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The Use of Ureates as Activators for Samarium Diiodide

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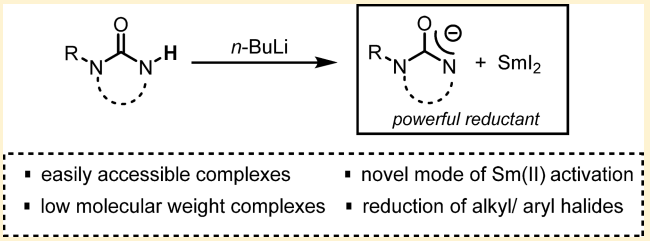
Supporting Information

ABSTRACT: A novel mode of SmI_2 activation has been developed using ureates as reaction promoters. Several ureates formed by treatment of the corresponding ureas with *n*-BuLi have been shown to activate SmI_2 to a substantial extent toward the reduction of 1-chlorodecane. Complexes formed from SmI_2 and various ureates have been shown to be useful for the reduction of a variety of organohalides, including substrates of low reactivity such as aryl fluorides. Because of ease of synthesis and low molecular weight, the conjugate base of triethylurea (TEU^-) was of primary focus. Visible spectroscopy and reactivity data are consistent with the hypothesis that the same complex is being formed when SmI_2 is combined with either 2 or 4 equiv of TEU^-, in spite of the greater reactivity of SmI_2/4 TEU^- with some alkyl halides. We propose that the active reductant is an N,O chelate formed between SmI_2 and 2 equiv of TEU^-.



INTRODUCTION

Samarium diiodide (SmI_2) continues to be one of the most important reagents for radical reduction in organic chemistry. A variety of organic functionalities are amenable to SmI_2-mediated reduction through complementary one- and two-electron processes.[1] However, for substrates which are reluctant toward radical reduction with SmI_2, additives can be employed to facilitate the reaction. The most common and historically important additive is hexamethylphosphoramide (HMPA, **1**, Figure 1), which was originally reported by Inanaga to decrease overall reaction times while substantially increasing the yields for the reduction of alkyl halides.[2] It has been established that HMPA primarily exerts its effect by coordinating to SmI_2 to form the THF-soluble complex $[SmI_2(HMPA)_4(THF)_2]^{2+}2I^-$.[3,4] This complex has proven so useful that the majority of samarium diiodide chemistry has been performed with HMPA as a cosolvent.[5] The primary drawback of this reduction system is the deleterious health effects associated with HMPA. HMPA has been shown to be mutagenic,[6] carcinogenic,[7,8] and antispermatogenic.[9] The polyhydroxylation of HMPA by cytochrome P450 oxidases is thought to be responsible for these undesirable health effects.[10] Furthermore, the use of HMPA has been banned in many laboratories.[11,12]

Chemists have expended a great deal of effort to develop alternative activators for SmI_2-mediated reactions. Transition metal salts, most importantly NiI_2, have proven useful for the facilitation of several reductive transformations involving alkyl halides,[13] imines,[14] anomeric pyridylsulfones,[15] acid chlorides,[16] and iminium triflates.[17,18] Recent mechanistic investigations by Flowers indicate that transmetalation of alkylsamarium to alkylnickel species is primarily responsible for the enhancement of reduction in the case of alkyl halide precursors.[19]

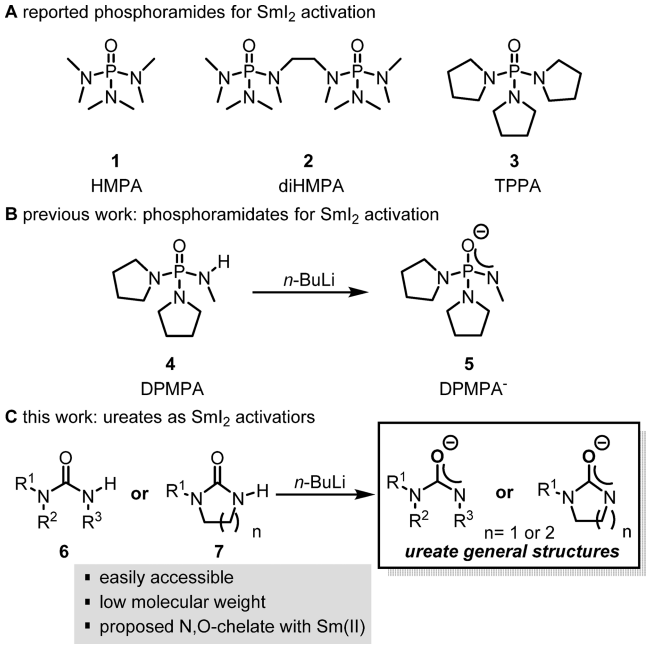


Figure 1. Activators of SmI_2.

Curran first reported the ability of water to enhance the reactivity of SmI_2 in THF.[20] The reduction of alkyl iodides, ketones, and sulfoxides proceeded more rapidly and in higher yield in the presence of H_2O. Subsequent work has explored the scope of substrates susceptible to reduction by SmI_2/

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H_2O.[21] Aromatic carboxylic acid derivatives[22] and *N*-acyl oxazolidines[23] can be reduced with SmI_2 in the presence of H_2O. These functionalities are resistant to reduction by SmI_2 in the absence of H_2O. Furthermore, Procter has employed SmI_2/H_2O for the chemoselective reduction of δ-lactones,[24] cyclic 1,3-diesters,[25] and barbituric acids.[26] High concentrations of H_2O are thought to lead to a dimeric Sm(II) aquo complex which functions as the initial electron donor in these reactions.[27,28]

Addition of triethylamine or pyrrolidine to the SmI_2/H_2O reduction system results in a further enhancement of reactivity. Synthetically useful reductions of alkyl halides,[29] conjugated alkenes and alkynes,[30] α,β-unsaturated esters,[31] unactivated esters,[32] carboxylic acids,[33] and amides[34] are known. The inclusion of the amine to the SmI_2/H_2O reaction mixture is thought to further enhance the reactivity of the reductant by removing a proton from a water molecule complexed to the Sm(III) species formed after the initial electron transfer to substrate.[35]

Electron-rich compounds such as 1,1,3,3-tetramethylguanidine (TMG),[36] 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU),[36] and 1,3-dimethyl-2-imidazolidinone (DMI)[37] have also been examined as possible SmI_2 activators and have some limited applications. The conjugate base of hexamethyldisilazine has proven to be extraordinarily effective for the activation of SmI_2 toward the reduction of alkyl and aryl fluorides.[38] The cosolvent *N*,*N*′-dimethylpropyleneurea (DMPU) has been successfully used in several instances as a surrogate for HMPA.[39] Although less effective than HMPA, DMPU is thought to activate SmI_2 in a similar manner, by coordination of its oxygen to Sm(II), resulting in an increase of electron density at the metal center.[40]

Over the past several years, we have been engaged in a program to develop phosphoramide-based alternative activators for SmI_2 (Figure 1A). The dimer of HMPA, diHMPA (**2**), has proven to be approximately $^1/_3$ as reactive as HMPA in most applications.[41] Tripyrrolidine phosphoric acid triamide (TPPA, **3**) was shown to be a substantially better activator of SmI_2 than HMPA in the reduction of alkyl halides and ketones.[42] The enhanced reactivity of this reducing system is attributed to both the increased basicity and the steric compactness of the pyrrolidino moiety in TPPA relative to the dimethylamino moiety in HMPA.[43,44] Reissig and co-workers have shown that SmI_2/TPPA is often superior to SmI_2/HMPA for the reductive dearomatization of γ-aryl ketones.[12] Recently, we have shown that the conjugate base of the phosphoramide, dipyrrolidinomethylaminophosphoric acid triamide (DPMPA, **4**), is an extremely efficient activator of SmI_2 (Figure 1B).[45] Complexes formed from 4 equiv of the anion derived from the deprotonation of DPMPA (**5**) and SmI_2 proved to be at least 100 times more reactive than the analogous SmI_2/HMPA complex as determined by the reduction of 1-chlorodecane. It is presumed that $DPMPA^-$ can deliver even greater electron density to the metal center of SmI_2, thus enhancing the reductive ability of the resultant species.

Herein, we report the extension of these efforts to the design of a series of ureates for the activation of SmI_2 as shown in Figure 1C. We envision the synthesis of compounds where the urea functionality is either acyclic/exocyclic (**6**) or endocyclic (**7**). A variety of advantages that ureates might exhibit relative to phosphoramides and phosphoramidates can be enumerated.

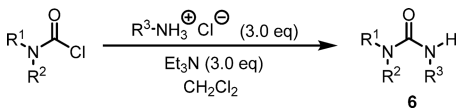
Because of the lower valency of the functional group's central atom, ureates will have a lower molecular weight relative to $DPMPA^-$. It is also reasonable to assume that, upon ureate ligation to Sm(II), the resultant complex would be less sterically encumbered, which might facilitate both inner- and outer-sphere reductive processes. Furthermore, unlike HMPA and DPMPA, the urea proligands will not possess *N*-methylphosphoramide moieties, which are known to produce mutagenic metabolites upon hydroxylation by cytochrome P450 oxidases.[10]

Although ureate complexes of Sm(II) have not been reported, several transition metal and lanthanide metal cations do complex with ureates to form unique organometallic species. Ureates have been shown to coordinate with Ti(IV),[46] Fe(III),[47] Zr(IV),[48] Pd(II),[49] Hf(IV),[50] W(VI),[51] and U(IV).[52] The Zr(IV) ureates are known to catalyze hydroamination reactions,[53] while the Pd(II) ureates are efficient catalysts for the Heck reaction of aryl bromides.[49]

RESULTS AND DISCUSSION

We began our investigation with the development of a general strategy toward the synthesis of the urea proligands which utilized inexpensive starting material, afforded a single product, and was amenable to scale-up. Our approach to the synthesis of a group of deprotonatable acyclic/exocyclic ureas is shown in Table 1. The appropriate *N*,*N*-dialkylcarbamoyl chloride was

Table 1. Synthesis of Acyclic/Exocyclic Ureas

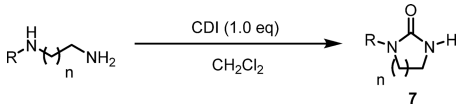


entry	R^1	R^2	R^3	product	yield (%)
1	Et	Et	Me	**6a**	76
2	Et	Et	Et	**6b**	84
3	Et	Et	*i*-Pr	**6c**	68
4	Et	Et	*t*-Bu	**6d**	91
5	*i*-Pr	*i*-Pr	Et	**6e**	98
6	$-(CH_2)_4-$		Et	**6f**	74

treated with an excess of primary amine salt and triethylamine in CH_2Cl_2 at room temperature.[54] After filtration, an extractive workup was performed. Bulb-to-bulb distillation afforded the typically crystalline products in good to excellent yield (entries 1−6).

A single step synthesis of endocyclic deprotonatable ureas was also developed (Table 2). In each case, an unsymmetrical diamine in CH_2Cl_2 was treated with 1,1′-carbonyldiimidazole (CDI).[55] After an aqueous workup with an acidic wash to remove the imidazole byproduct, good yields of the resultant ureas were obtained. It was determined that this approach was not practicable for the synthesis of ureas of less than six carbons

Table 2. Synthesis of Endocyclic Ureas



entry	R	*n*	product	yield (%)
1	*n*-Bu	1	**7a**	69
2	*n*-Pr	2	**7b**	71
3	*i*-Pr	2	**7c**	67

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due to the inability to efficiently separate the target compound from imidazole.

Deprotonatable ureas of lesser substitution which were used in this study and are commercially available (Figure 2) include acyclic ethylurea (**6g**), endocyclic 2-imidazolidinone (**7d**), and endocyclic propyleneurea (**7e**).

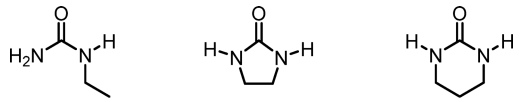
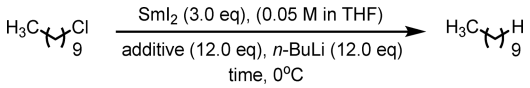


Figure 2. Commercially available deprotonatable ureas.

The reduction of 1-chlorodecane was chosen as a screening reaction to provide an initial assessment of the ability of each ureate to activate SmI_2. Ureates were formed *in situ* following *n*-BuLi addition to a solution of urea in THF (Table 3). In many cases (entries 1, 2, 7, 14, and 15), the formation of the ureate was evidenced by the development of a gel-like precipitate. The other ureates were THF-soluble. It was considered prudent to exclude a proton source from the reaction mixture because of the likely partial reprotonation of the ureates to the neutral urea. This would make assessment of the extent of activation difficult. Addition of the deep blue solution of SmI_2 in THF to the ureate resulted in the formation of a brown soluble complex in each case.

Table 3. Relative Reactivity of SmI_2 and Additive with 1-Chlorodecane



entry[a]	additive	yield (%) at 1 min[b]	yield (%) at 1 h[b]
1	**6a**	9	28
2	**6b**	16	32
3	**6c**	15	43
4	**6d**	0	0
5	**6e**	36	66
6	**6f**	5	28
7	**6g**	<1	<1
8	**6b**[c]	<1	<1
9	**6b**[d]	0	0
10	**6b**[e]	<1	1
11	**7a**	11	55
12	**7b**	43	77
13	**7c**	26	43
14	**7d**	10	13
15	**7e**	5	14
16	**1**[c]	<1	<1
17	**3**[c]	<1	<1
18	**4**	90	99
19	H_2O/pyrrolidine[c]	10	22
20	H_2O/pyrrolidine[c,f]	11	31

[a]1-Chlorodecane added last over 2 s. [b]Yield determined by GC with tetradecane as internal standard. [c]*n*-Bu-Li not used. [d]SmI_2 not used. [e]Deprotonation with NaH/DMF. [f]H_2O added last.

This color change is consistent with the complex formed between SmI_2 and $DPMPA^-$.[45] In screening studies of this sort, SmI_2 has typically been quenched with 0.1 M I_2 in hexane.[42,45,56,57] Because of the absence of a proton source in these reaction mixtures, a mixture of decane and 1-iododecane is formed upon quenching with I_2 in hexane as determined by GC−MS. Therefore, we used an open-air 0.1 M solution of *t*-BuOH in hexanes as the quench method in order to avoid the 1-iododecane side product. Thus, 1 min after the sequential addition of tetradecane (internal standard) and 1-chlorodecane were added to the SmI_2/ureate mixture, an aliquot was removed and quenched with *t*-BuOH in hexanes. A second aliquot was removed at 1 h. This order of addition, with 1-chlorodecane being added to a mixture of SmI_2 and ureate, is one of several possible orders of addition. A second order of addition will also be explored (*vide infra*).

Most of the ureates exhibited an ability to activate SmI_2 for the reduction of 1-chlorodecane. Acyclic ureas **6a−6c** which possess an increasing degree of substitution on the deprotonatable nitrogen, activate SmI_2 to a similar extent (entries 1−3, Table 3). Like **6a−6c**, the *t*-butyl congener **6d** forms a brown complex with SmI_2, but no reduction of 1-chlorodecane was observed (entry 4). Diisopropylethylurea (**6e**) proved to be somewhat more efficient at the activation of SmI_2 relative to **6a−c** (entry 5). Pyrrolidino-substituted urea **6f** was similar to **6a−c** in its ability to activate SmI_2 (entry 6). Ethylurea (**6f**) was not an effective activator of SmI_2 (entry 7). Entry 8 demonstrates that urea deprotonation is critical to reaction success. The neutral version of **6b**, triethylurea (TEU), forms a violet complex with SmI_2, but only traces of decane were observed under these mild reaction conditions. The necessity of SmI_2 in the reaction mixture is illustrated in entry 9. In the absence of SmI_2, no decane is produced. As has been shown previously, the presence of 12 equiv of LiBr in the reaction mixture does not sufficiently activate SmI_2 to allow for the reduction of 1-chlorodecane under these mild reaction conditions.[45] To further examine the potential role of Li^+ in this reduction system, the anion of **7b** was produced with NaH. This reaction was surprisingly sluggish. Success was achieved by heating TEU and NaH with DMF at 100 °C, cooling to rt, then removal of the DMF in vacuo. Addition of THF and SmI_2 afforded a dark brown suspension. This mixture afforded only small amounts of decane (entry 10).

The ureates derived from endocyclic ureas **7a−c** proved to be excellent activators of SmI_2. The ureate of *N*-propyl propyleneurea (**7b**, PPU^-, entry 12) was shown to be an especially good activator, the best of the ureates, although $DPMPA^-$ (entry 18) is substantially better. The anions derived from the two endocyclic commercially available ureas (**7d** and **7e**) were shown to be modest activators of SmI_2 (entries 14 and 15).

As expected, the neutral phosphoramides HMPA (entry 16) and TPPA (entry 17) afforded only trace amounts of decane under these conditions. On the other hand, the SmI_2/H_2O/pyrrolidine reagent system is capable of reducing 1-chlorodecane under these conditions (0.05 M SmI_2 at 0 °C). Using a protocol that most closely matches those described for the ureates in Table 3 with 1-chlorodecane being added last, yields of 10% and 22% were afforded at the 1 min and 1 h mark, respectively (entry 19). When the order of addition was modified to match those typically used for this reagent system (H_2O added last), the yields increased (entry 20).[58]

On the basis of this initial screening, three ureas were selected for further study. Triethylurea, TEU (**6b**), was selected for its ease of synthesis in multigram quantities, relatively low molecular weight, and its extended shelf life without discoloration. Its lack of *N*-methyl groups is also a desirable

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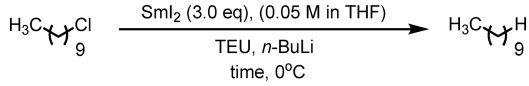
structural feature.[10,12] The endocyclic ureas *N*-butylimidazolidinone (BI, **7a**) and *N*-propyl propyleneurea (PPU, **7b**) were selected for their low molecular weight and greater degree of SmI_2 activation. It should be noted that PPU, the best urea activator found in this study, has a pair of undesirable properties. It is a low melting solid, which makes it difficult to manipulate. Furthermore, it is not bench stable, which is evident by its discoloration after a few days storage at room temperature.

Because of the centrality of triethylurea to our program, the next task was to further explore the reduction of 1-chlorodecane with SmI_2/TEU$^-$. Previous work has shown that the order of addition can be a significant factor in the success of SmI_2-mediated reactions.[45,59] The results in Table 3 were generated by the addition of 1-chlorodecane to a mixture of SmI_2 and TEU$^-$. This order of addition corresponds to method A in Table 4. The addition of SmI_2 to a mixture of

Table 4. Optimization of the Reduction of 1-Chlorodecane with SmI_2/TEU$^-$



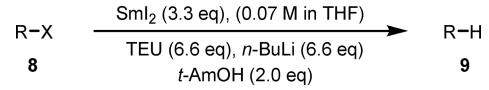
entry	TEU (equiv)	*n*-BuLi (equiv)	*t*-AmOH (2.0 equiv)	method[a]	yield (%) at 1 h[b]
1	12	12	no	A	32
2	12	12	no	B	85
3	3	3	no	B	21
4	6	6	no	B	66
5	9	9	no	B	76
6	12	12	yes	B	99
7	6	6	yes	B	92
8	6	6	yes	A	60

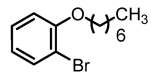
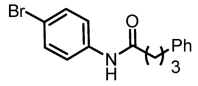
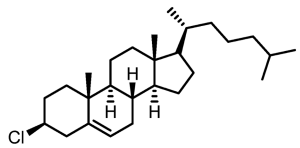
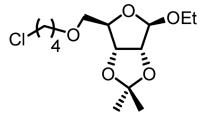
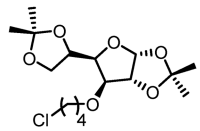
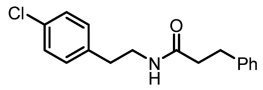
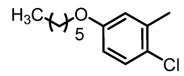
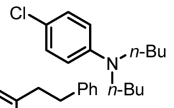
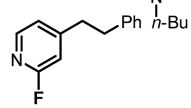
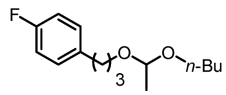
[a]Method A: 1-chlorodecane added last over 2 s. Method B: SmI_2 added last over 30 s. [b]Yield determined by GC with tetradecane as internal standard.

TEU$^-$ and 1-chlorodecane corresponds to method B. It is readily apparent that the order of addition is a significant factor in this reduction as well. Adding SmI_2 last (entry 2, method B) leads to a substantial increase in yield of the product decane relative to the addition of 1-chlorodecane last (entry 1, method A). It is unclear why the order of addition has such a dramatic effect on the efficiency of the reduction. The effect of changing the ratio of TEU$^-$ to SmI_2 using method B was also explored. Interestingly, even when a single equivalent of TEU$^-$ is present relative to SmI_2, the resultant blue-black solution is capable of reduction and a 21% yield of decane was obtained at the 1 h mark (entry 3). As expected, the yield of decane increased as the proportion of TEU$^-$ ligand was increased relative to SmI_2 (entries 2−5). Inclusion of a proton source and its effect on reaction efficacy was examined in entries 6−8. With the addition of *tert*-amyl alcohol (*t*-AmOH), there was an observed overall increase in the yield of decane (entry 6). *t*-AmOH was chosen as the proton source rather than the more typical *t*-BuOH because it is a liquid at rt, which simplifies the procedure. In the presence of this proton source, even the 1:2 complex afforded a near quantitative yield of decane at the 1 h mark with method B (entry 7). The addition of *t*-AmOH facilitated method A as well (entry 8).

The first synthetic application of SmI_2/ureate complexes to be explored is the reduction of alkyl and aryl halides. We began by focusing our efforts on the "low ratio" SmI_2/2 TEU$^-$/2 *t*-AmOH combination that was shown to be so effective in the optimization study described in Table 4 as well as the "high ratio" 1:4 complexes formed with the ureates TEU$^-$, BI$^-$, and PPU$^-$. Results for reductions of various alkyl halides with SmI_2/2 TEU$^-$/2 *t*-AmOH are shown in Table 5. Typically, these

Table 5. Reduction of R-X with SmI_2/2 TEU$^-$[a]



entry[a]	R-X (**8**)		% conversion[b]	% yield (**9**)
1	**8a**		100	91
2[c]	**8b**		100	94
3	**8c**		100	80
4	**8d**		100	87
5	**8e**		100	74
6[c]	**8f**		100	74
7	**8g**		71	45
8[d]			79	57
9	**8h**		24	11
10[d]			44	27
11	**8i**		100	73
12	**8j**		0	0

[a]SmI_2 added last over 30 s at 0 °C. [b]Conversions were measured by ^{1}H NMR integration calculated as a ratio of product to starting material. [c]Performed at −84 °C to rt. [d]5.0 equiv of SmI_2, 10.0 equiv of TEU, and 10.0 equiv of *n*-BuLi.

reactions are started at 0 °C and allowed to warm to room temperature overnight. Bromides are smoothly reduced as shown in entries 1 and 2. Because of the presence of the amide functional group in substrate **8b**, this reaction was started at −84 °C, and allowed to warm slowly to room temperature (entry 2). The survival of the amide functionality is noteworthy given that Procter has shown that the highly reactive reducing system SmI_2/H_2O/Et_3N converts amides to the corresponding

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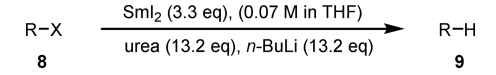
reduced alcohols.[34] Reduction of alkyl chlorides proceeded smoothly and afforded a single product in good to excellent yield (entries 3−5). These reaction conditions are substantially milder than what is required for the reduction of primary alkyl chlorides by SmI_2/4 HMPA (8 h at 60 °C).[2] Aryl chloride **8f** was cleanly reduced as well, once again with survival of the amide functional group (entry 6). Electron-rich aryl chlorides **8g** and **8h** proved more difficult to reduce. These reactions did not proceed to completion with the SmI_2/2 TEU^-/2 *t*-AmOH combination, even when additional reductant was provided (entries 7−10). The reduction of pyridyl fluoride **8i** proceeded to completion and was isolated in good yield (entry 11). Aryl fluoride **8j** was not reduced under these conditions (entry 12).

As was illustrated in Table 4, it is known that increasing the proportion of ureate in the reaction vessel enhances the reductive power of the mixture. We, therefore, performed a series of reductions with SmI_2/4 TEU^- as well as the more reactive SmI_2/4 BI^-, and SmI_2/4 PPU^-. As expected, reduction of alkyl chlorides worked well with SmI_2/4 TEU^- (Table 6, entries 1, 3, and 4). The importance of using the correct order of addition can once again be seen in entry 2. When cholesteryl chloride (**8c**) is added to SmI_2/4 TEU^-, large amounts of starting material remain in the decolorized reaction mixture upon workup. Chloroaryl ether **8g** was incompletely reduced by SmI_2/4 TEU^-, but could be completely reduced with the more reactive SmI_2/4 BI^-, and SmI_2/4 PPU^- (entries 5−7). Chloroaniline **8h** could be fully reduced only by the most reductive complex under study, SmI_2/4 PPU^- (entries 8−10). Aryl fluoride **8j** was amenable to complete reduction by SmI_2/4 PPU^- but not other SmI_2/ureate complexes (entries 11 and 12). Fluoroaryl ether **8k** can also be efficiently reduced by SmI_2/4 PPU^- (entry 13). Cholesteryl fluoride was fully resistant to reduction by SmI_2/4 PPU^- with or without the addition of 2 equiv of *t*-AmOH (entries 14 and 15).

Dichloride **10** was used to evaluate the ability of various SmI_2-based reagents systems to effect selective monodechlorination (Table 7). From previous work, it was expected that the aryl chloride bond would be more susceptible to reduction. Reduction of **10** with 3 equiv of SmI_2/4 HMPA in the presence of 2 equiv of *t*-AmOH provided a 76% yield of alkyl chloride **11**, trace amounts of the alternative product, aryl chloride **12**, and a 12% yield of the overreduction product **13** (entry 1). A modest improvement in selectivity was noted with SmI_2/TPPA (entry 2). Reduction with 3 equiv of SmI_2/2 TEU^- in the presence of 2 equiv of *t*-AmOH was more successful, providing almost exclusively the desired **11** (entry 3). When SmI_2/4 TEU^- was employed, the reaction went to completion but a substantial amount of **13** was observed. The highly reactive phosphoramidate-based reagent SmI_2/4 $DPMPA^-$ proved to be the least selective (entry 5). Thus, the SmI_2/2 TEU^- reagent system has thus been shown to be the most selective of those evaluated for the monoreduction of dichloride **10**.

To gain insight into the nature of the species formed during the addition of SmI_2 to TEU^-, a series of alkyl halides and unsaturated hydrocarbons were subjected to reduction. This method of estimating chemical reduction potential was employed because SmI_2/TEU^- complexes are not amenable to the determination of their thermodynamic reduction potential by cyclic voltammetry due to irreversible oxidation of the species in the electrochemical cell. The inability to obtain useful information about the reduction potential of very reactive SmI_2 complexes by cyclic voltammetry has been noted previously.[29,45] As pointed out by Procter, using the

Table 6. Reduction of R-X with SmI_2/4 Ureate$^-$ Complexes[a]



entry[a]	R-X (**8**)	urea	% conversion[b]	% yield (**9**)
1	**8c**	TEU	100	84
2[c]		TEU	52	44
3	**8d**	TEU	100	83
4	**8e**	TEU	100	79
5[d]	**8g**	TEU	75	55
6[d]		BI	100	77
7[d]		PPU	100	87
8[d]	**8h**	TEU	25	15
9[d]		BI	86	75
10[d]		PPU	100	83
11[d]	**8j**	BI	0	0
12[d]		PPU	100	85
13[d]	**8k**	PPU	100	74
14	**8l**	PPU	0	0
15[e]		PPU	0	0

[a]SmI_2 added last over 30 s at 0 °C. [b]Conversions were measured by ^1H NMR integration calculated as a ratio of product to starting material. [c]**8c** added last over 2 s. [d]4.0 equiv of SmI_2, 16.0 equiv of urea, and 16.0 equiv of *n*-BuLi. [e]2.0 equiv of *t*-AmOH.

reduction of hydrocarbons to estimate redox potentials often provides results that are substantially different than those obtained by cyclic voltammetry. For example, SmI_2 in THF has a thermodynamic redox potential of −0.89 V (vs SCE) as determined by cyclic voltammetry but can reduce the aromatic hydrocarbons acenaphthylene ($E_{1/2}$ = −1.65 V) and cyclooctatetraene ($E_{1/2}$ = −1.83 V).[60] In spite of the disparity in values obtained for thermodynamic redox potential by cyclic voltammetry and effective redox potential by determination of which substrates are susceptible to reduction, both methodologies have proven useful in the characterization of lanthanide complexes. It is also worthy of note that the unsaturated hydrocarbons are reduced by an outer-sphere mechanism,[58] while the outer-sphere character of the reduction of alkyl halides decreases from RBr to RCl, and presumably further still with R-F.[4]

Results for the determination of effective redox potential of both SmI_2/2 TEU^- and SmI_2/4 TEU^- are presented in Table

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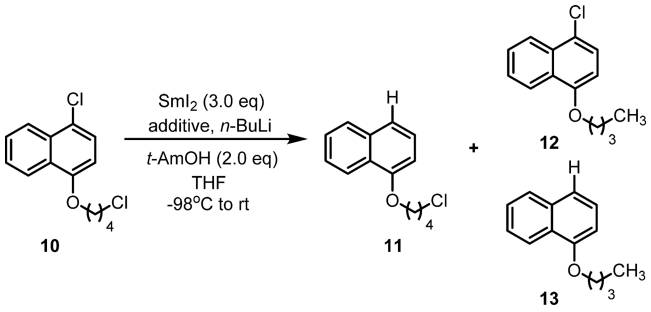
Table 7. Comparison of Additives in the Reduction of Dichloride 10[a]

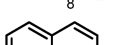
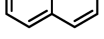
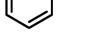
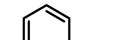


entry	additive (equiv)	*n*-BuLi (equiv)	% conversion[b]	yield (%)[c] 11	12	13
1	HMPA (12)		95	76	<1	12
2	TPPA (12)		96	85	<1	7
3	TEU (6)	6	92	85	<1	0
4	TEU (12)	12	100	75	<1	19
5	DPMPA (12)	12	82	52	<1	16

[a]SmI_2 (0.05 M) added last over 8 min. [b]Conversions were measured by ^{1}H NMR. Integration calculated as a ratio of product to starting material. [c]Isolated yields unless noted.

8. Interestingly, combinations of SmI_2 and TEU^- in both ratios behaved identically. On the basis of the ability of both

Table 8. Reduction of Hydrocarbons and 1-Halodecanes with SmI_2/TEU^- Complexes

entry	substrate	$E_{1/2}$(V)[a]	reduction with SmI_2/ 2 TEU[-b]	reduction with SmI_2/ 4 TEU[-b]
1		-2.21	✓	✓
2		-2.29	✓	✓
3		-2.61	✓	✓
4		-2.65	✓	✓
5		-2.79	✓	✓
6		-2.97	×	×
7		-4.00	×	×

[a]In volts vs SCE. [b]% yield > 90% using tetradecane as internal standard.

complexes to rapidly reduce *trans*-stilbene, 1-bromodecane, naphthalene, styrene, and 1-chlorodecane, but not 1-fluorodecane or benzene, an estimate of ca. −2.8 (vs SCE) for the effective reducing power of both SmI_2/2 TEU^- and SmI_2/4 TEU^- can be obtained. This represents an estimated increase in effective reducing power of approximately 1.0 V relative to SmI_2 in THF. For comparison, the estimates of effective reducing power of SmI_2/H_2O and SmI_2/H_2O/amine are −2.2[60] and −2.7 V[58] vs SCE, respectively, by this methodology.

Visible spectroscopy was also employed to characterize SmI_2/TEU^- complexes. The visible spectrum of SmI_2 in THF is typified by a set of three absorbance maxima around 422, 557, and 626 nm.[4,45] The solution is deep blue in color. Upon addition of a THF solution of SmI_2 to a single equivalent of TEU^-, the latter two absorption maxima broaden and shift to slightly lower maxima at 551 and 620 nm (Figure 3). This

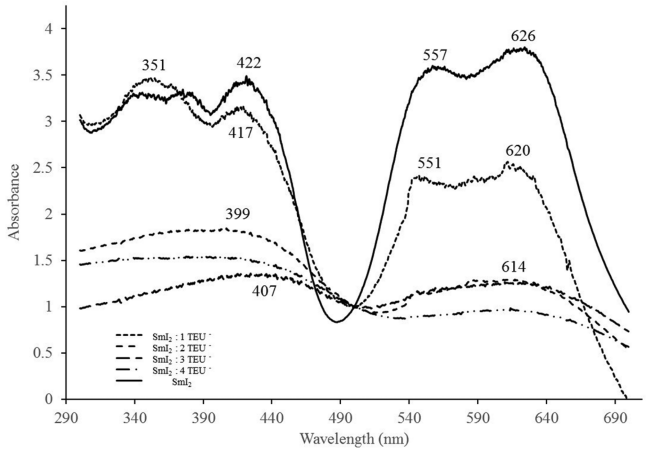


Figure 3. Normalized (at 500 nm) visible spectra recorded at 10 mM SmI_2 in THF.

solution appears blue-black in color. The visible spectra of the 1:2, 1:3, and 1:4 complexes of SmI_2 and TEU^-, although not identical, are strikingly similar in appearance, with a deep brown color, and *very* broad absorption maxima at 407 and 614 nm.

This is congruent with our experience examining $SmI_2/DPMPA^-$ mixtures. The 1:1 mixture of SmI_2 and $DPMPA^-$ is blue-black in color, with a broad peak at 546 nm, whereas the 1:2, 1:3, and 1:4 mixtures of $SmI_2/DPMPA^-$ are deep brown in color with a single broad absorbance band centered at 405 nm.[45]

The available evidence strongly suggests that the same complex is present whether SmI_2/2 TEU^-, SmI_2/3 TEU^-, or SmI_2/4 TEU^- is employed. As shown in Table 4, the dramatic increase in the yield of decane at 1 h in the reduction of 1-chlorodecane occurs when the ratio changes from 1:1 SmI_2/TEU^- (entry 3, 21%) to 1:2 SmI_2/TEU^- (entry 4, 66%). The smaller additional gains in reactivity of SmI_2/TEU^- with alkyl halides when greater than 2 equiv of TEU^- are employed in the reaction mixture can be explained by the role very polar species play in the activation of carbon−halogen bonds.[61] As detailed by Flowers, polar species such as HMPA coordinate to the carbon−halogen bond and activate the bond toward the initial reduction by $Sm(HMPA)_4(THF)_2^{2+}2I^-$.

We believe that the presence of TEU^- beyond the 2 equiv required to saturate the metal center with ureate ligand in the reaction mixture would similarly activate carbon−halogen bonds toward electron transfer from SmI_2/2 TEU^-. The visible spectra shown in Figure 3 are consistent with the presence of identical complexes at ratios of 1:2, 1:3, and 1:4 of SmI_2 and TEU^-. Dramatic changes occur in the visible spectra as the proportion of TEU^- increases in mixtures of SmI_2/TEU^- until a 1:2 ratio is achieved. Changes in the visible spectra essentially cease as the proportion of TEU^- is changed from 1:2 to 1:4. The results for the reduction of hydrocarbons and alkyl halides by the two different reagent mixtures (Table 8) also suggest that there are 2 equiv of TEU^- coordinated to SmI_2 in each case.

The evidence that the active reductant is a 1:2 complex of SmI_2 and TEU^- implies that the ligand is coordinating to the

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Sm(II) center as an N,O chelate. The coordination of two such ligands around the metal may preclude the incorporation of additional ureates. Indeed, structurally defined bis-N,O chelates of monoureates to Ti(IV) and Zr(IV) are known.[62]

CONCLUSION

In our preceding work we have developed a series of phosphoramide-based HMPA surrogates (DiHMPA, TPPA, $DPMPA^-$) for the activation of the important reducing agent SmI_2. This work focused on the synthesis, evaluation, use, and characterization of ureates for the activation of SmI_2. A series of deprotonatable ureas were screened for the ability to activate SmI_2 for the reduction of 1-chlorodecane. One acyclic urea, TEU, and two endocyclic ones, BI and PPU, were selected for further study. The SmI_2/TEU^- reducing system has been found to effectively reduce alkyl and aryl halides. The "low ratio" reagent system SmI_2/2 TEU^-/2 *t*-AmOH is a substantially more powerful reducing agent than SmI_2/4 HMPA and is capable of reducing a range of alkyl chlorides. Selective reductions are also possible. Haloamides can be selectively dehalogenated by this reagent. The alkyl halide component of an alkylaryl dichloride can be selectively reduced more efficiently by SmI_2/2 TEU^-/2 *t*-AmOH than by the four other SmI_2-based reagent systems that were evaluated. The "high ratio" complexes of SmI_2 with TEU^-, BI^-, and PPU^- are even more reactive and capable of the reduction of even more reluctant radical precursors such as electron-rich aryl chlorides and fluorides. The reduction of 1-chlorodecane with various SmI_2/ureate combinations, which was used as a screening reaction, accurately predicted the relative degree of activation of SmI_2 by TEU^-, BI^-, and PPU^- in subsequent synthetically relevant reductions.

Determination of which hydrocarbon and alkyl halide substrates are susceptible to reduction by SmI_2/2 TEU^-/2 *t*-AmOH and SmI_2/4 TEU^-/2 *t*-AmOH suggests that the same reductant may be present in both cases. Estimates of −2.8 (vs SCE) V for both SmI_2/2 TEU^-/*t*-AmOH and SmI_2/4 TEU^-/*t*-AmOH for thermodynamic redox potentials were obtained, which indicates they are more powerful reductants than the very useful SmI_2/H_2O and SmI_2/H_2O/amine reagent systems. Comparison of visible spectra of various ratios of SmI_2 and TEU^- suggests that two TEU^- ligands are sufficient to saturate the metal center.

EXPERIMENTAL SECTION

General. Dichloromethane, toluene, DMF, 1-chlorodecane, *i*-Pr_2NH, benzyl bromide, Et_3N, pyridine, pyrrolidine, and HMPA were distilled from CaH_2 prior to use. Tetrahydrofuran was distilled from Na/benzophenone and sparged with argon for 15 min prior to use. Water and pyrrolidine were also sparged with argon for 15 min prior to use. All ureas, TPPA, and DPMPA were azeotropically dried with toluene in Schlenkware prior to use in SmI_2 reactions. *n*-Butyllithium was purchased as a 2.5 M solution and used as received. The concentration of SmI_2 in THF was confirmed by titration with I_2.[63] Glass-coated stir bars were used for all SmI_2 reactions. All reactions were performed under a nitrogen or argon atmosphere in oven-dried glassware. Reagent transfer was accomplished using gastight syringes. NMR spectra were recorded at room temperature (300 MHz for ^1H and 75 MHz for ^{13}C) in $CDCl_3$. Chemical shifts are reported in δ parts per million referenced to residual solvent proton resonance of $CDCl_3$ (7.28 ppm) or the solvent carbon resonance of $CDCl_3$ (77.0 ppm). Column chromatography was accomplished using silica gel (70−230 mesh) as the stationary phase and mixtures of hexanes and ethyl acetate as the mobile phase. Thin-layer chromatography was performed using silica gel plates with fluorescent indicator. Visualization was accomplished by UV light (254 nm) or iodine.

GC−MS analyses were performed using a GC system equipped with a column of fused silica (length 30 m, internal diameter 0.25 mm, film 0.25 μm of diphenyl dimethyl polysiloxane) and an EI/CI ion trap detector. He was used as the carrier gas. The injector temperature was 250 °C. The initial oven temperature was 40 °C with an initial hold time of 2 min, with a 20 °C/min ramp to a final temperature of 300 °C and then held at that temperature for 6 min. A split ratio of 10 was employed.

GC analyses were performed using a GC system equipped with a column of fused silica (length 30 m, internal diameter 0.25 mm, film 0.25 μm of diphenyl dimethyl polysiloxane) and an FID detector. He was used as the carrier gas. The injector temperature was 250 °C. The initial oven temperature was 50 °C with an initial hold time of 2 min, with a 10 °C/min ramp to a final temperature of 250 °C and then held at that temperature for 10 min. A split ratio of 10 was employed.

High-resolution mass spectrometry was performed by direct insertion into the EI source. Ions were separated by a double focusing sector (magnetic and electric sectors) mass analyzer and then detected. Positive ion mode was employed.

Visible spectra were recorded at room temperature using a spectrometer coupled to a UV−vis−NIR source and a 300 μm transmission dip probe, capable of a transmission path length of 2 mm.

General Procedure for the Synthesis of 1,1-Diethyl-3-alkyl Ureas. Dichloromethane (11 mL) was added to diethylcarbamoyl chloride (2.80 mL, 0.0221 mol). The appropriate alkylamine hydrochloride (0.0663 mol) was added to the mixture. Triethylamine (9.3 mL, 0.066 mol) was added, and the heterogeneous mixture was allowed to stir at rt for 48 h. Water (15 mL) was added, and the mixture was extracted with $CHCl_3$ (5 × 20 mL). The resultant extract was washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distallation afforded the purified product.

*1,1-Diethyl-3-methylurea (**6a**).* Distillation (2 mmHg, 128−130 °C) yielded 2.18 g (76%) of the title compound **6a** as a white solid, mp 34−35 °C (lit.[64] 34−35 °C). IR (ATR) cm^{-1} 3227, 2970, 2931, 1622, 1526, 1490, 1375. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.85−4.63 (b, 1H), 3.18 (q, J = 7.1 Hz, 4H), 2.70 (d, J = 4.6 Hz, 3H), 1.03 (t, J = 7.1 Hz, 6H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 157.9, 40.7, 27.2, 13.6.[64]

*1,1-Diethyl-3-ethylurea (**6b**).* Distillation (0.4 mmHg, 140−145 °C) yielded 2.67 g (84%) of the title compound **6b** as a white solid, mp 60−62 °C (lit.[65] 62 °C). IR (ATR) cm^{-1} 3443, 2972, 2931, 2871, 1614, 1529, 1491, 1272. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.50−4.39 (b, 1H), 3.22−3.15 (m, 6H), 1.08−1.03 (m, 9H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 157.1, 40.8, 35.3, 15.5, 13.6.

*1,1-Diethyl-3-isopropylurea (**6c**).* Distillation (2 mmHg, 175−178 °C) yielded 2.38 g (68%) of the title compound **6c** as a white solid, mp 68−69 °C. IR (ATR) cm^{-1} 3359, 3332, 2972, 2929, 1611, 1530, 1491, 1224. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.11−3.96 (b, 1H), 4.00, (hept, J = 6.3 Hz, 1H), 3.24 (q, J = 7.1 Hz, 4H), 1.16−1.11 (m, 12H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 156.6, 42.3, 41.0, 23.6, 13.8.[66]

*1,1-Diethyl-3-tert-butylurea (**6d**).* Distillation (0.4 mmHg, 110−115 °C) yielded 3.49 g (91%) of the title compound **6d** as a white solid, mp 75−76 °C. IR (ATR) cm^{-1} 3333, 2967, 2929, 1621, 1528, 1489, 1357. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.23−4.11 (b, 1H), 3.22 (q, J = 7.1 Hz, 4H), 1.35 (s, 9H), 1.12 (t, J = 7.1 Hz, 6H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 156.5, 50.5, 40.9, 29.6, 13.8.[66]

*1,1-Diisopropyl-3-ethylurea (**6e**).* Dichloromethane (11 mL) was added to diisopropylcarbamoyl chloride (3.61 g, 0.0221 mol). Ethylamine hydrochloride (5.40 g, 0.0663 mol) was added to the mixture. Triethylamine (9.3 mL, 0.066 mol) was added, and the mixture was allowed to stir at rt for 48 h. Water (15 mL) was added, and the mixture was extracted with $CHCl_3$ (5 × 20 mL). The resultant extract was washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distillation (0.9 mmHg, 145−152 °C) yielded 3.74 g (98%) of the

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title compound **6e** as a white solid, mp 75−77 °C. IR (ATR) cm^{-1} 3318, 2968, 2929, 1609, 1525, 1452, 1314, 1301. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.21−4.09 (b, 1H), 3.89−3.80 (m, 2H), 3.30−3.21 (m, 2H), 1.22 (d, J = 6.9 Hz, 12H), 1.12 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 157.3, 44.9, 35.3, 21.3, 15.5.[67]

*3′-Ethyl Pyrrolidinecarboxamide (**6f**).* Dichloromethane (5.9 mL) was added to 1-pyrrolidinecarbonyl chloride (1.30 mL, 0.0118 mol). Ethylamine hydrochloride (2.89 g, 0.0354 mol) was added to the mixture. Triethylamine (4.9 mL, 0.035 mol) was added, and the mixture was allowed to stir at rt for 48 h. Water (10 mL) was added, and the mixture was extracted with $CHCl_3$ (5 × 15 mL). The resultant extract was washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distillation (1.3 mmHg, 175−180 °C) yielded 1.24 g (74%) of the title compound **6f** as a white solid, mp 83−84 °C. HRMS (EI) m/z: $[M^+]$ calcd for $C_7H_{14}N_2O$ 142.1101; found 142.1101. IR (ATR) cm^{-1} 3295, 2962, 2926, 2865, 1618, 1537, 1435, 1337. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 4.99−4.79 (b, 1H), 3.00−2.96 (m, 4H), 2.89−2.85 (m, 2H), 1.54−1.49 (m, 4H), 0.76 (t, J = 7.1 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 156.4, 44.6, 34.4, 24.7, 15.0.

General Procedure for the Synthesis of Endocyclic Ureas. Dichloromethane (65 mL) was added to the appropriate diamine (0.0259 mol). After cooling the stirred mixture in an ice-water bath, 1,1′-carbonyldiimidazole (4.20 g, 0.0259 mol) was added in four portions over 1 h to the mixture. The mixture was allowed to warm to rt and stir for 24 h. Water (10 mL) was added, and the mixture was extracted with $CHCl_3$ (5 × 25 mL). The resultant extract was stirred with 10% HCl (20 mL) for 30 min, then partitioned. The organic layer was washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure.

*N-Butylethylene Urea (**7a**).* Distillation (0.5 mmHg, 186−190 °C) yielded 2.54 g (69%) of the title compound **7a** as a white solid, mp 39−40 °C (lit.[68] 36−39 °C). IR (ATR) cm^{-1} 3209, 3090, 2952, 2930, 2867, 1684, 1495, 1457, 1439. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.36 (b, 1H), 3.41 (b, 4H), 3.16 (t, J = 7.2 Hz, 2H), 1.51−1.43 (m, 2H), 1.36−1.29 (m, 2H), 0.92 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 163.4, 44.9, 43.2, 38.3, 29.6, 19.9, 13.7.

*N-Propylpropylene Urea (**7b**).* Distillation (1.7 mmHg, 200−208 °C) yielded 2.61 g (71%) of the title compound **7b** as a white solid, mp 39−40 °C. HRMS (EI) m/z: $[M^+]$ calcd for $C_7H_{14}N_2O$ 142.1101; found 142.1102. IR (ATR) cm^{-1} 3232, 2960, 2933, 2872, 1637, 1516, 1454, 1305. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 6.96−5.98 (b, 1H), 3.34−3.23 (b, 6H), 1.97−1.89 (m, 2H), 1.61−1.48 (m, 2H), 0.87 (t, J = 7.4 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 156.6, 49.4, 45.2, 39.9, 21.4, 20.6, 11.0.

*N-iso-Propylpropylene Urea (**7c**).* Distillation (0.9 mmHg, 199−202 °C) yielded 2.46 g (67%) of the title compound **7c** as a white solid, mp 151−152 °C (lit.[69] 151−155 °C). IR (ATR) cm^{-1} 3284, 3197, 3053, 2960, 2969, 2929, 2852, 1644, 1499, 1446, 1309. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.06−4.88 (b, 1H), 4.72 (hept, J = 6.7 Hz, 1H), 3.30 (t, J = 5.6 Hz, 2H), 3.19 (t, J = 5.6 Hz, 2H), 1.97−1.89 (m, 2H), 1.13 (d, J = 6.8 Hz, 6H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 156.0, 43.9, 39.7, 37.7, 21.8, 19.2.

General Procedure for the Reduction of 1-Chlorodecane with SmI_2/4 Ureate (Method A). To an ice-cold mixture of the appropriate urea (2.28 mmol), THF (4.5 mL), and tetradecane (10.0 μL, 0.0384 mmol) was added 0.92 mL of a 2.5 M solution of *n*-BuLi in hexanes (2.3 mmol). This mixture was stirred for 5 min, and 6.2 mL of a 0.092 M solution of SmI_2 in THF (0.57 mmol) was added, and allowed to stir for 5 min. 1-Chlorodecane (38 μL, 0.19 mmol) was added, and the mixture was allowed to stir. Aliquots were removed at 1 min and 1 h and immediately quenched with a 0.1 M *tert*-butanol in hexanes solution. The aliquot was mixed with 0.1 mL of 0.1 M HCl and 1 mL of Et_2O. The Et_2O extract from this mixture was analyzed by GC and GC−MS to obtain the yield of decane (identity of the product confirmed by comparison with authentic material).

*1-Bromo-2-O-heptylbenzene (**8a**).* DMF (2.9 mL) was added to 2-bromophenol (500 mg, 2.9 mmol). DBU (0.65 mL, 4.3 mmol) and 1-bromoheptane (0.65 mL, 4.3 mmol) were added. The mixture was stirred and heated to 60 °C in a pressure tube for 24 h. After cooling for 5 min, water (10 mL) was added and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 15 mL). The combined organic layers were washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distillation (1.0 mmHg, 175−180 °C) afforded 0.665 g (82%) of the title compound **8a** as a colorless oil. HRMS (EI) m/z: $[M^+]$ calcd for $C_{13}H_{19}OBr$ 270.0625; found 270.0622. IR (ATR) cm^{-1} 2926, 2856, 1587, 1482, 1291, 1276. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.55 (dd, J = 7.8, 1.6 Hz, 1H), 7.29−7.24 (m, 1H), 6.92−6.81 (m, 2H), 4.04 (t, J = 6.5 Hz, 2H), 1.91−1.84 (m, 2H), 1.55−1.50 (m, 2H), 1.42−1.31 (m, 6H), 0.92 (t, J = 6.7 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 155.5, 133.3, 128.4, 121.6, 113.2, 112.3, 69.1, 31.8, 29.1, 29.1, 26.0, 22.6, 14.1.

*N-(4-Bromophenyl)-4-phenylbutanamide (**8b**).* Benzene (6.1 mL) was added to 4-phenylbutanoic acid (1.00 g, 0.00609 mol) and cooled in an ice-water bath. $(COCl)_2$ (0.94 mL, 0.011 mol) was added, and the mixture was stirred for 3 h, then concentrated under reduced pressure. CH_2Cl_2 (2.1 mL) was added to the crude mixture which was stirred and cooled in an ice-water bath. A solution of pyridine (3.0 mL), CH_2Cl_2 (1.0 mL), and 4-bromoaniline (1.25 g, 0.00731 mol) was slowly added. The mixture was warmed to room temperature and stirred overnight. Water (10 mL) and saturated $NaHCO_3$ (10 mL) were added and stirred for 30 min. The mixture was extracted with Et_2O (3 × 15 mL). The combined organic layers were washed with 10% NaOH (10 mL), water (10 mL), 10% HCl (10 mL), water (10 mL), and then concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, gradient ranging from 2% to 10% EtOAc in hexanes) to provide 1.86 g of the title compound **8b** (95%) as a white powder, mp 119−120 °C. HRMS (EI) m/z: $[M^+]$ calcd for $C_{16}H_{16}NOBr$ 317.0421; found 317.0412. IR (ATR) cm^{-1} 3289, 3065, 3023, 2943, 2867, 1657, 1590, 1520, 1489 cm^{-1}. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.44−7.41 (m, 4H), 7.34−7.19 (m, 6H), 2.73 (t, J = 7.4 Hz, 2H), 2.36 (t, J = 7.2 Hz, 2H), 2.12−2.05 (m, 2H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 171.1, 141.2, 136.9, 132.0, 128.5, 128.5, 126.1, 121.4, 116.8, 36.7, 35.0, 26.7.

*1-O-Ethyl-5-O-(4-chlorobutyl)-2,3-O-isopropylidene-β-D-ribofuranose (**8d**).* Prepared in accordance with a previously reported procedure as a colorless oil.[45] ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.08 (s, 1H), 4.68 (d, J = 6.0 Hz, 1H), 4.60 (d, J = 6.0 Hz, 1H), 4.31 (t, J = 7.6 Hz, 1H), 3.75−3.69 (m, 1H), 3.58 (t, J = 3.4 Hz, 2H), 3.52−3.40 (m, 5H), 1.95−1.84 (m, 2H), 1.76−1.71 (m, 2H), 1.50 (s, 3H), 1.34 (s, 3H), 1.19 (t, J = 7.1 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 112.3, 107.8, 85.3, 85.0, 82.2, 71.8, 70.4, 62.9, 45.0, 29.4, 27.0, 26.5, 25.0, 14.9.

*3-O-(4-Chlorobutyl)-1,2:5,6-di-O-isopropylidene-α-D-glucofuranose (**8e**).* Prepared in accordance with a previously reported procedure as a colorless oil.[70] ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.88 (d, J = 3.6 Hz, 1H), 4.54 (d, J = 3.7 Hz, 1H), 4.30−4.26 (m, 1H), 4.12−4.07 (m, 2H), 4.01−3.96 (m, 1H), 3.87 (d, J = 3.0 Hz, 1H), 3.69−3.64 (m, 1H), 3.59−3.54 (m, 3H), 1.91−1.84 (m, 2H), 1.77−1.71 (m, 2H), 1.51 (s, 3H), 1.43 (s, 3H), 1.36 (s, 3H), 1.33 (s, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 111.8, 109.0, 105.3, 82.5, 82.2, 81.2, 72.4, 69.6, 67.4, 44.8, 29.3, 27.0, 26.8, 26.8, 26.2, 25.4.

*N-[2-(4-Chlorophenyl)ethyl]phenylpropanamide (**8f**).* CH_2Cl_2 (3.0 mL) was added to hydrocinnamoyl chloride (0.44 mL, 0.0030 mol) and cooled in an ice-water bath with stirring. A solution of 2-(4-chlorophenyl)ethylamine (0.46 mL, 0.33 mol) in pyridine (0.29 mL, 0.0037 mol) was added slowly. The mixture was allowed to warm to rt and stir overnight. Water (10 mL) and saturated $NaHCO_3$ (10 mL) were added and stirred for 10 min. The mixture was extracted with Et_2O (3 × 15 mL). The combined organic layers were washed with 10% NaOH (10 mL), water (10 mL), 10% HCl (10 mL), water (10 mL), and then concentrated under reduced pressure. The residue was purified by recrystallization from a mixture of Et_2O in hexanes to provide 0.620 g (73%) of the title compound **8f** as a white powder, mp 116−117 °C. HRMS (EI) m/z: calcd for $C_{17}H_{18}NOCl$ 287.1071; found 287.1072. IR (ATR) cm^{-1} 3294, 3067, 3031, 2930, 2864, 1634, 1604, 1539, 1489, 1453. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.30−7.18 (m, 7H),, 7.00 (d, J = 8.3 Hz, 2H), 5.49−5.42 (b, 1H), 3.48−3.41 (m, 2H), 2.96 (t, J = 7.5 Hz, 2H), 2.71 (t, J = 6.9 Hz, 2H), 2.44 (t, J =

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7.5 Hz, 2H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 172.1, 140.8, 137.3, 132.3, 130.1, 128.7, 128.6, 128.4, 126.3, 40.5, 38.4, 35.0, 31.7.

*1-Chloro-2-methyl-4-O-hexylbenzene (**8g**).* DMF (6.6 mL) was added to 1-chloro-2-methyl-4-hydroxybenzene (1.00 g, 6.56 mmol). DBU (1.47 mL, 0.00986 mol) and 1-bromohexane (2.29 mL, 16.4 mmol) were added. The mixture was stirred and heated to 60 °C in a pressure tube for 24 h. After cooling for 5 min, water (10 mL) was added and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 15 mL). The combined organic layers were washed with 10% NaOH (10 mL) and water (10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distillation (0.6 mmHg, 143−150 °C) afforded 1.21 g (81%) of the title compound **8g** as a colorless oil. HRMS (EI) *m*/*z* calcd for $C_{13}H_{19}OCl$ 226.1119; found 226.1123. IR (ATR) cm^{-1} 2929, 2859, 1596, 1576, 1482, 1470 cm^{-1}. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.24 (d, *J* = 8.8 Hz, 1H), 6.80 (d, *J* = 3.0 Hz, 1H), 6.60 (dd, *J* = 8.7, 3.0 Hz, 1H), 3.93 (t, *J* = 6.6 Hz, 2H), 2.36 (s, 3H), 1.83−1.74 (m, 2H), 1.50−1.35 (m, 8H), 0.96−0.92 (m, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 157.7, 136.9, 129.5, 125.5, 117.1, 113.0, 68.2, 31.6, 29.2, 25.7, 22.6, 20.3, 14.1.

*N,N-Dibutyl-4-chlorobenzene (**8h**).* Prepared in accordance with a previously reported procedure as a colorless oil.[71] ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.16 (d, *J* = 9.2 Hz, 2H), 6.58 (d, *J* = 9.2 Hz, 2H), 3.29−3.24 (m, 4H), 1.63−1.53 (m, 4H), 1.44−1.32 (m, 4H), 0.99 (t, *J* = 7.3 Hz, 6H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 146.8, 128.9, 119.8, 112.8, 50.9, 29.3, 20.4, 14.0.

*2-Fluoro-4-(2-phenylethyl)pyridine (**8i**).* THF (7.0 mL) was added to (*i*-Pr)$_2$NH (755 μL, 5.40 mmol), and the mixture was cooled to −84 °C (EtOAc/liquid N_2). *n*-BuLi (1.98 mL, 5.00 mmol) was added, and the mixture was allowed to stir for 20 min. A solution of 2-fluoro-4-methylpyridine (500 mg, 4.50 mmol) in THF (2.0 mL) was added over 10 min. The mixture was allowed to warm to rt over 30 min, then recooled to −84 °C. Benzyl bromide (561 μL, 5.72 mmol) was added, and the mixture was allowed to warm to rt and stirred overnight. Water (15 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 15 mL). The combined organic layers were concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, 5% EtOAc in hexanes) to provide 723 mg (80%) of the title compound **8i** as a white solid, mp 64−66 °C. HRMS (EI) *m*/*z*: [M$^+$] calcd for $C_{13}H_{12}NF$ 201.0959; found 201.0958. IR (ATR) cm^{-1} 3063, 3030, 2929, 2863, 1607, 1554, 1454 cm^{-1}. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.11 (dd, *J* = 5.2, 0.6 Hz, 1H), 7.34−7.24 (m, 3H), 7.18−7.16 (m, 2H), 7.00−6.98 (m, 1H), 6.73 (s, 1H), 2.97 (app. s, 4H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 163.4 (d, *J* = 238.2 Hz), 156.4 (d, *J* = 7.8 Hz), 147.2 (d, *J* = 15.3 Hz), 140.1, 128.5, 128.3, 126.3, 121.6 (d, *J* = 3.8 Hz), 109.1 (d, *J* = 36.7 Hz), 36.8 (d, *J* = 2.8 Hz), 36.2.

*4-Fluoro-1-[3-butoxyethoxy)propyl]benzene (**8j**).* 3-(4-Fluorophenyl)-propan-1-ol was prepared in accordance with a previously reported procedure as a colorless oil.[33] ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.19−7.14 (m, 2H), 7.01−6.95 (m, 2H), 3.67 (t, *J* = 6.4 Hz, 2H), 2.70 (t, *J* = 7.4 Hz, 2H), 1.90−1.83 (m, 2H), 1.81 (b, 1H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 161.2 (d, *J* = 243.2 Hz), 137.4 (d, *J* = 3.1 Hz), 129.7 (d, *J* = 7.7 Hz), 115.1 (d, *J* = 21.4 Hz), 61.9, 34.2 (d, *J* = 1.0 Hz), 31.1. Dichloromethane (4.7 mL) was added to 3-(4-fluorophenyl)-propan-1-ol (634 mg, 4.70 mmol) and butyl vinyl ether (720 μL, 5.6 mmol). The mixture was stirred and cooled in an ice-water bath. *p*-Toluenesulfonic acid (5 mg) was added, and the mixture was kept at 0 °C and stirred for 30 min. Saturated $NaHCO_{3(aq)}$ (3 mL) was added, and the mixture was stirred for 5 min. The mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 10 mL). The combined organic layers were concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, 3% EtOAc in hexanes) to provide 0.452 g (38%) of the title compound **8j** as a colorless oil. HRMS (EI) *m*/*z*: [M$^+$] calcd for $C_{15}H_{22}O_2F$ 253.1598; found 253.1605. IR (ATR) cm^{-1} 2988, 2958, 2935, 2871, 1601, 1510, 1454, 1378 cm^{-1}. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.18−7.14 (m, 2H), 7.00−6.95 (m, 2H), 4.69 (q, *J* = 5.3 Hz, 1H), 3.64−3.55 (m, 2H), 3.46−3.39 (m, 2H), 2.69 (t, *J* = 7.1 Hz, 2H), 1.93−1.84 (m, 2H), 1.61−1.52 (m, 2H), 1.42−1.37 (m, 2H), 1.33 (d, *J* = 5.3 Hz, 3H), 0.94 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 161.1 (d, *J* = 243.1 Hz), 137.5 (d, *J* = 3.3 Hz), 129.7 (d, *J* = 7.9 Hz), 115.0 (d, *J* = 21.3 Hz), 99.8, 65.2, 64.2, 32.0, 31.7, 31.6 (d, *J* = 1.0 Hz), 31.6, 19.8, 19.4, 13.9.

*4-Fluoro-1-O-decylbenzene (**8k**).* DMF (4.5 mL) was added to 4-fluorophenol (1.00 g, 8.93 mmol). DBU (1.87 mL, 13.4 mmol) and 1-bromodecane (1.84 mL, 8.91 mmol) were added. The mixture was stirred and heated to reflux for 4 h. After cooling for 5 min, water (10 mL) was added and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 15 mL). The combined organic layers were washed with 10% NaOH (10 mL) and water (10 mL), and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, gradient ranging from hexanes to 1.5% EtOAc in hexanes) to provide 2.01 g (82%) of the title compound **8k** as a colorless oil. HRMS (EI) *m*/*z*: [M$^+$] calcd for $C_{16}H_{25}OF$ 252.1884; found 252.1883. IR (ATR) cm^{-1} 2923, 2854, 1505, 1469 cm^{-1}. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.01−6.96 (m, 2H), 6.87−6.83 (m, 2H), 3.93 (t, *J* = 6.6 Hz, 2H), 1.81−1.74 (m, 2H), 1.50−1.31 (m, 14H), 0.92 (t, *J* = 6.4, Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 157.1 (d, *J* = 237.7 Hz), 155.2 (d, *J* = 2.2 Hz), 115.7 (d, *J* = 23.0 Hz), 115.4 (d, *J* = 7.7 Hz), 68.6, 31.9, 29.6, 29.5, 29.4, 29.3, 29.3, 26.0, 22.7, 14.1.

*3β-Fluoro-5-cholestene (**8l**).* Prepared in accordance with a previously reported procedure[72] as a white solid, mp 94−96 °C (lit.[72] mp 96 °C). ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm). 5.40−5.39 (m, 1H), 4.50−4.29 (m, 1H), 2.46−2.42 (m, 2H), 2.04−1.89 (m, 3H), 1.88−1.52 (m, 2H), 1.49−0.86 (m, 21H), 1.03 (s, 3H), 0.93 (d, *J* = 6.5 Hz, 3H), 0.88 (d, *J* = 1.2 Hz, 3H), 0.86 (d, *J* = 1.2 Hz, 3H), 0.68 (s, 3H) ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 139.3 (d, *J* = 12.6 Hz), 123.1 (d, *J* = 12.6 Hz), 92.9 (d, *J* = 173.9 Hz), 56.7, 56.1, 50.0, 42.3, 39.7, 39.5, 39.3, 36.5, 36.4 (d, *J* = 10.8 Hz), 35.8, 31.9, 31.9, 28.9, 28.7, 28.3, 28.0, 24.3, 23.8, 22.8, 22.6, 21.1, 19.3, 18.7, 11.9.

General Procedure for the Reduction of Organohalides with 3.3 equiv SmI_2/6.6 equiv TEU$^-$/2 equiv *t*-AmOH. To an ice-cold mixture of 271 mg of TEU (1.88 mmol) and 1.5 mL of THF was added 0.75 mL of a 2.5 M solution of *n*-BuLi (1.9 mmol) in hexane. A solution of 0.00285 mol of the organohalide compound in 1.0 mL of THF was added. This mixture was stirred for 5 min; then 10.2 mL of a 0.092 M solution of SmI_2 (0.94 mmol) in THF was added, followed rapidly by 62 μL of *t*-AmOH (0.57 mmol). The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by silica gel column chromatography as described below.

General Procedure for the Reduction of Organohalides with 3.3 equiv SmI_2/13.2 equiv TEU$^-$. To an ice-cold mixture of 542 mg of TEU (3.76 mmol) and 1.0 mL of THF was added 1.50 mL of a 2.5 M solution of *n*-BuLi (3.8 mmol) in hexane. A solution of 0.285 mmol of the organohalide compound in 0.7 mL of THF was added. This mixture was stirred for 5 min; then 10.2 mL of a 0.092 M solution of SmI_2 (0.94 mmol) in THF was added. The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by silica gel column chromatography as described below.

*O-Heptylbenzene (**9a**).* (Table 5, entry 1). The residue was purified by column chromatography (SiO_2, gradient ranging from hexanes to 1% EtOAc in hexanes) to provide 50 mg (91%) of the title compound **9a** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm). 7.35−7.30 (m, 2H), 6.97−6.93 (m, 3H), 3.99 (t, *J* = 6.6 Hz, 2H), 1.85−1.78 (m, 2H), 1.62−1.31 (m, 8H), 0.95 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 159.2, 129.4, 120.5, 114.5, 67.9, 31.9, 29.4, 29.1, 26.1, 22.7, 14.2.[73]

*N-Phenyl-4-phenylbutanamide (**9b**).* (Table 5, entry 2). The residue was purified by column chromatography (SiO_2, gradient ranging from 2% to 10% EtOAc in hexanes) to provide 64 mg (94%) of the title compound **9a** as a white powder, mp 94−96 °C (lit.[74] mp 95−96 °C). ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.54 (d, *J* = 3.8 Hz, 2H), 7.36−7.10 (m, 8H), 2.72 (t, *J* = 7.4 Hz, 2H), 2.37 (t, *J* = 7.2 Hz, 2H), 2.13−2.03 (m, 2H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 171.2, 141.3, 137.9, 128.9, 128.4, 128.4, 126.0, 124.2, 119.9, 36.7, 35.0, 26.8.[75]

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*Cholest-5-ene (**9c**).* (Table 5, entry 3). The residue was purified by column chromatography (SiO_2, hexanes) to provide 84 mg (80%) of the title compound **9c** as a white powder. mp 93−94 °C (lit.[76] mp 95 °C). ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.30−5.28 (m, 1H), 2.34−2.19 (m, 1H), 2.07−1.92 (m, 3H), 1.92−1.69 (m, 3H), 1.69−1.32 (m, 12H), 1.32−0.79 (m, 11H), 1.02 (s, 3H), 0.92 (d, J = 6.4 Hz, 3H), 0.90 (d, J = 1.3 Hz, 3H), 0.88 (d, J = 1.3 Hz, 3H), 0.70 (s, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 143.7, 119.0. 56.9, 56.2, 50.6, 42.3, 39.9, 39.9, 39.6, 37.5, 36.2, 35.8, 32.9, 31.9, 31.9, 28.3, 28.1, 28.0, 24.3, 23.9, 22.9, 22.6, 20.8, 19.5, 18.7, 11.9.[77]

*1-O-Ethyl-5-O-butyl-2,3-O-isopropylidene-β-D-ribofuranose (**9d**).* (Table 5, entry 4). The residue was purified by column chromatography (SiO_2, gradient ranging from 1% to 3% EtOAc in hexanes) to provide 68 mg (87%) of the title compound **9d** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm). 5.07 (s, 1H), 4.67 (d, J = 6.5 Hz, 1H), 4.59 (d, J = 6.9 Hz, 1H), 4.30 (t, J = 6.9 Hz, 1H), 3.77−3.66 (m, 1H), 3.50−3.38 (m, 5H), 1.59−1.48 (m, 2H), 1.48 (s, 3H), 1.43−1.31 (m, 2H), 1.31 (s, 3H), 1.16 (t, J = 7.1 Hz, 3H), 0.91 (t, J = 7.3 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 112.2, 107.7, 85.3, 85.0, 82.3, 71.7, 71.2, 62.8, 31.7, 26.4, 25.0, 19.3, 14.9, 13.9.[45]

*3-O-Butyl-1,2:5,6-di-O-isopropylidene-α-D-glucofuranose (**9e**).* (Table 5, entry 5). The residue was purified by column chromatography (SiO_2, gradient ranging from 3% to 6% EtOAc in hexanes) to provide 66 mg (74%) of the title compound **9e** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 5.89 (d, J = 3.7 Hz, 1H), 4.54 (d, J = 3.7 Hz, 1H), 4.35−4.28 (m, 1H), 4.15−4.06 (m, 2H), 4.01−3.96 (m, 1H), 3.86 (d, J = 3.1 Hz, 1H), 3.65−3.48 (m, 2H), 1.57−1.52 (m, 2H), 1.50 (s, 3H), 1.44−1.34 (m, 2 H), 1.43 (s, 3H), 1.35 (s, 3H), 1.32 (s, 3H), 0.92 (t, J = 7.3 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 111.6, 108.7, 105.2, 82.4, 82.0, 81.1, 72.4, 70.3, 67.1, 31.7, 26.7, 26.7, 26.1, 25.3, 19.1, 13.7.[78]

*N-(2-Phenyl)ethyl-3-phenylpropanamide (**9f**).* (Table 5, entry 6). The residue was purified by column chromatography (SiO_2, gradient ranging from 5% to 20% EtOAc in hexanes) to provide 62 mg (74%) of the title compound **9f** as a white solid, mp 95−96 °C (lit.[79] mp 96−97 °C). ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.33−7.19 (m, 8H), 7.11 (d, J = 7.0 Hz, 2H), 5.48−5.28 (b, 1H), 3.53−3.47 (m, 2H), 2.99−2.94 (m, 2H), 2.76 (t, J = 6.9 Hz, 2H), 2.47−2.42 (m, 2H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 172.0, 140.8, 138.8, 128.7, 128.6, 128.5, 128.3, 126.4, 126.2, 40.5, 38.5, 35.6, 31.7.[79]

*1-O-Hexyl-2-methylbenzene (**9g**).* (Table 6, entry 6). To an ice-cold mixture of 648 mg of BI (4.56 mmol) and 1.5 mL of THF was added 1.80 mL of a 2.5 M solution of *n*-BuLi (4.6 mmol) in hexane. A solution of 65 mg (0.29 mmol) of **8g** in 1.0 mL of THF was added. This mixture was stirred for 5 min; then 12.4 mL of a 0.092 M solution of SmI_2 (1.1 mmol) in THF was added. The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by column chromatography (SiO_2, hexanes) to provide 42 mg (77%) of the title compound **9g** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.23−7.18 (m, 1H), 6.81−6.74 (m, 3H), 3.98 (t, J = 6.6 Hz, 2H), 2.37 (s, 3H), 1.84−1.77 (m, 2H), 1.53−1.36 (m, 6H), 0.98−0.93 (m, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 159.2, 139.4, 129.2, 121.3, 115.4, 111.4, 67.8, 31.7, 29.3, 25.8, 22.7, 21.6, 14.1.[80]

*N,N-Dibutylbenzene (**9h**).* (Table 6, entry 10). To an ice-cold mixture of 648 mg of PPU (4.56 mmol) and 1.5 mL of THF was added 1.80 mL of a 2.5 M solution of *n*-BuLi (4.6 mmol) in hexane. A solution of 68 mg (0.29 mmol) of **8h** in 1.0 mL of THF was added. This mixture was stirred for 5 min; then 12.4 mL of a 0.092 M solution of SmI_2 (1.1 mmol) in THF was added. The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by column chromatography (SiO_2, hexanes) to provide 49 mg (83%) of the title compound **9h** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.25−7.19 (m, 2H), 6.67−6.61 (m, 3H), 3.30−3.25 (m, 4H), 1.63−1.53 (m, 4H), 1.43−1.31 (m, 4H), 0.97 (t, J = 7.3 Hz, 6H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 148.1, 129.1, 115.0, 111.6, 50.7, 29.4, 20.3, 14.0.[81]

*4-(2-Phenylethyl)pyridine (**9i**).* (Table 5, entry 11). The residue was purified by column chromatography (SiO_2, gradient ranging from 5% to 15% EtOAc in hexanes) to provide 38 mg (73%) of the title compound **9i** as a white solid, mp 69−70 °C (lit.[82] mp 69 °C). ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.51, (d, J = 5.8 Hz, 2H), 7.31−7.09 (m, 7H), 2.95 (app. s, 4H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 150.5, 149.7, 140.7, 128.5, 128.4, 126.3, 123.9, 37.1, 36.6.[83]

*[3-Butoxyethoxy)propyl]benzene (**9j**).* (Table 6, entry 12). To an ice-cold mixture of 648 mg of PPU (4.56 mmol) and 1.5 mL of THF was added 1.80 mL of a 2.5 M solution of *n*-BuLi (4.6 mmol) in hexane. A solution of 72 mg (0.29 mmol) of **8j** in 1.0 mL of THF was added. This mixture was stirred for 5 min; then 12.4 mL of a 0.092 M solution of SmI_2 (1.1 mmol) in THF was added. The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by column chromatography (SiO_2, gradient ranging from hexanes to 1% EtOAc in hexanes) to provide 57 mg (85%) of the title compound **9j** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.33−7.21 (m, 5H), 4.70 (q, J = 5.3 Hz, 1H), 3.65−3.57 (m, 2H), 3.49−3.40 (m, 2H), 2.75−2.70 (m, 2H), 1.97−1.88 (m, 2H), 1.60−1.53 (m, 2H), 1.43−1.32 (m, 2H), 1.34 (d, J = 5.4 Hz, 3H), 0.94 (t, J = 7.3 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 142.0, 128.5, 128.3, 125.8, 99.8, 65.2, 64.5, 32.5, 32.0, 31.5, 19.9, 19.5, 13.9.[84]

*O-Decylbenzene (**9k**).* (Table 6, entry 13). To an ice-cold mixture of 648 mg of PPU (4.56 mmol) and 1.4 mL of THF was added 1.8 mL of a 2.5 M solution of *n*-BuLi (4.5 mmol) in hexane. A solution of 72 mg (0.29 mmol) of **8k** in 1.5 mL of THF was added. This mixture was stirred for 5 min; then 12.4 mL of a 0.092 M solution of SmI_2 (1.1 mmol) in THF was added. The mixture was allowed to warm to rt and stirred overnight. Water (10 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified by column chromatography (SiO_2, gradient ranging from hexanes to 1% EtOAc in hexanes) to provide 50 mg (74%) of the title compound **9k** as a colorless oil. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 7.34−7.29 (m, 2H), 6.99−6.92 (m, 3H), 3.99 (t, J = 6.6 Hz, 2H), 1.87−1.77 (m, 2H), 1.52−1.32 (m, 14H), 0.95−0.90 (m, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 159.2, 129.4, 120.5, 114.5, 67.9, 31.9, 29.6, 29.6, 29.5, 29.4, 29.3, 26.1, 22.7, 14.2.[85]

*1-(4-Chloro)butoxy-4-chloronaphthalene (**10**).* DMF (5.5 mL) was added to 4-chloro-1-naphthol (1.31 g, 0.00734 mol). DBU (1.97 mL, 0.0132 mol) was added, and the mixture was cooled with stirring to 0 °C. 1-Bromo-4-chlorobutane (1.45 mL, 0.0132 mol) was added, and the mixture was allowed to warm slowly to rt and stir for 24 h, then heated to 45 °C for an additional 24 h. Water (10 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (3 × 10 mL). The combined organic layers were concentrated under reduced pressure and purified by column chromatography (SiO_2, gradient ranging from hexanes to 2% EtOAc in hexanes) to provide 1.42 g (72%) of the title compound **10** as a colorless oil. HRMS (EI) m/z: [M^+] calcd for $C_{14}H_{14}OCl_2$ 268.0416; found 268.01414. IR (ATR) cm^{-1} 3071, 2955, 2873, 1621, 1588, 1456, 1424, 1374. ^{1}H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.32 (dd, J = 8.3, 1.2 Hz, 1H), 8.24 (dd, J = 9.0, 1.2 Hz, 1H), 7.68−7.54 (m 2H), 7.47 (d, J = 8.2 Hz, 1H), 6.70 (d, J = 8.3 Hz, 1H), 4.17−4.13 (m, 2H), 3.72−3.68 (m, 2H), 2.13−2.09 (m, 4H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 153.7, 131.3, 127.5, 126.6, 126.0, 125.8, 124.3, 123.2, 122.4, 104.6, 67.4, 44.8, 29.5, 26.6.

*General Procedure for the Reduction of 1-(4-Chloro)butoxy-4-chloronaphthalene (**10**), Table 7.* To an ice-cold mixture of the appropriate activator, 1.0 mL of THF and *n*-BuLi in hexanes (if required) were added. This mixture was cooled to −98 °C (CH_3OH/liquid N_2) and stirred for 5 min, and a solution of 77 mg (0.29 mmol) of dichloride **10** in 0.7 mL of THF was added. This mixture was stirred for 5 min; then 9.3 mL of a 0.092 M solution of SmI_2 (0.86 mmol) in THF was added, followed rapidly by 62 μL of *t*-AmOH (0.57 mmol). The mixture was allowed to warm to rt and stirred overnight. Water (8 mL) was added, and the mixture was extracted with a 2:1 mixture of hexanes and Et_2O (5 × 5 mL). The concentrated mixture was purified

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by column chromatography (SiO_2, gradient ranging from hexanes to 1% EtOAc in hexanes), affording products **11** through **13**.

*1-(4-Chlorobutoxy)naphthalene (**11**).* White solid, mp 41−42 °C. HRMS (EI) *m*/*z*: [M^+] calcd for $C_{14}H_{15}OCl$ 234.0817; found 234.0812. IR (ATR) cm^{-1} 3052, 2950, 2875, 1595, 1574, 1390. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.31−8.28 (m, 1H), 7.85−7.82 (m, 1H), 7.54−7.37 (m, 4H), 6.83 (d, *J* = 7.6 Hz, 1H), 4.23−4.19 (m, 2H), 3.73−3.70 (m, 2H), 2.15−2.11 (m, 4H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 154.5, 134.4, 127.4, 126.4, 125.8, 125.6, 125.1, 121.9, 120.2, 104.4, 67.0, 44.8, 29.5, 26.6.

*1-Butoxy-4-chloronaphthalene (**12**).* Colorless oil. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.37 (dd, *J* = 8.3, 0.6 Hz, 1H), 8.26 (d, *J* = 8.4, 0.6 Hz, 1H), 7.68−7.55 (m, 2H), 7.48 (d, *J* = 8.3 Hz, 1H), 6.72 (dd, *J* = 8.3 Hz, 1H), 4.13 (t, *J* = 6.3 Hz, 2H), 1.99−1.90 (m, 2H), 1.70−1.58 (m, 2H), 1.08 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 154.0, 131.3, 127.4, 126.7, 125.8, 125.8, 124.1, 122.8, 122.5, 104.5, 68.0. 31.3, 19.4, 13.9.[45]

*1-Butoxynaphthalene (**13**).* Colorless oil. ^1H NMR (300 MHz; $CDCl_3$ δ, ppm) 8.23−8.19 (m, 1H), 7.71−7.68 (m, 1H), 7.40−7.24 (m, 4H), 6.70 (dd, *J* = 7.1, 1.4 Hz), 4.04 (t, *J* = 6.4 Hz, 2H), 1.85−1.79 (m, 2H), 1.55−1.48 (m, 2H), 0.94 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (75 MHz; $CDCl_3$ δ, ppm) 154.9, 134.5, 127.4, 126.3, 125.9, 125.7, 125.0, 122.1, 119.9, 104.5, 67.8, 31.4, 19.5, 13.9.[86]

General Procedure for the Determination of Effective Redox Potential of SmI_2/2 TEU^- and SmI_2/4 TEU^-. To an ice-cold mixture of TEU (either 173 mg, 0.120 mmol, or 346 mg, 0.240 mmol), THF (6.0 mL), and tetradecane (10.0 μL, 0.0384 mmol) was added either 0.48 or 0.96 mL of a 2.5 M solution of *n*-BuLi in hexanes (either 0.12 or 0.24 mmol). This mixture was stirred for 5 min, and 6.5 mL of a 0.092 M solution of SmI_2 in THF (0.60 mmol) was added, and allowed to stir for 5 min. The substrate (0.20 mmol) was added, and the mixture was allowed to stir for 15 min. An aliquot was removed and immediately quenched with a 0.1 M *tert*-butanol in hexanes solution. The aliquot was mixed with 0.1 mL of 0.1 M HCl and 1 mL of Et_2O. The Et_2O extract was analyzed by GC and GC−MS to obtain the yield of reduced product (identity of the product confirmed by comparison with authentic material).

Visible Spectrum of 1:1 SmI_2/TEU^-. THF (15.9 mL) was added to a flask equipped with the UV−vis probe and 26 mg of TEU (0.18 mmol) and a background was taken. This mixture was cooled in an ice-water bath, and 0.072 mL of a 2.5 M solution of *n*-BuLi (0.18 mmol) in hexane was added. This mixture was stirred for 5 min and warmed to rt; then 2.0 mL of a 0.092 M solution of SmI_2 in THF (0.18 mmol) was added. After stirring for 1 min, the spectrum was acquired.

Visible Spectrum of 1:2 SmI_2/TEU^-. THF (15.9 mL) was added to a flask equipped with the UV−vis probe and 52 mg of TEU (0.36 mmol) and a background was taken. This mixture was cooled in an ice-water bath, and 0.14 mL of a 2.5 M solution of *n*-BuLi (0.36 mmol) in hexane was added. This mixture was stirred for 5 min and warmed to rt; then 2.0 mL of a 0.092 M solution of SmI_2 in THF (0.18 mmol) was added. After stirring for 1 min, the spectrum was acquired.

Visible Spectrum of 1:3 SmI_2/TEU^-. THF (15.8 mL) was added to a flask equipped with the UV−vis probe and 78 mg of TEU (0.54 mmol) and a background was taken. This mixture was cooled in an ice-water bath, and 0.22 mL of a 2.5 M solution of *n*-BuLi (0.54 mmol) in hexane was added. This mixture was stirred for 5 min and warmed to rt; then 2.0 mL of a 0.092 M solution of SmI_2 in THF (0.18 mmol) was added. After stirring for 1 min, the spectrum was acquired.

Visible Spectrum of 1:4 SmI_2/TEU^-. THF (15.7 mL) was added to a flask equipped with the UV−vis probe and 104 mg of TEU (0.72 mmol) and a background was taken. This mixture was cooled in an ice-water bath, and 0.29 mL of a 2.5 M solution of *n*-BuLi (0.72 mmol) in hexane was added. This mixture was stirred for 5 min and warmed to rt; then 2.0 mL of a 0.092 M solution of SmI_2 in THF (0.18 mmol) was added. After stirring for 1 min, the spectrum was acquired.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00733.

^1H and ^{13}C NMR of all title compounds (PDF)

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Notes

The authors declare no competing financial interest.

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