JOC Article

Estimating the Limiting Reducing Power of SmI_2/H_2O/Amine and YbI_2/H_2O/Amine by Efficient Reduction of Unsaturated Hydrocarbons

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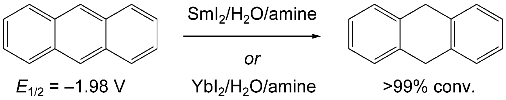

The mixture of samarium diiodide, amine, and water ($SmI_2/H_2O/Et_3N$) is known to be a particularly powerful reductant, but until now the limiting reducing power has not been determined. A series of unsaturated hydrocarbons with varying half-wave reduction potentials ($E_{1/2} = -1.6$ to -3.4 V, vs SCE) have been treated with $SmI_2/H_2O/Et_3N$ and $YbI_2/H_2O/Et_3N$, respectively. All hydrocarbons with potentials of -2.8 V or more positive were readily reduced with $SmI_2/H_2O/Et_3N$, whereas all hydrocarbons with potentials of -2.3 V or more positive were readily reduced using $YbI_2/H_2O/Et_3N$. This defines limiting values of the chemical reducing power of $SmI_2/H_2O/Et_3N$ to -2.8 V and of $YbI_2/H_2O/Et_3N$ to -2.3 V vs SCE.

Introduction

The development of new efficient synthetic methods lies at the heart of modern organic chemistry. Even though reduction reactions are among the most used transformations, there has not been much focus on the development of conceptually new methods. The most popular reagents involve hydrogen attached to a catalyst, hydride reagents, and dissolving metals.[1−4] There are also some examples of hydrogen atom transfer reactions such as the Meerwein−Pondorff−Verley reductions (MPV).[5] However, samarium diiodide (SmI_2) is rapidly becoming a widely appreciated selective reducing agent that mediates various important reduction and coupling reactions.[6−11] The reactions are intimately correlated with a relatively high degree of selectivity, especially in combination with HMPA.[12−16] Flowers and Skrydstrup have independently shown that the reducing power of SmI_2 increases approximately 0.9 V (compared to SmI_2 in THF) by the addition of HMPA.[17−20] The redox potential ($E°$) for SmI_2 in THF is -1.55 V vs Ag/AgNO$_3$. In the presence of at least 4 equiv of HMPA the redox potential increases to -2.35 V. This increase has been attributed to the replacement of the five THF molecules coordinated to the samarium(II) by four HMPA molecules.[21,22] The increase in reducing power not only gives faster reactions but also affects the chemoselectivity.[23−28] The presence of HMPA and a proton

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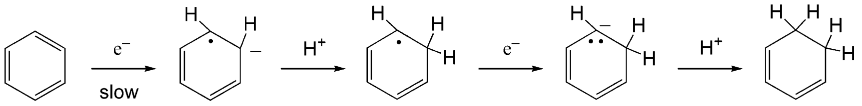
SCHEME 1. Suggested Mechanism for the Reduction of an Unsaturated Hydrocarbon



source in Ln(II) solutions also facilitates reduction of functional groups that are more difficult to reduce, e.g., alkyl halides.[13] There are reports in which other additives have been introduced because of the carcinogenic nature of HMPA.[29−33] In this context we have discovered that a combination of an amine, water, and SmI_2 results in a very potent reducing agent. The reagent mixture SmI_2/water/amine not only mediates instantaneous reductions of ketones and α,β-unsaturated esters and rapid reduction of halides (iodides, bromides, and chlorides) and conjugated alkenes but also effects coupling of aryl ketones and aryl imines and induces cleavage of allyl ethers.[24,34−39]

The use of SmI_2 has previously been focused mainly on radical coupling reactions, but the discovery of the SmI_2/water/amine mixtures has made SmI_2 a promising alternative to hydrides and hydrogen as a result of its mild but extremely fast reactions, as well as clean and simple workup procedures. The only requirement is that the reaction mixture is completely oxygen-free. Another advantage with SmI_2 is that it is not pyrophoric and does not require addition of a toxic transition metal such as palladium. (It has been proven in several health studies that certain metals, e.g., palladium in dental alloys, may cause illness, periodontal disease and poisoning.)

Recently, our group published a detailed kinetic study on the reduction of alkyl halides by SmI_2/H_2O/amine and suggested a mechanism for the rapid reductions.[40] It was shown that the rate of reduction is dependent on the basicity of the amine and that the transition state most likely consists of a dimeric Sm^{II} species. However, efforts to determine the redox potential of SmI_2/H_2O/amine by cyclic voltammetry were not completely successful.[38] The oxidation of Sm^{II} to Sm^{III} was irreversible, and it was not possible to obtain information on the reducing power of this potent reagent mixture.

Chauvin and co-workers reported in the late 1980s the rare earth metal reduction of unsaturated hydrocarbons and correlated the reactivity of Ce, Nd, Sm, and Yb with the reduction potentials of the hydrocarbons.[41] They found that the chemical reduction fits with standard electrochemical reductions for the first half-wave ($E_{1/2}$) of the hydrocarbons. A few years later, Evans and co-workers reported that decamethylsamarocene, $(C_5Me_5)_2Sm$, reacts with several polycyclic aromatic hydrocarbons.[42] From the potentials of the polycyclic compounds it was observed that $(C_5Me_5)_2Sm$ reacts with polycyclic aromatics that have half-wave potentials equal to or more positive than −2.22 V, vs SCE. In 2001, Fedushkin and co-workers used the same concept to probe the reactivity of thulium diiodide (TmI_2),[43] which is known to have a redox potential, $E°(M^{III}/M^{II})$, of −2.3 V vs SCE. On the basis of the reduction potentials of the hydrocarbons they estimated the effective chemical reducing power of TmI_2 to be approximately −2.0 V, vs SCE. These studies, by Chauvin, Evans, and Fedushkin with co-workers, give an estimate of the reducing powers for various lanthanide reagents, and it is clear that this method offers a rough approximation of the reactivity of the reagents when used in a series of similar compounds, even though the reactions were run in a different medium (THF rather than DMF).

It is important that only unsaturated hydrocarbons, containing nothing else but carbons and hydrogens, are used in these studies. Otherwise the substrate itself could compete with the bulk solvent THF for coordination with the lanthanide(II) to change the reaction mechanism from an outer- to an inner-sphere electron transfer (ET). The chemical reduction of, e.g., an aromatic compound such as benzene, would require two electrons and two protons to be completed (Scheme 1). The first electron transfer to the hydrocarbon occurs via an outer-sphere ET and this step should be the rate-determining step, since the aromaticity is lost in such a process.

Herein, we report on the high reducing power of SmI_2/water/amine and YbI_2/water/amine in the reduction of unsaturated hydrocarbons having $E_{1/2}$ values in the range −1.6 to −3.4 V vs SCE.

Results and Discussion

A large number of unsaturated hydrocarbons and alkylhalides, with their first half-wave potentials, $E_{1/2}$, ranging from −1.6 to −2.8 V vs SCE, were observed to be quantitatively reduced using SmI_2/H_2O/pyrrolidine (Figure 1 and Table 1). Benzene, with an $E_{1/2}$ of −3.4 V, was not reduced. This gives an estimate of the chemical reduction potential in the range of −2.8 to −3.4 V. However, it is most likely closer to −2.8 V since the reduction of 1-chlorodecane occurs at a very slow rate in comparison with other substrates.

We recently reported that the basicity of the amine affects the rate of reduction of alkyl halides.[40] Replacement of

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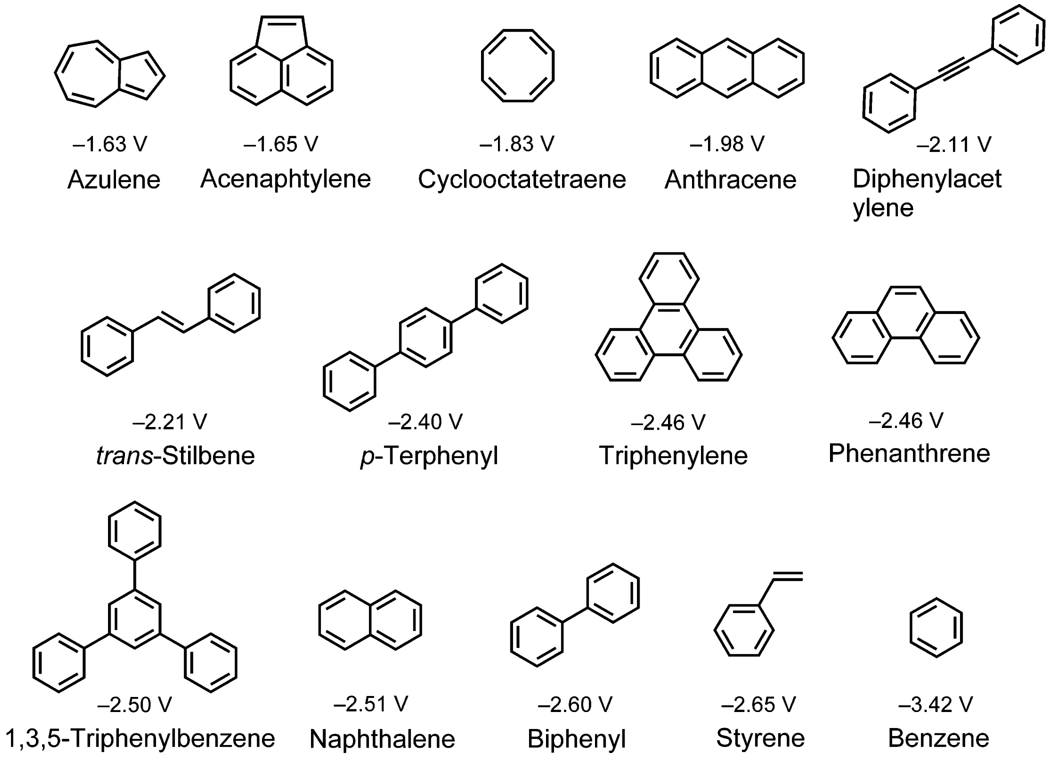


FIGURE 1. Unsaturated hydrocarbons used in this study together with their half reduction potentials, $E_{1/2}$, in DMF.

TABLE 1. Reduction of Hydrocarbons with LnI_2/H_2O/Amine[a]

entry	substrate	major product using SmI_2/H_2O/amine (% of product mixture)	major product using YbI_2/H_2O/amine (% of product mixture)	$-E_{1/2}$ (V)[b]
1	azulene	tetrahydroazulene (40)	dihydroazulene (95, four isomers)	1.63[42]
2	acenaphthylene[c]	acenaphtene (95)	acenaphtene (99)	1.65[42]
3	cyclooctatetraene	cyclooctadiene (95, three isomers)	cyclooctadiene (95, three isomers)	1.83[42]
4	anthracene[c]	9,10-dihydroanthracene (99)	9,10-dihydroanthracene (99)	1.98[42]
5	diphenylacetylene[c]	bibenzyl (99)	stilbene (95) + bibenzyl (trace)	2.11[44]
6	*trans*-stilbene[c]	bibenzyl (99)	bibenzyl (99)	2.21[45]
7	decyl bromide[c]	decane (99)	decane (99)	2.30[46]
8	*p*-terphenyl[d]	dihydro-*p*-terphenyl (75, three isomers)	no reaction	2.40[47]
9	triphenylene	dihydrotriphenylene (70)	no reaction	2.46[45]
10	phenanthrene[c]	9,10-dihydrophenanthrene (95)	no reaction	2.46[45]
11	1,3,5-triphenylbenzene[e]	dihydrotriphenylbenzene (85, two isomers)	no reaction	2.50[48]
12	naphthalene	1,4-dihydronaphthalene (78)	no reaction	2.51[45]
13	biphenyl	dihydrobiphenyl (63, two isomers)	no reaction	2.60[45]
14	styrene[c]	ethylbenzene (99)	no reaction	2.65[45]
15	decyl chloride	decane (99)	trace (<0.4)	2.8[46]
16	benzene	no reaction	no reaction	3.42[45]

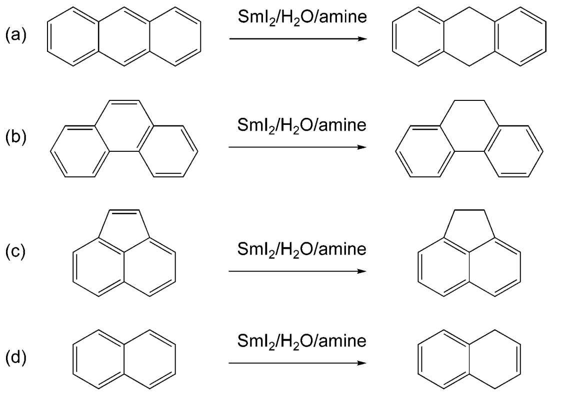
[a] LnI_2 (10 equiv), amine (20 equiv), and substrate (1 equiv) were mixed, and finally H_2O (30 equiv) was added. Samples were taken from the reaction vessel within 5 min. Products were analyzed by GC−MS. Comparable product distribution is achieved with triethylamine with pyrrolidine as amine. [b] Versus SCE. The accuracy of these values is approximately ±0.1 V due to solvent effects. [c] SmI_2 (2.5 equiv), amine (5.0 equiv), and substrate (1.0 equiv) were mixed, and finally H_2O (7.5 equiv) was added. Twice the amounts of reagents were used with diphenylacetylene for full reduction to bibenzyl. [d] Measured in dimethylamine/TBABr instead of DMF. [e] This value was recalculated from −3.08 V vs Ag/$AgNO_3$ to −2.50 vs SCE according to refs 17−19 and 49.

pyrrolidine with triethylamine gave the same result, although the unsaturated compounds were reduced at a much slower rate. Overall the reagent mixtures lead only to reduction without coupling reactions taking place.

Since an excess of SmI_2 has been used throughout the study, over-reduction is apparent in several cases. Therefore, some substrates yield complex product mixtures upon reduction. However, the formation of product mixtures can be expected on the basis of previous results.[36] Styrene derivatives are particularly easy to be reduced, whereas isolated double bonds are not reduced.

Depending on the nature of the unsaturated hydrocarbon, there is varying selectivity between different double bonds, which gives rise to different product distribution. It appears that reduction of polyaromatic hydrocarbons (PAH) with fused rings, such as anthracene and phenanthrene, gives one product preferentially (Scheme 2), whereas aromatics with single bond connected rings as in biphenyl and *p*-terphenyl give a mixture of several isomeric products. For this reason, the synthetic use is limited to fused PAHs. Nevertheless, the substrates in Table 1 still serve as indicators of the reducing abilities of various reducing agents.

SCHEME 2. Reduction of Fused PAHs a−d Gives One Preferred Product



The chemical reducing power of the considerably weaker reducing agent YbI_2 ($E_{1/2} = -1.02$ V vs $Ag/AgNO_3$)[50] was also evaluated in reductions of the PAHs. All unsaturated hydrocarbons with reduction potentials $E_{1/2}$ ranging from −1.6 to −2.30 V (vs SCE) were quantitatively reduced (Table 1). The alkyl halide decyl bromide was also efficiently reduced (entry 8). Interestingly, decyl chloride having significantly more negative reduction potential (−2.8 V) appears to undergo some reaction, although it only gave trace amounts (<0.4%) of the corresponding decane with a large excess of YbI_2 (10 equiv). The less reactive YbI_2/water/amine mixtures resulted in product mixtures somewhat less complex than those obtained using SmI_2/water/amine. SmI_2/water/amine is a more powerful reductant than YbI_2/water/amine. The substrates that have very similar reduction potentials for different double bonds and may undergo successive reductions are therefore more likely to yield more complex product mixtures in the case of using, e.g., excess SmI_2/water/pyrrolidine.

It was also validated that the half-wave potential of different unsaturated hydrocarbons correlated with the relative rate of reduction, i.e., the rate increases as the potential of the hydrocarbon becomes more positive. The logarithm of the relative rates of reduction (log(rel.rate)) were plotted versus the redox potentials ($-E_{1/2}$) of a few hydrocarbons (Figure 2). This gave a linear or nearly linear correlation between the rate and $E_{1/2}$. Therefore, the reaction most likely proceed through outer-sphere electron transfer (ET).[40,51−56]

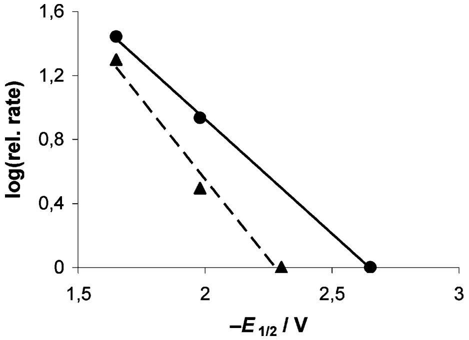
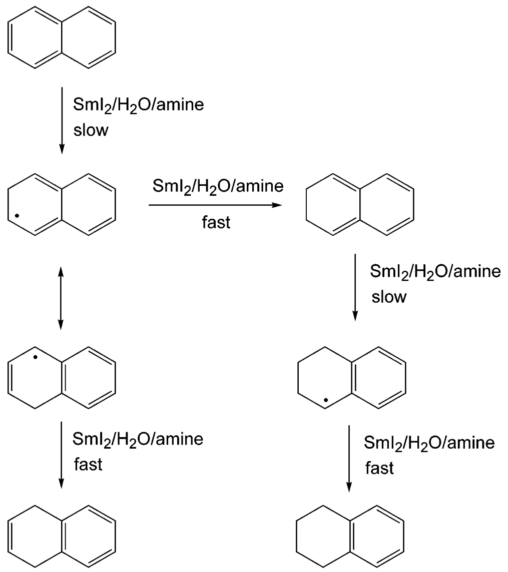


FIGURE 2. log(rel.rate) vs $-E_{1/2}$ for acenaphthylene, anthracene, and styrene with $SmI_2/H_2O/Et_3N$ (—) and for acenaphthylene, anthracene, and 1-bromodecane with YbI_2/H_2O/pyrrolidine (- - -).

SCHEME 3. Reduction of Naphthalene by Excess SmI_2/Water/Pyrrolidine, Yielding a Mixture of 1,4-Dihydro- and 1,2,3,4-Tetrahydronaphthalene



We propose that the reduction of the unsaturated hydrocarbons proceeds successively, with the first electron transfer being rate-determining, as illustrated for naphthalene in Scheme 3. There are no observable H_2O/D_2O kinetic isotope effects;[36] hence the protonation steps are considered very fast and have been left out for clarity. The mechanism for olefin reduction is likely similar to that for alkyl halides, both involving a slow outer-sphere ET from Sm^{II} to the substrate.[40]

Conclusion

In our preceding studies, the versatility of the powerful reagent mixture SmI_2/H_2O/amine has been proven in several types of reductions and coupling reactions. However, even though the mechanism of this reagent mixture is nowadays reasonably clear, the reducing power has until now been unknown. Comparison of several unsaturated hydrocarbons, with known $E_{1/2}$ values, provided us with a chemical limit of the effective reducing power for both SmI_2/H_2O/amine and YbI_2/H_2O/amine. The approximate limiting values for SmI_2/H_2O/amine and YbI_2/H_2O/amine are −2.8 V and −2.3 V vs SCE,

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respectively. Thus, the reducing powers have increased for about 1.8 V upon mixing them with water and amine. Since all reported $E_{1/2}$ values are measured in DMF, not THF, the exact values should be treated as rough estimates.

For synthetic purposes the LnI_2/H_2O/amine mixtures are well suited for the reduction of aromatic substrates with fused rings such as phenantrene, anthracene, and acenaphthylene, since only one major reduction product is formed. Unsaturated hydrocarbons with linked rings, as in for example biphenyl derivatives, usually give mixtures of isomers as reduction products.

Experimental Section

General. THF was distilled from sodium and benzophenone under nitrogen atmosphere. The amines were distilled under nitrogen atmosphere. SmI_2, additives, and solvents were stored under nitrogen atmosphere in a glovebox containing typically less than 1 ppm H_2O and O_2, respectively.

Reductions of Unsaturated Hydrocarbons. In a standard reduction, SmI_2 in THF (0.11 M, 10 equiv) was added to a dry Schlenk tube or round-bottomed flask, fitted with a septum and containing a magnetic stirrer bar, inside a glovebox with nitrogen atmosphere. The substrate (1 equiv) was added to the solution followed by the amine (20 equiv) and H_2O (30 equiv) at ambient temperature. The large excess of reagents was used to facilitate evaluation of the product distribution of multiply reduced samples. To avoid over-reduction of substrates with fused rings (e.g., acenaphthylene), only 2.5 equiv of SmI_2, 5.0 equiv of amine and 7.5 equiv of water should be used for reduction.

Small portions of the reaction mixture (200 μL) were removed with a gastight syringe within 5 min and quenched by air. To the quenched solution were added diethyl ether (1 mL) and HCl (0.1 M, 0.1 mL) (to dissolve the inorganic salts), and finally a few drops of saturated $Na_2S_2O_3$ were added to remove excess iodine. The organic layer was transferred to a vial and the product composition was analyzed with GC and GC−MS.

Gas Chromatography. The progress of the reaction was monitored using a GC fitted with a low-bleed achiral stationary phase (fused silica) column ($\phi = 0.25$ mm, length $= 25$ m), using nitrogen as carrier gas at a flow rate of 1 mL/min and an initial column temperature of 70 °C. The temperature program increased with a 10 °C/min to a final temperature of 300 °C. The injector temperature was 225 °C. The detector temperature was 250 °C (FID). The products were identified using GC−MS and/or authentic samples.

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