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Homogenous Catalysis

Reductive C(sp²)-Si Cross-Couplings by Catalytic Sodium-Bromine Exchange

Baptiste Neil, Thomas Deis, Louis Fensterbank, and Clément Chauvier*

Abstract: The metal-halogen exchange reaction constitutes one of the most important preparative routes towards polar organometallic reagents such as aryllithium or Grignard reagents. However, despite extensive developments over the past eight decades, this fundamental organometallic elementary step has only been exploited stoichiometrically. Against this background, we demonstrate that the sodium-bromine exchange reaction can be implemented in a catalytic setting as a mean to activate C(sp²)-Br bonds in a transition metal-free manner en route to the regioselective and general preparation of (hetero)aryl silanes. Simply treating structurally diverse (hetero)aryl bromides with *N-tert-butyl-N'-silyldiazenes* (*t*Bu-N=N-Si) as silylating reagents and inexpensive sodium alkoxides as catalytic promoters yields a range of aromatic organosilicon compounds under ambient conditions. Mechanistic studies provide solid evidence for the involvement of *tert*-butyl sodium as the C(sp²)-Br metalating agent.

Introduction

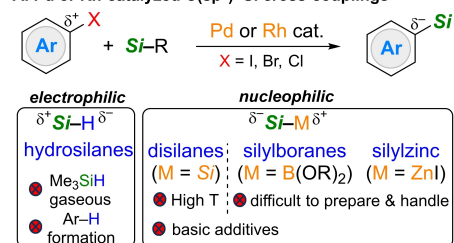
(Hetero)aryl silanes constitute an important class of organosilicon compounds that have found applications in organic synthesis as weakly-polarized, generally bench-stable aryl nucleophile synthons used for example in C-C cross-couplings,^[1] *ipso*-substitutions^[2] or Grignard-type additions.^[3] In addition, the silyl unit can bring beneficial properties to a target aromatic molecule or material, which have been exploited in medicinal chemistry,^[4] agrochemistry^[5] and materials science.^[6] These multifaceted applications have stimulated the development of increas-

ingly selective and environmentally-benign catalytic routes towards arylsilanes.

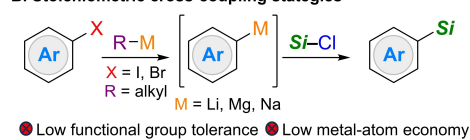
In recent years, intense research effort has been devoted to the optimization of catalytic systems able to mediate the atom-economical silylation of strong and ubiquitous unactivated C(sp²)-H bonds.^[7] However, achieving high site-selectivity without the assistance of pre-installed directing groups has remained challenging unless the arene substrates are electronically or sterically biased. For these reasons, the regioselective and often complementary site-selective introduction of a silyl group onto an (hetero)arene is still routinely carried out from pre-functionalized substrates. In particular, (hetero)aryl halides are privileged substrates because of their wide availability and the ease and predictivity with which C(sp²)-X bonds (e.g., X=I or Br) can be activated with redox-flexible transition metal-based catalysts, for example by oxidative addition.

A myriad of transition metal-catalyzed C(sp²)-Si cross-couplings (Scheme 1A) have thus been reported with (hetero)aryl halides (Cl, Br or I) as substrates and polarity-matched nucleophilic silylating reagents including disilanes^[8] or more polarized silicon nucleophiles that facilitate transmetalation steps such as silylboronate esters,^[9] silylsilanolates^[10] or silylzinc reagents.^[11] Hydrosilanes have

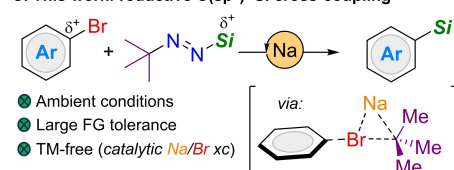
A. Pd or Rh-catalyzed C(sp²)-Si cross-couplings



B. Stoichiometric cross-coupling strategies



C. This work: reductive C(sp²)-Si cross-coupling



Scheme 1. State-of-the-art for the silylation of aryl halides

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also been used under Pd or Rh^[12] and dual Ni/photoredox^[13] catalysis, though the hydridic character of these formally electrophilic silylating reagents often favors dehalogenation over silylation pathways.^[14] Beyond halogenated substrates, arenes containing cyano,^[15] triflate,^[16] pivalate,^[17] thianthrene *S*-oxide^[18] and fluoride^[19] leaving groups have also emerged as competent coupling partners. Nevertheless, despite significant developments, these approaches mostly rely on expensive noble metals (Pd or Rh) and/or specialized ligands as well as on nucleophilic silylating reagents^[20] that display limited availability, stability and/or structural diversity compared to electrophilic ones (e.g. chlorosilanes and their derivatives).

The sophistication of the transition metal-catalyzed C(sp²)-Si cross-couplings contrasts with the relative simplicity of the stoichiometric organometallic routes (Scheme 1B). In such a setting, (hetero)aryl silanes are formed through the regioselective metalation of a C(sp²)-X (X=I or Br) bond, typically by metal-halogen exchange, followed by trapping the intermediate nucleophilic C(sp²)-M unit (M=Li, MgX or Na) with an electrophilic silicon source such as an alkoxy-^[21] or a chlorosilane.^[22] This overall metalation/silylation sequence not only benefits from the wide availability of both coupling partners but also from the existence of a range of thermodynamically unstable yet bottleable alkyl organometallic exchange reagents that rapidly and predictively mediate the key metal-halogen exchange reaction. Although alkyllithium (e.g., *n* or *t*BuLi) are most commonly used to that purpose,^[23] alternative alkylmetal exchange reagents based on Mg^[24] or Na^[25] have also been developed. Nevertheless, the robustness of this stoichiometric strategy comes at the expense of several limitations peculiar to the accumulation of highly reactive polar reagents, including a limited functional group tolerance, the need to employ cryogenic conditions and a low overall atom-economy because of the formation of stoichiometric amounts of metallic waste.

From the above considerations, we have sought to develop an alternative and general strategy towards the regioselective silylation of (hetero)aryl halides that would rest upon a cost-effective and environmentally-benign transition metal-free catalyst while proceeding with an electrophilic silylating reagent that could be readily prepared from widely available chlorosilanes. Towards this end, we have recently reported that the combination of *N*-*tert*-butyl-*N*'-silyldiazenes (*t*Bu-N=N-Si) with a catalytic amount of potassium alkoxides (e.g. *t*BuOK) enables the catalytic deprotonative silylation of unactivated C(sp²)-H and C(sp³)-H bonds through the steady-state formation of *tert*-butyl potassium (*t*BuK).^[26] Given the well-established ability of *tert*-butyl lithium (*t*BuLi) to engage in lithium-halogen exchange reactions with aryl bromides and iodides, we reasoned that the anionic decomposition of the *N*-*tert*-butyl-*N*'-silyldiazenes could also trigger the dehalogenative metalation of C(sp²)-X bonds, while being compatible with a catalytic regime.^[27]

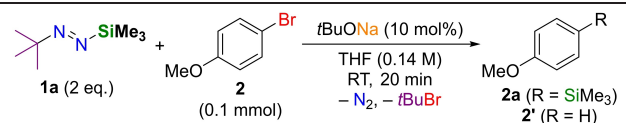
We herein demonstrate the validity of this hypothesis and show for the first time that the sodium- and lithium-bromine exchange reactions, traditionally cantoned to the

stoichiometric preparation of aryl organometallic reagents, can be implemented in a catalytic cycle as a transition metal-free C(sp²)-X metalation elementary step (Scheme 1C). A range of structurally diverse (hetero)aryl silanes have thus been prepared from the corresponding bromides in a general manner with *N*-*tert*-butyl-*N*'-silyldiazenes acting both as electrophilic silylating reagents and reductants in combination to inexpensive sodium or lithium alkoxides as catalytic promoters.

Results and Discussion

At the outset of the study, we explored the debrominative silylation of 4-bromoanisole **2** as a representative electron-rich aryl bromide substrate and Me₃Si-substituted diazene **1a** (Table 1 and S1 in the SI). Using *t*BuOK (10 mol %) as a catalytic promoter, the conversion remained low, plateauing at 36 % after 20 min and the arylsilane **2a** was produced in only 13 % yield (entry 2). Products of silylation *ortho* to the methoxy group as well as anisole (**2'**, 3 %) account for the remaining mass balance, thereby indicating that directed *ortho*-metalation pathways compete with the desired potassium-bromide exchange. Such deprotonative side reactions could largely be suppressed with sodium and lithium-based alkoxides, presumably because of the reduced kinetic basicity of organosodium and organolithium intermediates. With *t*BuONa (10 mol %), the silylation reaction was both extremely regioselective and rapid as **2a** was generated in 97 % yield within 20 min at room temperature and further isolated in 92 % yield after a straightforward purification by flash column chromatography (entry 1). In fact, the *t*BuONa-promoted reaction of **2** with **1a** can even be carried out open flask, without excluding air and moisture from both the THF solvent (containing 250 ppm BHT) and the

Table 1: Optimization of the silylation of 4-methylanisole (**2**) with **1a**.



Entry	Deviation from standard conditions	ρ	Yield 2a/2'
1	none	100	97 (92) ^a /3
2	<i>t</i> BuOK (10 mol%)	36	13/3
3	<i>t</i> BuOLi (20 mol%), 24 h	85	83/2
4	Open flask; <i>t</i> BuONa (30 mol% weighted under air); commercial THF.	81	67/13
5	MeONa (10 mol%), 57 h	88	83/5
6	Me ₃ SiONa (10 mol%)	100	98/0
7	1a (1.5 eq.)	94	90/4
8	<i>t</i> BuONa (5 mol%)	84	81/3
9	2_{Cl} instead of 2_{Br} , 24 h	< 5	0/0 %
10	2_I instead of 2_{Br}	56	47/1

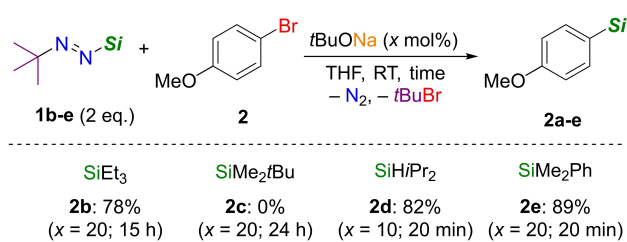
Conversion (ρ) and yields [all %] determined by calibrated GC using *n*-tetracosane as an internal standard.^[a] Isolated yield.

substrate. In such a setup, **2a** could still be formed in 67 % yield within 20 min with 30 mol % of *t*BuONa (entry 4) weighted under air. A careful examination of the byproducts generated upon silylation of **2** by NMR spectroscopy revealed that *tert*-butylbromide (*t*BuBr) was the major bromine-containing byproduct, thereby suggesting the involvement of *t*BuNa as the actual reducing agent of this overall cross-electrophile C(sp²)-Si coupling. Catalysis by adventitious traces of transition metals was ruled out on the basis of carefully-conducted ICP-MS analyses of the sublimed *t*BuONa promoter as well as representative experiments using various metal salts as catalysts (see the Supporting Information for details). The sodium-promoted formation of **2a** thus constitutes the first example of a catalytic silylation of an aryl halide that proceeds in the complete absence of a transition metal.^[28]

A similar reaction outcome was observed with *t*BuOLi (20 mol %), albeit a longer reaction time was needed to achieve a maximum of 85 % conversion (entry 3). Cost-effective sodium methoxide or less basic trimethylsilanolate (Me₃SiONa) performed equally well, though the low solubility of the former in THF required to increase the reaction time up to 57 h to reach 83 % yield of **2a** (entries 5–6). Finally, both the loading of *t*BuONa and the amount of diazene **1a** could be reduced without significant impact on the yield of **2a** (entries 7–8).

Under the optimal conditions, the silylation of 4-iodoanisole (**2_I**) and 4-chloroanisole (**2_{Cl}**) was also attempted so as to probe the halogen influence (entries 9–10). While the latter was found completely unreactive even towards side reactions, the iodide derivative reacted rapidly yet incompletely as catalytic turnovers halted at ca. 56 % conversion. While this trend parallels the well-established superior reactivity of aryl iodides and bromides compared to chlorides in the lithium-halogen^[29] or sodium-halogen^[25b] exchange reactions, the silylation outcome with **2_I** was surprising as aryl iodides are known to undergo metalation much more rapidly than bromides. In fact, a competition experiment between an equimolar amount of **2_I** and **2_{Br}** in the presence of diazene **1a** confirmed that **2_I** reacts ca. 10 times faster than **2_{Br}** (Scheme S1 in the SI). This result suggests that the decreased yield of **2a** from **2_I** originates not from a lack of reactivity but from the occurrence of competitive side reactions that prematurely shut down the catalytic activity (see below).

We next turned our attention to the scope of the reaction, first by examining the type of silyl groups that could be introduced onto the bromide substrate **2** (Scheme 2). Beyond the trimethylsilyl group, the SiEt₃ (from **1b**), SiH*i*Pr₂ (from **1d**) and SiMe₂Ph (from **1e**) could all be transferred in good to excellent yields. In contrast, no silylation occurred with the more sterically demanding diazene **1c** (SiMe₂*t*Bu) even with increased amounts of *t*BuONa and prolonged reaction times. These results paired with representative competition experiments between diazene **1a** and **1b** or **1d** (SiH*i*Pr₂ > SiMe₃ >> SiEt₃; Table S10 in the SI) indicate that the rate of silylation of **2** increases when the silicon atom is surrounded by smaller ligands.

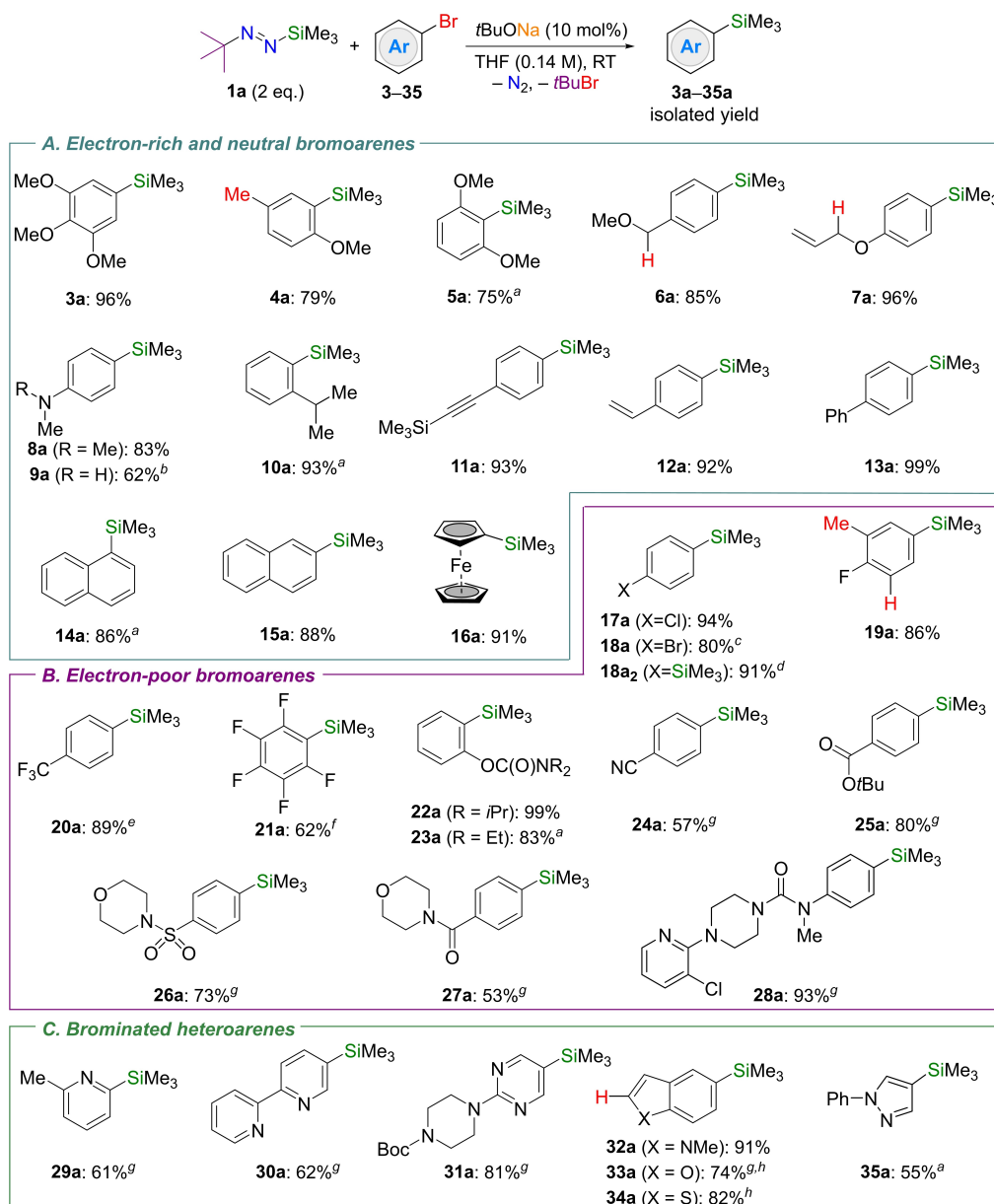


Scheme 2. Silylation of **2** with various diazenes. Yields refer to those of purified isolated products.

The substrate scope was subsequently evaluated with structurally diverse (hetero)aryl bromides, diazene **1a** as the trimethylsilyl source and *t*BuONa (10–30 mol %) as the catalytic promoter (Scheme 3). Electron-rich or neutral bromoarenes (**3–13**) were all efficiently silylated, affording the corresponding aryltrimethylsilanes in good to excellent yields within less than 1 h at room temperature. Specifically, methoxy groups are tolerated irrespective of their number and position (**3–6**) as well as the para-located allyloxy unit in **7**, which did not undergo isomerization nor cleavage that would be facile with Pd- or Ni-based catalysts known to readily afford π -allylmetal intermediates.^[30] Even strongly electron-releasing amino groups at the para position (**8–9**), including a protic -NHMe one, were well tolerated, thereby suggesting that the silylation reaction is marginally impacted by the electron richness of the arene core. Likewise, steric hindrance in the vicinity of the bromine atom as in the resorcinol **5** or isopropylbenzene **10**^[31] derivatives did not preclude the silylation to occur, though an increased amount of *t*BuONa (20 mol %) was needed in these cases to reach full conversion. Finally, the presence of conjugated unsaturated multiple C–C bonds (**11–13**) as well as less aromatic naphthyl (**14–15**) or ferrocenyl (**16**) backbones were also well tolerated.

Bromoarenes bearing various electron-withdrawing groups or atoms could also be silylated in moderate to excellent yields. For example, para-located chlorine, bromine and fluorine atoms as well as a trifluoromethyl group were well tolerated (**17–20**). Importantly, 1,4-dibromobenzene (**18**) could be mono- or bis-silylated selectively to give **18a** or **18a₂** in excellent yields, simply by adjusting the catalytic loading (10→20 mol %) and the amount of **1a** (1.4 eq.→3.5 eq.) used. In contrast, however, the pentafluorophenyl derivative **21a** could be satisfyingly silylated only from the corresponding iodide with an increased amount of *t*BuONa (30 mol %). Other electron-withdrawing groups including carbamates (**22–23**) and carbanion-sensitive cyano (**24**), ester (**25**), sulfonamide (**26**) and amide (**27**) substituents were all compatible with the reaction conditions.

The main side products formed upon silylation of **24–27** were the protodebrominated arenes (C–Br→C–H), formation of which could be minimized by increasing the catalytic loading of *t*BuONa (30 mol %). Closely monitoring the conversion of 4-bromobenzonitrile **24** as a representative electron-poor substrate with diazene **1a** and varying amounts of *t*BuONa indeed revealed that such a loading was optimal as full conversion was obtained and the desired



Scheme 3. Silylation of various aryl and heteroaryl bromides with diazene **1a**. Reaction conditions: (hetero)aryl bromide (0.5 mmol), **1a** (2.0 eq.), *t*BuONa (10 mol%) and THF (0.14 M) at RT. Reaction time indicated in the SI. Yields refer to those of purified isolated products. ^a*t*BuONa (20 mol%), ^b*t*BuONa (30 mol%) and **1a** (4 eq.). ^c**1a** (1.4 eq.), ^d*t*BuONa (20 mol%) and **1a** (3.5 eq.). ^eNMR yield. ^fC₆F₃ (**21**) as substrate, *t*BuONa (30 mol%) and NMR yield. ^g*t*BuONa (30 mol%). ^h**1a** (1.2 eq.)

silylated product **24a** was formed in 64 % GC-yield in a ca. 8:2 ratio with benzonitrile **24'** (see Figure S1 in the SI). The tolerance towards such electrophilic functional groups under non-cryogenic conditions suggests that the potential side nucleophilic additions are kinetically less favorable than the key silylation event, though more electrophilic carbonyl or nitro groups were not tolerated.

The C(sp²)-Br silylation reaction could also largely be transposed to heteroaryl bromides, including pyridine (**29–30**), pyrimidine (**31**), indole (**32**), benzofuran (**33**), benzothiophene (**34**) or pyrazole (**35**) derivatives. In the case of **35**, no silylation occurred on the phenyl ring as would be expected from the established directing ability of this

heterocycle. The desired product **35a** was isolated in 55 % yield and was produced along with some isomerized products presumably arising from halogen dance-type pathways.^[32]

Finally, it is worth noting that the silylation of a C(sp²)-Br bond was also faster than and thus orthogonal to any type of C-H bond silylation event that we had previously shown to be kinetically possible with *tert*-butyl substituted silyldiazenes and alkoxides as catalytic promoters. As an illustration, the substrates **4**, **6**, **7**, **19** and **32–34** contain a C(sp²)-Br bond that coexists with potentially reactive C(sp²)-H and/or C(sp³)-H bonds (marked in red in Scheme 3). In all instances, the silylation occurred selec-

tively at the brominated position rather than at the C₂ position (**32–34**), in the vicinity of a fluorine atom (**19**) or at benzylic or allylic positions (**4, 6–7**). Such an orthogonality is primarily enabled by the use of sodium-based catalysts because deprotonative side-pathways readily occurs with these substrates when *t*BuOK is employed.

Overall, the above-outlined reaction scope demonstrates that the electrophilic silylating reagent **1a** offers a credible alternative to the nucleophilic trimethylsilyl sources that had thus far been used to prepare aryltrimethylsilanes (Ar–SiMe₃) under transition metal catalytic conditions, including hexamethyldisilane Me₃Si–SiMe₃^[33] or the more recently reported trimethylsilylsilanolate (NaOMe₂Si–SiMe₃)^[10b] and silylzinc reagent Me₃SiZnI·TMEDA.^[11]

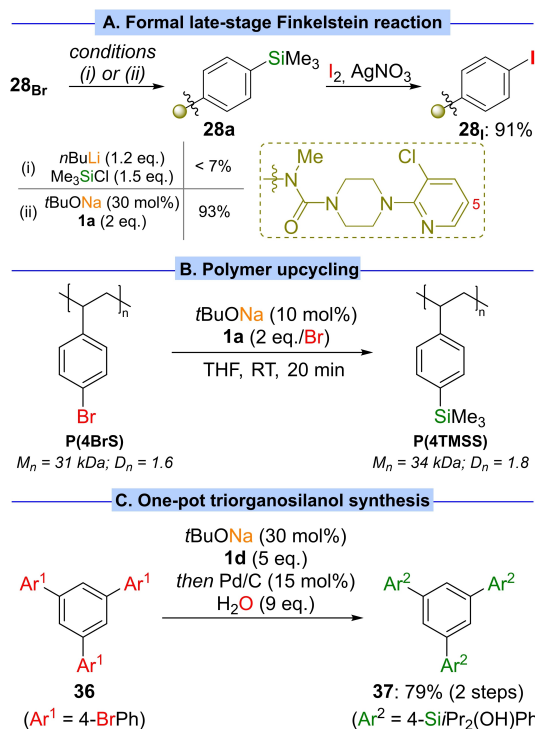
The present catalytic silylation protocol also complements or even surpasses classical stoichiometric metalation/silylation strategies. For example, when the late-stage silylation of the medicinally-relevant^[34] and polyfunctional compound **28** (Scheme 3B and Scheme 4A) was attempted with *n*BuLi followed by the addition of Me₃SiCl at –78 °C, a complex mixture of products was obtained, among which **28a** was formed in very low yield (<7%). In contrast, **28a** was isolated in 93% yield with the silylation system composed of **1a** and *t*BuONa (30 mol%), further demonstrating that a urea and a fragile aminated 3-chloropyridine motif were compatible with the catalytic reaction conditions. Although the SiMe₃ group may have a beneficial effect on the pharmacokinetic properties of **28a**, it also provides a versatile handle for further functionalization and thus

formation of analogues of **28** through electrophilic *ipso*-substitution. To illustrate this further, **28a** was converted into the iodinated product **28i** in 91% yield and with superb regioselectivity, despite the presence of the electron-rich 2-aminopyridine ring that readily reacts at the 5-position through S_EAr (Scheme 4A).^[35] The overall transformation **28_{Br}**→**28_i** therefore corresponds to a late-stage Finkelstein-type replacement of the bromide by an iodine atom *enabled* by the intermediate silylation.

To further demonstrate the synthetic utility and high efficiency of the sodium-mediated C(sp²)–Br bond silylation reaction with diazene **1a**, we have sought to mediate the upcycling of a pre-formed and commercially-available poly(4-bromostyrene) homopolymer (**P(4BrS)**, Scheme 4B). **P(4BrS)** contains an average of ca. 169 bromide atoms per polymeric chain (*M_n* ≈ 31 kDa as determined by SEC with PS standards in THF) including some buried deep into the polymeric network. All bromides were replaced by a Me₃Si group upon reaction with diazene **1a** to afford the homopolymer product **P(4TMSS)** both cleanly as judged by multi-nuclear NMR and IR spectroscopy and without significant chains modification (*M_n* ≈ 36 kDa as determined by SEC with PS standards in THF). This synthetic approach toward such a polysilylated polymer is more flexible than those based on the anionic polymerization of silylated styrene monomers^[36] because diverse silyl groups can be introduced from the same, well-defined polymeric assembly. It also obviates the need to use a large excess of Oshima's trialkylmagnesate complex *i*-Pr(*n*-Bu)₂MgLi that was used by Spring and co-workers to modify copolymerized poly(4-bromostyrene) beads through a stoichiometric magnesium-bromide exchange/silylation sequence.^[37]

Finally, we demonstrated that the catalytic silylation protocol is applicable to polysilylation reactions and compatible with further functionalization steps without isolation nor purification of the crude silylated products. For example, the high-yielding threefold silylation of **36** with SiH*i*Pr₂-substituted diazene **1d** could be directly coupled, after removal of the volatiles, to a Pd/C-catalyzed silane oxidation to afford the triarylsilanol **37** in 79% yield over two steps (Scheme 4C). Interestingly, related tripodal compounds based on the Si(*i*Pr)₂OH unit have been used as ligands of molybdenum complexes for alkyne metathesis^[38] or as precursors of self-assembled supramolecular architectures through H-bonding.^[39] In these cases, however, the installation of the SiH*i*Pr₂ group from the corresponding tribrominated arenes requires excess of pyrophoric reagents (e.g., *t*BuLi), cryogenic conditions (as low as –125 °C) as well as solvent- and labor-intensive work-up procedures prior to the oxidative step, further highlighting the increased practicality and safety profile of the present one-pot two-step catalytic sequence.

From a mechanistic standpoint, the high regioselectivity of the silylation reaction and the formation of *t*BuBr as the main byproduct taken together with our previous studies^[26] all point to a mechanistic scenario where a *tert*-butylmetal species (e.g. *t*BuNa) engage into a thermodynamically-favored metal-halide exchange with the (hetero)aryl halide substrates. Such a metalation elementary step has been



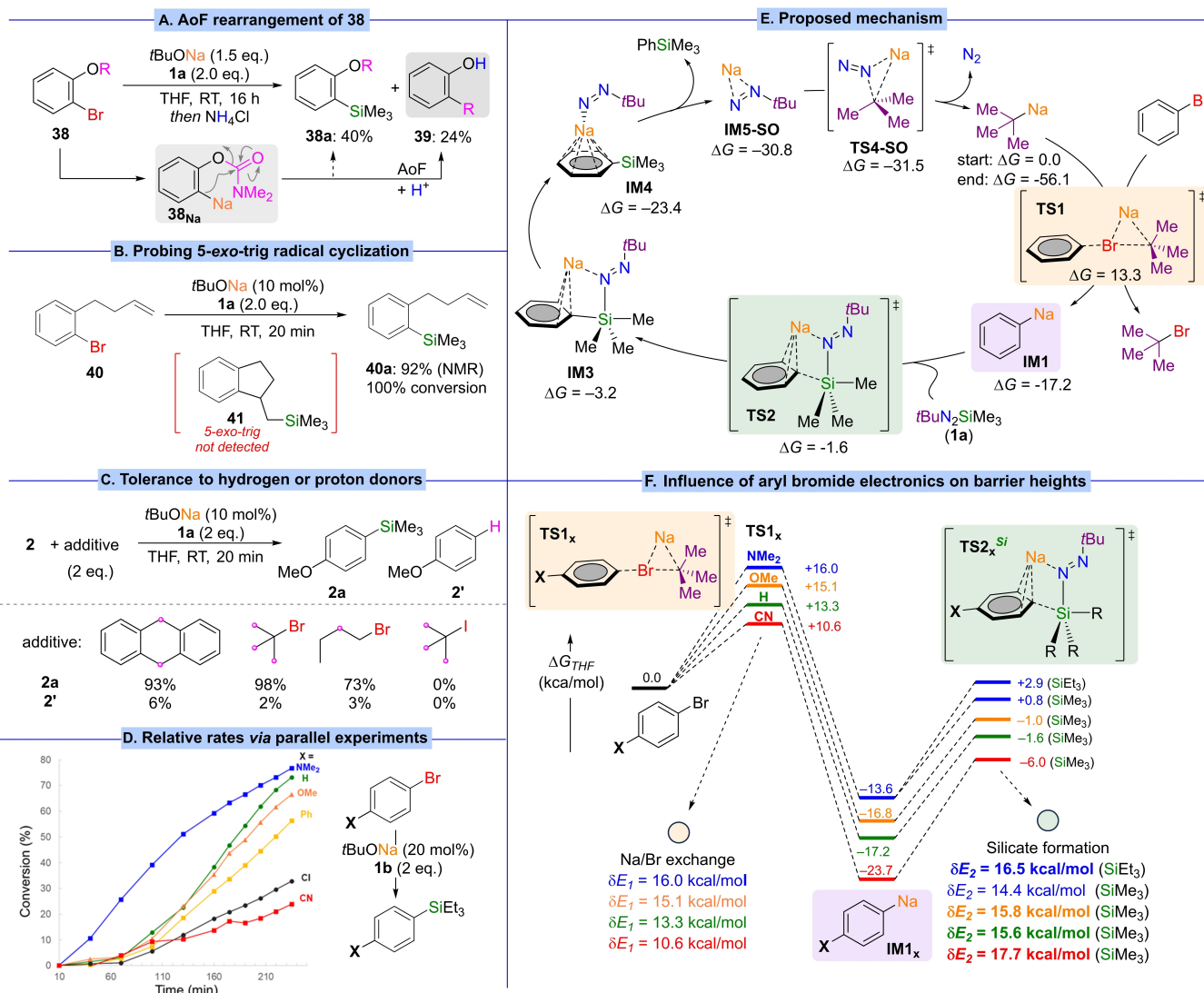
Scheme 4. Synthetic interest and applications. Yields refer to those of purified isolated products. Experimental details are given in the SI.

thoroughly investigated with organolithium reagents in general, and *t*BuLi in particular. Notably, compelling experimental^[40] evidence has been gathered to support an anionic pathway that accounts for the irreversible formation of aryllithium species from aryl halides and alkyllithium through the formation (as transition state or intermediate) of ate complexes.

Capitalizing on this background, we first verified that arylsodium species can be generated from the corresponding aryl bromides. Because the typical C–Br silylation reactions with diazene **1a** and *t*BuONa proceed too rapidly to be monitored by NMR spectroscopy, we submitted the *o*-bromophenyl dimethylaminocarbamate **38** to various silylation conditions and investigated the formation of salicylamide products arising from the *anionic ortho*-Fries (AoF) rearrangement. When **38** was treated with **1a** and a stoichiometric amount of *t*BuONa (1.5 eq.), two main products could be isolated after an acidic workup, including

the rearranged salicylamide **39** in 24% yield and the arylsilane **38a** arising from the exchange of the bromide by a Me₃Si group in 40% yield (Scheme 5A). Under otherwise identical conditions, the silylation pathway could be completely suppressed when the bulkier Et₃Si-substituted diazene **1b** was employed and the rearranged phenol **39** was isolated in an improved 54% yield. Importantly, no reaction occurred between **38** and *t*BuONa in the absence of **1a** or **1b**. These results indicate that the combination of *t*BuONa with **1a** or **1b** triggers a sodium-bromide exchange with **38** affording the arylsodium intermediate **38_{Na}** that can further evolve through the unimolecular AoF rearrangement and/or a bimolecular silylation pathway.

Further evidence for the involvement of arylsodium rather than aryl radical intermediates comes from the reaction of the alkenyl substrate **40**.^[41] When the latter was reacted under the optimized silylation conditions, the expected arylsilane **40a** was produced in 92% yield within



Scheme 5. Experimental (A–D) as well as computational (E–F) mechanistic investigations. Gibbs free energies (kcal/mol) were calculated at the B3LYP-D3 (PCM = THF)/Def2TZVP//B3LYP-D3 (PCM = THF)/6-31 + G(d) level of theory.

20 min (Scheme 5B). The indane product **41** that would arise from a 5-*exo*-trig radical cyclization known to occur at a rate greater than 10^8 s^{-1} could not be detected by GC-MS and NMR spectroscopy.^[42] In addition, the silylation of 4-bromoanisole (**2**) with diazene **1a** still afforded **2a** in 93 % yield in the presence of an excess of 9,10-dihydroanthracene (2 eq., Scheme 5C), thereby proving the absence of inhibiting effect of this well-established hydrogen atom donor ($\text{BDE}_{\text{C-H}} = 78 \text{ kcal/mol}$).

Finally, we sought to shed more light on the intriguing compatibility between the thus-established anionic regime of the sodium-promoted silylation reaction and the presence of the tertiary alkyl halide byproducts generated upon sodium-halide exchange, which were initially deemed sensitive to ionic elimination pathways. It is indeed well-established that the use of 2 molar equivalents of *t*BuLi with respect to the halide substrate is generally beneficial to mediate lithium-halogen exchange reactions, the second equivalent allowing the irreversible formation of isobutene and LiX from *t*BuLi and *t*BuX.^[43] In our case, such a pathway that could occur from any basic intermediate (e.g. *t*BuONa, *t*BuNa or ArNa) would suppress the catalytic activity because the weakly nucleophilic NaX salt would be incapable to sustain turnovers. Although we have gathered spectroscopic evidence that ionic elimination does occur to some extent, it remains kinetically non-competitive with the silylation pathway as far as aryl bromide substrates are concerned (Scheme 5C). For example, adding twice the theoretical amount of *t*BuBr to a solution of **2** and *t*BuONa (10 mol %) prior to adding the diazene **1a** did not prevent the silylation from readily occurring as **2a** was still formed in 98 % yield. Under identical conditions, even the primary isomer *n*BuBr (2 eq.) was found compatible, though the yield of **2a** was lowered to 73 %. In sharp contrast, however, the catalytic activity was completely suppressed when *tert*-butyl iodide (2 eq.) was used as additive (ca. 5 % conversion). Because base-promoted elimination pathways are notoriously faster with alkyl iodides than bromides, we therefore attribute the decreased yield of silylation of 4-iodoanisole in particular (**2i**, entry 10 in Table 1) to an early elimination of NaI that cannot sustain the catalytic turnovers. In this case, because anisole **2'** was barely observed, the elimination presumably involves *t*BuNa rather than the corresponding arylsodium as Brønsted base according to: $t\text{BuNa} + t\text{BuI} \rightarrow t\text{BuH} + \text{isobutene} + \text{NaI}$

From the above-mentioned experimental observations, the mechanism depicted in Scheme 5E is proposed along with energetic supports from DFT calculations (see Figures S5 and S6 in the Supporting Information for details). At the outset, an initiation pathway generates *tert*-butyl sodium from *t*BuONa and **1a** (not shown). Subsequently, *t*BuNa engages into a sodium-bromide exchange with PhBr through the “bromate” transition state **TS1** that lies only 13.3 kcal/mol above the starting materials. Such a linear geometry was found unstable towards a spontaneous dissociation into *t*BuBr and PhNa (**IM1**, $\Delta G = -17.2 \text{ kcal/mol}$) as no ate-complex structure could be located as an energy minimum on the potential energy surface. The arylsodium intermediate then interacts with the silylated diazene **1a** through a

ative N–Na bond (**IM2**, not shown) that ultimately leads to the silicate species **IM3** via the four-centered **TS2**. An essentially barrierless Berry pseudorotation-type isomerization (**TS3**, $\Delta G^\ddagger = -3.3 \text{ kcal/mol}$; not shown) eventually induces the release of the silylated product PhSiMe₃ through the dissociation of the diazenyl unit *t*Bu–N=N–Na in **IM4**. In line with these computational findings, the reaction of commercial PhLi (rather than PhNa) with **1a** rapidly afforded PhSiMe₃ (69 % yield as determined by calibrated GC). From this point, the denitrogenation of the diazenyl-sodium complex can take place according to different pathways, which are all computed to be extremely rapid. The most-energetically favorable consists in the barrierless denitrogenation of the side-on sodium diazenyl complex **IM5-SO**, which regenerates *t*BuNa in a highly exergonic manner ($\Delta G = -25.3 \text{ kcal/mol}$ from **IM5-SO**). Overall, the silylation of PhBr with diazene **1a** proceeds with a low energetic span ($\delta E = +15.0 \text{ kcal/mol}$) that corresponds to the rate-determining formation of the silicate species **IM3** via **TS2**.

The predictive value and validity of this computational model can be further gauged by comparing it with the experimental results obtained on the relative reactivity of various aryl bromides and diazenes. As a first validation, the model allows to rationalize how the electronics of substituents on the arene ring of the aryl bromide substrates impacts the kinetics of the silylation reaction (Scheme 5F). Experimentally, we have found that the silylation of various *para*-substituted aryl bromides with Et₃Si-substituted diazene **1b** is faster when the substituents are more electron-donating (NMe₂ (**8**) > OMe (**2**) > Ph (**13**) > Cl (**17**) > CN (**24**), Scheme 5D). Because this reactivity order contradicts the rate acceleration of metal-bromine exchange reactions with electron-deficient aryl bromides,^[40,44] which is also well grasped computationally (**TS1_X** in Scheme 5F), it strongly suggests that the silicate formation also remains rate-determining with substituted arenes. In line with these findings, the calculations show that the energy barriers associated with **TS2_X** are lower for electron-rich arenes than for electron-poor ones (Scheme 5F, X=CN > H ≈ OMe > NMe₂) and generally greater than those associated with **TS1_X** (and always so when the silyl group is Et₃Si). As such, the overall rate of silylation is predicted to increase when the corresponding arylsodium intermediate **IM1_X** is more nucleophilic. Conversely, when electron-poor aryl bromides such as the cyano derivative **24** are used as substrates, the reduced nucleophilicity of e.g. **IM1_{CN}** translates into a slower C–Si bond formation, which may thus compete with the ionic elimination pathway involving the *t*BuBr byproduct. This would explain why protodebrominated arene products were mostly observed from aryl bromides bearing strongly electron-withdrawing substituents.

Finally, the computational model also reproduces well the experimentally-determined silyl group influence on the kinetics of the silylation reaction as the computed energy barriers associated with **TS2_{H^{Si}}** steadily increase from SiH*i*Pr₂ to SiEt₃ (Scheme S6B in the SI; $\delta E = 12.6, 15.6$ and 18.2 kcal/mol for *Si* = SiH*i*Pr₂, SiMe₃ and SiEt₃, respectively).

Conclusion

In conclusion, we have demonstrated that a range of (hetero)arylsilanes can be prepared via the organosodium-catalyzed silylation of C(sp²)-Br bonds with *tert*-butyl-substituted silyldiazenes. This transformation displays a broad scope, both in terms of the silyl groups that can be introduced and the functional groups that are tolerated, and occurs rapidly with superb regioselectivity under ambient, transition metal-free conditions. As such, it offers a credible alternative to the established arylsilane preparation methods of the state-of-the-art including the C-H silylation protocols. Experimental and computational investigations all point to an anionic mechanism involving *t*BuNa and arylsodium intermediates, whereby the key C(sp²)-Br bond cleavage takes place through a sodium-bromine exchange elementary step that could be exploited, for the first time, in a catalytic setting. Key to success was the use of sodium-based promoters^[45] (and to a lesser extent lithium-based ones) to prevent unproductive and turnover-suppressing ionic elimination pathways with the *t*BuBr byproduct that readily occur with the more basic organopotassium derivatives.

Supporting Information

The authors have cited additional references within the Supporting Information.^[1,28]

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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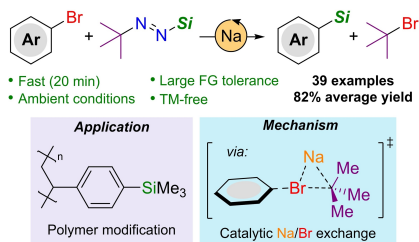
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Research Article

Homogenous Catalysis

B. Neil, T. Deis, L. Fensterbank,
C. Chauvier* [e202419496](#)

Reductive C(sp²)-Si Cross-Couplings by
Catalytic Sodium-Bromine Exchange



The first example of a chemical transformation that exploits the sodium-bromine exchange reaction *catalytically* is presented. Using stable *tert*-butyl-substituted silyldiazenes ($t\text{Bu-N=N-SiR}_3$) as silylating reagents, various (hetero)aryl bromides have been converted to the corresponding organo-silicon compounds using inexpensive sodium alkoxides as catalytic promoters. Mechanistic studies point to the involvement of *tert*-butylsodium ($t\text{BuNa}$) that mediates the key Na/Br exchange event.