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Mechanistic Studies of Proton-Donor Coordination to Samarium Diiodide**

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In memory of Dmitry Rudkevich

Alcohols, glycols, and glymes are commonly used as additives in numerous reductions and reductive coupling reactions of samarium diiodide (SmI_2).[1,2] Typically alcohols and glycols are used as proton donor sources, whereas glymes are used as coordinating additives. All of these additives have been shown to exert an influence on the regiochemical[3,4] and stereochemical[5,6] outcomes of numerous SmI_2-mediated reactions. The seminal work of Hoz et al. demonstrated that the interplay between proton-donor coordination and acidity is likely to play an important mechanistic role in reductions.[7] Studies by Dahlén and Hilmersson have shown that coordinating alcohols enhance the rate of ketone reduction substantially and that the rate increase is proportional to the number of ethereal oxygen atoms in the proton donor source.[8] More recent studies in our group have shown that the high affinity of water for SmI_2 in THF leads to substrate reduction through a unique mechanistic pathway involving a Sm^{II}–water complex.[9] Taken together, these studies show that proton-donor coordination enhances the reactivity of SmI_2. Unfortunately, the paucity of well-characterized systems for which the structures of the ground-state reductants are known limits our understanding of the mechanistic rationale for this phenomenon. Presented herein are crystallographic, spectroscopic, and kinetic studies on substrate reduction by SmI_2 in solutions containing diethylene glycol (dg), diethylene glycol monomethyl ether (dgme), and diglyme (dgde). These studies show 1) that initial coordination of the additives liberates THF or iodide from SmI_2, thus providing open coordination sites for substrate, 2) that saturation of SmI_2 with the additive decreases its reactivity, and 3) that replacement of a hydroxyl proton with a methyl group significantly decreases the affinity of the additive for SmI_2.

In searching for appropriate systems to explore, we sought proton donors and related systems that would have a high affinity for Sm^{II} and simultaneously provide stable complexes that could be characterized. Many complexes of SmI_2 with tri- and tetraglyme provide complex aggregates which would complicate mechanistic analysis.[10] We were drawn to the structure of the $[Sm(dgde)_3]^{2+}$ cation.[11] This species is unique among Sm^{II}–glyme structures because it is monomeric, thus indicating that an opportunity existed for isolation and characterization of complexes of dg, dgme, and dgde with SmI_2. Furthermore, this system offers an opportunity to examine the impact of subtle changes to the system through substitution of the proton of the hydroxyl group with methyl substituents.

To initially examine the system, the UV/Vis spectrum of SmI_2 (1 mmol in THF) was monitored in the presence of increasing amounts of dg, dgme, and dgde. A subset of these experiments is displayed in Figure 1. Upon addition of two equivalents of dg, the long-wavelength absorption peaks of SmI_2 ($\lambda_{max} = 555$ and 618 nm) begin to merge, indicating coordination. Upon further addition of dg, the long-wavelength absorption peak decreases in intensity, and a new absorption appears at 476 nm. During this process the solution turned from blue to red, consistent with the spectral changes shown in Figure 1. Addition of more than eight equivalents of dg produces no further changes in the UV/Vis

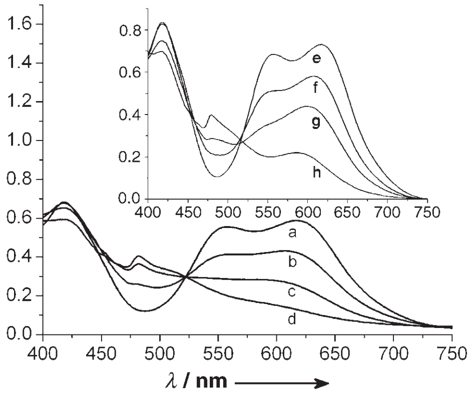

Figure 1. UV/Vis spectra of SmI_2 (1 mmol) in THF (a) with increasing amounts of dg (b = 2, c = 6, and d = 8 equivalents). Inset shows UV/Vis spectra of SmI_2 (1 mmol) in THF (e) with increasing amounts of dgme (f = 30, g = 80, h = 500 equivalents).

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spectrum. The isosbestic point at 522 nm is consistent with the conversion of the SmI_2–thf complex to a Sm^{II}–dg complex. The inset of Figure 1 shows addition of successive portions of dgme. Similar behavior was observed, but much higher concentrations of dgme were required to produce a Sm^{II}–dgme complex. Addition of dgde showed no perceptible changes to the UV/Vis spectrum of SmI_2 even at high concentrations (500 equivalents, see the Supporting Information). These experiments show that the affinity of the additives for SmI_2 in THF is in the order dg > dgme > dgde and indicate that replacement of a hydroxyl proton on dg with a methyl substituent significantly alters the affinity of the additive for Sm^{II}.

We next set out to crystallize the series of complexes to gain an understanding of the structures formed in solution. Addition of an eight-equivalent excess of dg to 0.1 M SmI_2 in THF under an argon atmosphere provided ruby-red crystals of $[Sm(dg)_3]I_2$ (Figure 2) upon standing overnight. Inspection of the structure clearly shows that the iodide ions are displaced to the outer sphere. The UV/Vis spectrum of the crystals in THF was identical to that of a solution of SmI_2 containing three equivalents of dg (Figure 1). Isolation of crystals of $[Sm(dgme)_3]I_2$ (see the Supporting Information) was accomplished through a similar procedure but required 100 equivalents of dgme to produce crystals. Finally, blue crystals of *cis*-$[SmI_2(dgde)_2]$ were obtained by addition of a 100-equivalent excess of dgde to a 0.1 M solution of SmI_2 in THF (see the Supporting Information).

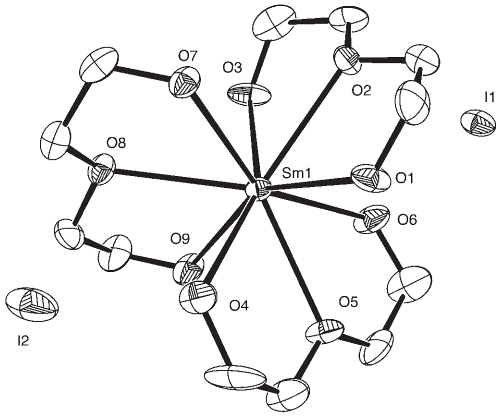


Figure 2. Molecular structure of $[Sm(dg)_3]I_2$ shown with 20% probability displacement ellipsoids. H atoms have been omitted for clarity. Samarium–oxygen bond lengths [Å]: Sm1–O6 2.587(11), Sm1–O1 2.590(10), Sm1–O4 2.603(10), Sm1–O9 2.618(11), Sm1–O3 2.624(11), Sm1–O7 2.635(11), Sm1–O5 2.657(10), Sm1–O8 2.666(10), Sm1–O2 2.728(10).

Comparison of the Sm–O bond lengths for the coordinated ligands in each structure is informative. In $[Sm(dg)_3]I_2$, $d(Sm{-}O) = 2.590(10)$, 2.728(10), and 2.624(11) Å for the first ligand; 2.587(11), 2.657(10), and 2.603(10) Å for the second ligand; and 2.635(11), 2.666(10), and 2.618(11) Å for the third ligand. From this analysis, it is apparent that in the case of two coordinating ligands, the central Sm–O bond is elongated with respect to the terminal oxygen atoms. In the third dg ligand, however, all three Sm–O bond lengths are very similar. In $[Sm(dgme)_3]I_2$, $d(Sm{-}O) = 2.585(6)$, 2.679(5), and 2.653(6) Å for the first ligand; 2.638(5), 2.702(5), and 2.610(5) Å for the second ligand; and 2.554(6), 2.711(5), and 2.717(5) Å for the third ligand. For two chelating ligands, elongation of the bond to the internal O atom is observed, and in the third ligand, two Sm–O bond lengths are quite long. Furthermore, in each dgme ligand, the hydroxyl oxygen atom has a shorter Sm–O bond than the methoxy oxygen atom. Analysis of the $[SmI_2(dgde)_2]$ structure shows that the two dgde ligands have the following Sm–O bond distances: for the first ligand $d(Sm{-}O) = 2.656(3)$, 2.688(3), and 2.696(3) Å; for the second ligand $d(Sm{-}O) = 2.650(3)$, 2.642(3), and 2.702(3) Å. In each ligand, one terminal Sm–OCH_3 bond is elongated. The Sm–I bond lengths of 3.3081(4) and 3.3185(4) Å are consistent with other eight-coordinate Sm^{II} complexes, and all data are similar to those previously reported for this structure.[12]

The crystallographic data show that in both $[Sm(dg)_3]I_2$ and $[Sm(dgme)_3]I_2$, the first two ligands have shorter contacts than the third ligand, suggesting that the latter has a lower affinity. Replacement of a hydroxyl hydrogen atom with a methyl group leads to a longer Sm–O bond, and the replacement of both hydroxyl hydrogen atoms with methyl groups decreases the affinity to such an extent that only two ligands coordinate to Sm^{II}, leaving the iodides bound to the inner sphere. The crystallographic data is consistent with the UV/Vis spectrum and indicates that the emergence of the absorption at 476 nm is due to formation of the complexes $[Sm(dg)_3]I_2$ and $[Sm(dgme)_3]I_2$.

Because coordinating additives are known to alter the reducing power of Sm^{II}, cyclic voltammetry was employed to characterize the impact of addition of dg, dgme, and dgde to SmI_2 in THF. In the absence of additive, a quasi-reversible voltammogram was obtained with an estimated $E_{1/2}$ value of -1.57 ± 0.05 V versus a saturated $Ag/AgNO_3$ electrode.[13] Addition of a large excess of dgme or dgde had no measurable impact on the potential compared to SmI_2 alone. Addition of dg led to moderate changes in the redox properties. Samples containing four equivalents of dg provided an estimated $E_{1/2} = -1.63 \pm 0.05$ V, and samples containing ten equivalents of dg gave an estimated $E_{1/2} = -1.70 \pm 0.05$ V. Further addition of dg had no impact on the redox potential. While addition of dg to SmI_2 produces a more powerful reductant in comparison to dgme and dgde, its effect is modest in comparison to other additives.[14]

To further study the mechanistic impact of coordination on the reactivity of Sm^{II}, the rates of reactions of SmI_2 with benzyl bromide were monitored in the presence of increasing amounts of dg, dgme, and dgde to determine the relationship between the affinity of each ligand for Sm^{II} and the impact on the reactivity of the resulting complex. Benzyl bromide was chosen as a model substrate to simplify the kinetic analysis.[9b,15] Initial experiments were designed to determine the rate orders of additive, SmI_2, and benzyl bromide. All rate studies were carried out at 25 °C under pseudo-first-order conditions with the concentration of benzyl bromide kept high relative to that of SmI_2 using a stopped-flow spectrophotometer. Analysis of reaction products showed that the presence of dg and dgme provided toluene exclusively as product, whereas the presence of dgde gave bibenzyl as product. To determine the rate order of dg, dgme, and dgde, a series of kinetic experiments were initiated in which the rate of reduction of benzyl bromide was monitored over a range of additive concentrations as summarized in Figure 3 and Table 1. In the case of dg, the reaction is approximately first-order in additive at concentrations up to 6 mM (3 equivalents), whereas at higher concentrations, the reaction is nearly inverse first-order. These findings are consistent with the involvement of one equivalent of dg in the reduction of benzyl bromide at lower concentrations of additive. The inverse first-order behavior of dg at higher concentrations is consistent with dg displacement in the transition state of the reduction.

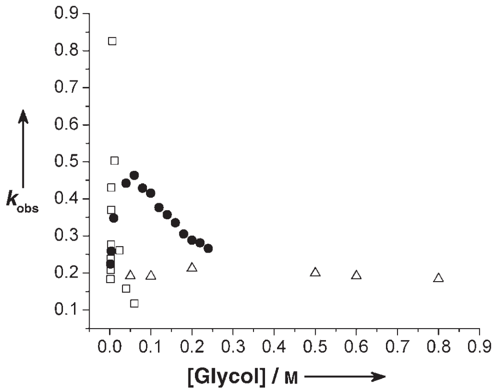


Figure 3. Plot of k_{obs} vs. [dg] (□), [dgme] (●), and [dgde] (△) for the reduction of benzyl bromide (100 mM) by SmI$_2$ (2 mM) at 25 °C.

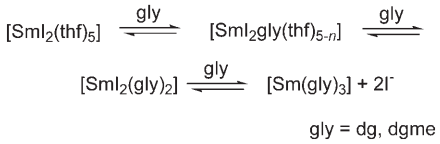
Table 1: Summary of rate studies for the reduction of benzyl bromide (BnBr) by SmI$_2$ in THF containing dg, dgme, or dgde.

	Rate order		
[dg]	dg[a]	SmI$_2$[b]	BnBr[c]
2–6 mM	1.1 ± 0.1	0.96 ± 0.05	0.9 ± 0.1
6–60 mM	−0.87 ± 0.03		
[dgme]	dgme[a]	SmI$_2$[b]	BnBr[c]
2–30 mM	0.29 ± 0.02	1.03 ± 0.05	0.99 ± 0.03
30–240 mM	−0.46 ± 0.03		
[dgde]	dgde[a]	SmI$_2$[b]	BnBr[c]
50–800 mM	0	1.0 ± 0.1	0.93 ± 0.07

[a] The concentration of SmI$_2$ in all experiments is 2 mM and the concentration of BnBr is 100 mM. [b] Rate order was extracted using the fractional rates method. [c] Rate order determined from concentrations of BnBr ranging from 25–100 mM.

Examination of dgme reveals similar but less pronounced behavior. At dgme concentrations up to 60 mM (30 equivalents), the rate order is 0.29 ± 0.02. At concentrations above 60 mM, the rate order of dgme is −0.46 ± 0.03. Addition of dgde over a large concentration range had no measurable impact on the rate of reduction of benzyl bromide by SmI$_2$. Further experiments using deuterated dg provided a deuterium isotope effect of 0.92 ± 0.04, thus demonstrating that proton transfer does not occur in the rate-limiting step of the reduction. The rate orders of benzyl bromide and SmI$_2$ were approximately first order over the entire concentration range of additives examined in these studies.

Taken together, these studies provide the following experimental observations: 1) The affinity of the additives for SmI$_2$ in THF is in the order dg > dgme > dgde. 2) Sm^{II} can accommodate the coordination of two diglyme and two iodide ligands. 3) The impact of additive on the rate of benzyl bromide reduction is proportional to the affinity of the additive for SmI$_2$. 4) Additives capable of displacing iodide from SmI$_2$ increase the rate of substrate reduction. 5) The highest rate of substrate reduction by SmI$_2$ is achieved at an additive concentration lower than that required for formation of [Sm(dg)$_3$]I$_2$ or [Sm(dgme)$_3$]I$_2$ in solution. Concentrations of dg or dgme that drive the equilibrium to the coordinatively saturated complexes decrease the rate of substrate reduction. 6) Only dg provided a modest increase in the reducing power of SmI$_2$. On the basis of these observations, we propose that the data support the equilibrium process shown in Scheme 1. Upon coordination of one equivalent of dg or dgme, solvent is displaced from the inner sphere of SmI$_2$. Addition of a second equivalent of additive displaces remaining solvent, and further addition displaces the iodide ligands.



Scheme 1. Possible equilibrium for the coordination of dg and dgme to SmI$_2$ in THF.

The enhanced reactivity and positive reaction order for dg or dgme below concentrations necessary for coordinative saturation of samarium are consistent with displacement of iodide (or solvent) by the additive to open up coordination sites for substrate in the activated complex.[16] Higher concentrations of dg or dgme inhibit interaction of substrate with samarium, and additive displacement is necessary for reduction. Although dg does increase the reducing power of SmI$_2$, it does so at concentrations that saturate the coordination sphere of the Sm center. As a consequence, the driving force for increased reactivity of SmI$_2$ upon addition of dg (or other coordinating proton donors) is due predominantly to solvent or iodide displacement. With this information in hand, we are currently examining reactions in which proton transfer to substrate plays an important mechanistic role to ascertain the importance of proton transfer from Sm–donor complexes versus bulk solution.

Experimental Section

THF was dried using a solvent purification system produced by Innovative Technology, Inc. (Newburyport, MA). SmI$_2$ was prepared by stirring Sm metal and iodine in THF until the characteristic color of Sm^{II} appeared. The concentration of SmI_2 was determined by iodometric titration or by the method developed by Hilmersson.[17] Benzyl bromide, dg, dgme, and dgde were dried over activated molecular sieves. Dried solvents and reagents were stored in an Innovative Technology, Inc. drybox containing an argon atmosphere and a platinum catalyst for drying.

UV/Vis experiments were performed on a Shimadzu UV-1601 spectrophotometer controlled by UV Probe software (version 1.11). All rates were determined using an SX-18 MV stopped-flow spectrophotometer (Applied Photophysics Ltd., Surrey, UK) at 25 °C. Cyclic voltammograms for SmI_2 and the SmI_2–additive complexes were measured as described in reference [9b], except the concentration of SmI_2 in each experiment was 15 mM.

Crystals of $[Sm(dg)_3]I_2$ were prepared by diluting dg (76 μL) in THF (5 mL) and adding SmI_2 (1.0 mL, 0.10 M in THF) to the flask with subsequent final dilution to 10 mL. The solution was shaken thoroughly and allowed to stand open in the drybox to permit slow evaporation. Red crystals began to appear after a few hours, and the solution was allowed to stand overnight. The bulk solution was discarded, and the crystals were collected and dried under slight vacuum. Crystals of $[Sm(dgme)_3]I_2$ and $[SmI_2(dgde)_2]$ were prepared using analogous procedures employing dgme (1.2 mL) or dgde (1.4 mL). Crystals of $[Sm(dgme)_3]I_2$ were ruby-red, whereas crystals of $[SmI_2(dgde)_2]$ were blue.

Crystal structure analysis data for $[Sm(dg)_3]I_2$: $C_{12}H_{30}I_2O_9Sm$, $M_r = 722.51$, monoclinic, space group $P2(1)/c$, $a = 16.121(4)$, $b = 14.581(4)$, $c = 10.438(3)$ Å, $\beta = 106.911(4)°$, $V = 2347.7(10)$ Å^3, $Z = 4$, $\rho_{calcd} = 2.044$ Mg m^{-3}, $\mu = 5.164$ mm^{-1}, $F(000) = 1368$, 12252 reflections collected, 2478 unique, GOF = 0.825, $R_1 = 0.0525$, $wR_2 = 0.1281$.

Crystal structure analysis data for $[Sm(dgme)_3]I_2$: $C_{15}H_{36}I_2O_9Sm$, $M_r = 764.90$, orthorhombic, space group $Pna2(1)$, $a = 17.2297(12)$, $b = 9.9738(7)$, $c = 15.2855(10)$ Å, $V = 2626.7(3)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.933$ Mg m^{-3}, $\mu = 4.621$ mm^{-1}, $F(000) = 1464$, 31086 reflections collected, 8200 unique, GOF = 0.988, $R_1 = 0.0469$, $wR_2 = 0.1120$.

CCDC-649549 ($[Sm(dg)_3]I_2$) and CCDC-649550 ($[Sm(dgme)_3]I_2$) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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[1] a) G. A. Molander, *Chem. Rev.* **1992**, *92*, 29–68; b) G. A. Molander, C. R. Harris, *Chem. Rev.* **1996**, *96*, 307–338; c) P. G. Steel, *J. Chem. Soc. Perkin Trans. 1* **2001**, 2727–2751; d) D. J. Edmonds, D. Johnston, D. J. Procter, *Chem. Rev.* **2004**, *104*, 3371–3404; e) A. Dahlén, G. Hilmersson, *Eur. J. Inorg. Chem.* **2004**, 3393–3404.

[2] R. A. Flowers II, E. Prasad in *Handbook on the Physics and Chemistry of Rare Earths*, *Vol. 36* (Eds.: K. A. Gschneidner, Jr., J.-C. G. Bünzli, V. K. Pecharsky), Elsevier, **2006**, chap. 230, pp. 393–473.

[3] A. Yoshida, T. Manamoto, J. Inanaga, K. Mikani, *Tetrahedron Lett.* **1998**, *39*, 1777–1780.

[4] T. K. Hutton, K. W. Muir, D. J. Procter, *Org. Lett.* **2003**, *5*, 4811–4814.

[5] D. J. Edmonds, K. W. Muir, D. J. Procter, *J. Org. Chem.* **2003**, *68*, 3190–3198.

[6] a) H. Lodberg Pedersen, T. B. Christensen, R. J. Enemærke, K. Daasbjerg, T. Skrydstrup, *Eur. J. Org. Chem.* **1999**, 565–572; b) T. B. Christensen, D. Riber, K. Daasbjerg, T. Skrydstrup, *Chem. Commun.* **1999**, 2051–2052; c) H. C. Aspinall, N. Greeves, C. Valla, *Org. Lett.* **2005**, *7*, 1919–1922.

[7] S. Hoz, A. Yacovan, I. Bilkis, *J. Am. Chem. Soc.* **1996**, *118*, 261–262.

[8] A. Dahlén, G. Hilmersson, *Tetrahedron Lett.* **2001**, *42*, 5565–5569.

[9] a) P. R. Chopade, E. Prasad, R. A. Flowers II, *J. Am. Chem. Soc.* **2004**, *126*, 44–45; b) E. Prasad, R. A. Flowers II, *J. Am. Chem. Soc.* **2005**, *127*, 18093–18099.

[10] M. Vestergren, B. Gustafsson, A. Johansson, M. Håkansson, *J. Organomet. Chem.* **2004**, *689*, 1723–1733.

[11] J. P. White III, H. Deng, E. P. Boyd, J. Gallucci, S. G. Shore, *Inorg. Chem.* **1994**, *33*, 1685–1694.

[12] A. Sen, V. Chebolu, A. L. Rheingold, *Inorg. Chem.* **1987**, *26*, 1821–1823.

[13] This value is within experimental error of previous reports. a) R. J. Enemærke, K. Daasbjerg, T. Skrydstrup, *Chem. Commun.* **1999**, 343–344; b) M. Shabangi, M. L. Kuhlman, R. A. Flowers II, *Org. Lett.* **1999**, *1*, 2133–2135.

[14] a) M. Shabangi, R. A. Flowers II, *Tetrahedron Lett.* **1997**, *38*, 1137–1140; b) M. Shabangi, J. M. Sealy, J. R. Fuchs, R. A. Flowers II, *Tetrahedron Lett.* **1998**, *39*, 4429–4432; c) R. J. Enemærke, T. Hertz, T. Skrydstrup, K. Daasbjerg, *Chem. Eur. J.* **2000**, *6*, 3747–3754.

[15] a) C. P. Andrieux, I. Gallardo, J.-M. Saveant, K.-B. Su, *J. Am. Chem. Soc.* **1986**, *108*, 638–647; b) J.-M. Saveant, *J. Am. Chem. Soc.* **1987**, *109*, 6788–6795.

[16] E. Prasad, B. W. Knettle, R. A. Flowers II, *J. Am. Chem. Soc.* **2004**, *126*, 6891–6894.

[17] A. Dahlén, G. Hilmersson, *Eur. J. Inorg. Chem.* **2004**, 3020–3024.