Instantaneous SmI_2/H_2O/Amine-Mediated Reductions in THF

Anders Dahlén and Göran Hilmersson*[a]

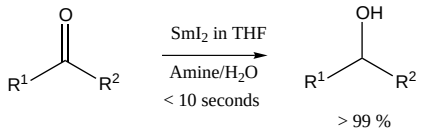
Abstract: The SmI_2-mediated reductions of ketones, imines, and α,β-unsaturated esters have been shown to be instantaneous in the presence of H_2O and an amine in THF. The SmI_2-mediated reductions are not only shown to be fast and quantitative by the addition of H_2O and an amine, but the workup procedures are also simplified. Competing experiments with SmI_2/H_2O/amine confirmed that α,β-unsaturated esters could be selectively reduced in the presence of ketones or imines. Comparison of analogue ligands showed that nitrogen and phosphorus ligands are superior to oxygen and sulfur ligands in these reductions. The trialkylphosphine 1,2-bis(dimethylphosphino)ethane (DMPE) provided a primary kinetic isotope effect, yielding a k_H/k_D of 4.5.

Keywords: functional groups · N ligands · reduction · selectivity · samarium

Introduction

Ever since Kagan developed the versatile coupling and reducing reagent samarium diiodide in THF in the late 1970's,[1, 2] there has been a remarkable activity in discovering new reactions in which this reagent can be utilized.[3–10] It has been found to be especially useful in coupling reactions between alkyl halides and ketones, also known as the Barbier reaction,[11, 12] between aromatic carbonyls (pinacol coupling),[13, 14] and between aldehydes and α,β-unsaturated esters (ketyl–olefin coupling).[15, 16] The reducing power of samarium diiodide in THF is sensitive to the presence of co-solvents, for example, hexamethylphosphoramide (HMPA),[17, 18] *N*,*N*′-dimethyl-*N*,*N*′-propyleneurea (DMPU),[19–22] and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU).[23] HMPA has been found to increase the oxidation potential of SmI_2 from -1.33 to -2.05 V, indicated by linear sweep voltammetry,[24] or its standard potential from -0.98 to -1.75 V vs SCE, indicated by cyclic voltammetry.[25] Addition of these additives makes it possible to fine-tune the reactivity, thereby altering the experimental conditions and the outcome of the reaction. However, the very popular HMPA is carcinogenic, and the discovery of a replacement for this additive is therefore of great concern. The influence of other solvents or additives on SmI_2-mediated reactions has been reported, although HMPA appears to be superior.[4]

Recently we reported that SmI_2, water, and simple amines, such as triethylamine (Et_3N), *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) and *N*,*N*,*N*′,*N*′′,*N*′′-pentamethyldiethylenetriamine (PMDTA), reduced dialkyl ketones to alcohols instantaneously at 20.0 °C (Scheme 1).[26] It was shown that



Scheme 1. Instantaneous reduction of ketones induced by amine/H_2O.

two equivalents of amine and three equivalents of water had to be used for each oxidized samarium diiodide in order to achieve the instantaneous and complete reduction. This powerful combination was also shown to be superior to other methods, including the widely used HMPA/alcohol mixtures.[5] The increase in rates of the SmI_2-mediated reduction exceed 100000 compared to that of water or amine alone. Previously Cabri et al. reported that the addition of triethylamine accelerates the SmI_2/H_2O-mediated cyclization of aryl radicals and olefins.[27]

Herein we wish to report the use of the reagent mixture SmI_2/H_2O/amine in various reactions. It has been shown that this method can be applied to different types of functional groups and that reduction takes place both quantitative and in a matter of seconds (Figure 1).

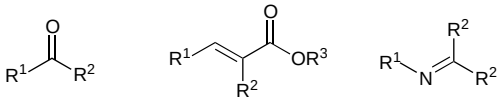


Figure 1. Functional groups investigated in this study.

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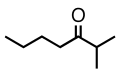
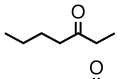
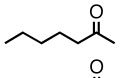
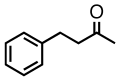
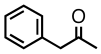
Results and Discussion

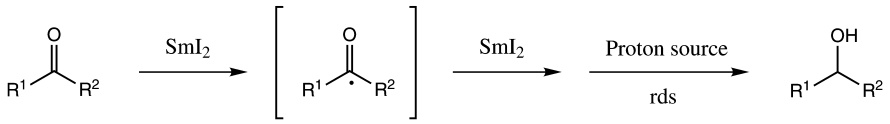
Reduction of ketones by diols: The impact of chelating alcohols for the SmI_2-mediated reduction of heptan-3-one was investigated in a previous study.[28] It was found that proton donors that contain coordinating ether functions, for example, mono-, di-, and triglycol methyl ethers, reduced heptan-3-one more efficiently than the nonchelating proton-donor methanol. Diols were found to be superior to monoalcohols in this reduction. The existence of a primary kinetic isotope effect proved that the proton transfer is part of the rate-determining step (rds) (Scheme 2).

To verify the generality of this conclusion several other dialkyl ketones were studied. The results initially found for heptan-3-one turned out to be general for all dialkyl ketones tested, and the diol di(ethyleneglycol) was the most efficient proton source. Each ketone was quantitatively reduced, into its respective alcohol, in excess SmI_2 (7 equiv) and diglycol (7 equiv), to ensure minimization of variations in concentration (pseudo-first-order rate conditions).[28] A direct comparison of the initial rates of the diglycol-mediated reductions of ketones revealed that the steric crowding around the carbonyl carbon is reflected in the rate of these reductions. It also became evident that the phenyl substituents significally affect the rates (Figure 2).

Table 1. Relative rates in the SmI_2/H_2O/amine-mediated reduction of ketones compared to 2-methyl-heptan-3-one.[a–c]

Entry	Substrate	Relative rate (2 equiv Et_3N)	Relative rate (1 equiv TMEDA)	Relative rate (0.67 equiv PMDTA)
1	 **1**	**1.0**	**1.0**	**1.0**
2	 **2**	2.6	2.7	2.5
3	 **3**	7.1	8.3	7.0
4	 **4**	13	14	12
5	 **5**	23	30	21
6	 **6**	31	39	33
7	 **7**	59	77	63

[a] The amount of amine corresponds to two R_3N per SmI_2. [b] In a typical experiment two or more substrates were introduced into a mixture of SmI_2 and amine. Water was added slowly under vigorous stirring until a white precipitate and a clear organic layer was obtained. The respective yields of the reactants were determined by GC. [c] The data were obtained from several separate experiments and the relative error is less than 10%.



Scheme 2. SmI_2-mediated ketone reduction accelerated by alcohols.

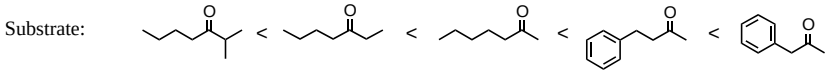


Figure 2. Comparison of the reactivity of different ketones by using SmI_2/diglycol in THF.

Reduction of ketones by the SmI_2/H_2O/amine mixtures: Applying the SmI_2-mediated reduction promoted by amine/H_2O to these ketones resulted in complete reduction in less than ten seconds for all dialkyl ketones investigated. Thus, the very fast rate of reduction did not allow initial rate studies by GC analysis as above. However, we performed competitive experiments, by introducing mixtures of two or more substrates into the same reaction mixture, and could in this manner compare the very fast reactions. Large differences in relative rates were achieved between the ketones (Table 1).

The substrates with the least steric requirements and the substrates with electron-withdrawing groups, for example, phenyls, were again proven to be reduced in preference of the aliphatic, bulky substrates. Three different amines were used in these experiments: Et_3N, TMEDA, and PMDTA. The relative rates between the more reactive ketone cyclohexanone and the less reactive ketone 2-methyl-heptan-3-one is approximately 77:1 in the presence of TMEDA. Interestingly the results with Et_3N or PMDTA are almost identical, but with TMEDA a slightly larger increase in relative rates was observed upon going from the more sterically hindered to the less sterically hindered ketones. This may be an effect of the steric requirements of the amines. We can not exclude a possible change in the reducing power of SmI_2 coordinated to amines. However, it is most unlikely that a bulky amine like Et_3N can compete with the bulk solvent THF as a ligand for SmI_2.

SmI_2 has been known to mediate pinacol couplings ever since the early days of the samarium diiodide era, especially with aryl ketones, under mild conditions.[13] Acetophenone is reported to undergo reductive coupling in 30 seconds yielding the pinacol product (95%).[13] However, reduction of acetophenone is also reported in the presence of MeOH.[1] Applying the SmI_2/H_2O/amine mixtures to the substrates described in Table 1 led to quantitative reduction of the ketones to their corresponding alcohols, independently of the addition order of the additives. However, when aryl-substituted ketones was studied, that is, acetophenone, mainly pinacol coupling products were obtained if water was added after the addition of the aryl ketone. (All products described in this article were isolated and analysed by ^{1}H-NMR and/or GC/MS.) However, mixing SmI_2, amine, and water prior to dropwise addition of acetophenone yielded mostly phenylethanol (Scheme 3). Thus, it is apparent that the order of additions of the additives is crucial for the SmI_2/H_2O/amine reduction of aryl-substituted ketones.

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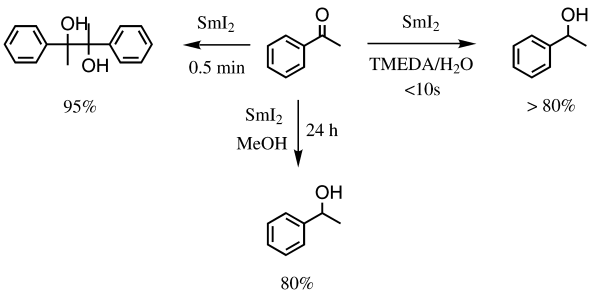


Scheme 3. Different pathways for acetophenone in SmI_2-mediated reactions.

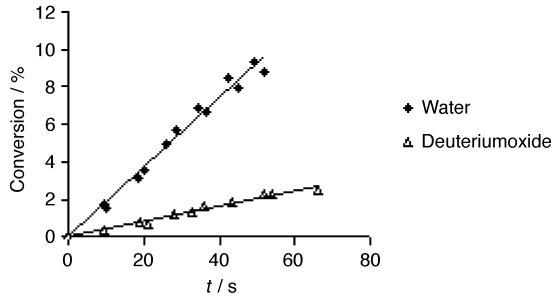


Figure 4. Primary kinetic isotope effect for the reduction of 2-methylheptan-3-one using excess SmI_2, DMPE, and H_2O/D_2O.

Rate comparison of nitrogen, phosphorus, oxygen, and sulfur analogues in the reduction of ketones: The discovery of the highly efficient SmI_2/H_2O/amine-mediated reductions of ketones opened our eyes for analogue Lewis bases with oxygen, phosphorus, and sulfur.

Reduction of 4-phenyl-2-butanone (1 equiv) with seven equivalents of 1,2-dimethoxyethane (DME) or 1,2-bis(methylsulfanyl)ethane (MSE) gave only 40% conversion after 24 hours in the presence of excess water (17.5 equiv). However, the phosphorus-containing analogue, 1,2-bis(dimethylphosphino)ethane (DMPE), resulted in complete reduction of 4-phenyl-2-butanone in approximately 30 minutes with excess water. As mentioned earlier 4-phenyl-2-butanone is completely reduced in less than ten seconds by using SmI_2/H_2O/TMEDA (Figure 3).

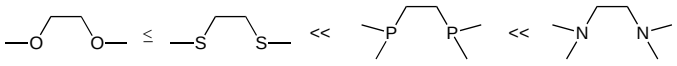


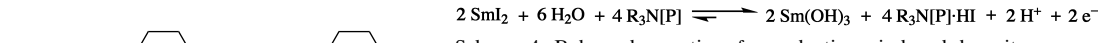
Figure 3. Comparison of analogous ligands in the reduction of 4-phenyl-2-butanone.

The conclusion of these results is that neither oxygen nor sulfur analogues accelerate the reduction of 4-phenyl-2-butanone in the presence of excess water, since similar yields are reached with water alone. However, DMPE/H_2O gave a considerable rate enhancement, relative to the rates of DME/H_2O-, MSE/H_2O-, H_2O-, or DMPE-accelerated reductions. The results also confirmed that the TMEDA/H_2O mixture was superior to its Lewis base analogues, with O, S, or P, reducing any dialkyl ketone tested in less than ten seconds in excess water.

The DMPE/H_2O-accelerated reduction is sufficiently slow for detailed kinetic studies; therefore, several separate experiments were conducted to determine the rate-determining step for the SmI_2/H_2O/DMPE-promoted reduction of ketones. Two substrates, 4-phenyl-2-butanone and 2-methyl-heptan-3-one, were tested separately for the existence of a primary kinetic isotope effect (PKIE) in the SmI_2-mediated (7 equiv) reduction in the presence of DMPE (7 equiv) and H_2O or D_2O (17.5 equiv). A PKIE was attained for the reduction of both substrates, yielding a k_H/k_D of 4.5 ± 0.3 for 2-methyl-heptan-3-one, indicating a rate-determining proton transfer (Figure 4).

The reduction of 4-phenyl-2-butanone was very fast and the evident PKIE could not be exactly determined. A PKIE for the amine analogue could not be achieved, since the reactivity of this mixture is far too high for initial rate measurement in the reduction of ketones with our current method. However, we believe that the rate-determining steps of the N and P ligands are similar.

Why are the phosphorus and nitrogen ligands so incredibly effective relative to their oxygen and sulfur analogues? Both trialkylphosphorus ligands and amines have the ability to form insoluble hydrohalide salts. Oxygen and sulfur lack this ability; this makes them considerably less effective in these reactions. Thus, the formation of amine and phosphorus salts during the progress of the reaction increases the rate of reduction, because of the increase in the equilibrium constant (Scheme 4).

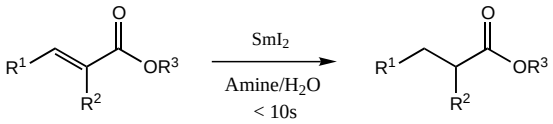


Scheme 4. Balanced equation for reductions induced by nitrogen or phosphorus ligands.

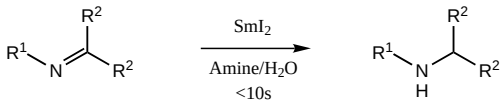
Based on this result we propose that the main reason for the enormous rate enhancements observed for nitrogen and phosphorus ligands is the rapid precipitation of byproducts; this drives the reaction forward according to Le Chateliers Principle. Amines are more effective than trialkylphosphorus ligands in the reduction of dialkyl ketones because of more effective formation and precipitation of the salts in the reaction.

Reductions of α,β-unsaturated esters: Reductions and competing reactions involving α,β-unsaturated esters were also performed by using the novel method with SmI_2/H_2O/amine. Reduction of α,β-unsaturated esters has previously been studied in detail in the presence of HMPA, indicating that the substituents affect the reactivity.[29–31] A possible side-reaction in these reductions is reductive coupling between two double bonds as reported by Inanaga et al.[32] However, no side-reaction could be detected in the amine/H_2O-induced reduction. The α,β-unsaturated esters were quantitatively and instantaneously reduced by the powerful mixture of SmI_2/H_2O/amine yielding the corresponding esters as the only products (Scheme 5).

The expected reactivity order, also verified in a recent report containing rate constants in SmI_2-mediated HMPA/alcohol reductions,[30] between the α,β-unsaturated esters investigated confirmed that substrates containing bulky,



Scheme 5. Instantaneous SmI_2-H_2O-mediated reduction of α,β-unsaturated esters induced by amines.



Scheme 6. Instantaneous SmI_2/H_2O-mediated reduction of imines induced by amines.

electron-donating groups react slower than substrates that contain electron-withdrawing groups (Table 2).

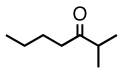
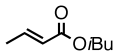
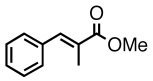
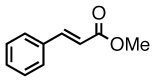
The experimental data shows that the relative reactivity between α,β-unsaturated esters and ketones is very high. Competition between 2-methyl-heptan-3-one and any cinnamate gave exclusive reduction of the α,β-unsaturated esters, leaving the ketone unreacted.

Reductions of imines: Knettle and Flowers recently reported on HMPA-induced $SmBr_2$-mediated reduction of ketimines.[33] Reaction times of 15 minutes yield 99% of the corresponding amine. The SmI_2-mediated reduction promoted by amine and water quantitatively reduced the imines below in less than ten seconds (Scheme 6).

Competitive experiments between ketones and imines were also performed. (For imines the entire reaction mixture had to be quenched to obtain accurate results, due to precipitation of the products. *n*-Decan was used as an internal standard.) Exclusive reduction of the faster reacting ketone cyclohexanone **7** was accomplished versus the slower reacting imine **11**; the relative rate is approximately 700:1 using TMEDA. Further comparison of the relative rates shows that the cinnamates are reduced exclusively to both imines and ketones. TMEDA gave larger differences in relative rates, while almost identical relative rates were obtained using Et_3N and PMDTA (Table 3).

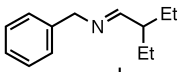
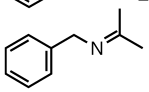
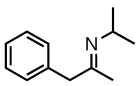
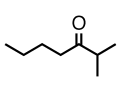
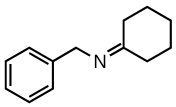
During the investigation of the reduction of imines it was also noticed that aryl-substitution on the imine carbon atom led to imino–pinacol coupling as the main product, in close analogy with the results of the arylketone reduction described above. The iminebenzylidenephenylamine does not react with SmI_2 in the absence of additives at room temperature. During reflux in THF the imino–pinacol coupling is completed in 30 minutes (Scheme 7);[33, 34] the addition of MeOH at room temperature does not give reduction of the imine to the corresponding amine, as would be expected, instead smaller amounts of imino–pinacol product were obtained. However,

Table 2. Relative rates in the SmI_2/H_2O/amine-mediated reduction of α,β-unsaturated esters compared to 2-methyl-heptan-3-one.[a–d]

Entry	Substrate		Relative rate (2 equiv Et_3N)	Relative rate (1 equiv TMEDA)	Relative rate (0.67 equiv PMDTA)
1		**1**	**1.0**	**1.0**	**1.0**
3		**8**	52	67	55
4		**9**	7.6×10^2	10×10^2	7.6×10^2
5		**10**	15×10^3	24×10^3	18×10^3

[a] The amount of amine corresponds to two R_3N per SmI_2. [b] In a typical experiment two or more substrates were introduced into a mixture of SmI_2 and amine. Water was added slowly under vigorous stirring until a white precipitate and a clear organic layer was obtained. The respective yield was determined by GC. [c] The relative rates were determined by competition with **6**, and then arbitrarily relative to 2-methyl-heptan-3-one. [d] The data were obtained from several separate experiments and the relative error is less than 10%.

Table 3. Relative rates in the SmI_2/H_2O/amine-mediated reduction of imines compared to 2-methyl-heptan-3-one.[a–c]

Entry	Substrate		Relative rate (2 equiv Et_3N)	Relative rate (1 equiv TMEDA)	Relative rate (0.67 equiv PMDTA)
1		**11**	0.09	0.11	0.08
2		**12**	0.37	0.74	0.39
3		**13**	0.66	1.6	0.56
4		**1**	**1.0**	**1.0**	**1.0**
5		**14**	3.4	8.3	3.0

[a] The amount of amine corresponds to two R_3N per SmI_2. [b] In a typical experiment two or more substrates were introduced into a mixture of SmI_2 and amine. Water was added slowly under vigorous stirring until a white precipitate and a clear organic layer was obtained. The respective yields of the reactants were determined by GC. [c] The data were obtained from several separate experiments and the relative error is less than 10%.

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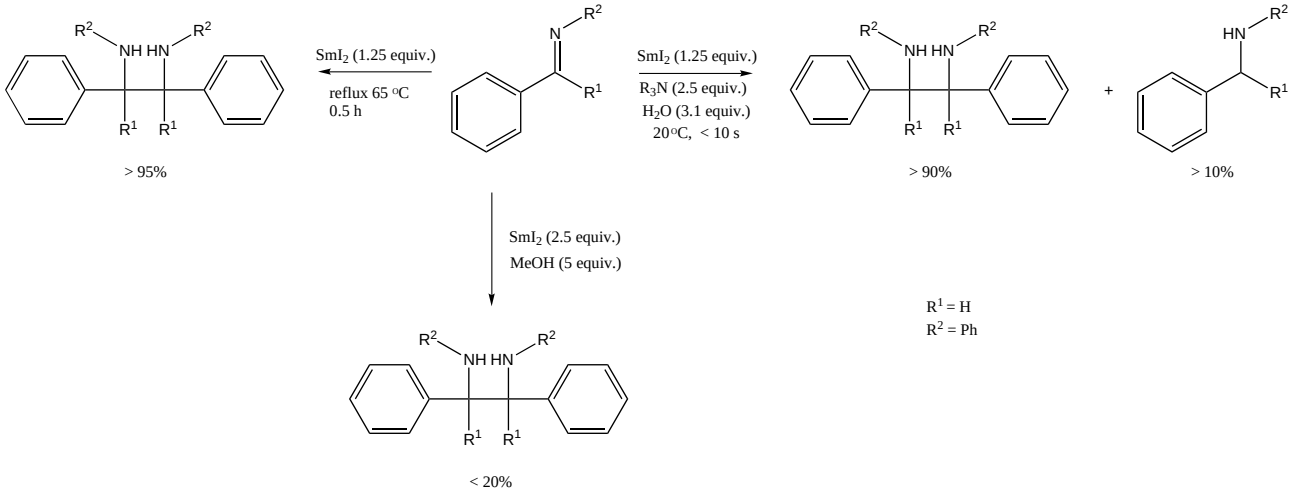

Scheme 7. Different pathways for benzylidenephenylamine in SmI_2-mediated reactions.

the SmI_2/H_2O/TMEDA mixture resulted in primarily imino–pinacol product (>90%) and smaller amounts of the reduced imine, when water was slowly added to SmI_2 subsequent to amine and imine (determined by ^1H and ^{13}C NMR spectroscopy). Mainly imino–pinacol (>60%) was observed even when the imine was added after the amine and water. No reaction could be detected in the absence of H_2O.

This is very interesting, since it opens up a new, milder pathway for the somewhat more difficult imino–pinacol coupling. Refluxing conditions may be destructive for functional groups and/or protective groups; this can be avoided with this new, improved method, which is instantaneous at room temperature. The generality of the imino–pinacol coupling reaction is currently under investigation.

IR and ^1H NMR analysis and of precipitated salts: The white salts formed in the reactions were filtrated, washed with diethyl ether, and finally dried yielding fine, white powders. The powders were analyzed by FTIR and ^1H NMR spectroscopy. The IR analysis gave strong signals in the region 2500–3000 cm^{-1}, which reveal the existence of amine hydrohalides. These signals disappeared after basic workup with sodium hydroxide and diethyl ether, since the amines are released and removed. The very strong signals around 3445 cm^{-1} point also towards the existence of hydrogen bonds (OH stretching), which may belong to $Sm(OH)_3$. This signal did not disappear after the basic workup.

The ^1H NMR analysis of the precipitate, dissolved in $CDCl_3$, also supported the occurrence of hydrohalide salts, since signals with shifts downfield of the reference ligands were obtained, in addition to weak signals between 10–11 ppm, which belong to NH^+. Mixtures containing PMDTA gave several signals, which may be an effect of unequal amounts of HI per amine function. However, after basic workup with sodium hydroxide only the ^1H signals from the pure amines were detected. (The IR and NMR data for the Et_3N, TMEDA, and PMDTA salts can be found in the Experimental Section.)

Effective workup procedures on larger scale

Ketones and α,β-unsaturated esters: In an ordinary reaction two slightly different workup procedures may be employed; in the first alternative the reaction mixture, which includes inorganic samarium salts and precipitated amines, is dissolved in HCl (0.1M), extracted with diethyl ether, and finally washed with $Na_2S_2O_3$ and brine. The organic layer is then dried over Na_2SO_4 and after evaporation the product is sufficiently pure for further use. This workup is the most common for samarium diiodide reactions reported earlier in the literature.[13, 35]

In the second alternative, the precipitated materials are removed initially by centrifugation or filtration. This is particularly advantageous, since the product remains in the solution. The supernatant is then diluted with diethyl ether, washed with $Na_2S_2O_3$ and brine, and finally dried over Na_2SO_4 and evaporated. The yield will not be affected by this slightly faster workup.

However, the fact is that the only workup needed for these reactions is simple filtration of the precipitated materials followed by evaporation of THF, on condition that correct proportions of amine and water are added to the samarium diiodide reagent. Only the byproducts are precipitated, while the product remains dissolved. This extremely short workup is particularly convenient for water-soluble products, which would dissolve into the water layer during workup.

Imines: Since the method for SmI_2/H_2O/amine-mediated reductions is based on precipitating all byproducts, that is, $Sm(OH)_3$ and HI salts of amines, the workup described above can not be employed, since the product in this case will also form HI and HCl salts. Instead excess NaOH (1M) is added to the reaction mixture, which is then extracted by, for instance, diethyl ether. The samarium salts, that is, $Sm(OH)_3$, remain in the water layer, while the amines are extracted into the organic layer. The organic layer is then washed with $Na_2S_2O_3$ and brine. Finally the organic layer is dried over Na_2SO_4 and after evaporation the product is satisfactorily pure for further

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use. The use of triethylamine is recommended as additive in the SmI_2/H_2O/amine induced reduction of imines, since it can be easily removed by evaporation.

Conclusion

The generality of the instantaneous SmI_2/H_2O/amine mediated reduction of ketones, α,β-unsaturated esters, and imines has been shown. It has also been shown that high selectivity could be obtained in the competition between α,β-unsaturated esters and ketones or imines. The precipitation of insoluble hydrohalide and samarium salts increases the rate of reduction. The formation of hydrohalide salts is supported by the fact that the trialkylphoshine DMPE as well as amines strongly accelerate these reductions. This was also established by IR and ^{1}H NMR analysis of the precipitates of the nitrogen ligands. As a result of the addition of H_2O and amine to SmI_2 the equilibrium of the reduction is pushed forward, thereby driving the reaction to completion. The combination of SmI_2 in THF, amine, and water certainly qualifies as an excellent replacement for the toxic HMPA/alcohol mixtures, since it not only has been shown to bring about quantitative and fast reductions for several functional groups, but also to simplify the workup procedures substantially.

Experimental Section

General: In a standard procedure, SmI_2 in THF (2.5 equiv, 0.1 M, Aldrich) was added to a dry Schlenk tube, containing a magnetic stirrer bar and fitted with a septum, inside a glove box under nitrogen atmosphere. The ligand (5 equiv R_3N) and the proton donor, that is, H_2O (6.25 equiv), were added under stirring. The substrate (1 equiv), at 20.0 °C was then added to this mixture. The reaction was finished in a few seconds, as soon the reaction mixture was mixed thoroughly. A white precipitate and a colorless, clear organic layer indicated the completion of the reaction.

In experiments involving initial rate measurements small portions of the mixture (100 μL) was removed by syringe and quenched with I_2 in *n*-hexane (0.1 M, 0.1 mL) including *n*-decan as internal standard when needed. Diethyl ether (1 mL) and HCl (0.1 mL, 0.12 M), to dissolve the inorganic salts, to the quenched solution was added and finally saturated $Na_2S_2O_3$ (5 dr.) to remove excess iodine. The clear organic layer was transferred to a vial and analyzed by GC. This procedure was repeated at least two times to ensure accurate results.

The ketones/alcohols and imines/amines were separated using a CPWAX 52CB column (Ø = 25 mm, length = 25 m), with hydrogen as carrier gas at a flow rate of 2 mL min^{-1}. The standard method includes an injector temperature of 225 °C, a column temperature at initially 100 °C for 8 min, then heated to 165 °C (10 °C min^{-1}) for 20 min, and finally to 200 °C (10 °C min^{-1}) for 10 min. The detector temperature was 250 °C (FID).

The α,β-unsaturated esters/saturated esters were separated by using a CP-Sil 8 CB low-bleed column (Ø = 25 mm, length = 30 m), with hydrogen as carrier gas at a flow rate of 1 mL min^{-1}. The standard method includes an injector temperature of 225 °C, and a column temperature at initially 70 °C for 4 min, followed by heating to 250 °C (10 °C min^{-1}) for 10 min. The detector temperature was 250 °C (FID).

IR and NMR data for Et_3N salts: IR (KBr): $\tilde{\nu}$ = 3442 (vs), 2950 (vs), 2768 (s) 2680 (s), 2478 (m), 1616 (m), 1464 (s), 1420 (s), 1399 (s), 1166 (m), 1035 cm^{-1} (s); ^{1}H NMR (400 MHz, 25 °C, $CDCl_3$): δ = 1.47 (t, 9H; CH_3), 3.17 (q, 6H; CH_2), 10.7 ppm (br s, NH^+).

IR and NMR data for TMEDA salts: IR (KBr): $\tilde{\nu}$ = 3446 (vs), 2889 (s), 2650 (vs), 2448 (s), 1617 (m), 1480 (s), 1398 (s), 1150 (w), 994 (s), 972 cm^{-1} (s); ^{1}H NMR (400 MHz, 25 °C, $CDCl_3$): δ = 1.92 (br s, OH), 2.56 (s, 12H; CH_3), 2.93 ppm (s, 4H; CH_2).

IR and NMR data for PMDTA salts: IR (KBr): $\tilde{\nu}$ = 3450 (vs), 2933 (s), 2720 (s) 2448 (w), 1636 (m), 1472 (s), 1394 (s), 997 (m), 962 cm^{-1} (m); ^{1}H NMR (400 MHz, 25 °C, $CDCl_3$): δ = 1.80 (br s, OH), 2.38 (s, 3H; CH_3), 2.74 (s, 9H; CH_3), 2.86 (s, 4H; CH_2), 3.02 (s, 4H; CH_2), 3.74 ppm (s, 3H; CH_3).

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