Silylated Cyclohexadienes: New Alternatives to Tributyltin Hydride in Free Radical Chemistry**

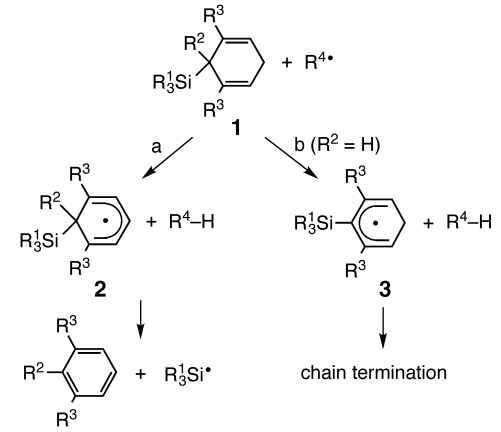
Armido Studer* and Stephan Amrein

Although tin hydrides (Bu_3SnH, Ph_3SnH, Me_3SnH) have successfully been used in free radical chemistry over the last 40 years,[1] there are drawbacks associated with such tin-based radical reducing agents. The toxicity of organostannanes necessitates special handling in their disposal, and problems with product purification are often observed. Many approaches have therefore been presented to circumvent these problems.[2] Protocols in which tin hydrides are used in catalytic amounts have been described.[3] In addition polymer-bound,[4] fluorous,[5] water-[6] and acid-soluble[7] tin hydrides have been prepared. Special workup procedures for tin-mediated reactions have been introduced;[8] but, in all these systems, trace quantities of tin can remain after standard laboratory purification. Recently, disilaanthracenes[9] and tetraaryldisilanes[10] were used in radical reactions instead of tin hydrides; however, these silanes are difficult and labor-intensive to prepare. Substituted germanes[11] are expensive, and phosphorus-based reducing agents[12] are not well-developed. Polarity reversal catalysis using silanes together with thiols has only found limited application in radical chemistry.[13] The best alternative to the tin hydrides documented thus far is Chatgilialoglu's tris(trimethylsilyl)silane ($(TMS)_3SiH$),[14] which is easily oxidized by air. We now introduce silylated 1,4-cyclohexadienes as new, readily prepared radical reducing agents. We demonstrate that they can replace the toxic tin hydrides in various radical reactions such as dehalogenations, deselanations, deoxygenations, cyclizations, and intermolecular radical addition reactions [Eq. (1)].

(1)

(X = Cl, Br, I, SePh, OCSOPh)

It is well known that cyclohexadienes can serve as hydrogen donors in alkyl radical reductions.[15, 16] However, 1,4-cyclohexadiene is not a tin hydride substitute in alkyl halide reductions since the cyclohexadienyl radical formed after initial hydrogen transfer cannot propagate a radical chain by halogen abstraction. With appropriate substituents the 1,4-cyclohexadienes should participate as reducing agents in radical chain reactions: We speculated that silylated cyclohexadienes **1** would function as a substitute for tin hydrides in radical dehalogenations (Scheme 1). Reduction of a radical $^{\bullet}R^4$ by **1** should afford cyclohexadienyl radical **2** (path a).

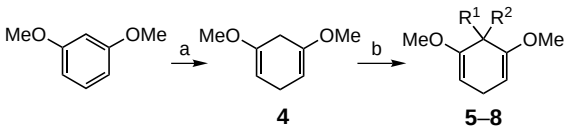


Scheme 1. 1,4-Cyclohexadienes **1** as radical reducing agents.

Fragmentation (rearomatization) of **2** will then give the corresponding silyl radical which is able to propagate the chain by halogen abstraction. If $R^2 = H$, pathway b can occur leading to chain termination. In order to drive the fragmentation of **2** towards the desired formation of the silyl radical, substituent R^2 should neither be a hydrogen atom[17] nor a substituent which would afford a stabilized radical upon fragmentation.

We considered the ready multigram synthesis of any new hydrogen donor to replace tin hydride an important criteria. Based on this practical and the mechanistical considerations discussed above, **5**–**7** were prepared starting from commercially available resorcin dimethyl ether by Birch reduction (→**4**) and subsequent one-pot silylation–methylation (Scheme 2). For example on a 30g-preparative scale, **5** was obtained in 80% overall yield as a crystalline solid that can easily be stored.[18] Moreover, the sequence we have developed allows ready access to new derivatives of this type.

To test whether these new reagents serve as effective replacements for tin hydrides, we first studied the dehalogenation of 1-bromoadamantane with **5** (1.3 equiv, 0.3 equiv α,α'-azobisisobutyronitrile (AIBN)) in various solvents (0.2 M).



5 ($R^1 = SiMe_2tBu$, $R^2 = Me$)
6 ($R^1 = SiiPr_3$, $R^2 = Me$)
7 ($R^1 = SiMe_3$, $R^2 = Me$)
8 ($R^1 = SiMe_2tBu$, $R^2 = H$)

Scheme 2. a) NH_3, Na, EtOH, Et_2O; 95%. b) 1. *t*BuLi, HMPA, THF; 2. $R'_2R''SiCl$; 3. *n*BuLi; 4. $(MeO)_2SO_2$.

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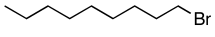
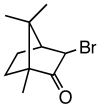
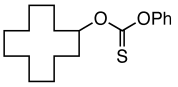
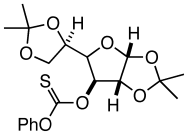
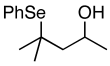
In refluxing hexane, reduction occurred quantitatively (Table 1, entry 1). Slightly lower yields were obtained when the reaction was performed in benzene (78%),[19] *t*BuOH (80%), or THF (60%). Subsequent experiments were therefore conducted in hexane (Table 1). Reduction of 1-bromoadamantane with **6** worked equally well (entry 2), whereas adamantane was obtained in only 35% in the reduction with the trimethylsilyl derivative **7** (entry 3); but **7** was completely consumed. We further found that **7** slowly decomposes even at 4 °C. Consequently, owing to its instability, **7** is not a suitable tin hydride substitute. Si-reagent **8** lacking the methyl substituent (R^2=H) afforded adamantane in only 27% yield (entry 4).[20] Thus, **5** and **6** became the reagents of choice for our subsequent studies.

Table 1. Radical reductions of various substrates using **5**–**8** (1.3 equiv) and AIBN (0.3 equiv) in refluxing hexane (0.2 M).

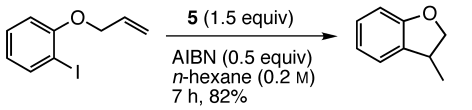
Entry	RX	Si Reagent	*t* [h]	Yield (RH)[a] [%]
1		**5**	5.5	99
2		**6**	4.5	99
3		**7**	7	35
4		**8**	8	27
5		**5**	3.5	99
6		**6**	4	99
7		**5**	5	98
8		**6**	3.5	99
9		**5**	18	99[b]
10		**6**	15	92[b]
11		**6**	7.5	76[b]
12		**6**	2	99
13[c]		**5**	15	58
14[d]		**6**	16	93
15		**5**	15	74[b]
16		**6**	15	92[b]
17		**5**	18	91[b]
18		**5**	5	63[b]

[a] Yield determined by GC analysis using $C_{14}H_{30}$ as internal standard. [b] Yield of isolated product. [c] With two equivalents of **5** and 0.6 equivalents of AIBN. [d] With three equivalents of **6** and one equivalent of AIBN.

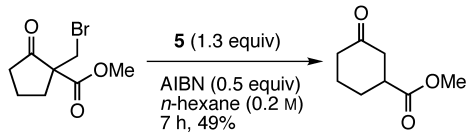
In addition to AIBN, other radical initiators can be used for the reduction of bromoadamantane with **5** such as Et_3B (0.2 equiv)/O_2[21] (99%). The same reaction at room temperature afforded only traces of adamantane. Either the reduction step or the rearomatization or even both processes are too slow at room temperature. Pleasingly, the reduction can be conducted perfectly well under an atmosphere of air (≈22% O_2) without using an initiator to give adamantane in quantitative yield (99%).[22]

To test the scope and the limitations of **5** and **6**, a series of reductions using various radical precursors that are typically employed was studied (Table 1). Primary, secondary, and aromatic halogenides were efficiently reduced (entries 5–14, Table 1). Barton–McCombie deoxygenation[23] of secondary alcohols using phenyl thionocarbonate esters[24] worked equally well (entries 15–17).[25] As expected, phenylselanides are readily reduced with **5** (entry 18).

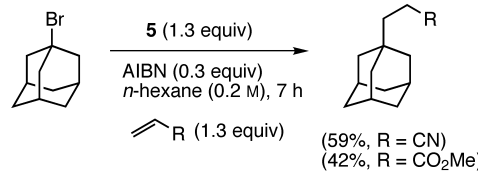
Another common set of synthetic reactions that utilize trialkyltin hydrides are radical cyclizations and intermolecular addition reactions. Cyclization of *o*-iodophenyl allyl ether [Eq. (2)] and the Beckwith–Dowd ring enlargement reaction[26] could be conducted with our new reagent [Eq. (3)]. Intermolecular addition reactions worked rather well [Eq. (4)]. Importantly, the syringe pump technique is not necessary to conduct these intermolecular addition reactions. Furthermore, the olefin is used in only a small excess (1.3 equiv).[27]



(2)



(3)



(4)

Finally, we also estimated the rate constant of the hydrogen transfer from reagent **5** to a primary radical. We have chosen the 5-*exo*-cyclization of the 5-hexenyl radical as the free radical clock.[28] A rate constant of $1 \times 10^5\,M^{-1}\,s^{-1}$ was estimated for the reduction of the intermediate primary alkyl radical at 70 °C. Thus, hydrogen transfer from **5** is about 10 times slower than the corresponding reaction with $(TMS)_3SiH$,[29] about 55 times slower than that with Bu_3SnH,[30] and almost as fast as that with Bu_3GeH.[31]

With the presented readily accessible, radical reducing agents, reagents are available that can replace the toxic tin hydrides commonly applied.

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[19] It is well known that silyl radicals add to benzene and are thus precluded from propagating a chain; therefore short chains would to be expected in benzene and account for the reduction of bromoadamantane not proceeding to completion. C. Chatgilialoglu, K. U. Ingold, J. C. Scaiano, *J. Am. Chem. Soc.* **1983**, *105*, 3292.
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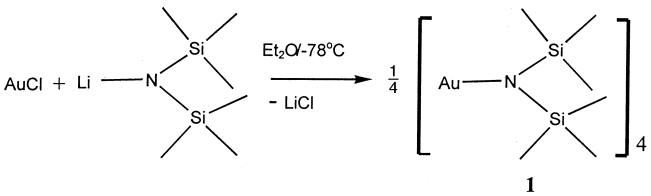
[{Au[μ-N(SiMe$_3$)$_2$]}$_4$]: The First Base-Free Gold Amide**

Scott D. Bunge, Oliver Just, and William S. Rees, Jr.*

Dedicated to Professor Herbert Schumann on the occasion of his 65th birthday

Throughout the Periodic Table, the use of the bis(trimethylsilyl)amido ligand $N(SiMe_3)_2^-$ has played a central role in the synthesis and characterization of metal and metalloid complexes with low coordination numbers.[1] Despite the extensive use, only a few examples of noble- or heavier coinage-metal derivatives have been reported. This deficiency may be attributed to the instability of these compounds, which arises from the combination of a soft metal with a hard amide ligand.[2] Herein, the first synthesis and X-ray structural characterization of a base-free homoleptic gold(I) di(silyl)amide, [{Au(μ-N(SiMe$_3$)$_2$)}$_4$] (**1**), is reported.

The gold(I) amide **1** was prepared in 19% yield by the metathesis reaction of lithium bis(trimethylsilyl)amide with gold(I) chloride in diethyl ether (Scheme 1). ^{1}H NMR and ^{13}C NMR spectroscopic analyses of **1** in $CDCl_3$ revealed the presence of singlets at $\delta = 0.34$ and 6.707, respectively. The EI and CI mass spectra revealed a tetranuclear parent ion, with the expected fragment ions.



1

Scheme 1. Synthetic route leading to the formation of **1**.

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