Silyl Radical Cascade Cyclization of 2-Isocyanothioanisole toward 2-Silylbenzothiazoles through Radical Initiator–Inhibitor Symbiosis

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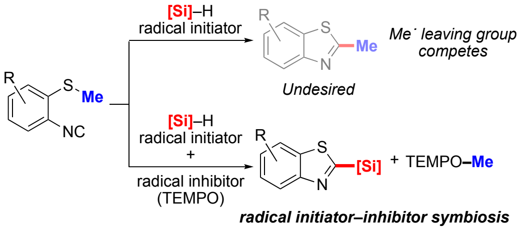
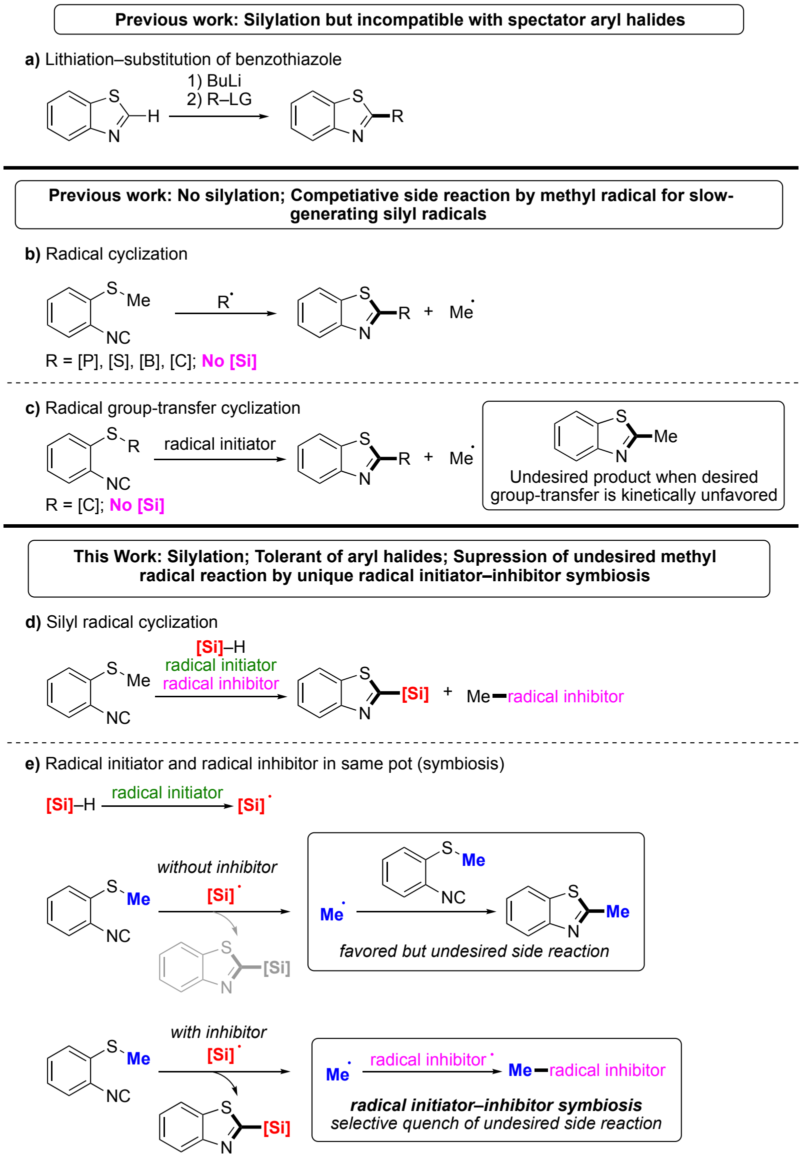


Abstract: A demethylative silyl radical cascade cyclization of 2-isocyanothioanisoles toward 2-silylated benzothiazole building blocks has been developed. The development of a "radical initiator–inhibitor symbiosis" system solves the challenge of otherwise dominant methyl-radical triggered side reactions brought about by kinetically unfavored generation of reactive silyl radical species. The products accessed in this protocol are amendable to various downstream functionalization reactions, including the quick construction of a topoisomerase II inhibitor via a Hiyama cross-coupling reaction and of an antiviral agent via a fluoride-/hydroxide-free nucleophilic substitution to acyl chloride.

Benzothiazole derivatives, especially those functionalized at the 2 position, are common motifs in natural products, pharmaceuticals, and fluorescent compounds.[1] Therefore, the development of syntheses to access 2-derivatized benzothiazoles has been a popular research area. Traditionally, this class of structures is prepared by construction of the benzothiazole first, followed by functionalization at the 2 position via a lithiation–substitution sequence in a second synthetic step (Scheme 1a).[2–4] Although this type of synthetic route is generally efficient, it requires use of a organolithium reagent, which is undesirable due to its pyrophoricity and incompatibility with spectator aryl halides. Alternatively, demethylation-triggered radical cascade cyclization of 2-isocyanothioanisole derivatives toward other functionalized heterocycles has received significant attention in recent years due to its mild and metal-free reaction conditions, high atom economy, and high regioselectivity (Scheme 1b).[5] A conceptually similar radical-mediated group-transfer cyclization has also been developed with the same advantages (Scheme 1c).[5,6]

To date, the aforementioned radical strategies have been used successfully for preparation of 2-phosphorus, 2-sulfur, 2-boron, and 2-carbon substituted benzothiazoles;[5] however, the synthesis of 2-silylbenzothiazoles remains a significant challenge through this advantageous route, presumably due to the kinetically slow hydrogen atom abstraction process from silicon–hydrogen bonds leading to the requisite generation of silyl radicals.[7,8] Because of this inherit problem, the methyl radicals generated in the demethylation process and radicals generated by radical initiators are known to compete with desired reactions, resulting in significant amounts of undesired methylation[6,9,10] (here, plausibly rather than the desired silylation reaction).

Scheme 1. Comparison of Previous Methods to This Work



We became interested in developing a synthetic strategy to access 2-silylbenzothiazoles by a radical cascade route in part because organosilicon reagents are useful building blocks that can undergo various functionalization reactions, such as Hiyama cross-coupling,[11,12] Tamao oxidation,[13] and Hosomi-Sakurai reactions[14].[15,16] For 2-silylbenzothiazole derivatives specifically, these building blocks can undergo additional transformations, such as nucleophilic substitution to acyl chlorides without fluoride or oxide activation needed at the silicon.[2,17,18] Organosilicon compounds are nontoxic[11,12,15] which is particularly important for industrial applications, and introduction of a silyl group into drug molecules can increase lipophilicity, improve potency, and alter metabolic rate.[15,19–21] Other applications of organosilicon compounds include biological imaging, drug release technology, and mapping inhibitor binding.[15,22] Therefore, the ability to access 2-silylbenzothiazoles by a radical cascade route would be advantageous.

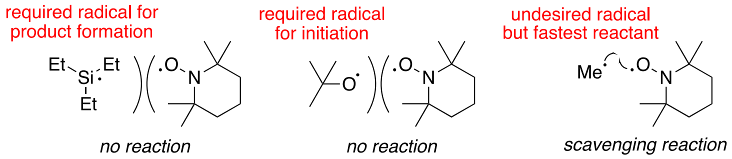
This report introduces a unique synthetic strategy that enables access of 2-silylbenzothiazoles via a silyl-radical triggered-cascade cyclization of 2-isocyanothioanisole substrates (Scheme 1d). The enabling mechanistic concept is to circumvent the aforementioned kinetic problem by development of a radical initiator–inhibitor symbiosis system in which the undesired methyl-radical-initiated side reactions are successfully suppressed while the desired initiator- and silyl-radical reactions are unaffected (Scheme 1e). This symbiosis is in contrast to typical initiator-based radical cyclization reactions wherein addition of a radical inhibitor results in quenching of the desired reaction.[23–27]

Investigations were started by using **1a** as model substrate and Et_3SiH as model silane source. When 1.5 equiv di-*tert*-butylperoxide (DTBP) was used as radical initiator in toluene, 20% of the desired product was produced as determined by ^1H NMR spectroscopy relative to an internal standard, with a full consumption of substrate. A more detailed analysis by ^1H NMR spectroscopy showed that 2-benzylated (45%) and 2-methylated (29%) products composed the majority of the mass balance. This suggested that toluene was noninnocent as a solvent, and instead participated competitively in the cyclization cascade via generation of a benzyl radical

(Entry 1, Table 1). To avoid generation of undesired radical species from solvent, radical inert solvents, such as DMSO and DMA, were then used (Entries 2–3, Table 1). However, no conversion occured in these solvents. Use of $PhCF_3$ as a solvent resulted in elimination of the 2-benzyl byproduct by preventing competing formation of benzyl radicals (Entry 4, Table 1); however, the conversion to the desired silylated product **2a** remained low (25%). Instead, conversion to another undesired product, 2-methylbenzothiazole (**2'**, R = Me), increased significantly in its proportion of the mass balance (to 64%). To increase the statistical favorability of the desired silyl-radical reaction, the stoichiometry of Et_3SiH was next increased to 20 equiv (Entry 5, Table 1). Increasing the amount of silane improved the yield of the desired product by approximately 10%, however, the undesired methyl-radical reaction was still dominant. Changing the radical initiator to AIBN failed to improve the desired conversion (Entry 6, Table 1). Instead, AIBN induced another undesired side reaction, resulting in a 2-cyanodimethyl product formed by trapping of the AIBN radical decomposition products.

Substantial reaction optimization thus showed that the slow abstraction of hydrogen from the relatively inert Si–H bond to form the desired silyl radical appeared to be the singular limiting factor preventing higher reaction yields. The sluggishness of this step apparently introduced undesired kinetic opportunity for alternative trapping by the range of other possible undesired radicals (i.e., methyl, benzyl, 2-cyanodimethyl). At this point, we envisioned that the reaction might be difficult to further optimize by increasing the rate of H–Si abstraction due to the unfavored generation of silyl radical.[7] Therefore, we decided to adopt a different strategy: to suppress the undesired methyl-radical-initiated side reactions. We postulated that addition of a sterically hindered radical inhibitor, such as TEMPO, could effectively scavenge the methyl radical in the reaction mixture. Meanwhile, the desired di-*tert*-butylperoxide decomposition process, the silyl radical, and the silyl-radical initiated cyclization intermediates may plausibly not be scavenged, due to their higher steric hindrance and thus plausible increased persistence toward sterically encumbered TEMPO (Scheme 2). Because both a radical initiator and a radical inhibitor—two reagents that typically quench each other—work together here to promote the desired reaction, we find it helpful to consider this process as a “radical initiator–inhibitor symbiosis”.

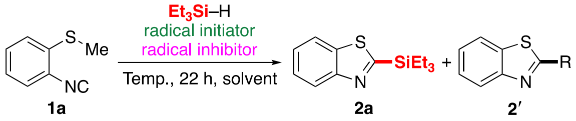
Scheme 2. Envisioned Radical Initiator–Inhibitor Symbiosis



To develop this approach, TEMPO was first introduced to the reaction in di-*tert*-butylperoxide:TEMPO ratios equal to either 2:1 or 3:1. These ratios lead to effective suppression of the undesired methyl-radical side reaction, however, the overall conversion dropped, leaving most substrate unreacted (Entries 7, 8, and 11, Table 1). This result suggested that the symbiosis strategy was promising in its ability to selectively quench the methyl radical, but indicated that TEMPO may begin to scavenge the desired radical species that are required to initiate the cyclization cascade as well, at these low ratios of initiator-to-TEMPO. By increasing the di-*tert*-butylperoxide–TEMPO ratio to 10:1 and 6:1, full conversion could be achieved; however, now undesired 2-*tert*-butoxy and 2-methyl products were produced in significant amounts (Entries 9, 10, Table 1). Finally, doubling the reaction concentration increased the ^{1}H NMR spectroscopy yield of the desired product **2a** to 85% without significant side products (Entry 13, Table 1). Further increasing the reaction concentration, to neat, resulted in less desired product **2a** (Entry

14, Table 1). Slow addition of a premixed solution of **1a**, DTBP, and TEMPO into 5 equiv Et_3SiH (attempted in order to maintain high silane concentrations in the reaction mixture albeit with less equiv of silane) was similarly ineffective (Entry 15, Table 1).

Table 1. Reaction Condition Optimization Data



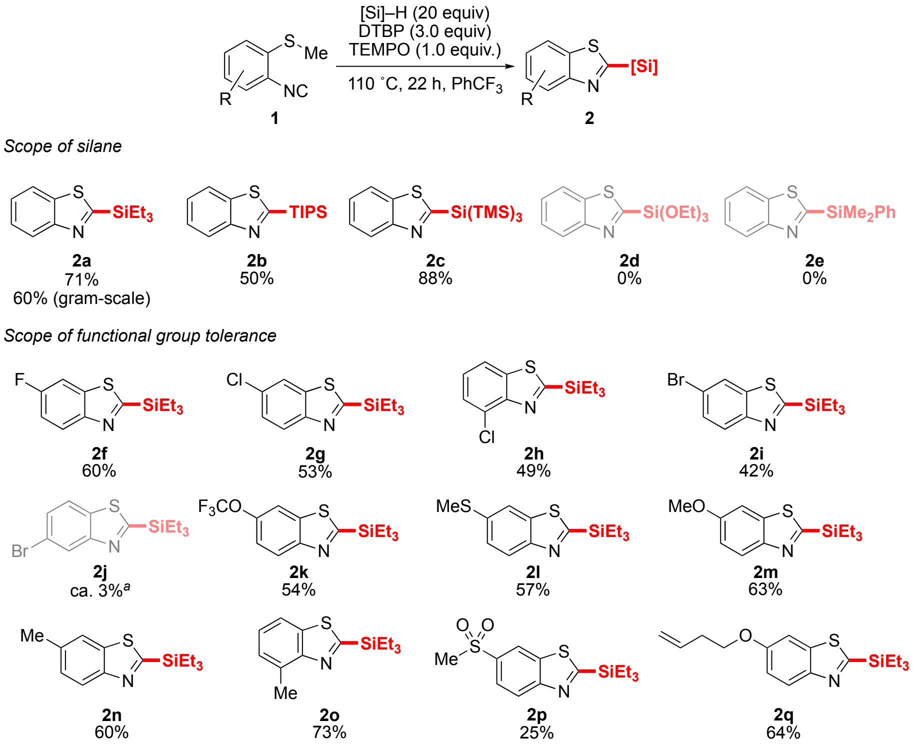
Entry	Radical initiator (equiv)	Temperature (˚C)	Solvent (mL)	equiv of Et_3SiH	Radical inhibitor (equiv)	^1H NMR yield of **2a** (%)	^1H NMR yield of **2′** (%)	^1H NMR quantity remaining of **1a** (%)
1	DTBP (1.5)	110	toluene (2.0)	5	N/A	20	45 (R = CH_2Ph) 29 (R = Me)	0
2	DTBP (1.5)	110	DMSO (2.0)	5	N/A	0	N.D.	0
3	DTBP (1.5)	110	DMA (2.0)	5	N/A	0	N.D.	0
4	DTBP (1.5)	110	$PhCF_3$ (2.0)	5	N/A	25	64 (R = Me)	0
5	DTBP (1.5)	110	$PhCF_3$ (2.0)	20	N/A	35	41 (R = Me)	0
6	AIBN (1.5)	85	$PhCF_3$ (2.0)	20	N/A	31	17 (R = $CCNMe_2$)	0
7	DTBP (1.0)	110	$PhCF_3$ (2.0)	20	TEMPO (0.5)	14	N/A	90
8	DTBP (2.0)	110	$PhCF_3$ (2.0)	20	TEMPO (1.0)	24	N/A	90
9	DTBP (5.0)	110	$PhCF_3$ (2.0)	20	TEMPO (0.5)	35	60 (R = O^tBu) 24 (R = Me)	0
10	DTBP (3.0)	110	$PhCF_3$ (2.0)	20	TEMPO (0.5)	50	34 (R = O^tBu) 35 (R = Me)	0
11	DTBP (3.0)	110	$PhCF_3$ (2.0)	20	TEMPO (1.0)	10	N/A	90
12	DTBP (3.0)	110	$PhCF_3$ (3.0)	20	TEMPO (1.0)	38	3 (R = Me)	49
13	**DTBP**	**110**	**$PhCF_3$**	**20**	**TEMPO**	**85**	**N/A**	**0**

	(3.0)		(1.0)		(1.0)			
14	DTBP (3.0)	110	neat	20	TEMPO (1.0)	26	N/A	55
15[a]	DTBP (3.0)	110	PhCF$_3$ (1.0 + 1.0)	5	TEMPO (1.0)	trace	N/A	0

[a] Slow addition of **1a**, DTBP and TEMPO into Et$_3$SiH

With the optimized reaction conditions in hand, the reaction scale was increased for isolation purposes, and the reaction scope was next investigated (Scheme 3). Implementation of different silanes lead to products **2a–2c** in moderate-to-high yields. Standard conditions with triethylsilane and substrate **1a** produced **2a** in 71%. Substrate **1a** was also amendable to gram-scale reaction albeit in lowered yield (60%). When more sterically demanding TIPS–H was used as the silane source, the desired reaction still proceeded to yield **2b**, albeit a lower yield (50%). Supersilane, H–Si(SiMe$_3$)$_3$, resulted in an improved reaction efficiency, generating **2c** in 88%. This improved yield is most likely due to the ease of hydrogen atom abstraction during Si(SiMe$_3$)$_3$ radical generation.[28,29] Conversely, when H–Si(OEt)$_3$ was used as the silane source, no desired transformation into **2d** is observed, likely due to the significantly reduced rate of hydrogen atom abstraction from H–Si(OEt)$_3$.[7] Only intractable decomposition of substrate occurred. The synthesis of **2e** from H–SiMe$_2$Ph was also unsuccessful, and analysis of crude reaction mixture via ^{1}H NMR spectroscopy demonstrated that protodesilylation was the major undesired transformation.

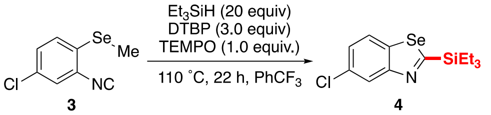
Scheme 3. Substrate Scope



^{a} mass recovery (see Experimental Section for details)

Further studies of the reaction scope indicated that aryl halides (F, Cl, and Br) at different positions of substitution were generally tolerated (42%–60%; **2f**–**2i**), with more radical reactive bromides[30] (**2i** and **2j**) typically giving lowered yields than radical-inert fluoride (**2f**). Interestingly, 5-bromide product **2j** resulted in much lower yield than the corresponding 6-bromide counterpart (**2i**). Analysis of the crude reaction mixture for **2j** showed multiple unidentifiable decomposition products, indicating the electronics of the substrate is crucial to the efficiency of the reaction and/or the stability of the desired product. Bromide **2i** is unsuitable for preparation by prior lithiation–silylation routes due to the sensitivity of the bromide toward competing lithium–halogen exchange, highlighting the complementarity of the current radical route.

We were then interested in evaluating the tolerance of homolytically sensitive carbon–hydrogen bonds. Different from the observation during solvent-optimization experiments, wherein toluoyl radical was found to add during cyclization, substrates containing benzylic carbon–hydrogen bonds were tolerated with moderate-to-good yields (**2n** and **2o**). Similarly, homoallylic groups were also tolerated with 64% yield (**2q**). Additional functional groups that were tolerated include esters (**2m**), thioesters (**2l**), and trifluoromethyl esters (**2k**). The access to **2l** suggests undesired oligomerization or polymerization through the extra SMe group is not of pronounced concern. Product **2k** may gain additional interest because trifluoromethyl groups are common in pharmaceuticals.[31,32] ^{1}H NMR spectroscopic analysis of the crude reaction mixture leading to **2p** showed substantial competing decomposition, which may arise from either decomposition of the starting material or product.



3

4
40%

(eq 1)

Additionally, we have demonstrated the conceptual expansion of this chemistry toward the synthesis of 2-silylbenzoselenazoles (eq 1). The desired product could be gained under similar reaction conditions to the benzothiazole counterparts. However, in this case, only 40% yield was achieved. Both product decomposition (via likely protodesilylation, as observed by ^{1}H NMR spectroscopy in the crude reaction mixture) and the plausible of the instability of substrate **3** contribute to diminished yield.

To gain mechanistic insight into the silyl radical cascade reaction, a series of experiments were conducted. The first mechanistic question was if TEMPO intercepts the undesired methyl radical as initially envisioned. This hypothesis was evaluated by analyzing the crude reaction mixture via both GC–MS and ^{1}H NMR spectroscopy. The scavenged product **TEMPO–Me**[33] was observed by both analytical methods (Scheme 4a), suggesting that TEMPO intercepts the methyl radical as proposed.

Because it was observed that introduction of excess of di-*tert*-butylperoxide with TEMPO present can still result in production of 2-methylbenzothiazole (Entries 9–10, Table 1), we suspected that methyl radical could not only originate from the substrate, but also from β-scission of *tert*-butoxy radical[34] (Scheme 4b). To gain insight into the sources of methyl radical, a deuterium tracer experiment was performed (Scheme 4b). By using **1a-*d*$_3$** as the substrate, both **TEMPO–CD$_3$** and **TEMPO–Me**[33] were observed by GC–MS and/or NMR spectroscopy. This outcome established that both substrate and di-*tert*-butylperoxide are sources of methyl radical. This two-source situation is likely a reason why introducing large excess of silane still does not result in outcompeting the undesired methyl-radical triggered process in the absence of TEMPO (Entry 5, Table 1).

There are two plausible mechanisms of TEMPO-methyl-radical interception, as described in Scheme 4c. In the first plausible mechanism, after cyclization, intermediate **5** is generated, followed by generation of methyl radical as a leaving group. This is a commonly accepted mechanism in a previously reported radical-triggered demethylative-cascade-cyclization reaction.[5] Alternatively, TEMPO might assist the reaction through methyl abstraction, wherein TEMPO acquires the methyl directly from **5**, and in which no free methyl radical is generated.

To differentiate between these two mechanisms, a double-label crossover experiment was performed (Scheme 4c). In this reaction, TEMPO was left out, in order to allow methyl radical to react uninhibited under otherwise similar reaction conditions. This reaction produced four methylated products: **6** and **6-*d*$_3$**, and **7** and **7-*d*$_3$**. Compound **6** is the protio-crossover product, and **7** is the protio-noncrossover product. Similarly, **6-*d*$_3$** is the deuterio-noncrossover product, and **7-*d*$_3$** is the deuterio-crossover product. The two crossover products were observed via GC–MS. To rule out possibility of partial crossover due to the interference of methyl radical generated by β-scission of the *tert*-butoxy radical, ^{1}H and ^{2}H NMR experiments were also performed: Examination of the crude reaction mixture by ^{1}H NMR spectroscopy characterized the ratio of **6**:**7** as ca. 1:1, meaning there was complete scrambling/complete loss of label integrity. Examination of the crude reaction mixture through analysis of deuterium signals by ^{2}H NMR spectroscopy characterized the ratio of **6-*d*$_3$**:**7-*d*$_3$** as ca. 1:1, further supporting complete scrambling/complete loss of label integrity. Therefore, it is most plausible that free methyl radical is generated from substrate under reaction conditions.

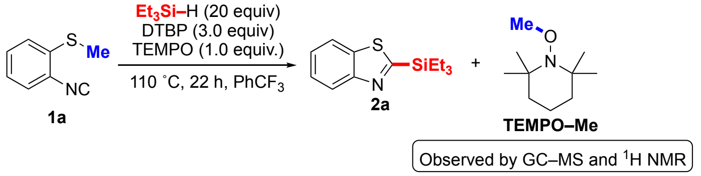
As mentioned in the introduction, we had the working hypothesis that the existing challenge of developing these reactions was the slow generation of the requisite silyl radical, especially compared to the fast undesired methyl radical pathways. This hypothesis would make hydrogen-atom-abstraction from the silane the rate determining step (RDS). Yet, experimentally, these relative rates had not been tested. To test this hypothesis, an intermolecular competition experiment was performed (Scheme 4e). Substrates **1a-*d*$_3$** and **1n** were chosen for this intermolecular competition experiment because their corresponding products (**2a** and **2n**) have high isolated yields (showing effective reactions), yet their ^{1}H NMR spectra show very different resonances, suggesting their electronics may be sufficiently different to produce differences in rates of cyclization. The key difference between this relative rate experiment (Scheme 4e) and the previously described crossover experiment (Scheme 4d) was the change in limiting reagent which created the presence of excess substrates. This modification in relative reagent quantities was performed to enable the accurate detection of rate differences between the two substrates.

Thus, in one pot, excess **1a-*d*$_3$** (1.0 equiv) and **1n** (1.0 equiv) were subjected to reaction conditions with di-*tert*-butylperoxide as the limiting reagent (0.5 equiv). A small amount of TEMPO (0.15 equiv) was added to allow partial formation of silylated products and partial formation of methylated products. Under these conditions, unreacted starting material remained at the end of the reaction, enabling effective characterization of relative rates of product formation. Six products were produced from this reaction: protiomethyl **6** and **7** (produced in ca. 1:1 as determined by ^{1}H NMR spectroscopy), deuteromethyl **6-*d*$_3$**:**7-*d*$_3$** (produced in ca. 1:1 as determined by ^{2}H NMR spectroscopy) and silylated **2a** and **2n** (produced in ca. 1:1, as determined by ^{1}H NMR spectroscopy). Thus, no substrate selectivity occurred for preferential reaction of **1a-*d*$_3$** or **1n**. Therefore, the substrate appears to have limited effect, which is consistent with the hypothesis that slow H-atom abstraction from the silane is the RDS as initially proposed; however, the product-determining step (regardless of position relative to RDS) may simply exbibit limited substrate selectivity.

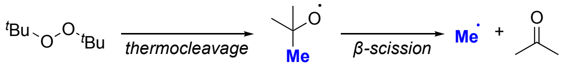
Scheme 4. Mechanistic Studies

Conclusion: TEMPO scavenges methyl radical equivalent

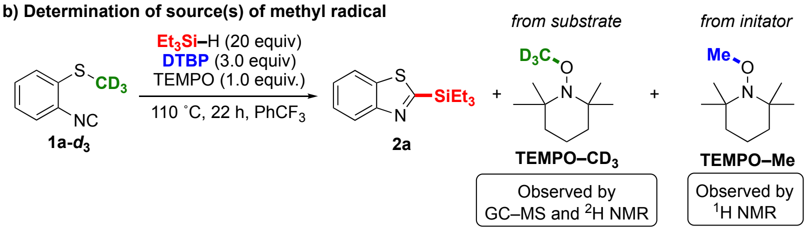
a) Determination of function of TEMPO



Conclusion: Both substrate and DTBP initiator are methyl radical sources

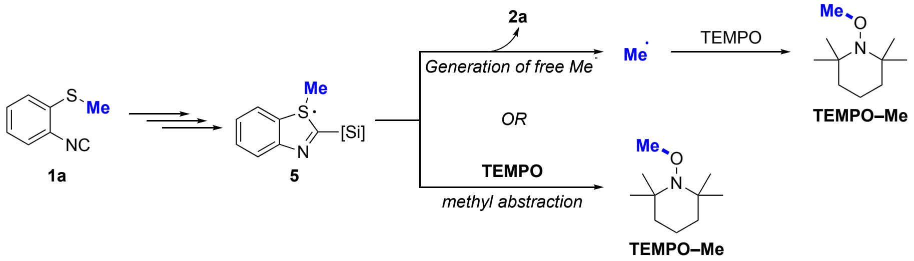


b) Determination of source(s) of methyl radical

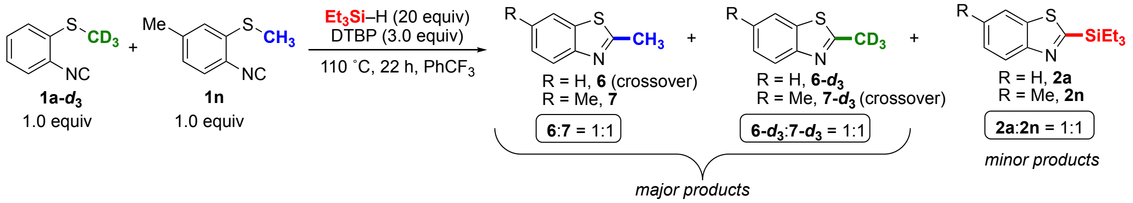


Conclusion: Full crossover occurs, therefore free methyl radical leaves substrate, followed by interception by TEMPO

c) Two plausible mechanisms of methyl radical interception by TEMPO

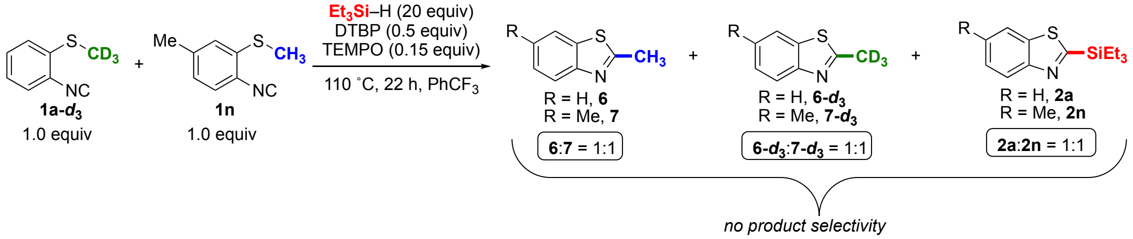


d) Crossover experiment in absence of TEMPO: is free methyl radical generated? Yes.

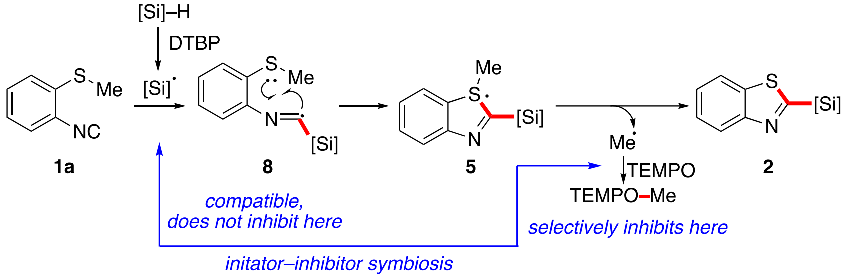


Conclusion: Substrate unlikely to be involved in rate determining step (RDS), so *H*-atom abstraction from silane is plausible RDS

e) Intermolecular competition experiment: with excess substrates and initiator as limiting reagent

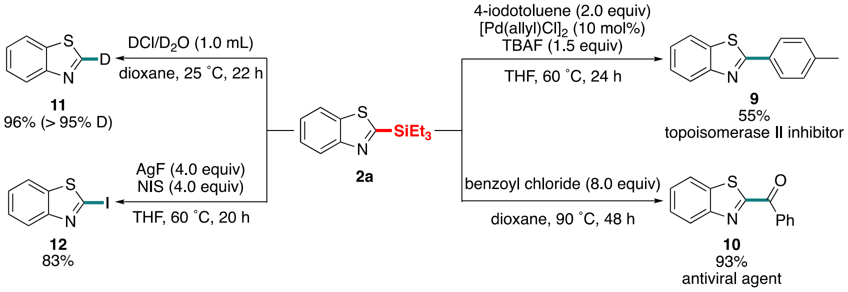


Scheme 5. Plausible Di-*tert*-Butylperoxide–TEMPO Symbiosis Silyl Radical Cascade Cyclization Mechanism



With the results of these mechanistic studies and the previous reports of cyclization reactions (other than silicon, i.e., phosphorus, boron, sulfur, and carbon; Scheme 1b),[5] a plausible mechanism is proposed (Scheme 5). In the first step, the radical initiator di-*tert*-butylperoxide fragments and reacts with silane to generate silyl radical.[35–38] Then, the silyl radical adds to the isocyano group[35] of **1a** to generate imidoyl-radical-containing intermediate **8**. This imidoyl radical then reacts with an electron from the lone pair on the sulfur in **8** to cyclize, forming intermediate **5**.[5,6] After release of free methyl radical, the desired product **2** is generated.[5] The released methyl radical is trapped by TEMPO to prevent undesired side reactions that otherwise presented unique complications to the development of the silicon-radical cyclization route. Key to the success of the method, TEMPO does not react competitively with the silyl radical or the needed initiation products of the radical initiator di-*tert*-butylperoxide under optimized reaction conditions. Thus, the radical initiator and radical scavenger act together productively in the di-*tert*-butylperoxide–TEMPO symbiosis mechanism.

Scheme 6. Downstream Functionalization



Synthetic Utility. To demonstrate the synthetic utility of reaction products **2**, a series of downstream functionalization reactions were performed (Scheme 6). Synthesis of **9**, a topoisomerase II inhibitor,[39] was achieved via Pd-catalyzed Hiyama cross-coupling reaction in 55%. The success of this Hiyama reaction is interesting because organosilicon agents that are sufficiently reactive for Hiyama coupling typically require silicon to be substituted with heteroatoms (such as halogens or oxygen), and only few notable examples with aryl(triethyl)silanes are reported.[40] By treating **2a** with excess benzoyl chloride without addition of fluoride or hydroxide, antiviral agent **10**[41,42] was synthesized in 93%. Another transformation of **2a** without addition of activating agent is demonstrated in the synthesis of **11**, wherein the triethylsilyl group was substituted with deuterium by treating **2a** with DCl/D_2O solution (96%). Lastly, 2-iodobenzothiazole (**12**) was synthesized by treating **2a** with NIS in the presence of AgF (83%).

In conclusion, a method has been developed for synthesis of 2-silylated benzothiazoles via silyl-radical-triggered cascade cyclization of 2-isocyanothioanisoles. The unique radical initiator–inhibitor symbiosis system solves the challenge of undesired side reactions triggered by methyl radical byproducts, as demonstrated by a series of mechanistic studies. The demonstration of this symbiosis strategy may inspire broader development of desirable radical reactions that have so far been limited by a slow atom-abstraction or cyclization step. The synthetic usefulness of the products is demonstrated by four downstream functionalization reactions, including an unorthodox Hiyama cross-coupling reaction towards a topoisomerase II inhibitor. This method provides a complementary tool to synthesize 2-silylated benzothiazole derivatives that cannot be prepared by the traditional lithiation method, thus offering broader access of 2-silylated benzothiazole derivatives as building blocks for organic synthesis.

EXPERIMENTAL SECTION

General Information. All reagents and solvents were used as received from commercial suppliers unless otherwise stated. Tetrahydrofuran (THF) and triethylamine (Et_3N) were dried by passing through an alumina column under argon pressure on a push still solvent system. Dioxane was dried over CaH_2, degassed using three freeze-pump-thaw cycles, and vacuum transferred before use. $PhCF_3$ was purchased from MilliporeSigma in a Sure/Seal bottle and used without further purification. Ultrapure water (Milli-Q H_2O) was generated by using Milli-Q Gradient A10 System. Reactions at elevated temperatures were heated and stirred using preheated aluminum pie-blocks. Analytical thin layer chromatography (TLC) was performed using Merck F_{250} plates and visualized under UV irradiation at 254 nm, or using a basic aqueous solution of potassium permanganate. Flash chromatography was conducted using a Teledyne Isco Combiflash® R_f 200 Automatic Flash Chromatography System, and Teledyne Isco Redisep® 35–70 µm silica gel columns or C18 reversed-phase columns. All proton and carbon nuclear magnetic resonance (^1H and ^{13}C NMR) spectra were recorded on a Bruker DRX-400 spectrometer, Bruker DRX-500 spectrometer outfitted with a cryoprobe, or a Bruker AVANCE-600 spectrometer. Deuterium nuclear magnetic resonance (^{2}H NMR) spectra were recorded on a Bruker AVANCE-600 spectrometer. Fluorine nuclear magnetic resonance (^{19}F NMR) spectra were recorded on a Bruker DRX-400 spectrometer or a Bruker AVANCE-600 spectrometer. All coupling constants are reported in Hertz (Hz). Chemical shifts were reported in ppm and referenced to the residual protiated solvent peak ($\delta_H = 7.26$ ppm for $CDCl_3$ and $\delta_H = 2.50$ ppm for d_6-DMSO in ^{1}H NMR spectroscopy experiments; $\delta_C = 77.16$ ppm for $CDCl_3$, $\delta_C = 39.52$ ppm and for d_6-DMSO in ^{13}C NMR spectroscopy experiments); ^{2}H NMR chemical shifts were reported in ppm and referenced to the deuterated solvent peak ($\delta_D = 7.26$ ppm for $CDCl_3$ in ^{2}H NMR spectroscopy experiments). High-resolution mass spectrometry (HRMS) data were obtained at the Mass Spectrometry Facility of the University of California, Irvine (UCI) using ESI and CI as ionization techniques with TOF mass analyzers, and the specific ionization technique and type of mass analyzer are noted in the characterization section of each individual compound. GC–MS experiments in mechanistic study section were acqured using an Agilent Technologies 7890A GC system equipped with an Agilent Technologies 5975C inert XL EI/CI MSD at the Dong Research Group at UCI. Reaction schemes and chemical structures of products and synthetic intermediates are shown in the Supplimental Information (SI).

Procedure A: Synthesis of 2-isocyanothioanisole Substrates

General remark: unless specifically stated, all reactions were performed in 5.00 mmol scale.

Step 1:

*2-Aminothioanisole derivatives (**SI-2**):* Prepared according to a modified reported procedure.[6] To a 100 mL round-bottom flask equipped with a condenser, 2-aminobenzothiazole derivative (**SI-1**)

(5.00 mmol, 1.00 equiv), KOH (10.1 g, 180. mmol, 36.0 equiv), and a stir bar were added, followed by adding Milli-Q water (35 mL). The resulting reaction mixture was heated to 120 °C using a pie-block for 24 h. Then, the reaction mixture was cooled to 25 °C, followed by addition of methyl iodide (0.31 mL, 5.0 mmol, 1.0 equiv) via a syringe, and the resulting mixture was stirred at 25 °C for 1 h. The crude reaction mixture was extracted with DCM (3 × 20 mL), and the combined organic layers were dried over $MgSO_4$ and then filtered through a Celite plug (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product (**SI-2**) was used for the next step without further purification.

Step 2:

General remark: the following procedure was also used for synthesis of (5-chloro-2-isocyanophenyl)(methyl)selane (**3**)

*N-(2-(methylthio)phenyl)formamide derivatives (**SI-3**):* Prepared according to a modified reported procedure.[43] To a 100 mL round-bottom flask equipped with a condenser, 2-(methylthio)aniline derivative (**SI-2**) (5.00 mmol, 1.0 equiv) and a stir bar were placed, followed by toluene (13 mL) and formic acid (2.6 mL, 5.0 mmol, 1.0 equiv). The resulting reaction mixture was heated to 110 °C in an aluminum pie-block for 20 h while stirring. Then, the reaction mixture was cooled to 25 °C, followed by quenching with saturated $NaHCO_3$(aq) (ca. 80 mL). The organic phase was further rinsed with saturated $NaHCO_3$(aq) (3 × 5 mL), all aqueous phases were combined, and the combined aqueous phases were extracted with DCM (3 × 20 mL). (The pH of the combined aqueous phase was determined by using pH paper, and if the pH value was below 7, more rounds of saturated $NaHCO_3$(aq) rinse were performed until the combined aqueous phases showed a pH above or equal to 7.) The combined organic phases were dried over $MgSO_4$ and then filtered through a Celite plug (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product (**SI-3**) was used for the next step without further purification.

*2-isocyanothioanisole derivatives (**1**):* Prepared according to a modified reported procedure.[6] To a 100 mL oven-dried round-bottom flask, *N*-(2-(methylthio)phenyl)formamide derivative (**SI-3**) (5.00 mmol, 1.0 equiv) and a stir bar were placed. The flask was capped with a septum. The septum was pierced with a needle leading to a Schlenk line. The system was degassed on high vacuum for ca. 5 min, following by refilling the system with N_2. Under dynamic N_2, 13 mL dry THF and Et_3N (2.8 mL, 20. mmol, 4.0 equiv) were added via two separate syringes, followed by cooling the resulting solution to 0 °C using an ice bath. At this temperature, $POCl_3$ (0.93 mL, 10. mmol, 2.0 equiv) was added dropwise under dynamic N_2, and the resulting solution was stirred at 0 °C for 1 h under N_2. The reaction was quenched with saturated $NaHCO_3$(aq) (ca. 30 mL), and the aqueous layer was extracted with DCM (3 × 20 mL). The combined organic phases were dried over $MgSO_4$ and then filtered through a Celite plug (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product was purified by silica gel flash column chromatography, using the specific solvents described below. The purified product was stored in a –30 °C freezer of a N_2- or Ar-filled glovebox (to avoid previously observed gradual decomposition at room temperature (ca. 25 °C) in air).

*(2-isocyanophenyl)(methyl)sulfane (**1a**):* Prepared according to Procedure A (10.0 mmol scale), and purified by flash column chromatography (silica, 0−25% EtOAc in hexanes) to afford a brown oil (1.37 g, 92%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.43–7.32 (m, 2H), 7.26–7.22 (m, 1H), 7.21–7.12 (m, 1H), 2.53 (s, 3H). The ^{1}H NMR spectrum is in agreement with previously reported spectral data,[9]

*(2-isocyanophenyl)(methyl-d$_3$)sulfane (**1a-d$_3$**)*: Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a dark red liquid (0.609 g, 80%). ^{1}H NMR (600 MHz, CDCl$_3$): δ 7.427.30 (m, 2H), 7.29–7.20 (m, 1H), 7.15 (td, J = 7.7, 1.3 Hz, 1H). ^{2}H NMR (92 MHz, CDCl3): δ 2.51 (s, 3D). The ^{1}H NMR spectrum is in agreement with previously reported spectral data,[6] and the ^{2}H NMR spectrum is newly reported herein. (^{13}C satellites are visible alongside the solvent peak in the ^{2}H NMR spectrum.)

*(5-fluoro-2-isocyanophenyl)(methyl)sulfane (**1f**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−20% EtOAc in hexanes) to afford a yellow solid (0.403 g, 48%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.33 (dd, *J* = 8.7, 5.2 Hz, 1H), 6.91 (dd, *J* = 9.1, 2.7 Hz, 1H), 6.87–6.77 (m, 1H), 2.52 (s, 3H). This spectrum is in agreement with previously reported spectral data.[44]

*(5-chloro-2-isocyanophenyl)(methyl)sulfane (**1g**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−20% EtOAc in hexanes) to afford a yellow solid (0.576 g, 63%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.27 (d, *J* = 8.5 Hz, 1H), 7.17 (d, *J* = 2.1 Hz, 1H), 7.12

(dd, *J* = 8.4, 2.1 Hz, 1H), 2.53 (s, 3H). This spectrum is in agreement with previously reported spectral data.[44]

*(3-chloro-2-isocyanophenyl)(methyl)sulfane (**1h**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−20% EtOAc in hexanes) to afford a slightly yellow solid (0.154 g, 17%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.29 (t, *J* = 8.0 Hz, 1H), 7.24 (dd, *J* = 8.1, 1.4 Hz, 1H), 7.12 (dd, *J* = 7.8, 1.4 Hz, 1H), 2.54 (s, 3H). This spectrum is in agreement with previously reported spectral data.[45]

*5-bromo-2-isocyanophenyl)(methyl)sulfane (**1i**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a beige solid (0.878 g, 77%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.33 (d, *J* = 2.0 Hz, 1H), 7.30–7.26 (m, 1H), 7.20 (d, *J* = 8.4 Hz, 1H), 2.53 (s, 3H). This spectrum is in agreement with previously reported spectral data.[44]

*4-bromo-2-isocyanophenyl)(methyl)sulfane (**1j**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a light yellow solid (0.796 g, 70%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.55–7.45 (m, 2H), 7.11 (d, *J* = 8.4 Hz, 1H), 2.51 (s, 3H). This spectrum is in agreement with previously reported spectral data.[44]

*(2-isocyano-5-(trifluoromethoxy)phenyl)(methyl)sulfane (**1k**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a light yellow solid (0.635 g, 54%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.38 (d, *J* = 8.6 Hz, 1H), 7.03 (s, 1H), 7.00

(ddd, *J* = 8.6, 2.4, 1.2 Hz, 1H), 2.54 (s, 3H). This spectrum is in agreement with previously reported spectral data.[46]

*(4-isocyano-1,3-phenylene)bis(methylsulfane) (**1l**):* Prepared according to Procedure A using 6-thiocyanatobenzo[*d*]thiazol-2-amine (**SI-1l**) as starting material, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a yellow solid (0.331 g, 34%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.32 –7.14 (m, 1H), 7.05 (d, *J* = 1.9 Hz, 1H), 6.97 (dd, *J* = 8.3, 2.0 Hz, 1H), 2.52 (s, 3H), 2.50 (s, 3H). This spectrum is in agreement with previously reported spectral data.[45]

*(2-isocyano-5-methoxyphenyl)(methyl)sulfane (**1m**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−25% EtOAc in hexanes) to afford a yellow solid (0.624 g, 70%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.26 (d, *J* = 4.4 Hz, 1H), 6.72 (d, *J* = 2.6 Hz, 1H), 6.64 (dd, *J* = 8.7, 2.6 Hz, 1H), 3.83 (s, 3H), 2.50 (s, 3H).This spectrum is in agreement with previously reported spectral data.[9]

*(2-isocyano-5-methylphenyl)(methyl)sulfane (**1n**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a yellow solid (0.129 g, 16%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.23 (d, *J* = 8.0 Hz, 1H), 7.06–7.01 (m, 1H), 6.94 (ddd, *J* = 8.1, 1.8, 0.8 Hz, 1H), 2.51 (s, 3H), 2.37 (s, 3H). This spectrum is in agreement with previously reported spectral data.[9]

*(2-isocyano-3-methylphenyl)(methyl)sulfane (**1o**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a yellow solid (0.129 g, 16%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.24 (d, *J* = 7.8 Hz, 1H), 7.10–7.01 (m, 2H), 2.51 (s, 3H), 2.43 (s, 3H). This spectrum is in agreement with previously reported spectral data.[44]

*(2-isocyano-5-(methylsulfonyl)phenyl)(methyl)sulfane (**1p**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−70% EtOAc in hexanes) to afford a yellow solid (0.513 g, 45%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.75 (d, *J* = 1.8 Hz, 1H), 7.70 (dd, *J* = 8.2, 1.9 Hz, 1H), 7.52 (d, *J* = 8.2 Hz, 1H), 3.08 (s, 3H), 2.60 (s, 3H). This spectrum is in agreement with previously reported spectral data.[9]

*(5-(but-3-en-1-yloxy)-2-isocyanophenyl)(methyl)sulfane (**1q**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−15% EtOAc in hexanes) to afford a brown liquid (0.079 g, 7%). ^{1}H NMR (600 MHz, CDCl$_3$): δ 7.35–7.17 (m, 1H), 6.72 (d, *J* = 2.6 Hz, 1H), 6.63 (ddd, *J* = 8.7, 2.6, 1.1 Hz, 1H), 5.89 (ddtd, *J* = 17.0, 10.2, 6.7, 1.1 Hz, 1H), 5.37–4.82 (m, 2H), 4.03 (td, *J* = 6.6, 1.1 Hz, 2H), 2.55 (qq, *J* = 6.6, 1.3 Hz, 2H), 2.50 (s, 3H). ^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$): δ 167.0, 159.6, 138.2, 134.0, 128.4, 118.0, 117.6, 112.4, 110.5, 67.8, 33.6, 15.1. HRMS (CI-TOF): m/z calcd for $C_{12}H_{13}NOS$ ($[M]^+$) = 219.0718, found 219.0716.

*(5-chloro-2-isocyanophenyl)(methyl)selane (**3**):* Prepared according to Procedure A, and purified by flash column chromatography (silica, 0−25% EtOAc in hexanes) to afford a brown solid (0.3573 g, 31%). ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.53–6.96 (m, 3H), 2.39 (s, 3H).^{13}C{^{1}H} NMR

(125 MHz, $CDCl_3$): δ 169.2, 132.2, 130.7, 130.1, 129.7, 127.2, 7.0. HRMS (CI-TOF): m/z calcd for C_8H_6ClNSe ($[M]^+$) = 230.9351, found 230.9346. It was observed that this product can either decompose on column or in air during the concentration process; after the first column chromatography process was complete, the chromatogram showed a good separation from impurities. However, the ^1H NMR spectrum indicated that the purified product still contained an/some impurity/ies. Therefore, a second column chromatography process was performed, but the second chromatogram showed signals of undesired product(s) that had presumably already been removed in the first purification. These impurities can be seen in the ^1H NMR spectrum of **3** in the SI.

Synthesis of 6-(but-3-en-1-yloxy)benzo[*d*]thiazol-2-amine (SI-1q)

Prepared according to a modified reported procedure.[47] To a 100 mL round-bottom flask equipped with a condenser, 2-amino-6-hydroxybenzothiazole (**SI-1-OH**) (0.831 g, 5.00 mmol, 1.00 equiv), K_2CO_3 (0.831 g, 5.00 mmol, 1.00 equiv), BTEAC (0.0570 g, 0.025 mmol, 5.00 mol %), and a stir bar were placed, followed by adding 20 mL MeCN and homoallylic bromide (2.6 mL, 5.0 mmol, 1.0 equiv). The resulting reaction mixture was heated to 100 °C a pie-block for 20 h. Then, the solvent was removed in vacuo. The crude reaction mixture was re-suspended in DI water (ca. 40 mL), and the resulting aqueous phase was extracted with DCM (3 × 20 mL). All organic phases were combined and dried over $MgSO_4$. The drying agent was removed via Celite plug vacuum filtration (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product (**SI-1q**) was used for the next step (Step 1 of Procedure A) without further purification.

Synthesis of 2-((methyl-*d*$_3$)thio)aniline (SI-2a-*d*$_3$)

Prepared according to a modified reported procedure.[6] To a 100 mL oven-dried septum capped round-bottom flask charged with a stir bar, 2-aminothiophenol (0.54 mL, 5.0 mmol, 1.0 equiv) and 5 mL dry MeOH was added via syringes, and the resulting solution was cooled to 0 °C under N_2. To an over-dried scintillation, KO^{t}Bu (0.561 g, 5.00 mmol, 1.00 equiv) was charged in a N_2-filled glovebox, and the vial was capped with a septum cap and sealed with electrical tape. Then, the vial was removed from the glovebox, and connected to a N_2 Schlenk line. Under dynamic N_2, 15 mL dry MeOH was added using syringe. After KO^{t}Bu was fully dissolved, the resulting solution was added to the reaction flask dropwise at 0 °C under N_2, and the resulting mixture was stirred at this temperature for 45 min before adding CD_3I (0.32 mL, 5.0 mmol, 1.0 equiv) using a syringe under N_2. The resulting solution was stirred for ca. 1 h at 25 °C under N_2 before being quenched with saturated NH_4Cl(aq) (ca. 40 mL). The resulting aqueous phase was extracted with DCM (3 × 20 mL). All organic phases were combined and dried over $MgSO_4$. The drying agent was removed via Celite plug vacuum filtration (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product (**SI-2a-*d*$_3$**) was used for the next step (Step 2 of Procedure A) without further purification.

Synthesis of 4-chloro-2-(methylselanyl)aniline (SI-6)

Prepared according to a modified reported procedure.[48] To a 100 mL round-bottom flask, MeSeSeMe (0.276 g, 1.47 mmol, 0.54 equiv) and a stir bar were placed, followed by adding 25 mL MeOH. To the resulting solution, $NaBH_4$ (0.226 g, 5.98 mmol, 2.2 equiv) was added slowly while stirring at 25 °C. After the solution color disappeared, substrate **SI-4** (1.84 g, 5.00 mmol, 1.00 equiv) was added slowly, and the reaction mixture was stirred at 25 °C for 21 h. The reaction was quenched with DI water (ca. 40 mL), and the resulting aqueous phase was extracted with DCM (3 × 20 mL). All organic phases were combined and dried over $MgSO_4$. The drying agent was removed via Celite plug vacuum filtration (Celite in a medium glass frit funnel). The filtrate was concentrated in vacuo, and the crude product (**SI-5**) was used for the next step without further purification.

*4-chloro-2-(methylselanyl)aniline (**SI-6**):* Prepared according to a modified reported procedure.[48] To a 100 mL oven-dried round-bottom flask equipped with a condenser, **SI-5** (9.20 mmol, 1.00 equiv), Zn (5.63 g, 86.2 mmol, 9.4 equiv), NH_4Cl (2.95 g, 55.2 mmol, 6.0 equiv), and a stir bar were placed, followed by capping the system with a septum. The system was degassed on high vacuum for ca. 5 min, following by refilling the system with N_2 using a N_2 balloon. Under static N_2, 35 mL dry THF was added via a syringe, followed by heating the resulting suspension to 80 °C using pie-block for 22 h under static N_2. Then, the crude reaction was filtered through a Celite plug (Celite in a medium glass frit funnel) and the filtration cake was rinsed with DCM (3 × 20 mL). All organic phases were combined and dried over $MgSO_4$. The drying agent was removed via Celite plug vacuum filtration (Celite in a medium glass frit funnel), and the filtrate was concentrated in vacuo. The crude product was the next step (Step 2 of Procedure A) without further purification.

Procedure B: Reaction optimization

In a N_2-filled glovebox, substrate **1a** (0.0298 g, 0.20 mmol, 1.0 equiv), TEMPO, and a stir bar were charged into a 1 dram vial, followed by adding Et_3SiH, radical initiator, and dry solvent via syringes. (The equiv of TEMPO, Et_3SiH, radical initiator, and solvent were variable as indicated in Table 1.) Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using an aluminum pie-block in the glovebox. After 22 h, the reaction was cooled to 25 °C and removed from the glovebox. The solvent was removed in vacuo. [Note: For the nonvolatile solvents DMA and DMSO, an alternative procedure was used: solvents were removed by rinsing the crude reaction mixture with DI water (3 × 5 mL). The combined aqueous layers were extracted with DCM (3 × 5 mL). Then, all organic layers were combined and concentrated in vacuo. To avoid losing material, no drying agent was used.] To the residue was added 1,1,2,2-tetrachloroethane (TeCA) as the internal standard via a Pasteur pipette while the sample sat on a balance. The mass of the added TeCA was recorded, $CDCl_3$ (0.4 mL) was added, and a single-scan ^1H NMR spectrum was acquired for the calculation of conversion to products and ^1H NMR spectroscopy yields. Assignments for the following byproducts were referred to previously reported spectral information: 2-methylbenzo[*d*]thiazole,[49] 2-benzylbenzo[*d*]thiazole,[50] 2-(benzo[*d*]thiazol-2-yl)-2-methylpropanenitrile[51]; assignment for byproduct (2-(*tert*-butoxy)benzo[*d*]thiazole) was based on the following characteristic signals: δ 7.97 (m, 2H) and the O*t*Bu signal 1.10 (s, 9H).

Procedure C: Synthesis of 2-silyl benzothiazole and 2-silyl benzoselenazole derivatives

In a N_2-filled glovebox, substrate **1** or **3** (0.20 mmol, 1.0 equiv), TEMPO (0.0313 g, 0.20 mmol, 1.0 equiv), and a stir bar were charged into a 1 dram vial, followed by adding silane (4.0 mmol, 20. equiv), DTPB (0.11 mL, 0.60 mmol, 3.0 equiv), and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using a pie-block in the glovebox while stirring at this temperature. After 22 h, the reaction was cooled to 25 °C, and the solvent was removed in vacuo to afford the crude product. The purified product was obtained by flash column chromatography (normal phase and/or reverse phase[52]) or preparatory thin layer chromatography (prep TLC). The chromatography or prep TLC solvents are described below.

Attempted Alternative Synthesis of 2-(triethylsilyl)benzo[*d*]thiazole (2a) via Slow Addition (Entry 15, Table 1)

In a N_2-filled glovebox, to a 20 mL scintillation vial (“reaction vial”) charged with a stir bar was added Et_3SiH (0.16 mL, 1.0 mmol, 5.0 equiv) and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped with a screw-on septum cap and sealed with electrical type. To a 1 dram vial, substrate **1a** (0.0298 g, 0.20 mmol, 1.0 equiv) and TEMPO (0.0313 g, 0.20 mmol, 1.0 equiv) were charged, followed by adding DTPB (0.11 mL, 0.60 mmol, 3.0 equiv) and 1.0 mL dry $PhCF_3$ via syringes. Then, the resulting solution was transferred into a 3 mL syringe with a long needle, and the needle was inserted to the reaction vial through the septum in the septum cap. The conjunction between the needle and the septum was sealed with grease as an added precaution against loss of solvent upon heating. Then, the 3 mL syringe was then placed onto a syringe pump, and the reaction vial with the reaction solution was heated to 110 °C using a preheated aluminum pie-block in the glovebox while stirring at this temperature. The solution in the 3 mL syringe was slowly added to the reaction vial by the syringe pump over 10 h, and upon completion of addition, the reaction was stirred at 110 ˚C for another 12 h, and then allowed to cool to ambient temperature. The reaction vial was removed from the glovebox, and solvent was removed in vacuo. The concentrated residue was dissolved in $CDCl_3$. An ^1H NMR spectrum was acquired. However, the ^1H NMR spectrum showed significant amount of unidentifiable decomposition product and only trace amount of desired product (<5%).

*2-(triethylsilyl)benzo[d]thiazole (**2a**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a colorless liquid (0.0352 g, 71%). ^1H NMR (500 MHz, $CDCl_3$): δ 8.19 (ddd, J = 8.2, 1.2, 0.7 Hz, 1H), 7.97 (ddt, J = 8.0, 1.3, 0.6 Hz, 1H), 7.48 (ddt, J = 8.3, 7.1, 0.9 Hz, 1H), 7.40 (ddt, J = 8.1, 7.1, 0.9 Hz, 1H), 1.12–1.04 (m, 9H), 1.03–0.95 (m, 6H). This spectrum is in agreement with previously reported spectral data.[53]

*2-(triisopropylsilyl)benzo[d]thiazole (**2b**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a colorless liquid (0.0293 g, 50%). ^1H NMR (400 MHz, d_6-DMSO): δ 8.17 (dt, J = 7.7, 1.9 Hz, 2H), 7.63–7.41 (m, 2H), 1.47 (h, J = 7.4

Hz, 3H), 1.15 (d, *J* = 7.4 Hz, 18H). This spectrum is in agreement with previously reported spectral data.[54]

2-(1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)benzo[d]thiazole (***2c***): Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0–5% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0671 g, 88%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.07 (ddd, *J* = 8.1, 1.2, 0.6 Hz, 1H), 7.90 (ddd, *J* = 7.9, 1.3, 0.7 Hz, 1H), 7.42 (ddd, *J* = 8.2, 7.1, 1.2 Hz, 1H), 7.33 (ddd, *J* = 7.9, 7.1, 1.2 Hz, 1H), 0.30 (s, 27H). ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$): δ 172.8, 156.6, 137.3, 125.3, 124.4, 123.0, 121.1, 1.1. HRMS (ESI-TOF): m/z calcd for $C_{16}H_{31}NSSi_4H$ ([M + H]$^+$) = 382.1333, found 382.1323.

6-fluoro-2-(triethylsilyl)benzo[d]thiazole (***2f***): Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0–10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a slightly yellow liquid (0.0320 g, 60%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.11 (ddd, *J* = 8.9, 4.8, 1.1 Hz, 1H), 7.63 (ddd, *J* = 8.1, 2.6, 1.0 Hz, 1H), 7.22 (tdd, *J* = 8.9, 2.6, 1.1 Hz, 1H), 1.07 (td, *J* = 7.8, 7.2, 1.2 Hz, 9H), 0.99 (s, 6H). ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$): δ 174.7 (d, *J* = 3.6 Hz), 161.5, 156.5 (d, *J* = 1026.2 Hz), 137.3 (d, *J* = 11.4 Hz), 124.3 (d, *J* = 9.5 Hz), 114.6 (d, *J* = 25.1 Hz), 107.6 (d, *J* = 26.2 Hz), 7.38, 3.8. ^{19}F NMR (565 MHz, $CDCl_3$): δ –116.94 (q, *J* = 7.8 Hz). HRMS (CI-TOF): m/z calcd for $C_{13}H_{18}FNSSi$ ([M]$^+$) = 267.0913, found 267.0922.

*6-chloro-2-(triethylsilyl)benzo[d]thiazole (**2g**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0303 g, 53%). ^{1}H NMR (600 MHz, CDCl$_3$): δ 8.08 (dd, *J* = 8.8, 1.3 Hz, 1H), 7.94 (q, *J* = 1.3, 0.7 Hz, 1H), 7.44 (ddt, *J* = 8.7, 2.1, 1.0 Hz, 1H), 1.06 (ddt, *J* = 8.1, 7.3, 1.1 Hz, 9H), 0.97 (dddt, *J* = 8.8, 8.0, 6.9, 1.2 Hz, 6H).^{13}C{^{1}H} NMR (151 MHz, CDCl): δ 175.6, 154.9, 137.5, 131.3, 126.6, 124.1, 121.3, 7.4, 3.8. HRMS (ESI-TOF): m/z calcd for $C_{13}H_{18}ClNSSiH$ ([M + H]$^+$) = 284.0696, found 284.0696.

*4-chloro-2-(triethylsilyl)benzo[d]thiazole (**2h**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0276 g, 49%). ^{1}H NMR (600 MHz, CDCl$_3$): δ 7.85 (dt, *J* = 8.0, 1.4 Hz, 1H), 7.49 (dt, *J* = 7.7, 1.3 Hz, 1H), 7.31 (td, *J* = 7.9, 1.5 Hz, 1H), 1.15–1.05 (m, 9H), 0.99 (dtt, *J* = 8.7, 7.0, 1.6 Hz, 6H). ^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$): δ 176.1, 153.2, 138.0, 128.5, 126.0, 125.6, 120.2, 7.4, 3.9. HRMS (CI-TOF): m/z calcd for $C_{13}H_{18}ClNSSi$ ([M]$^+$) = 283.0618, found 283.0623.

*6-bromo-2-(triethylsilyl)benzo[d]thiazole (**2i**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0276 g, 42%). ^{1}H NMR (600 MHz, CDCl$_3$): δ 8.10 (t, *J* = 1.9 Hz, 1H), 8.02 (dd, *J* = 8.7, 1.6 Hz, 1H), 7.57 (dt, *J* = 8.7, 2.0 Hz, 1H), 1.12–1.02 (m, 9H), 1.01–0.87 (m, 6H). ^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$): δ 175.7, 155.2, 138.0, 129.3, 124.5, 124.2, 119.1, 7.4, 3.8. HRMS (CI-TOF): m/z calcd for $C_{13}H_{18}BrNSSi$ ($[M]^+$) = 327.0117, found 327.0114.

*5-bromo-2-(triethylsilyl)benzo[d]thiazole (**2j**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a colorless liquid (0.0020 g, 3% mass recovery; ^{1}H NMR spectrum showed signals for grease which could either come from solvent, glassware, or product. No further purification was performed due to low isolation mass). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.42–8.24 (m, 1H), 7.82 (dt, *J* = 8.4, 0.8 Hz, 1H), 7.50 (dt, *J* = 8.5, 1.5 Hz, 1H), 1.12–0.93 (m, 15H). Apparent $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$): δ 128.2, 126.4, 122.9, 7.4, 3.8. (Some of the aromatic signals were not detectable due to small quantity of sample.) HRMS (CI-TOF): m/z calcd for $C_{13}H_{18}BrNSSi$ ($[M]^+$) = 327.0117, found 327.0113.

*2-(triethylsilyl)-6-(trifluoromethoxy)benzo[d]thiazole (**2k**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−5% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0361 g, 54%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.17 (dd, *J* = 8.8, 1.6 Hz, 1H), 7.82 (dd, *J* = 2.4, 1.2 Hz, 1H), 7.45–7.31 (m, 1H), 1.15 –1.02 (m, 9H), 1.02–0.87 (m, 6H). $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$): δ 176.6, 154.8, 146.7 (d, *J* = 2.0 Hz), 137.1, 124.2, 119.8, 114.1, 7.4, 3.8. ^{19}F NMR (565 MHz, $CDCl_3$): δ –58.03. HRMS (CI-TOF): m/z calcd for $C_{14}H_{18}F_3ONSSi$ ($[M]^+$) = 333.0830, found 333.0832.

*6-(methylthio)-2-(triethylsilyl)benzo[d]thiazole (**2l**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0335 g, 57%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.06 (dd, *J* = 8.6, 0.9 Hz, 1H), 7.90–7.72 (m, 1H), 7.39 (ddd, *J* = 8.6, 1.9, 0.9 Hz, 1H), 2.55 (d, *J* = 1.0 Hz, 3H), 1.16–1.02 (m, 9H), 0.97 (dtt, *J* = 8.7, 6.9, 1.3 Hz, 6H). $^{13}C\{^{1}H\}$ NMR (151 MHz, $CDCl_3$): δ 173.8, 154.4, 137.3, 135.9, 125.6, 123.4, 118.9, 16.8, 7.4, 3.8. HRMS (ESI-TOF): m/z calcd for $C_{14}H_{21}NS_2SiH$ ($[M + H]^+$) = 296.0963, found 296.0967.

*2-(triethylsilyl)-6-(trifluoromethoxy)benzo[d]thiazole (**2m**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−15% EtOAc in hexanes to afford a light yellow liquid (0.0353 g, 63%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.05 (d, *J* = 8.9 Hz, 1H), 7.40 (d, *J* = 2.6 Hz, 1H), 7.09 (dd, *J* = 8.4, 2.4 Hz, 1H), 3.88 (d, *J* = 1.2 Hz, 3H), 1.15–1.01 (m, 9H), 1.01–0.83 (m, 6H). $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$): δ 171.8, 157.9, 151.2, 137.7, 123.9, 115.5, 103.7, 55.9, 7.4, 3.8. HRMS (CI-TOF): m/z calcd for $C_{14}H_{18}F_3NOSSi$ ($[M]^+$) = 333.0830, found 333.0832.

*6-methyl-2-(triethylsilyl)benzo[d]thiazole (**2n**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0314 g, 60%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.06 (d, *J* = 8.3 Hz, 1H), 7.81–7.70 (m, 1H), 7.29 (dd, *J* = 8.4, 1.7 Hz, 1H), 2.50 (s, 3H), 1.15–1.03 (m, 9H), 1.01–0.92 (m, 6H). $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$): δ 173.4, 154.6, 136.5, 135.2, 127.4, 123.0, 121.4, 21.6, 7.4, 3.8. HRMS (ESI-TOF): m/z calcd for $C_{14}H_{21}NSSiH$ ($[M + H]^+$) = 264.1242, found 264.1241.

*4-methyl-2-(triethylsilyl)benzo[d]thiazole (**2o**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by the second normal phase column chromatography (100% pentanes) to afford a light yellow liquid (0.0383 g, 73%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 7.79 (ddd, *J* = 8.1, 2.0, 1.2 Hz, 1H), 7.42–7.16 (m, 3H), 2.82 (t, *J* = 0.8 Hz, 3H), 1.14–1.04 (m, 9H), 1.01–0.91 (m, 6H). $^{13}C\{^1H\}$ NMR (151 MHz, CDCl): δ 172.8, 155.8, 136.2, 133.6, 126.1, 124.9, 119.0, 18.7, 7.4, 4.0. HRMS (ESI-TOF): m/z calcd for $C_{14}H_{21}NSSiH$ ($[M + H]^+$) = 264.1242, found 264.1244.

*6-(methylsulfonyl)-2-(triethylsilyl)benzo[d]thiazole (**2p**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−25% EtOAc in hexanes) to afford a light yellow liquid (0.0164 g, 25%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.61 (d, *J* = 1.9 Hz, 1H), 8.32 (d, *J* = 8.6 Hz, 1H), 8.01 (dd, *J* = 8.6, 1.9 Hz, 1H), 3.12 (s, 3H), 1.17–1.04 (m, 9H), 1.04–0.82 (m, 6H). $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$): δ 181.4, 158.9, 137.0, 136.9, 124.4, 124.4, 122.3, 45.1, 7.3, 3.7. HRMS (ESI-TOF): m/z calcd for $C_{14}H_{21}NO_2S_2SiH$ ($[M + H]^+$) = 328.0861, found 328.0863.

*6-(but-3-en-1-yloxy)-2-(triethylsilyl)benzo[d]thiazole (**2q**)*: Prepared according Procedure D, and purified by a normal phase column chromatography (silica, 0−15% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0407 g, 64%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.05 (d, *J* = 9.0 Hz, 1H), 7.40 (d, *J* = 2.5 Hz, 1H), 7.09 (dd, *J* = 9.0, 2.4 Hz, 1H), 5.92 (ddt, *J* = 16.9, 10.2, 6.7 Hz, 1H), 5.34–5.01 (m, 2H), 4.08 (t, *J* = 6.7 Hz, 2H), 2.58 (qd, *J* = 6.7, 1.5 Hz, 2H), 1.06 (t, *J* = 7.8 Hz, 9H), 1.00–0.75 (m, 6H). $^{13}C\{^1H\}$ NMR (151 MHz,

$CDCl_3$): δ 171.8, 157.2, 151.2, 137.6, 134.4, 123.8, 117.3, 115.9, 104.7, 68.0, 33.8, 7.4, 3.8. HRMS (ESI-TOF): m/z calcd for $C_{17}H_{25}NOSSiH$ ($[M + H]^+$) = 320.1505, found 320.1521.

*6-(but-3-en-1-yloxy)-2-(triethylsilyl)seleno[d]thiazole (**4**)*: Prepared according Procedure D, and purified by a prep TLC (10% EtOAc in hexanes), followed by reverse phase column chromatography (C18, 100% MeCN) to afford a light yellow liquid (0.0263 g, 40%). This compound was found to decompose at ambient temperature in air over the course of one day, and therefore was stored –20 ˚C under nitrogen. ^1H NMR (600 MHz, $CDCl_3$): δ 8.38–8.12 (m, 1H), 7.92 (dd, *J* = 8.4, 1.2 Hz, 1H), 7.31 (ddd, *J* = 8.5, 2.1, 1.3 Hz, 1H), 1.14–1.03 (m, 9H), 0.99–0.87 (m, 6H). $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$): δ 184.5, 159.2, 137.6, 131.9, 125.7, 125.6, 125.0, 7.4, 4.0. HRMS (ESI-TOF): m/z calcd for $C_{13}H_{18}ClN^{76}SeSiH$ ($[M + H]^+$) = 328.0168, found 328.0157.

Gram-Scale Synthesis of 2a

In a N_2-filled glovebox, substrate **1a** (1.09 g, 7.31 mmol, 1.0 equiv), TEMPO (1.14 g, 7.31 mmol, 1.0 equiv), and a stir bar were charged into an oven-dried 100 mL round-bottom flask, followed by addition of Et_3SiH (23 mL, 0.15 mol, 20. equiv), DTPB (4.0 mL, 22 mmol, 3.0 equiv), and dry $PhCF_3$ (30 mL) via syringes. Then, an air condenser (Vigreux Distilling Column) was connected to the reaction flask, and the top of the condenser was sealed with a septum. The reaction mixture was heated to 110 °C using a pie-block in the glovebox while stirring at this temperature. After 22 h, the reaction was cooled to 25 °C, and the flask was removed from the glovebox. The solvent was removed in vacuo to afford the crude product, which was purified by a normal phase column chromatography (silica, 0−10% EtOAc in hexanes), followed by a reverse phase column chromatography (C18, 100% MeCN) to afford a colorless liquid (1.08 g, 60%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.19 (d, *J* = 8.2 Hz, 1H), 7.97 (d, *J* = 8.0 Hz, 1H), 7.53–7.44 (m, 1H), 7.44–7.36 (m, 1H), 1.12–1.04 (m, 9H), 1.03–0.91 (m, 6H). This spectrum is in agreement with previously reported spectral data.[53]

Hiyama cross-coupling for synthesis of 2-(*p*-tolyl)benzo[*d*]thiazole (9)

Prepared according to a modified reported procedure.[55] In a N_2-filled glovebox, 2-(triethylsilyl)benzo[*d*]thiazole **2a** (0.0374 g, 0.150 mmol, 1.0 equiv), 4-iodotoluene (0.0654 g, 0.300 mmol, 2.0 equiv), $[Pd(allyl)Cl]_2$ (0.0055 g, 0.015 mmol, 10 mol%), and a stir bar were charged into a 1 dram vial. Dry THF (0.6 mL) was added via a syringe. To the resulting solution, TBAF (0.23 mL of 1.0 M THF solution in a Sure/Seal bottle, 0.23 mmol, 1.5 equiv) was added via a syringe. The reaction vial was capped and the reaction mixture was heated to 60 °C using a pie-block in the glovebox while stirring at this temperature. After 24 h, the reaction was cooled to 25 °C, and removed from the glovebox. The solvent was removed in vacuo to afford the crude product, which was purified via a flash column chromatography (0–15% EtOAc in hexanes) to afford the purified product as a yellow solid (0.019 g, 55%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.11–8.04 (m, 1H), 7.99 (d, *J* = 8.0 Hz, 2H), 7.93–7.85 (m, 1H), 7.48 (tt, *J* = 7.1, 1.2 Hz, 1H), 7.37 (ddd, *J* = 8.2, 7.2, 1.1 Hz, 1H), 7.30 (d, *J* = 7.9 Hz, 2H), 2.43 (s, 3H). This spectrum is in agreement with previously reported spectral data.[56]

Synthesis of benzo[*d*]thiazol-2-yl(phenyl)methanone (10)

Prepared according to a modified reported procedure.[18] In a N_2-filled glovebox, 2-(triethylsilyl)benzo[*d*]thiazole **2a** (0.0374 g, 0.150 mmol, 1.0 equiv) and a stir bar were charged into a 1 dram vial, followed by adding 0.5 mL dry dioxane via a syringe. To the resulting solution, benzoyl chloride (0.14 mL, 1.20 mmol, 8.0 equiv) was added via a syringe. The reaction vial was capped and the reaction mixture was heated to 90 °C using a pie-block in the glovebox while stirring at this temperature. After 48 h, the reaction was cooled to 25 °C, and the vial was removed from the glovebox. The solvent was removed in vacuo to afford the crude product, which was purified via a flash column chromatography (0–10% EtOAc in hexanes) to afford the purified product as a white solid (0.033 g, 93%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.62–8.48 (m, 2H), 8.32–8.14 (m, 1H), 8.08–7.94 (m, 1H), 7.73–7.64 (m, 1H), 7.63–7.52 (m, 4H). This spectrum is in agreement with previously reported spectral data.[57]

Synthesis of benzothiazole-2-*d* (11)

In a N_2-filled glovebox, 2-(triethylsilyl)benzo[*d*]thiazole **2a** (0.0374 g, 0.150 mmol, 1.0 equiv) and a stir bar were charged into a 1 dram vial, followed by adding 1.0 mL dry dioxane via a syringe. The reaction vial was capped with a septum cap and sealed with electrical tape. Then, the reaction vial was removed from the glovebox, and a N_2 balloon was connected via a needle at the septum. To the resulting solution, DCl/D_2O (1.0 mL of 25 % wt solution) was added via a syringe, and the reaction mixture was stirred at 25 °C for 22 h. Then, the solvent was removed in vacuo to afford the crude product, which was purified via a flash column chromatography (0–15% EtOAc in hexanes) to afford the purified product as a transparent liquid (0.020 g, 96%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.15 (d, *J* = 8.2 Hz, 1H), 7.97 (d, *J* = 8.0 Hz, 1H), 7.53 (ddd, *J* = 8.2, 7.1, 1.2 Hz, 1H), 7.45 (ddd, *J* = 8.1, 7.2, 1.1 Hz, 1H). ^{2}H NMR (92 MHz, CDCl3): δ 9.05 (s, 1D). The ^{1}H NMR spectrum is in agreement with previously reported spectral data,[58] and the ^{2}H NMR spectrum is newly reported herein. (^{13}C satellites are visible alongside the solvent peak in the ^{2}H NMR spectrum.)

Synthesis of 2-iodobenzothiazole (12)

Prepared according to a modified reported procedure.[59] In a N_2-filled glovebox, 2-(triethylsilyl)benzo[*d*]thiazole **2a** (0.0374 g, 0.150 mmol, 1.0 equiv), AgF (0.0761 g, 0.600 mmol, 4.0 equiv), NIS (0.0135 g, 0.600 mmol, 4.0 equiv), and a stir bar were charged into a 1 dram vial, followed by adding 0.75 mL dry THF via a syringe. The reaction vial was capped and the reaction mixture was heated to 60 °C using a pie-block in the glovebox while stirring at this temperature. After 20 h, the reaction was cooled to 25 °C, and the vial was removed from the glovebox. The solvent was removed in vacuo to afford the crude product, which was purified via a flash column chromatography (0–9% EtOAc in hexanes) to afford the purified product as a white solid (0.033 g, 83%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.04 (ddd, *J* = 8.1, 1.3, 0.7 Hz, 1H), 7.85 (ddd, *J* = 7.9, 1.4, 0.7 Hz, 1H), 7.42 (dddd, *J* = 23.9, 7.8, 7.3, 1.3 Hz, 2H). This spectrum is in agreement with previously reported spectral data.[60]

Experimental procedure for Determination of function of TEMPO (Scheme 4a)

In a N_2-filled glovebox, substrate **1a** (0.0298 g, 0.20 mmol, 1.0 equiv), TEMPO (0.0313 g, 0.20 mmol, 1.0 equiv), and a stir bar were charged into a 1 dram vial, followed by adding Et_3SiH (0.64 mL, 4.0 mmol, 20. equiv), DTPB (0.11 mL, 0.60 mmol, 3.0 equiv), and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using a pie-block in the glovebox. After 22 h, the reaction was cooled to 25 °C and removed from the glovebox. Then ca. 10 µL crude reaction mixture was transferred to a GC vial via an airtight syringe, and diluted with EtOAc (ca. 1 mL), followed by acquisition of GC–MS spectra.

Experimental Procedure for Determination of Source(s) of Methyl Radical (Scheme 4b)

In a N_2-filled glovebox, substrate **1a-*d*₃** (0.0305 g, 0.20 mmol, 1.0 equiv), TEMPO (0.0313 g, 0.20 mmol, 1.0 equiv), and a stir bar were charged into a 1 dram vial, followed by adding Et_3SiH (0.64 mL, 4.0 mmol, 20. equiv), DTPB (0.11 mL, 0.60 mmol, 3.0 equiv), and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using a pie-block in the glovebox while stirring at this temperature. After 22 h, the reaction was cooled to 25 °C and the vial was removed from the glovebox. Then ca. 10 µL crude reaction mixture was transferred to a GC vial via an airtight syringe, and diluted with EtOAc (ca. 1 mL), followed by acquisition of GC–MS spectra. The remaining crude reaction was concentrated in vacuo, followed by acquisition of ^1H and ^2H NMR spectra.

Experimental Procedure for Crossover Experiment (Scheme 4d)

In a N_2-filled glovebox, substrate **1a-*d*$_3$** (0.0305 g, 0.20 mmol, 1.0 equiv), **1n** (0.0327 g, 0.20 mmol, 1.0 equiv), and a stir bar were charged into a 1 dram vial, followed by adding Et_3SiH (0.64 mL, 4.0 mmol, 20. equiv), DTPB (0.11 mL, 0.60 mmol, 3.0 equiv), and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using a pie-block in the glovebox. After 22 h, the reaction was cooled to 25 °C and removed from the glovebox. Then ca. 10 µL crude reaction mixture was transferred to a GC vial via an airtight syringe, and diluted with EtOAc (ca. 1 mL), followed by acquisition of GC–MS spectra. The remaining crude reaction was concentrated in vacuo, followed by acquisition of ^1H and ^2H NMR spectra.

Experimental Procedure for Intermolecular Competition Experiment (Scheme 4e)

In a N_2-filled glovebox, substrate **1a-*d*$_3$** (0.0305 g, 0.20 mmol, 1.0 equiv), **1n** (0.0327 g, 0.20 mmol, 1.0 equiv), TEMPO (0.0047 g, 0.030 mmol, 0.15 equiv) and a stir bar were charged into a 1 dram vial, followed by adding Et_3SiH (0.64 mL, 4.0 mmol, 20. equiv), DTPB (18 µL, 0.10 mmol, 0.5 equiv), and 1.0 mL dry $PhCF_3$ via syringes. Then, the reaction vial was capped and the reaction mixture was heated to 110 °C using a pie-block in the glovebox. After 22 h, the reaction was cooled to 25 °C and removed from the glovebox. Then, ca. 10 µL crude reaction mixture was transferred to a GC vial via an airtight syringe, and diluted with EtOAc (ca. 1 mL), followed by acquisition of GC–MS spectra. The remaining crude reaction was concentrated in vacuo, followed by acquisition of ^1H and ^2H NMR spectra with 1-scan acquisitions.

ASSOCIATED CONTENT

Supporting Information: Reaction schemes for Experimental Section, characterization data, GC–MS traces, and ^1H, ^2H, ^{13}C, and ^{19}F NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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