme 1). Our calculations (for full details, see Supporting Information) show that the twisted alkene structure is 6.3 kcal/mol higher in energy than the one where the central C=C bond is twisted, while the TS for 5-exo dig cyclization is 12.6 kcal/mol higher. Due to the small singlet-triplet energy gap of 7.7 kcal/mol at the minimum geometry, it is possible that the triplet state is deactivated by intersystem crossing before it has time to cyclize. This interpretation is consistent with the observed lack of reactivity, as the calculations indicate that the non-benzannelated system would react in the same way as the benzannelated system once cyclization has occurred.

The role of triplet state antiaromaticity: So exactly why is benzannelation crucial for the cyclization reaction? The aromatic enynes in this study can be viewed as styrenes with a phenylacetylene substituent at the ortho position of the benzene ring, and since benzene rings are central structural motifs we probed if the photochemical properties of the benzannelated enynes can be rationalized with Baird's rule on triplet state aromaticity and antiaromaticity (*i.e.*, the reversal to Hückel's rule for (anti)aromaticity in the S_0 state).[19,21,42,43] One of us previously studied the effect of triplet state (anti)aromaticity on *Z*/*E*-photoisomerizations of annulenyl substituted olefins.[44] For styrenes it was found that twisting of the olefin double bond resulted in relief of T_1 state antiaromaticity and gain of some closed-shell Hückel aromaticity of the phenyl group, as evidenced by a series of aromaticity indices, changes in bond length alternation, and spin densities. However, the inclusion of radical accepting groups at the para position of a phenyl group allowed further delocalization of the triplet excitation and a relative stabilization of the planar geometry. Now, is the radical accepting phenylacetylene group sufficiently strong to suppress the triplet state antiaromaticity of the central benzene ring, or is the structure with a perpendicularly twisted olefin favored due to relief of T_1 state antiaromaticity? In the former case, we would not expect olefin twisting, and therefore no concomitant cyclization reaction. Consequently, the observed reactivity supports olefin twisting due to triplet state antiaromaticity relief of the benzene ring, similar as previously observed for styrene.[44]

Indeed, the interplay between the S_0 aromaticity and T_1 antiaromaticity of the central benzene ring is paramount in understanding the observed reactivity. The $NICS(1)_{zz}$ values[42] calculated at the B3LYP/6-311+G(d,p) level reveal that this benzene ring goes from

aromatic in S_0 to antiaromatic in the vertically excited T_1 state because the NICS(1)$_{zz}$ values calculated at the two sides of the benzene ring are -23.8 and -24.3 ppm in S_0 versus 29.2 and 29.4 ppm T_1 (Figure 7). The latter two NICS(1)$_{zz}$ values correspond to an antiaromatic character which is approximately half that of benzene in its T_1 state (67.3 ppm). When the olefinic C=C bond is twisted half the amount of regular closed-shell Hückel aromaticity of benzene in S_0 (-29.3 ppm) is retrieved as values of -14.8 and -15.0 ppm are calculated, similar to that of the parent benzyl radical (-18.8 ppm). Furthermore, ACID plots show that the vertical excitation leads to an antiaromatic character of the benzene ring of the enyne segment (Figure 7, where clockwise currents indicate aromaticity, counter-clockwise antiaromaticity), and this antiaromaticity is relieved by structural relaxation and twisting of the olefin bond, restoring also partial closed-shell Hückel aromaticity.

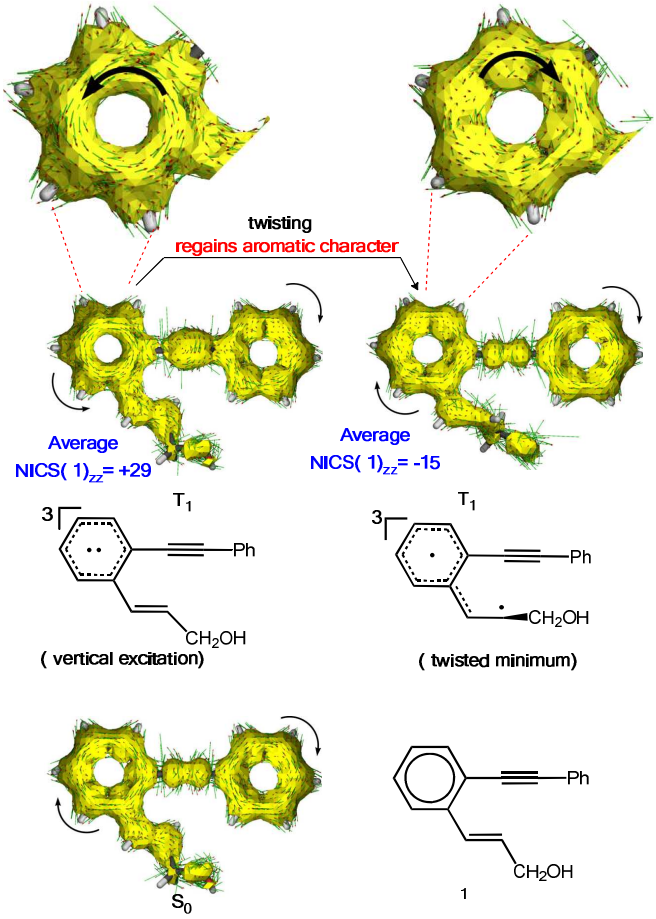


Figure 7. ACID plot of **1a** in the S_0 and T_1 states. Clockwise currents indicate aromaticity in both benzene rings in the S_0 state while counterclockwise currents indicate antiaromaticity in the left benzene ring in the T_1 state. Twisting of the alkene double bond in T_1 regains aromatic character, indicated by the weak clockwise current in the left benzene ring while the right ring has fully regained its aromaticity, as evidenced by the clockwise current.

Finally, the energy changes upon alkene twisting in the benzannelated and non-benzannelated enynes allows for a rough energy estimate for T_1 antiaromaticity relief and aromaticity gain. In the benzannelated case, going from a constrained planar structure to a twisted one releases 8.5 kcal/mol (in electronic energy), while the twisted diallylic form of the non-benzannelated compound is favored by 7.3 kcal/mol over the terminally twisted structure. This value is in line with the 4.4 kcal/mol in favor of the twisted diallylic form calculated for 1,3,5-hexatriene with B3LYP/6-31G(d).[45] Thus, an estimate of the effect of the central benzene ring on the twisting as compared to a central C=C double bond, which has no T_1 antiaromaticity to alleviate, is 15-16 kcal/mol.

Fragmentation and H-transfer in cyclic diradical intermediates. Having elucidated the cyclization step we went on to evaluate the mechanistic scenarios for the fragmentation/hydrogen atom abstraction sequence. For the T_1 state, we found that direct C-C bond scission, which forms a vinyl fulvene monoradical, is unfavorable with a calculated barrier of 31.7 kcal/mol. An intramolecular hydrogen abstraction from the pendant OH group to form a heterocentered triplet 1,4-diradical is a more favorable route (with a computed barrier of 17.4 kcal/mol) After intersystem crossing (ISC), this diradical can subsequently fragment via C-C bond scission and simultaneous C-O double bond formation in a self-terminating process, leading to the closed-shell fulvene and formaldehyde as products.

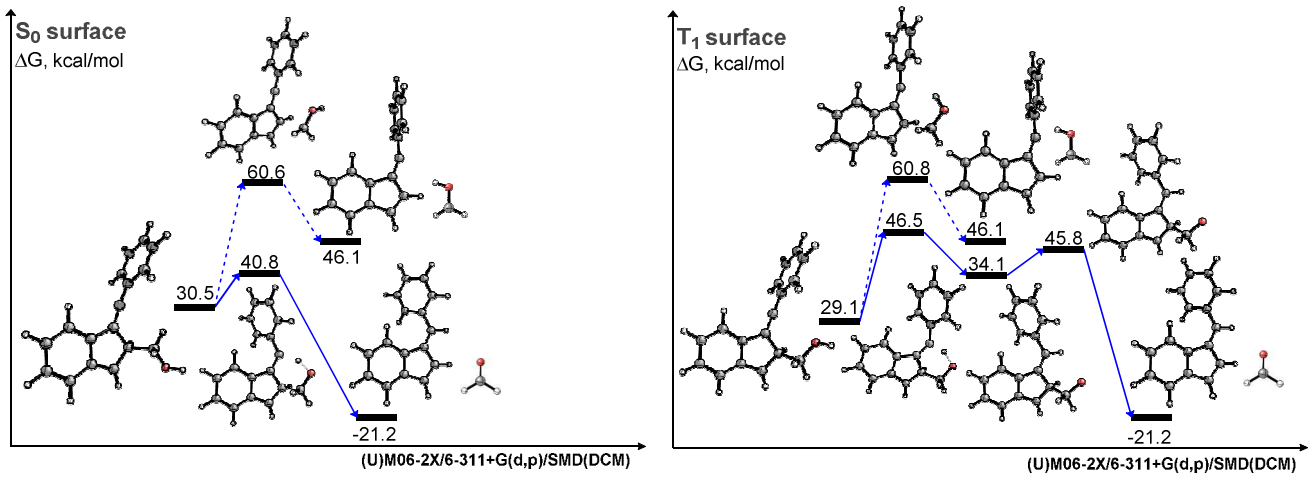


Figure 8. Singlet and triplet surface of the fragmentation step for fulvene formation explored computationally using (U)M06-2X/6-311+G(d,p)/SMD(DCM).

However, the singlet surface allows an even more facile concerted mechanism in which hydrogen atom abstraction is coupled with fragmentation (Figure 8, left). In this case, the initial 5-endo-trig singlet diradical directly fragments into the closed-shell fulvene product as well as formaldehyde in a *self-terminating* concerted process with a barrier of 10.3 kcal/mol. Since the two odd-electron centers are spatially separated and have different symmetry, coupling between them and the respective singlet/triplet separation are expected to be small.[46] The low energy gap of ~1 kcal/mol between the S_0 and T_1 states at the 5-endo-trig diradical geometry should allow facile interconversion between the states to assist this pathway. As shown in Figure 9, bond lengths in the TS are consistent with concerted H-transfer. The O-H bond is weakened (1.22 Å vs. 0.96 Å in the diradical intermediate) by the exocyclic radical as an incipient C-H bond forms, indicated by the relatively short distance of 1.39 Å between C_6 and H_5. This structural change is coupled with a weakening of the bond between C_2 and C_3 (1.65 Å vs. 1.53 Å) assisted by the endocyclic radical on C_1. The C_1-C_2 and C_3-O_4 internuclear distance is relatively short indicating that double bond formation and latent formaldehyde release is cooperatively assisted by the two radical centers.

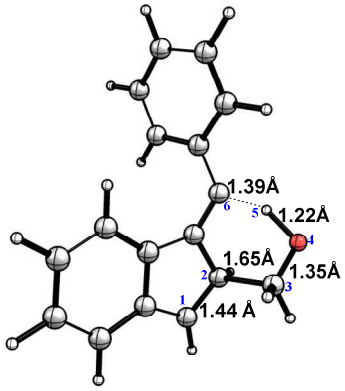
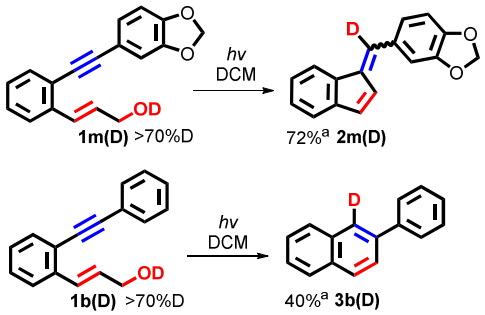


Figure 9. Selected interatomic distances (Å) for the transition state structure for the self-terminating HAA/C-C bond fragmentation.

In order to gain deeper insight into the nature of the fragmentation/H-abstraction steps, we performed photolysis of the deuterated substrates prepared via H/D exchange in the presence of D_2O (Scheme 2). Deuterium incorporation in fulvene and naphthalene products upon irradiation of deuterated enynes further supports the proposed mechanism and the self-terminating feature of this process.



Scheme 2. Deuterium incorporation in the observed products supports the proposed mechanisms. [a] Percentage of deuterium incorporation in the product.

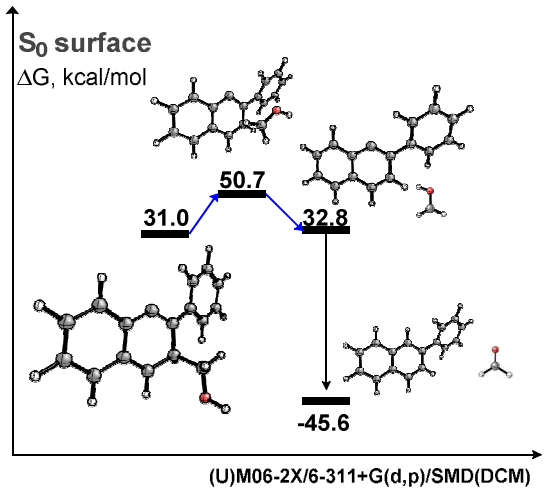
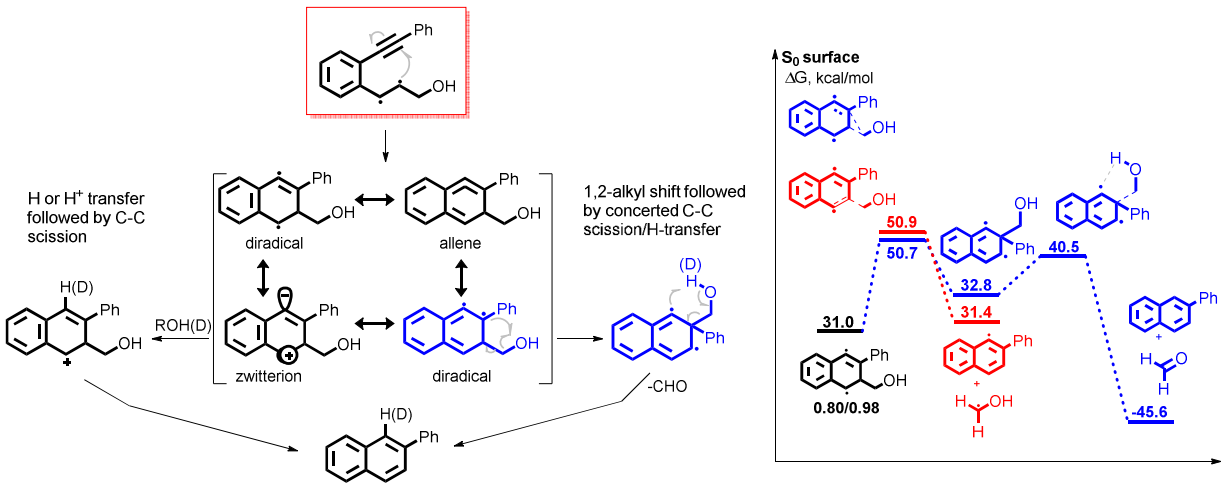


Figure 10. The singlet surface for the termination/fragmentation of C_1-C_6 diradical.

D-incorporation in the naphthalene is consistent with the earlier results of op den Brouw and Laarhoven[32b] (confirmer later by Sajimon and Lewis[32c]) who suggested a zwitterionic nature of cyclized products based on the D-transfer from O-deuterated alcohols. Recent computational work of Schreiner and Hopf, found that the cyclic products derived from benzannelated enynes have diradical (rather than strained allene) character[15] whereas we have previously illustrated the generality of diradical/zwitterion dichotomy in related species.[2,3] It is unclear, at this point why deuterium incorporation is incomplete. We plan to investigate this process in additional detail in the future work.

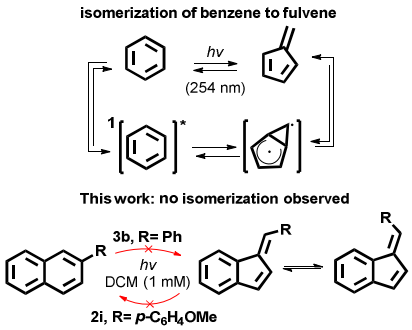


Scheme 3. Left: The alternative allene/diradical/zwitterion mechanism. Right: two possible mechanisms for intramolecular H-transfer. The blue pathway corresponds to the self-terminating enyne/naphthalene transformation where the radical centers are translocated via 1,2-shift of the CH_2OH group.

Our preliminary computational data suggest that a more detailed analysis of the final steps of this cascade transformation is warranted (Figure 10). For example, we have an additional possibility for intramolecular H-atom transfer that involves a new intramolecular rearrangement illustrated in Scheme 3, right. In this process, the 1,2-shift of CH_2OH group relocates the latter towards a radical center and sets up a concerted fragmentation and H-abstraction sequence that would lead to intramolecular H(D) transfer to the naphthyl α-carbon. The calculated activation barriers for the 1,2-shift and direct fragmentations are almost identical at the M06-2X/6-311+G(d,p) level of theory.

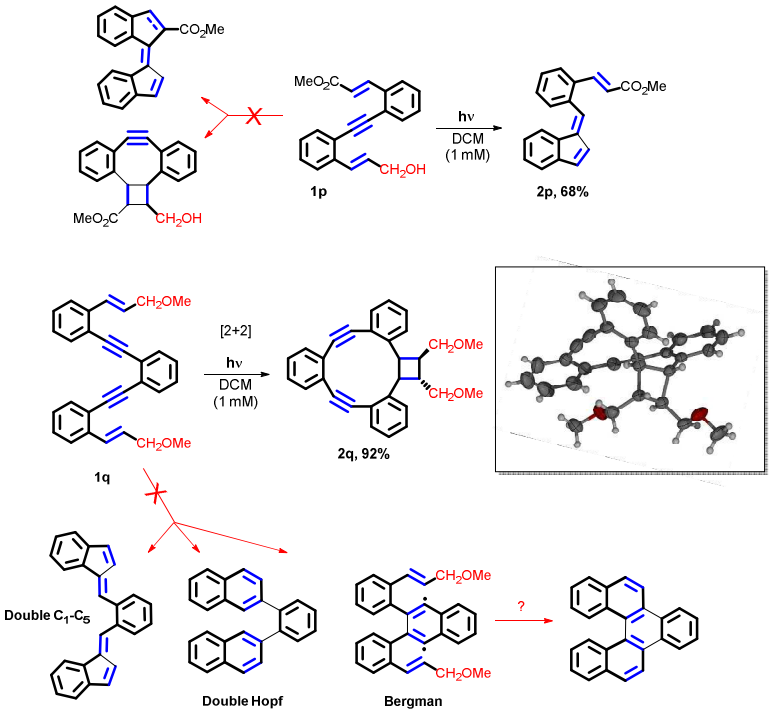
Isomerization. Under the reaction conditions, isomerization of the benzofulvene products took place. Continued photolysis led to photostationary states with varying E/Z ratios for different substrates. The structure of the E-benzofulvene stereoisomer (for compound **2h** and **2m**) was confirmed by X-ray crystal structures (See SI). Computations showed that the more stable ground state E fulvene isomer is 1.9 kcal/mol lower in energy than the initially formed Z isomer, although the exact photostationary state composition cannot be predicted from these computations.

Naphthalene Formation. It is known that fulvene is a primary valence isomerization product, obtained from the photolysis of benzene in a three-step process via prefulvene and 1,3-cyclopentadienylcarbene intermediates (Scheme 4, top).[47] The thermal automerization of naphthalene has been suggested in the literature[48] to occur by reversible formation of benzofulvene either via carbene intermediates or direct dyotropic rearrangements. We found that irradiation of substituted naphthalene **3b** in 1 mM DCM did not promote isomerization as only the starting naphthalene was recovered and no trace of benzofulvene was observed. The reverse process in which fulvene **2i** was irradiated solely resulted in the isomerization of the fulvene double bond without formation of naphthalene.



Scheme 4. Naphthalene derivatives **3** and benzofulvene derivatives **2** do not interconvert.

Competition with the photochemical Bergman reaction: Irradiation of an extended diene **1p** led to clean formation of a monofulvene **2p**.To further probe the scope and limitations of the present reaction, we also investigated the possibility by combining two enyne moieties in one molecule, **1q**. Two interesting mechanistic scenarios were possible: photochemical Bergman cyclization of the enediyne moiety[49] followed by attack at the pendant alkene or C_1-C_5 cyclization of enynes followed by attack at the pendant alkyne. However, extending the conjugation led to a change in photochemical reactivity and the formation of a 12-membered enediyne product via [2+2] cycloaddition as shown in Scheme 5. Although this finding suggest that the limitations for the cycloaromatization based photochemical pathways exist in the presence of more favorable transformations, it also illustrates the potential of enyne photochemistry for the preparation of strained alkynes, an interesting class of compounds now exploited in many fields of science.[50] We plan to investigate the reasons for this switch in reactivity and the scope of limitation of this approach to strained alkynes in future work.



Scheme 5. [2+2] addition of extended enyne/enediyne system results in an interesting 12-membered cyclic enediyne.

CONCLUSIONS

In conclusion, the present work describes the triplet excited state cyclization/fragmentation of benzannelated enynes into substituted benzofulvenes. The formation of the final fulvene product is remarkable for several reasons. Not only does it *formally* correspond to a stereoelectronically unfavorable 5-endo-trig cyclization mode, it does so in an overall ideal self-terminating process,[51] which circumvents the energetically unfavorable intramolecular H-shifts necessary to afford the product. Incorporating C-C bond cleavage into the photochemical self-terminating cyclizations of enynes allows the use of alkenes as alkyne equivalents without the need for external oxidizing agents.[18] Furthermore, this work provides, to the best of our knowledge, the only efficient examples of the C_1C_5 counterpart of the Hopf cyclization in its photochemical incarnation, one of the four basic archetypical diyne and enyne cyclizations and illustrates the potential of excited state antiaromaticity alleviation to initiate and control photochemical reactions.

ASSOCIATED CONTENT

Supporting Information

Full experimental details, ^{1}H NMR, ^{13}C NMR spectra for all of the prepared compounds, X-ray crystallographic data for selected products, and computational details for all calculated structures are provided in the SI. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interests.

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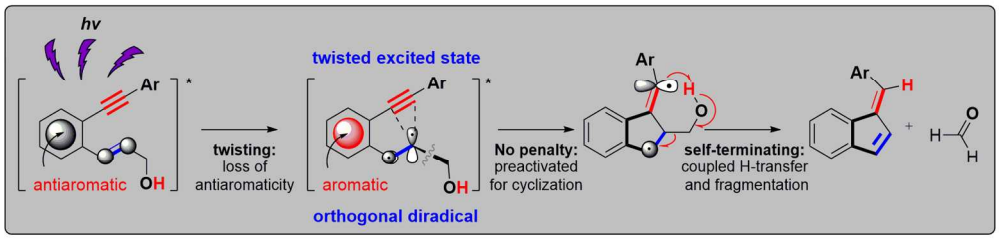

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