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Domino Fragmentations in Traceless Directing Groups of Radical Cascades: Evidence for the Formation of Alkoxy Radicals via C−O Scission

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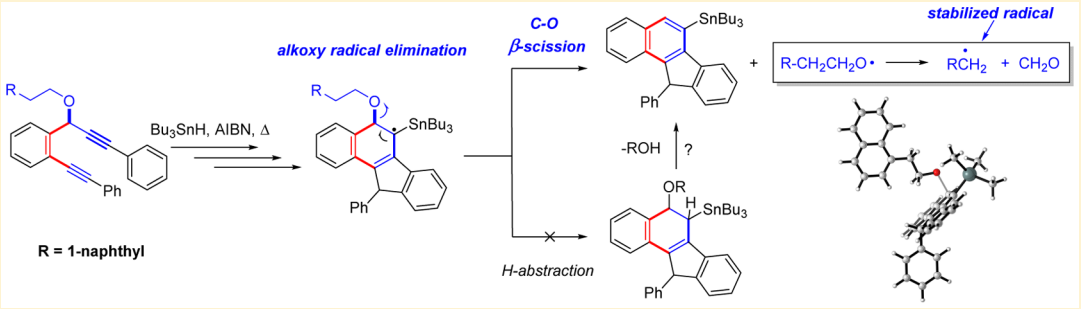
Supporting Information



ABSTRACT: Direct evidence for the formation of alkoxy radicals is reported in radical cascades using traceless directing groups. Despite the possibility of hydrogen abstraction in the fragmenting step, followed by loss of R-OH, *β-scission* is preferred for the formation of alkoxy radicals. For the first time, the C-O radical was intermolecularly trapped using a silyl enol ether. Various C−X fragmenting groups were explored as possible traceless directing groups for the preparation of extended polyaromatics. Computational evidence shows that a combination of aromatization, steric and stereoelectronic effects assists the fragmentation to alkoxy radicals. Additionally, a new through-space interaction was discovered between O and Sn in the fragmentation as a specific transition state stabilizing effect.

INTRODUCTION

Reaction cascades that combine cyclizations with fragmentations offer unique advantages for the synthesis of precisely functionalized cyclic compounds.[1] In particular, the final fragmentation step can adjust the oxidation state, eliminate a directing group, and/or provide an entropic driving force that renders the overall cascade irreversible. Consequently, fragmentations play an important role in the arsenal of fundamental chemical steps available to a synthetic chemist.

In our recent work, we disclosed the conversion of skipped oligoalkynes into functionalized polyaromatic ribbons assisted by the traceless OR directing groups[1b] (Scheme 1). The key mechanistic feature of this cascade is the "boomerang" transposition of the radical center through the sequence of bond forming steps. In the first step, the presence of the directing OR group ensures chemo- and regioselective attack of the Sn-radical on the multifunctional substrate and formation of reactive vinyl radical. This radical has σ-symmetry where the radical center is orthogonal to the π-system. As a result, it is not delocalized and highly reactive. The sequence of subsequent cyclizations involves fast and selective *exo*-dig ring closures, each of which produces an analogous vinyl radical that reacts at the next appropriately positioned alkyne moiety. However, once the last alkyne has reacted, the final cyclization has to target a different functionality: the terminal aryl group.

This step produces a delocalized π-radical with significant radical density that "comes back" to the locus of the initial attack, the carbon atom adjacent to the directing OR group. Our mechanistic hypothesis was that radical density at this carbon would facilitate OR fragmentation (radical β-scission) with the assistance from the bulky SnR_3 moiety that pushes the breaking C−O bond closer to the optimal alignment with the radical center. The resulting departure of the directing OR group makes this structural element traceless in the overall cascade and provides a reactive O-centered radical for the propagation of the cascade.

Utilization of an alkoxy radical as a leaving group on carbon is unusual. These species are generally produced from cleavage of much weaker O−N, O−O, or O−I bonds (Scheme 2).[2]

Perhaps, one of the reasons why homolytic C−O scission is not commonly used in organic radical chemistry is the relatively high typical C−O bond dissociation energy,[3] leading to the expectation of the OR moiety to be a poor leaving group in a radical process. Considering the scarcity of homolytic C−O fragmentations, an alternative mechanistic hypothesis seems plausible. In this scenario, the C-centered radical is quenched via intermolecular H-abstraction to give an intermediate which is converted into the final aromatic product via the loss of

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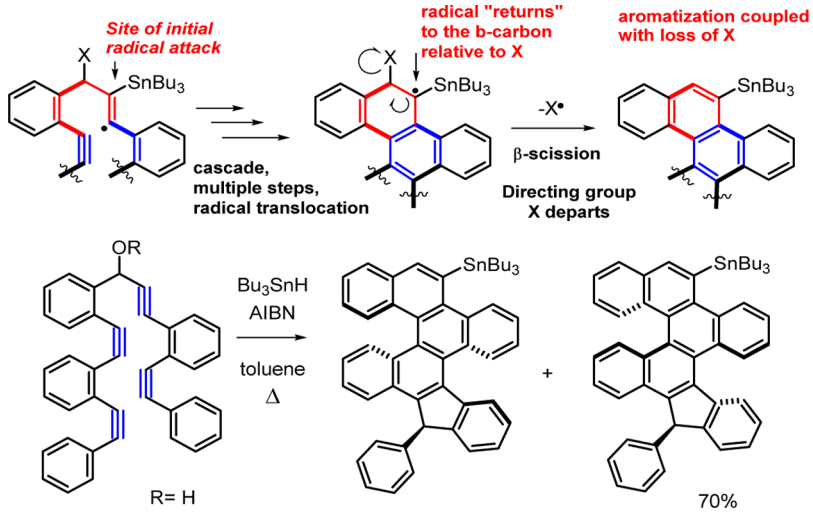
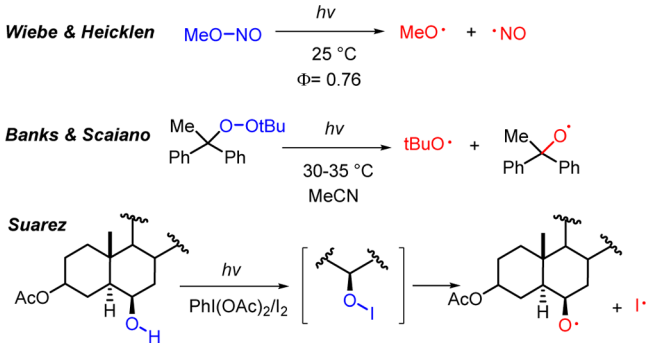
Scheme 1. Directing Groups X Are "Traceless" If Cyclization Cascade Is Terminated by C−X Fragmentation

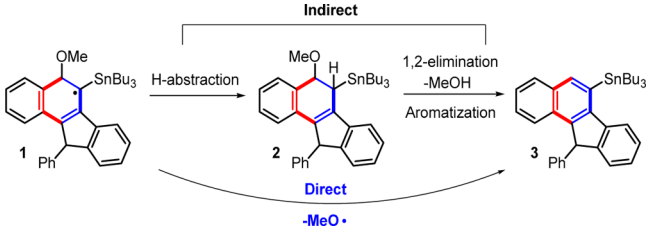


Scheme 2. Representative Examples of Alkoxy Radical Fragmentation from Weak O−N, O−O, O−I Bonds



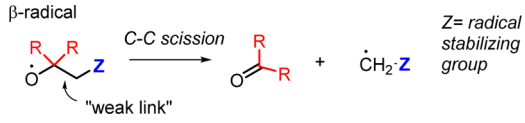
methanol (Scheme 3). The last step occurs after the radical cascade is terminated.

Scheme 3. Alternative Aromatization Routes: The Indirect Route through Intermolecular H-Abstraction and MeOH Elimination (Top) and Direct Radical C−O Scission (Bottom)



In order to resolve this mechanistic ambiguity and to test whether the C−O radical fragmentation can be confidently added to the arsenal of tools for synthetic radical chemistry, we have attempted to trap O-centered radicals with appropriate reagents. Furthermore, we have designed OR leaving groups with a "weak link", a bond that can undergo scission in the presence of a β-radical. In our design described in Scheme 4, the driving force for this scission would come from the combination of thermodynamic stability of the carbonyl group and electronic effects in the translocated radical.

Scheme 4. Formation of Stabilized Radical and Formaldehyde through a Weak Link Design



We have recently used a similar sequence for driving an otherwise thermodynamically unfavorable process to completion.[4] In the present work, we illustrate the utility of such fragmentations as a mechanistic tool.

COMPUTATIONAL METHODS

Potential energy profiles for this cascade transformation were evaluated with Gaussian 09 using the (U)M06-2X functional,[5] capable of providing a relatively accurate description of reaction and activation energies for a variety of chemical processes including radical reactions.[6] The LanL2DZ basis set was used for Sn-substituted molecules. Molecules and orbitals were rendered with Chemcraft 1.7[7a] and CYLView.[7b] Frequencies were calculated to confirm each stationary point as either a minimum or a first-order saddle point. The electronic structures of reactive intermediates were analyzed with NBO 3.0.[8] The ΔG values for all reactions were calculated at 110 °C. A truncated version of the attacking radical ($SnMe_3$) was used instead of $SnBu_3$.

RESULTS AND DISCUSSION

In our first attempt to trap the putatively formed methoxy radicals, we relied on the earlier findings of Sammis and coworkers,[9] who reported the increased *intra*molecular reactivity of O-radicals toward vinyl silyl ethers. We extended the use of this electron-rich π-functionality for an *inter*molecular trapping using the vinyl silyl ether **8**. This substrate was prepared by deprotonation of aldehyde **S9**, followed by quenching of the resulting enolate with *tert*-butyldimethylsilyl triflate (TBSOTf). Interestingly, the E:Z ratio (15:85) in the product showed cis preference for the bulky TBS group (Scheme 5A). Computational analysis into this selectivity uncovered H-bonding between the oxygen and the ortho Ar hydrogen in the product (Scheme 5B). It is possible that similar H-bonding interaction can lead to stabilization of the *Z*-enolate derived from **S9**.

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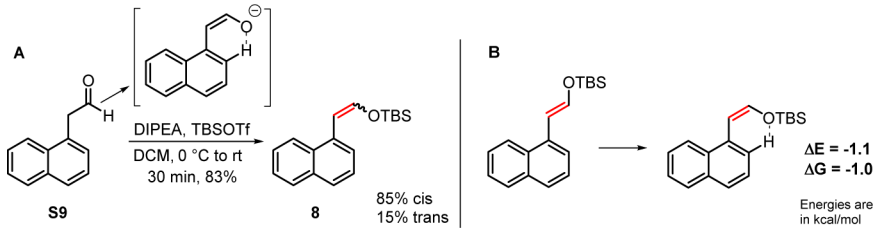
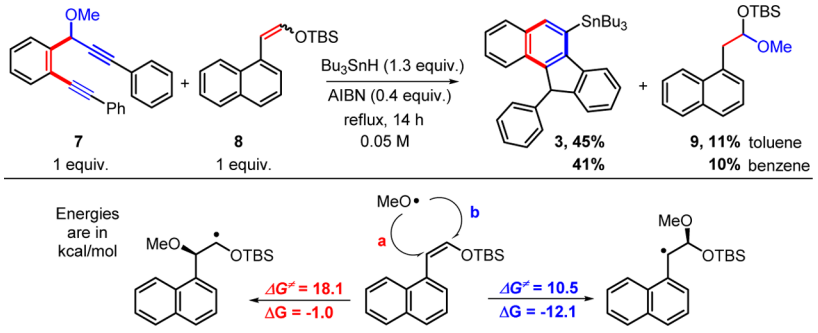
Scheme 5. (A) Synthesis of Silyl Enol Ether. (B) Computed Cis Preference for Silyl Enol Ether



Scheme 6. Top: Alkoxy Radical Trapping Using a Vinyl Silyl Ether.[11] Bottom: Regioselective Preference for Alkoxy Radical Attack[a]



[a]Calculated Gibbs free energies at 110 °C in kcal/mol.

Because of the instability of the trapped product toward hydrolysis, we found it more convenient to convert it to a previously synthesized[10] aldehyde **S9** with TBAF prior to the analysis.

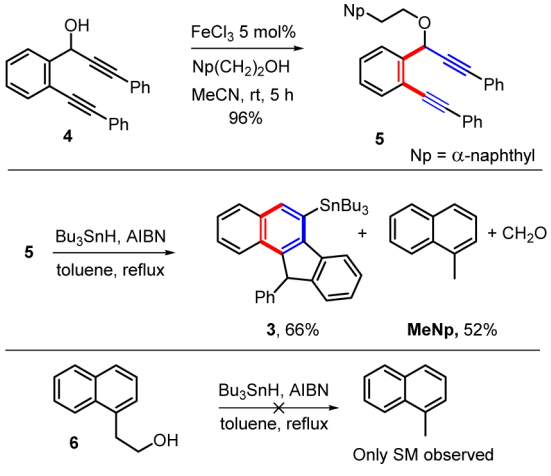
The alkoxy radical trapping experiment was performed using **7** and **8** in a 1:1 ratio under radical forming conditions in refluxing toluene. Although the trapping experiment was successful, the mixed TBS-methyl acetal product **9** was produced in low yield. The regioselectivity of this *inter*molecular radical addition to the *Z*-alkene is different from that reported for the *intra*molecular version of this process,[9] but fully consistent with the computational predictions of 7 kcal/mol difference in the two addition barriers (Scheme 6, bottom). The regioselective preference for the radical addition is also consistent with the gain of benzylic and anomeric stabilization for the radical that leads to the observed product which is 11.1 kcal/mol more stable than its regioisomer.

The ratio of two products **3** and **9** suggests that only 1/4th of the formed OMe radical finds the vinyl silyl ether before deactivation. Because such deactivation can occur through hydrogen abstraction and/or β-scission to formaldehyde, we tested if H-abstraction from toluene is the main reason for the low yield by repeating the trapping experiment in benzene. The C−H BDE of benzene is ∼113 kcal/mol, which is 23 kcal/mol greater than the C−H BDE of toluene. The experiment again was successful, but the relative ratio of products remained the same.

Although this experiment provided strong evidence for the alkoxy radical formation, the yields of the trapped products were rather low. In the following section, we describe how we solved this problem by designing a new mechanistic tool for unambiguous detection of O-centered radical formation. This design couples the initial radical C−O scission with another fast fragmentation through a weak link shown in Scheme 7.[12]

The tethered naphthyl group was attached to a skipped enediynol **4** through $FeCl_3$-promoted nucleophilic substitution[13] to give the cyclization/fragmentation precursor **5** in 96% yield (Scheme 7, top). We found this method to be more convenient than the earlier used base-assisted reaction of the alcohol with MeI.[1b] With substrate **5** in hand, the radical cyclization was performed with Bu_3SnH and AIBN in refluxing toluene. The radical cascade gave stannyl-11-phenyl-11*H*-benzo[*a*]fluorene (**3**) in 66% yield along with 52% of 1-methylnaphthalene (Scheme 7, middle).[14] Support for the formation of an alkoxy radical from this reaction is two-fold: (1) Evidence for the β-scission comes from the presence of 1-methylnaphthalene and aldehyde peaks in the ^{1}H NMR spectrum of the reaction mixture (see the SI). The appearance of a peak at δ 9.79 ppm[15] is consistent with the presence of

Scheme 7. Top: $FeCl_3$-Catalyzed Substitution To Generate the Fragmentation Precursor 5. Middle: Radical Cyclization and Domino Fragmentation of 5. Bottom: Control Experiment with 2-Naphthylethanol under Radical Forming Conditions



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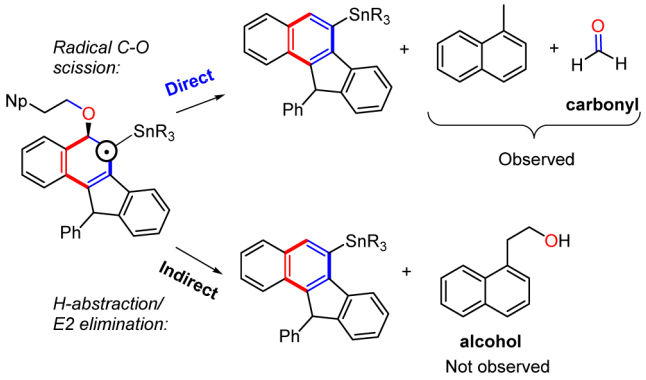
formaldehyde. (2) Evidence against the indirect pathway comes from the absence of 2-naphthylethanol.

To make sure that 2-naphthylethanol **6** was not present under the reaction conditions, we have also performed the control experiment to eliminate the unlikely scenario formation of an O-centered radical based on the abstraction of a hydrogen atom from the alcohol by the $SnBu_3$ radical (Scheme 7, bottom). One could expect such a process to be thermodynamically uphill based on the differences in the BDEs of O−H and Sn−H bonds (>100[3,16] and 78[17] kcal/mol, respectively). Indeed, exposure of 2-naphthylethanol to the combination of Bu_3SnH and AIBN in refluxing toluene did not lead to the formation of the fragmented 1-methylnaphthalene product. Stability of **6** under the cascade conditions confirms that **6** was not formed transiently to react further. In summary, this result clearly shows that H-abstraction/E2 elimination does not operate because it would give different products (Scheme 8).

Scheme 8. Direct Pathway Makes 1-Methylnaphthalene and Formaldehyde, Whereas Indirect Pathway Makes Only the Alcohol



In the next step, we have evaluated the potential energy profile for the observed double fragmentation cascade computationally (Scheme 9). The calculated barrier for the 1st (C−O) fragmentation is 2.4 kcal/mol lower than the barrier for the 2nd (C−C) fragmentation, but both fragmentations are calculated to be sufficiently fast at the reaction conditions. The overall thermodynamic driving force for the domino process is −3.1 kcal/mol with each of the fragmentation steps exergonic by ∼1.5 kcal/mol.

We have compared the rates of the intermolecular (addition) and intramolecular (fragmentation) approaches for trapping of alkoxy radical that we have described earlier by performing a radical cyclization/fragmentation cascade of naphthyl-substituted enyne **5** in the presence of the silyl enol ether **8** (Scheme 10). Only the fragmentation products were observed in yields similar to experiments in the absence of the intramolecular trap **8**. These results demonstrate that fragmentation is so fast that it occurs before the alkoxy radical could be trapped intermolecularly.

Note that both fragmentation steps were designed to be weakly exergonic to render the fragmentation thermodynamically feasible but without imposing a large additional preference that could promote the radical pathway. The computed barrier for the OCH_2CH_2Np fragmentation is ∼4 kcal/mol *higher* than the calculated barrier for OMe fragmentation (*vide infra*). These data indicate that the C−C scission is not coupled to (and does not assist in) the initial C−O bond rupture.

A priori, one can suggest two factors contributing to the favorable fragmentation *kinetics* for the usually strong C−O bond: (a) the stereoelectronic assistance via the favorable alignment of the breaking bond with the adjacent radical center and (b) the thermodynamic assistance via developing aromaticity.

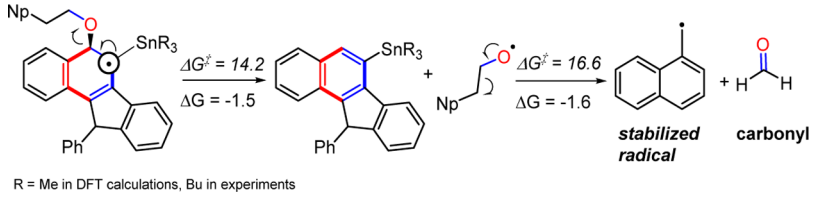
The former feature arises from an interplay of sterics and stereoelectronics. One can expect that, due to its bulkiness, the SnR_3 group can force the OR group closer to the nearly perpendicular geometry of the fragmentation TS. This steric component can enhance stereoelectronic interaction of the breaking C−O bond with the radical center that ultimately leads to the departure of the OR radical[18] by increasing population of the σ^*_{C-O} orbital in the TS and assisting aromatization.

It is interesting to compare the magnitude of this radical assistance to C−O scission with the magnitude of hyperconjugation associated with the classic anomeric effect, i.e., the other system where the C−O bond is weakened by the interaction of a p-donor and a vicinal σ^*_{C-O} acceptor.[19] NBO analysis indicates that the magnitudes of these two effects are remarkably similar: 14.6 kcal/mol of stabilization due to $n_O \rightarrow \sigma^*_{C-O}$ interaction[20] vs 16.7 kcal/mol for the $p_C \rightarrow \sigma^*_{C-O}$ interaction (Figure 1).

Furthermore, NBO analysis of the intermediate indicates the presence of symmetry enhanced interaction between the cyclic π-system and the C−O bond that has the key features of hyperaromaticity (Figure 2B). Such symmetry effects on the efficiency of radical hyperconjugation are known as the Whiffen effect (Figure 2A).[21] The β-scission step was evaluated using NICS(1) values[22] shown in Figure 2C. The NICS values suggest that hyperaromaticity is rather small in the reactant but gets progressively large in the TS before evolving in the fully developed product aromaticity.

In order to explore the possible role of steric assistance in the fragmentation step, we have varied the size of substituents at the propargylic position and tested the reactivity of ethoxy, isopropoxy, and *tert*-butoxy analogues of substrate **5** (Scheme 11, entries **10**−**12**). Whereas the yields of the polycyclic target **3** from the ethoxy, methoxy,[23] and isopropoxy precursors were

Scheme 9. Formation of Formaldehyde through Fragmentation of O-Centered Radical and Benzylic Radical[a]



[a]Calculated Gibbs free energies at 110 °C in kcal/mol.

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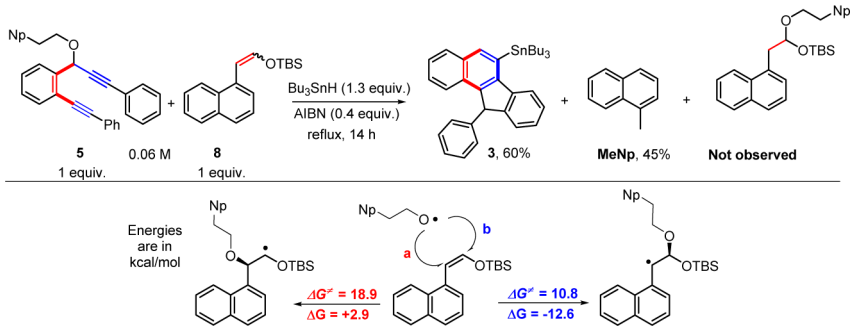
Scheme 10. Fragmentation of an Alkoxy Radical Is Faster Than Attack of an Alkene[a]



[a]Calculated Gibbs free energies at 110 °C in kcal/mol.

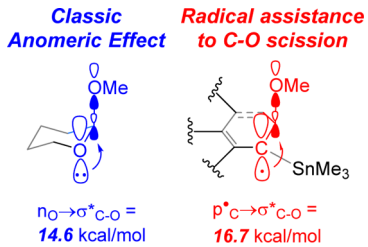


Figure 1. Comparison of anomeric effect vs the β-radical C−O scission using NBO analysis.

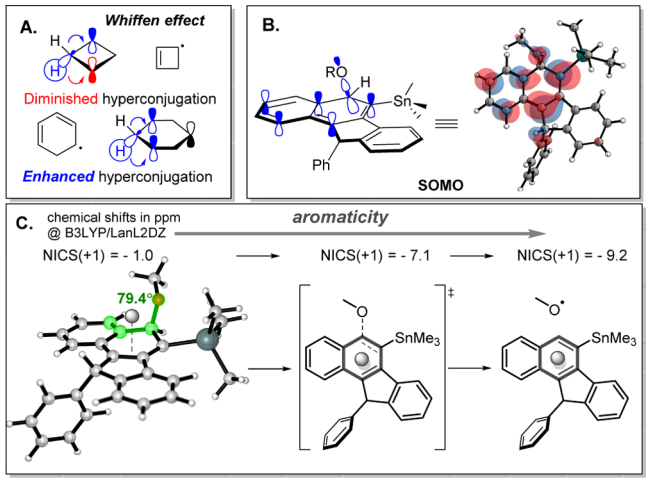


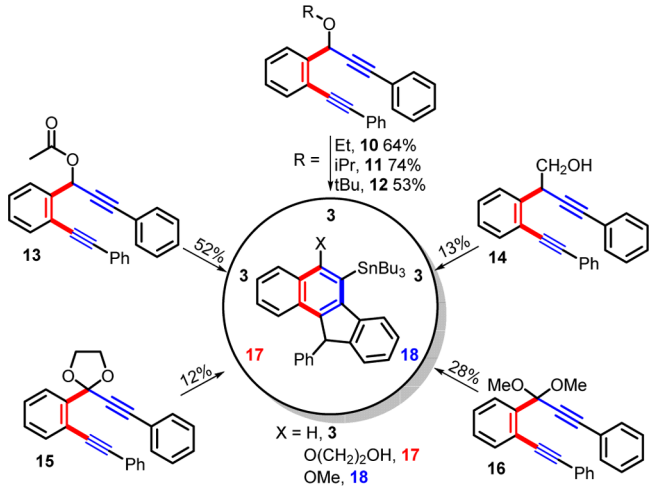
Figure 2. (A) Symmetry can enhance or diminish conjugative effect. (B) Symmetry-enhanced π/C−O hyperconjugation. (C) NICS evaluation of aromaticity in the β-scission process.

similar (64−74%), reaction yield drops slightly (53%) for the *t*-Bu substrate **12**. One has to note, however, that the yield cannot provide direct information about the fragmentation, which is unlikely to be the rate-determining step here.[24]

We have also explored additional variations in the nature of the traceless directing group. The radical reaction of propargylic acetate **13** gave 52% yield of **3**, suggesting that this cascade can be used as a new route to the formation of acyloxy radicals. Acyloxy radicals are useful in radical chemistry,[25] but their preparation via C−O bond scission is generally difficult (BDE of the C−O bond is ∼70 kcal/mol).[16]

In addition, we have investigated the possibility to employ C−C β-scission[26] for terminating this radical cascade. Indeed, the reaction of alcohol **14** led to the formation of **3**, albeit in low yield (13%). The observed loss of the CH_2OR moiety

Scheme 11. Scope of X-Directing/Fragmenting Groups



offers strong evidence for the radical cascade termination - E2 elimination via the C−C bond scission is highly unlikely. The low yield is consistent with the calculated barrier for radical fragmentation (∼21 kcal/mol) which seems to be the upper limit for this fragmentation process in refluxing toluene.

Finally, we also used acetals **15** and **16** to test whether it is possible to have additional functionality in the polyaromatic product. Unfortunately, the O-functionalized polyaromatics (**17** and **18**) were produced in low yield (12% and 28%, respectively) because this substitution pattern accelerated the competing direct thermal cycloaromatization to the products **19** and **20** (55% and 60%), respectively (Table 1).[27] This observation is consistent with the earlier reports of thermal intramolecular dehydro Diels−Alder reactions for activated skipped enediynes by Dominguez and Saa.[28]

The calculated barriers and reaction energies for selected C−X scissions are shown in Figure 3. The calculated trends reflect the competition between several factors such as intrinsic stability of the departing radical and its interaction with the vicinal R_3Sn moiety. If one concentrates on the enthalpy by removing the entropy term, every single fragmentation reaction is endothermic (Figure 3B). Entropy plays a major role in the C−X scission by increasing the exergonicity of the reaction and lowering the activation barrier in most of the cases. For the analyses of the fragmentations, we will discuss these reactions in terms of their free energies (Figure 3A).

Computations find the fragmentation of acetals **15** and **16** to be endergonic because it leads to the loss of stabilizing

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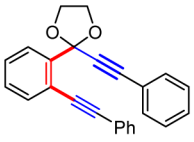
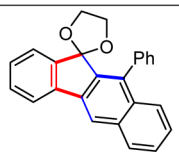
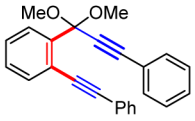
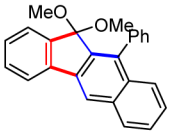
Table 1. Thermal Cycloaromatization Side Products under Bu_3SnH/AIBN/Toluene/Reflux Conditions

Entries	Products
 15	 19, 55%
 16	 20, 60%

anomeric effect present in these reactants.[20] This unfavorable effect is reflected by the 6−10 kcal/mol increase in the activation barriers in comparison to the −OMe substrate. For the cyclic acetal, the counterproductive effect of the loss of anomeric reactant stabilization augments the decrease in the entropic gain.

β-Scission of C−C bonds in the radical derived from substrate **14** shows relatively high $\Delta G^{\ddagger}$ despite the *2c,3e* stabilizing assistance in the fragmented radical.[1a] Fragmentations of alkoxy radicals have significantly lower barriers. It is tempting to associate this observation with the relative efficiencies of $p_C \rightarrow \sigma^*_{C-O}$ and $p_C \rightarrow \sigma^*_{C-C}$ hyperconjugation in the TS. X = OMe shows the best combination of exergonicity with a low activation barrier. The relative instability of the OH radical renders its formation 12.4 kcal/mol endergonic. On the other hand, the exergonicity decreases for OEt and increases afterward as expected from steric decompression in the fragmentation step. However, barriers for the OEt, O*i*Pr, and O*t*Bu fragmentations reveal an unexpected trend—the barrier increases for OEt, slightly decreases for O*i*Pr, and then increases again for O*t*Bu. This trend is a violation of the generally observed correlation between kinetics and thermodynamics for a family of similar reactions.[29] Although the loss of the *t*-BuO radical is the *most* exothermic of the four processes, it proceeds through the activation barrier that is *higher* than that for the loss of OMe and O*i*Pr radicals.

Analysis of the fragmentation TS geometries gives a glimpse into the origin of this anomalous behavior (Figure 4). Only for

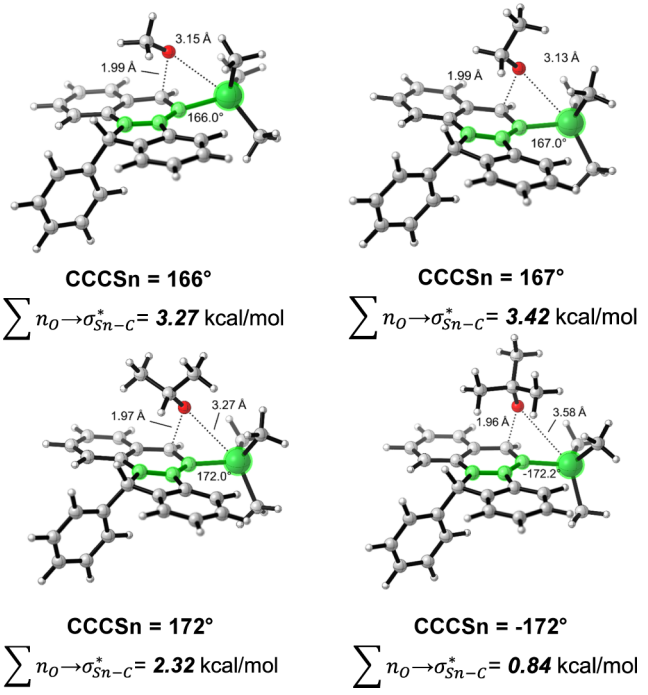


Figure 4. Geometries of the alkoxy radical elimination TSs support the importance of O···Sn interactions.

the *t*BuO substituent, the two "bulky" groups (OR and $SnMe_3$) are pushed to the opposite directions. In the MeO, EtO, and *i*PrO fragmentation transition states, the $SnMe_3$ group is tilted *toward* the OR group, indicating the presence of an attractive O···Sn interaction in these systems. This interaction provides a previously unidentified stabilizing force that assists the OR radical formation. NBO analyses are consistent with the presence of such *through-space* interactions, as it decreases as the bulkiness of the R group increases, pushing the Sn group away.

Comparison of the TS and reactant geometries (Figure 5) suggests that this interaction is specific to the TS. The reactant geometries for both O*i*Pr and O*t*Bu radicals is dominated by

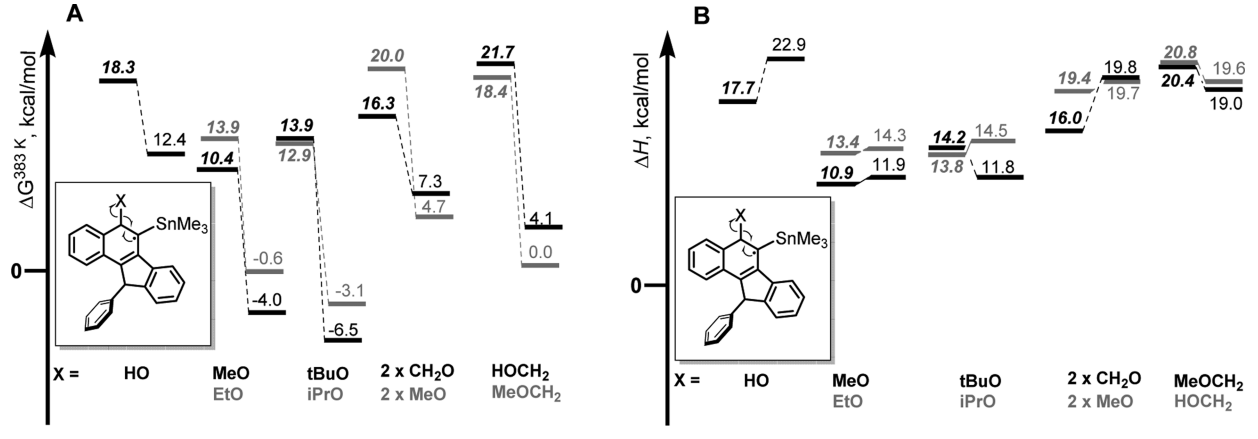


Figure 3. (A) Calculated $\Delta G^{\ddagger}$ and ΔG of C−X scission. (B) Calculated $\Delta H^{\ddagger}$ and ΔH of C−X scission.

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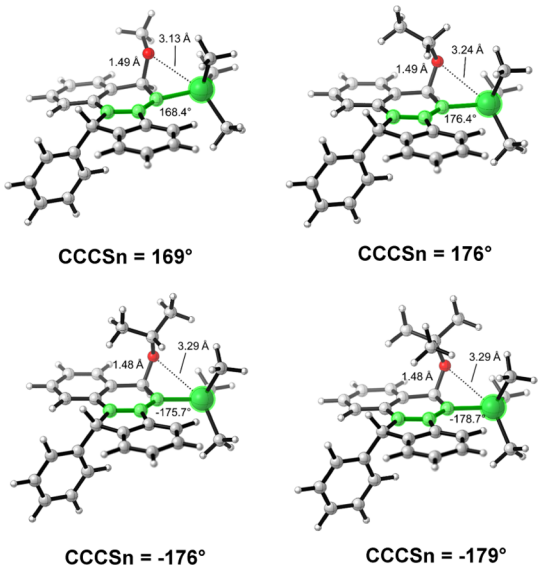

Figure 5. Geometries of the alkoxy radical elimination SMs.

sterics (the CCCSn dihedral is negative). The geometries of OMe and OEt substrates reveal positive CCCSn dihedrals, but the deviations from planarity are much smaller than they are in the TS.

In summary, this work provides clear evidence for the formation of O-centered radicals via C−O fragmentation and offers the first glimpses in the interplay of steric and stereoelectronic effects in this process. It also identified the new O···Sn through-space interaction that selectively stabilizes transition states for the fragmentation of OR bonds adjacent to a stannyl moiety. We plan to further explore the generality of such new supramolecular forces in future work.

EXPERIMENTAL SECTION

Toluene (anhydrous), 2-bromobenzaldehyde, 2-(naphthalen-1-yl)-ethanol, *tert*-butyl alcohol, ethanol (anhydrous), tributyltin hydride, and AIBN were purchased and used for experiments with no additional purification. THF or tetrahydrofuran (no stabilizer, chromatography grade) and acetonitrile (super gradient for HPLC) were used on a Glass Contour SPS-4 Solvent Purification System. Ethyl acetate and hexanes (ACS reagent grade) were purchased and used for column chromatography. DCM or dichloromethane and diisopropylethylamine were distilled over CaH_2 before use. Column chromatography was performed using silica gel Kieselgel 60 (70−230 mesh) or Kieselgel 60 (230−400 mesh), and preparatory thin layer chromatography was performed using a 1000 μm glass backed plate containing UV dye. Melting points were obtained using a melting point apparatus. Infrared spectra (IR) were obtained using a Michelson-type IR instrument; absorptions are reported in reciprocal centimeters. An AccuTOF mass spectrometer analyzer was used. ^{1}H NMRs were run on 400 and 600 MHz spectrometers in $CDCl_3$, and all ^{13}C NMRs were run on 100 and 150 MHz spectrometers in $CDCl_3$. Proton chemical shifts are given relative to the residual proton signal of $CDCl_3$ (7.26 ppm). Carbon chemical shifts were internally referenced to the $CDCl_3$ (77.00 ppm) signal. All *J*-coupling values are reported in hertz (Hz). δ is in ppm. The following abbreviations were used for multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublet, dt = doublet of triplet, dq = doublet of quartet, m = multiplet, quin = quintuplet, sext = sextet, sep = septet, sepd = septet of doublets, br = broad.

Procedure for Synthesis of Compound (4). *Synthesis of 2-(Phenylethynyl)benzaldehyde (**S1**).* To a flame-dried round-bottom flask purged with argon were added 2-bromobenzaldehyde (0.216 g, 1.17 mmol), $Pd(PhCN)_2Cl_2$ (0.022 g, 0.0583 mmol), and CuI (0.011g, 0.0583 mmol) in 15 mL of triethylamine; then P(*t*-Bu)$_3$ (1 M in toluene) (1.2 mL, 0.117 mmol) was added. The solution was outgassed with argon for 30 min, followed by dropwise addition of neat phenylacetylene (0.15 mL, 1.40 mmol). The reaction was stirred overnight and was worked up by washing with saturated NH_4Cl solution (20 mL), extracted with EtOAc twice (2 × 15 mL), and dried with Na_2SO_4, and solvents were removed in vacuo. The crude reaction mixture was purified by column chromatography in 5% ethyl acetate/hexanes to afford **S1** as an orange oil (92% yield, 0.227 g) which matches spectral data previously reported in the literature.[30]

*Synthesis of 3-Phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-ol (**4**).* To a flame-dried round-bottom flask purged with argon were added phenylacetylene (0.33 mL, 3.06 mmol) and 10 mL of THF. The round-bottom flask was cooled to −78 °C using an acetone/dry ice bath, followed by dropwise addition of *n*-BuLi (1.3 mL, 2.3 M in hexane) (3.06 mmol), and then stirred for 45 min. **S1** (0.526 g, 2.55 mmol) dissolved in 5 mL of THF was added slowly and brought to room temperature after 2 h and allowed to stir overnight. The reaction was worked up by washing with saturated NH_4Cl solution (30 mL), extracted with EtOAc (3 × 15 mL), and dried with Na_2SO_4, and solvents were removed in vacuo. The crude reaction mixture was purified by column chromatography in 3% ethyl acetate/hexanes to afford **4** as an orange oil (93% yield, 0.731 g) which matches spectral data previously reported in the literature.[31]

General Procedure for Synthesis of Compounds (5), (7), and (10). *1-(2-((3-Phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-yl)-oxy)ethyl)naphthalene (**5**).* To 3-phenyl-1-(2-(phenylethynyl)-phenyl)prop-2-yn-1-ol **4** (0.100 g, 0.324 mmol) dissolved in acetonitrile (1 mL) was added (**6**) (0.163 g, 3 equiv) under no exclusion of air or moisture. $FeCl_3$ (0.003 g, 0.05 equiv) was added in one portion. The reaction was stirred for 5 h and monitored by TLC until full consumption of starting material. The crude reaction mixture was washed with 1 M HCl (10 mL) and extracted with EtOAc (3 × 10 mL). Collected organics were washed with brine solution and then passed through a plug of neutral alumina, and solvent was removed in vacuo. The crude reaction mixture was purified by column chromatography in 10% ethyl acetate/hexanes to afford **5** (96% yield, 0.144 g) as a clear oil. IR (neat, cm^{-1}) 3058, 2863, 2218, 1490, 1069, 753, 689; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (d, *J* = 8.4 Hz, 1H), 7.88−7.80 (m, 2H), 7.71 (dd, *J* = 6.1, 3.4 Hz, 1H), 7.58 (dd, *J* = 7.6, 1.5 Hz, 1H), 7.55−7.49 (m, 2H), 7.47−7.28 (m, 14H), 5.98 (s, 1H), 4.22 (dt, *J* = 8.9, 7.5 Hz, 1H), 3.99 (dt, *J* = 9.3, 7.7 Hz, 1H), 3.50 (t, *J* = 7.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.3, 134.5, 133.7, 132.2, 132.1, 131.8, 131.5, 128.8, 128.6, 128.4, 128.4, 128.3, 128.2, 127.5, 127.0, 126.8, 125.9, 125.5, 125.4, 123.7, 123.1, 122.6, 122.4, 94.3, 87.2, 87.0, 86.9, 70.3, 69.6, 33.3; HR-MS-ESI(+) was performed, calculated as $C_{35}H_{26}NaO$ $[M + Na]^+$ = 485.1881, found 485.1872.

*1-(1-Methoxy-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)benzene (**7**).* Compound **7** was synthesized using the general procedure. Purified by column chromatography using 10% ethyl acetate/hexanes (71% yield, 0.067 g) as a yellow oil which matches spectral data previously reported in the literature.[27]

*1-(1-Ethoxy-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)benzene (**10**).* Compound **10** was synthesized using the general procedure. Purified by column chromatography using 10% ethyl acetate/hexanes (73% yield, 0.055 g) as a pale yellow oil. IR (neat, cm^{-1}) 3027, 2921, 2216, 1494, 1076, 728, 690; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (dd, *J* = 7.8, 1.3 Hz, 1H), 7.60−7.54 (m, 3H), 7.50−7.45 (m, 2H), 7.44−7.28 (m, 8H), 5.89 (s, 1H), 3.94 (dq, *J* = 9.1, 7.0 Hz, 1H), 3.69 (dq, *J* = 9.2, 7.0 Hz, 1H), 1.32 (t, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.5, 132.2, 131.8, 131.5, 128.8, 128.4, 128.4, 128.4, 128.2, 128.2, 127.4, 123.1, 122.7, 122.4, 94.1, 87.3, 86.9, 86.8, 69.9, 64.9, 15.2; HR-MS-ESI(+) was performed, calculated as $C_{25}H_{20}OK$ $[M + K]^+$ = 375.1151, found 375.1162.

Procedure for Synthesis of Compound (13). *3-Phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-yl Acetate (**13**).* A flame-dried round-bottom flask was purged with argon. 3-Phenyl-1-(2-(phenyl-ethynyl)phenyl)prop-2-yn-1-ol **4** (0.325 g, 1.05 mmol) was added to the round-bottom flask using 5 mL of DCM. Pyridine (0.87 mL, 10.7

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mmol) and a catalytic amount of DMAP (0.006 g, 0.053 mmol) were added. The resulting solution was cooled on an ice bath to 0 °C. Acetyl chloride (0.15 mL, 2.1 mmol), previously distilled, was added neat into the reaction mixture slowly over 5 min. A white precipitate formed immediately. After full consumption of starting material based on TLC analysis, the reaction mixture was pushed through a plug of silica gel using diethyl ether (dichloromethane dissolves the precipitate). The solvents were concentrated down, and then the crude mixture was purified by column chromatography using 5% ethyl acetate/hexanes to give **13** (0.339 g, 92% yield) as a pale yellow oil. IR (neat, cm^{-1}) 3061, 2921, 2228, 1793, 1491, 1217, 753, 689; ^1H NMR (400 MHz, $CDCl_3$) δ 7.92 (dd, J = 7.5, 1.6 Hz, 1H), 7.64−7.58 (m, 3H), 7.52 (dd, J = 7.4, 2.2 Hz, 2H), 7.46−7.32 (m, 8H), 7.20 (s, 1H), 2.13 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.6, 138.1, 132.3, 131.9, 131.6, 128.9, 128.7, 128.6, 128.5, 128.3, 128.2, 128.0, 122.8, 122.7, 122.1, 95.0, 87.2, 86.1, 85.1, 64.4, 20.9; HR-MS-ESI(+) was performed, calculated as $C_{50}H_{36}O_4Na$ $[2M + Na]^+$ = 723.2511, found 723.2505.

Procedure for Synthesis of Compounds (11) and (12). *1-(1-Isopropoxy-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)benzene (**11**).* To 3-phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-yl acetate **13** (0.100 g, 0.285 mmol) dissolved in acetonitrile (1 mL) was added isopropanol (65 μL, 0.856 mmol) under no exclusion of air or moisture. $FeCl_3$ (0.002 g, 0.0142 mmol) was added in one portion. The reaction was stirred at 40 °C for 24 h. The crude reaction mixture was washed with 1 M HCl (10 mL) and extracted with EtOAc (3 × 10 mL). Collected organics were washed with brine solution, then passed through a plug of neutral alumina, and solvent was removed in vacuo. The crude reaction mixture was purified by column chromatography in 5% ethyl acetate/hexanes to afford **11** (0.084 g, 84% yield) as a light orange oil. IR (neat, cm^{-1}) 3060, 2971, 2930, 2219, 1491, 1121, 1038, 754, 690; ^1H NMR (400 MHz, $CDCl_3$) δ 7.88 (d, J = 7.9 Hz, 1H), 7.58 (dt, J = 6.6, 1.6 Hz, 3H), 7.50−7.29 (m, 10H), 6.01 (d, J = 2.1 Hz, 1H), 4.11 (sepd, J = 6.2, 1.9 Hz, 1H), 1.36 (d, J = 6.3, 1.7 Hz, 3H), 1.28 (d, J = 6.2, 1.7 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.1, 132.2, 131.7, 131.5, 128.9, 128.4, 128.2, 128.1, 128.1, 127.7, 123.1, 122.8, 122.1, 93.9, 88.1, 87.1, 86.2, 70.1, 67.3, 22.8, 21.9; HR-MS-ESI(+) was performed, calculated as $C_{26}H_{22}ONa$ $[M + Na]^+$ = 373.1568, found 373.1564.

*1-(1-(tert-Butoxy)-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)-benzene (**12**).* To 3-phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-yl acetate **13** (0.100 g, 0.285 mmol) dissolved in acetonitrile (1 mL) was added *tert*-butanol (82 μL, 0.856 mmol) under no exclusion of air or moisture. $FeCl_3$ (0.002 g, 0.0142 mmol) was added in one portion. The reaction was stirred at 40 °C for 28 h. The crude reaction mixture was washed with 1 M HCl (10 mL) and extracted with EtOAc (3 × 10 mL). Collected organics were washed with brine solution, then passed through a plug of neutral alumina, and solvent was removed in vacuo. The crude reaction mixture was purified by column chromatography in 5% ethyl acetate/hexanes to afford **12** (0.042 g, 40% yield) as an orange oil. IR (neat, cm^{-1}) 3061, 2973, 2930, 2219, 1491, 1181, 1045, 752, 688; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 7.9, 1.3 Hz, 1H), 7.61−7.56 (m, 2H), 7.53 (dd, J = 7.6, 1.4 Hz, 1H), 7.43−7.35 (m, 6H), 7.32−7.25 (m, 4H), 6.03 (s, 1H), 1.38 (s, 9H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 143.2, 132.0, 131.6, 131.5, 128.9, 128.4, 128.4, 128.0, 128.0, 127.5, 127.5, 123.2, 123.2, 120.8, 94.2, 90.5, 87.3, 85.2, 75.7, 62.8, 28.6; HR-MS-ESI(+) was performed, calculated as $C_{27}H_{24}ONa$ $[M + Na]^+$ = 387.1725, found 387.1720.

Procedure for Synthesis of Compound (14). *2-(2-(Phenylethynyl)phenyl)oxirane (**S2**).* To a flame-dried round-bottom flask purged with argon were added sodium hydride 60% in oil (0.048 g, 1.19 mmol) and trimethylsulfonium iodide (0.304 g, 1.49 mmol) and 5 mL of DMSO. After 15 min of stirring at room temperature, **S1** (0.205 g, 0.994 mmol) was added in 5 mL of DMSO and the color of the reaction changed to deep red. After an hour, the color changed to brown (indication of reaction completion). The reaction was diluted with ether (10 mL), washed with water (20 mL), and extracted with ether (3 × 15 mL). The combined organics were washed with brine and dried with Na_2SO_4. Purification by column chromatography using 5% ethyl acetate/hexanes gave **S2** (0.124 g, 57% yield) as a yellow oil. Matches spectral data previously reported in the literature.[32]

*4-Phenyl-2-(2-(phenylethynyl)phenyl)but-3-yn-1-ol (**14**).* To a Schlenk flask flame-dried and purged with argon were added phenylacetylene (42 μL, 0.381 mmol) and 0.5 mL of THF. The flask was cooled to −50 °C. *n*-BuLi (0.15 mL, 2.6 M in hexanes) (0.381 mmol) was added and stirred for 45 min. Chlorotitanium triisopropoxide (0.099 g, 0.381 mmol) was dissolved in 0.5 mL of THF and added to the round-bottom flask and stirred for 10 min. After addition of **S2** (0.042 g, 0.191 mmol) to the round-bottom flask, the reaction was brought to room temperature and stirred for 14 h. For workup, the reaction was diluted with ether (5 mL) and washed with NH_4Cl (10 mL). The aqueous layer was washed with ether (3 × 10 mL); then the combined organics were washed with brine (3 × 10 mL) and dried with magnesium sulfate. Purification by column chromatography using 8% ethyl acetate/hexanes, gave **14** (0.042 g, 68% yield) as a yellow oil. IR (neat, cm^{-1}) 3399, 3060, 2925, 2877, 2216, 1492, 1061, 753, 689; ^1H NMR (400 MHz, $CDCl_3$) δ 7.74 (dd, J = 7.8, 1.3 Hz, 1H), 7.60−7.54 (m, 3H), 7.52−7.47 (m, 2H), 7.42−7.27 (m, 8H), 4.78 (dd, J = 7.4, 5.1 Hz, 1H), 4.06 (ddd, J = 10.4, 8.0, 5.2 Hz, 1H), 3.87 (ddd, J = 10.3, 7.4, 4.8 Hz, 1H), 2.01 (t, J = 6.9 Hz, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 139.5, 132.3, 131.8, 131.6, 128.8, 128.5, 128.4, 128.3, 128.3, 128.2, 127.3, 123.0, 122.9, 122.3, 94.3, 88.3, 86.8, 84.8, 66.7, 40.5; HR-MS-ESI(+) was performed, calculated as $C_{24}H_{18}NaO$ $[M + Na]^+$ = 345.1255, found 345.1276.

Procedure for Synthesis of Acetylenic Ketals (15) and (16). *1-(2-Bromophenyl)-3-phenylprop-2-yn-1-ol (**S3**).* Phenylacetylene (0.71 mL, 6.49 mmol) and THF (30 mL) were added to a flame-dried round-bottom flask purged with argon. The round-bottom flask was brought to −78 °C using a dry ice/acetone bath. *n*-BuLi (2.8 mL, 2.3 M in hexane) (6.49 mmol) was added dropwise. The resulting mixture was allowed to stir for 45 min at the same temperature. 2-Bromobenzaldehyde (0.63 mL, 5.40 mmol) was added neat over 10 min. The resulting yellow-orange mixture was taken off the dry ice/acetone bath after 2 h and stirred at room temperature overnight. The crude reaction mixture was worked up by washing with saturated NH_4Cl solution (20 mL) and extracted with EtOAc (3 × 15 mL). After drying with Na_2SO_4, the solvents were removed in vacuo. The crude reaction mixture was purified by column chromatography in 10% ethyl acetate/hexanes to afford **S3** in 95% yield (1.47 g, 5.13 mmol) as a yellow oil. Matches spectral data previously reported in the literature.[33]

*1-(2-Bromophenyl)-3-phenylprop-2-yn-1-one (**S4**).* 1-(2-Bromophenyl)-3-phenylprop-2-yn-1-ol (0.679 g, 2.37 mmol) was added to a flame-dried round-bottom flask purged with argon, followed by the addition of DCM (10 mL). Activated manganese dioxide (2.06 g, 10 equiv) was added in portions, and the formation of gas bubbles in the reaction mixture was observed. The heterogeneous mixture was stirred and monitored by TLC until full consumption of starting material. The reaction mixture was filtered through Celite with DCM and purified by flash chromatography using 10% ethyl acetate/hexanes to afford **S4** in 92% yield (0.621 g, 2.17 mmol) as an orange oil. Matches spectral data previously reported in the literature.[34]

*2-(2-Bromophenyl)-2-(phenylethynyl)-1,3-dioxolane (**S5**).* To a round-bottom flask equipped with a Dean−Stark trap were added 1-(2-bromophenyl)-3-phenylprop-2-yn-1-one (0.938 g, 3.29 mmol), ethylene glycol (0.22 mL, 3.95 mmol), and *p*-toluenesulfonic acid (0.013 g, 0.0657 mmol) and 20 mL of benzene. The reaction mixture was brought to reflux for 1 day and monitored by TLC and revealed only partial conversion. After no change, the solvents were removed in vacuo and purified by column chromatography (2% ethyl acetate/hexanes) to give **S5** in 36% isolated yield (0.387 g, 1.17 mmol) as an orange oil; 99% yield based on recovered starting material. IR (neat, cm^{-1}) 3063, 2893, 2193, 1489, 1202, 1025, 755, 688; ^1H NMR (400 MHz, $CDCl_3$) δ 7.88 (dd, J = 7.9, 2.1 Hz, 1H), 7.70−7.63 (m, 1H), 7.48 (dt, J = 7.8, 2.1 Hz, 2H), 7.37−7.29 (m, 4H), 7.23 (dt, J = 7.7, 2.0 Hz, 1H), 4.40−4.29 (m, 2H), 4.21−4.09 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.8, 134.7, 131.8, 130.2, 128.7, 128.1, 127.5, 126.9, 121.8, 121.4, 101.8, 85.7, 85.5, 65.1; HR-MS-ESI(+) was performed, calculated as $C_{17}H_{13}BrNaO_2$ $[M + Na]^+$ = 350.9997, found 350.9984.

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*1-Bromo-2-(1,1-dimethoxy-3-phenylprop-2-yn-1-yl)benzene (**S6**).* 1-(2-Bromophenyl)-3-phenylprop-2-yn-1-one (0.130 g, 0.459 mmol) was added to a flame-dried round-bottom flask and put under argon. 3 mL of MeOH, distilled twice over Mg, was added, followed by trimethylorthoformate (60 μL, 0.551 mmol) and *p*-toluenesulfonic acid (0.009 g, 0.0459 mmol). The reaction mixture was allowed to stir for 24 h at room temperature. Solvents were removed, and the crude was purified by column chromatography using silica gel (pH 6−7) in 5% ethyl acetate/hexanes, which gave **S6** in 26% yield based on recovered starting material (0.040 g, 0.119 mmol) as an amber oil. IR (neat, cm^{-1}) 3063, 2893, 2193, 1489, 1202, 1025, 755, 688; ^1H NMR (400 MHz, $CDCl_3$) δ 7.85 (dd, J = 7.9, 1.7 Hz, 1H), 7.62 (dd, J = 7.9, 1.3 Hz, 1H), 7.47−7.41 (m, 2H), 7.33−7.28 (m, 1H), 7.27−7.21 (m, 3H), 7.16 (ddd, J = 7.9, 7.4, 1.8 Hz, 1H), 3.31 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.4, 134.8, 131.9, 129.9, 129.2, 128.7, 128.1, 126.9, 121.9, 121.6, 96.9, 85.8, 85.0, 50.0; HR-MS-ESI(+) was performed, calculated as $C_{17}H_{15}BrNaO_2$ $[M + Na]^+$ = 353.0153, found 353.0142.

*2-(2-Iodophenyl)-2-(phenylethynyl)-1,3-dioxolane (**S7**).* To a flame-dried Schlenk flask purged with argon were added 2-(2-bromophenyl)-2-(phenylethynyl)-1,3-dioxolane (0.178 g, 0.541 mmol) and 5 mL of THF. The flask was brought to −78 °C, and *n*-BuLi (0.26 mL, 2.5 M in hexane) (0.649 mmol) was added dropwise, and the color of the mixture changed from dark orange to deep purple. After 15 min, iodine (0.171 g, 2.5 equiv) was added all at once and the color changed back to orange, and the mixture was brought to room temperature and stirred for 4 h. Saturated $Na_2S_2O_3$ solution (15 mL) was added, and the aqueous phase was extracted twice with diethyl ether (30 mL). The organics were washed with water again and dried with Na_2SO_4, and solvents were removed in vacuo. It could not be purified, so the crude mixture was taken to the next step of Sonagashira reaction. Using 1,2-dichloroethane as an internal standard gave **S7** in 52% yield (0.106 g, 0.281 mmol).

*1-(1,1-Dimethoxy-3-phenylprop-2-yn-1-yl)-2-iodobenzene (**S8**).* To a flame-dried Schlenk flask purged with argon were added 1-bromo-2-(1,1-dimethoxy-3-phenylprop-2-yn-1-yl)benzene (0.130 g, 0.392 mmol) and 3.5 mL of THF. The flask was brought to −78 °C, and *n*-BuLi (0.18 mL, 2.45 M in hexane) (0.431 mmol) was added dropwise, and the color of the mixture changed from amber to opaque purple. After 15 min, iodine (0.075 g, 1.5 equiv) was added all at once and the color changed to brown, then to green, and back to orange. The reaction was brought to room temperature and stirred for 2 h. Saturated $Na_2S_2O_3$ solution (15 mL) was added, and the aqueous phase was extracted twice with diethyl ether (20 mL). The organics were washed with water again and dried with Na_2SO_4, and solvents were removed in vacuo. It could not be purified, so the crude mixture was taken to the next step of Sonagashira reaction. Using 1,2-dichloroethane as an internal standard gave **S8** in 61% yield (0.091 g, 0.239 mmol).

*2-(Phenylethynyl)-2-(2-(phenylethynyl)phenyl)-1,3-dioxolane (**15**).* To an oven-dried round-bottom flask under argon equipped with a stir bar were added 2-(2-iodophenyl)-2-(phenylethynyl)-1,3-dioxolane (0.106 g, 0.281 mmol), $Pd(PPh_3)_2Cl_2$ (0.010 g, 0.014 mmol), CuI (0.005 g, 0.0281 mmol), and 5 mL of triethylamine. The resulting solution was outgassed with argon for 30 min. Neat phenylacetylene (37 μL, 0.337 mmol) was added over 10 min. The reaction was stirred for 18 h at room temperature and monitored by TLC. The reaction was run through a plug of Celite, washed with $NaHCO_3$ (2 × 15 mL), extracted with EtOAc (3 × 10 mL), and dried with Na_2SO_4, and solvents were removed. The crude mixture was purified by column chromatography (silica gel pH 6−7) using 10% ethyl acetate/hexanes to give **15** in 60% yield (0.059 g, 0.168 mmol) as a yellow oil. IR (neat, cm^{-1}) 3062, 2894, 2224, 1492, 1280, 1071, 755, 690; ^1H NMR (600 MHz, $CDCl_3$) δ 7.95−7.89 (m, 1H), 7.68−7.60 (m, 1H), 7.55 (ddt, J = 5.6, 2.7, 1.3 Hz, 2H), 7.45−7.40 (m, 2H), 7.39−7.34 (m, 2H), 7.34−7.28 (m, 5H), 7.25−7.21 (m, 2H), 4.46−4.31 (m, 2H), 4.28−4.17 (m, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 139.9, 134.1, 131.8, 131.4, 128.9, 128.6, 128.2, 128.1, 128.1, 127.8, 126.2, 123.7, 121.9, 121.6, 102.3, 94.6, 88.4, 86.3, 85.5, 65.3; HR-MS-ESI(+) was performed, calculated as $C_{25}H_{18}NaO_2$ $[M + Na]^+$ = 373.1204, found 373.1206.

*1-(1,1-Dimethoxy-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)-benzene (**16**).* To an oven-dried round-bottom flask under argon equipped with a stir bar were added 1-(1,1-dimethoxy-3-phenylprop-2-yn-1-yl)-2-iodobenzene (0.090 g, 0.239 mmol), $Pd(PPh_3)_2Cl_2$ (0.008 g, 0.0119 mmol), CuI (0.004 g, 0.0239 mmol), and 4 mL of triethylamine. The resulting solution was outgassed with argon for 30 min. Neat phenylacetylene (31 μL, 0.286 mmol) was added over 10 min. The reaction was stirred for 4 h at room temperature and monitored by TLC. The reaction was run through a plug of Celite, washed with $NaHCO_3$ (2 × 15 mL), extracted with EtOAc (3 × 10 mL), and dried with Na_2SO_4, and solvents were removed. The crude mixture was purified by column chromatography (silica gel pH 6−7) using 3% ethyl acetate/hexanes to give **16** in 76% yield (0.064 g, 0.181 mmol) as a light yellow oil. IR (neat, cm^{-1}) 3059, 2936, 2829, 2196, 1490, 1114, 1064, 753, 688; ^1H NMR (400 MHz, $CDCl_3$) δ 7.87−7.81 (m, 1H), 7.66−7.61 (m, 1H), 7.58−7.53 (m, 2H), 7.40−7.33 (m, 4H), 7.32−7.28 (m, 3H), 7.25−7.17 (m, 3H), 3.41 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.5, 133.9, 131.8, 131.5, 128.5, 128.3, 128.1, 128.0, 127.9, 127.7, 127.0, 123.8, 122.1, 121.9, 97.2, 94.7, 88.4, 86.0, 85.7, 50.3; HR-MS-ESI(+) was performed, calculated as $C_{25}H_{20}NaO_2$ $[M + Na]^+$ = 375.1361, found 375.1358.

Synthetic Scheme A. General Procedure for the Synthesis of Compounds (3), (17), (18). *Tributyl(11-phenyl-11H-benzo[a]-fluoren-6-yl)stannane (**3**).* A round-bottom flask connected to a water jacketed condenser was flame-dried and purged with argon. 1-(2-((3-Phenyl-1-(2-(phenylethynyl)phenyl)prop-2-yn-1-yl)oxy)ethyl)-naphthalene (**5**) (0.118 g, 0.255 mmol) was added to the round-bottom flask with 3 mL of anhydrous toluene and outgassed with argon for 10 min, followed by heating in an oil bath at 110 °C. Bu_3SnH (96 μL, 0.357 mmol) and AIBN (0.012 g, 0.0765 mmol) were dissolved in 2 mL of toluene and outgassed with argon for 10 min. Using a syringe pump, Bu_3SnH and AIBN were added into the reaction vessel (1 mL/h). The reaction was allowed to stir for 14 h or until full consumption of starting material based on TLC analysis. The reaction was flushed through a Celite plug with DCM, and solvents were removed under pressure. 1,2-Dichloroethane was added as an NMR internal standard which gave 66% yield of **3**, which matches previously reported spectral data in the literature.[27]

*Synthesis of 2-((11-Phenyl-6-(tributylstannyl)-11H-benzo[a]-fluoren-5-yl)oxy)ethan-1-ol (**17**) and 2-((11-Phenyl-11H-benzo[a]-fluoren-5-yl)oxy)ethan-1-ol (**17′**).* A round-bottom flask connected to a water jacketed condenser was flame-dried and purged with argon. 2-(Phenylethynyl)-2-(2-(phenylethynyl)phenyl)-1,3-dioxolane (**15**) (0.047 g, 0.134 mmol) was added to the round-bottom flask with 1 mL of anhydrous toluene and outgassed with argon for 10 min, followed by heating in an oil bath at 110 °C. Bu_3SnH (51 μL, 0.187 mmol) and AIBN (0.007 g, 0.0402 mmol) was dissolved in 2 mL of toluene and outgassed with argon for 10 min. Using a syringe pump, Bu_3SnH and AIBN were added into the reaction vessel (1 mL/h). The reaction was allowed to stir for 14 h or until full consumption of starting material based on TLC analysis. The reaction was flushed through a Celite plug with DCM, and solvents were removed under pressure. 1,2-Dichloroethane was added as an NMR internal standard which gave 12% yield of **17**. The reaction mixture was dissolved in DCM (10 mL) and 3 M HCl (10 mL) and stirred for 1 h and monitored by TLC analysis. $NaHCO_3$ was slowly added until gas formation stopped. The aqueous layer was extracted with DCM (3 × 10 mL) and dried with Na_2SO_4, and solvents were removed under pressure. Column chromatography was performed using a gradient of 2% and 4% ethyl acetate/hexanes and gave **17′** (5 mg, 11% isolated yield) as a beige solid (mp 161−164 °C). IR (neat, cm^{-1}) 3264, 3056, 2921, 1586, 1215, 735, 699; ^1H NMR (600 MHz, $CDCl_3$) δ 8.39−8.26 (m, 1H), 7.78 (d, J = 7.5 Hz, 1H), 7.66−7.57 (m, 1H), 7.41−7.32 (m, 4H), 7.32 (s, 1H), 7.26−7.18 (m, 4H), 7.16−7.08 (m, 2H), 5.27 (s, 1H), 4.44 (t, J = 4.5 Hz, 2H), 4.27−4.06 (m, 2H), 2.22−2.09 (m, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 155.2, 149.6, 141.8, 141.1, 139.3, 135.2, 131.0, 128.8, 127.9, 127.1, 127.0, 126.9, 126.7, 125.7, 124.8, 124.6, 124.5, 122.9, 119.3, 97.9, 69.9, 61.7, 53.6; HR-MS-ESI(+) was performed, calculated as $C_{25}H_{20}NaO_2$ $[M + Na]^+$ = 375.1361, found 375.1360.

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Synthesis of Tributyl(5-methoxy-11-phenyl-11*H*-benzo[*a*]-fluoren-6-yl)stannane (18) and 5-Methoxy-11-phenyl-11*H*-benzo[*a*]fluorene (18′). A round-bottom flask connected to a water jacketed condenser was flame-dried and purged with argon. 1-(1,1-Dimethoxy-3-phenylprop-2-yn-1-yl)-2-(phenylethynyl)benzene (**16**) (0.074 g, 0.209 mmol) was added to the round-bottom flask with 2 mL of anhydrous toluene and outgassed with argon for 10 min, followed by heating in an oil bath at 110 °C. Bu_3SnH (79 μL, 0.294 mmol) and AIBN (0.010 g, 0.0629 mmol) were dissolved in 2 mL of toluene and outgassed with argon for 10 min. Using a syringe pump, Bu_3SnH and AIBN were added into the reaction vessel (1 mL/h). The reaction was allowed to stir for 14 h or until full consumption of starting material based on TLC analysis. The reaction was flushed through a Celite plug with DCM, and solvents were removed under pressure. 1,2-Dichloroethane was added as an NMR internal standard which gave 28% yield of **18**. The reaction mixture was dissolved in DCM (10 mL) and 3 M HCl (10 mL) and stirred for 1 h and monitored by TLC analysis. $NaHCO_3$ was slowly added until gas formation stopped. The aqueous layer was extracted with DCM (3 × 10 mL) and dried with Na_2SO_4, and solvents were removed under pressure. Column chromatography was performed using 5% ethyl acetate/hexanes and gave **18′** (6 mg, 10% isolated yield) as a beige solid (mp 153−156 °C). IR (neat, cm^{-1}) 3063, 2930, 2852, 1587, 1452, 1217, 757, 699; ^1H NMR (400 MHz, $CDCl_3$) δ 8.31 (dt, *J* = 8.5, 0.9 Hz, 1H), 7.80 (dt, *J* = 7.5, 0.9 Hz, 1H), 7.59 (dt, *J* = 8.0, 0.9 Hz, 1H), 7.41−7.31 (m, 4H), 7.30 (s, 1H), 7.25−7.18 (m, 4H), 7.15−7.09 (m, 2H), 5.27 (s, 1H), 4.16 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 156.4, 149.6, 141.9, 141.3, 139.3, 134.6, 130.9, 128.8, 127.9, 127.0, 126.9, 126.8, 126.7, 125.8, 124.8, 124.5, 124.3, 123.1, 119.3, 96.6, 55.7, 53.6; HR-MS-ESI(+) was performed, calculated as $C_{24}H_{17}O$ $[M]^+$ = 321.1279, found 321.1277.

Thermal cycloaromatization product of (**15**) to *10-phenylspiro-[benzo[b]fluorene-11,2′-[1,3]dioxolane]* (**19**) using conditions from synthetic Scheme A. 1,2-Dichloroethane was added as NMR internal standard to the reaction mixture containing **19** which gave **19** in 55% yield. Column chromatography was performed using a gradient of 2% and 4% ethyl acetate/hexanes and gave **19** (9 mg, 20% isolated yield) as a yellow solid (mp 185−188 °C). IR (neat, cm^{-1}) 3056, 2924, 1496, 1252, 1072, 747, 701; ^1H NMR (600 MHz, $CDCl_3$) δ 8.00 (s, 1H), 7.91−7.86 (m, 1H), 7.78−7.72 (m, 1H), 7.59−7.27 (m, 11H), 4.10−3.99 (m, 2H), 3.19−3.09 (m, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 146.2, 138.5, 138.2, 137.9, 137.4, 137.3, 134.9, 133.8, 130.8, 130.0, 128.8, 128.2, 127.5, 127.1, 126.9, 126.5, 125.7, 123.3, 120.3, 117.8, 113.4, 65.7; HR-MS-ESI(+) was performed, calculated as $C_{25}H_{18}NaO_2$ $[M + Na]^+$ = 373.1204, found 373.1207.

Thermal cycloaromatization product of (**16**) to *11,11-dimethoxy-10-phenyl-11H-benzo[b]fluorene* (**20**) using conditions from synthetic Scheme F. 1,2-Dichloroethane was added as NMR internal standard to the reaction mixture containing **20** which gave **20** in 60% yield. Column chromatography was employed; however, **20** hydrolyzed to the ketone 10-phenylbenzo[*b*]fluorenone, which ketal could not be isolated. The cyclized ketone matches previously reported spectra.[35] ^1H NMR (600 MHz, $CDCl_3$) δ 7.94 (s, 1H), 7.89−7.87 (d, *J* = 8 Hz, 1H), 7.78−7.76 (d, *J* = 8 Hz, 1H), 7.64−7.52 (m, 7H), 7.39−7.31 (t, *J* = 8 Hz, 4H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 192.2, 144.0, 138.3, 136.6, 136.3, 135.4, 134.6 133.8, 129.6, 129.1, 128.9, 128.7, 128.0, 127.9, 126.7, 124.1, 120.6, 118.6.

Procedure for Synthesis of Silyl Enol Ether (8). *2-(Naphthalen-1-yl)acetaldehyde (**S9**).* An oven-dried flask was put under argon, and Dess−Martin reagent (0.219 g, 0.516 mmol, 1.2 equiv) was weighed out and transferred to the reaction vessel. Methylene chloride (4 mL) was used to dissolve 2-(naphthalen-1-yl)ethan-1-ol (0.074 g, 0.43 mmol) and transferred all at once at room temperature. The reaction was monitored by TLC analysis and showed full consumption of starting material after 2 h. The reaction mixture was diluted with DCM and washed with $Na_2S_2O_3$ (10 mL), extracted with DCM (2 × 10 mL), followed by saturated $NaHCO_3$ solution (15 mL), and extracted again with DCM (2 × 10 mL). The combined organics were washed with brine solution (20 mL) and dried with Na_2SO_4, and solvents were removed under pressure. The crude reaction mixture was filtered through a silica gel plug (pH 6−7) in 20% ethyl acetate/hexanes and gave **S9** (0.408 mmol, 95% yield) and matches previously reported spectra.[36]

*tert-Butyldimethyl((2-(naphthalen-1-yl)vinyl)oxy)silane (**8**).* To an oven-dried flask under argon was added **S9** (0.146 g, 0.857 mmol) in 8 mL of methylene chloride. The reaction flask was put on an ice water bath. Diisopropylethylamine (0.3 mL, 1.71 mmol) was added all at once to the reaction flask and stirred for 15 min. Freshly distilled *tert*-butyldimethylsilyl triflate/TBSOTf (0.24 mL, 1.03 mmol) was added all at once and the color changed from clear to yellow. The reaction was allowed to stir for 15 min at 0 °C, followed by another 15 min at room temperature, and checked by TLC analysis. Once the reaction was complete, the reaction was quenched with saturated $NaHCO_3$ solution (15 mL) and extracted with DCM (3 × 10 mL), and combined organics were washed with brine (15 mL) and dried with Na_2SO_4. Once the solvents were removed under pressure, the crude mixture was purified using flash chromatography (silica gel pH 6−7) with 5% ethyl acetate/hexanes to afford **8** (0.202 g, 0.712 mmol, 83% yield, 85% cis: 15% trans) as a clear oil. R_f = 0.78 in 10% ethyl acetate/hexanes; IR (neat, cm^{-1}) 3048, 2929, 2857, 1635, 1256, 1100, 776; (both cis and trans reported for NMR); ^1H NMR (600 MHz, $CDCl_3$) δ 8.16 (dd, *J* = 7.3, 1.2 Hz, 1H), 8.14−8.11 (m, 1H), 8.11−8.08 (m, 0.15H), 7.88−7.81 (m, 1H), 7.72 (dd, *J* = 13.4, 8.0 Hz, 1H), 7.53−7.39 (m, 4H), 6.96 (dd, *J* = 11.9, 0.9 Hz, 0.12H), 6.74 (d, *J* = 11.9 Hz, 0.14H), 6.69 (d, *J* = 6.7 Hz, 1H), 6.02 (d, *J* = 6.7 Hz, 1H), 1.03 (d, *J* = 0.8 Hz, 1H), 0.97 (d, *J* = 0.7 Hz, 9H), 0.28 (d, *J* = 0.7 Hz, 1H), 0.23 (d, *J* = 0.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 143.6, 141.1, 133.6, 131.7, 131.1, 128.5, 128.3, 126.7, 126.2, 125.6, 125.4, 125.4, 125.1, 124.3, 123.9, 122.8, 110.1, 104.9, 25.6, 18.2, −5.1, −5.3; APPI-FT-ICR(+) was performed, calculated as $C_{18}H_{24}OSi$ $[M]^+$ = 284.1591, found 284.1589.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01052.

Crystallographic data for **19** (CIF)

^1H NMR, ^{13}C NMR, crystal structure data for compound **19**, and computational details (PDF)

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Notes

The authors declare no competing financial interest.

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