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Twenty five years of organic chemistry with diiodosamarium

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Abstract

An historical account of the introduction of samarium diiodide in organic chemistry is presented in the first section, with the main initial results obtained. The basic organic transformations published in the author laboratory and by other groups during the initial period (1977–1987) are detailed. Some of the progresses subsequently obtained will be selected such as various transformations in synthesis, including asymmetric synthesis and total synthesis of natural products. The possible use of SmI_2 in catalytic amount together with a terminal reducing agent is discussed. In the conclusion is summarized the wide scope of the chemistry induced by SmI_2 with some comments on the future of this chemistry.

Keywords: Diiodosamarium; Reduction; Coupling reactions; Ketyl; Radicals; Lanthanides(II)

1. Introduction

We became interested into the rare-earth chemistry in the early 1970s after reading a paper of Hinckley, where was described the novel use of tris-pivaloylato-europium as shift reagent in ^{1}H NMR spectroscopy [1]. We used this approach in collaborative works to analyze the spectra of complex molecules such as sugars [2–4]. Later, we decided to investigate the potential of lanthanide derivatives as tools in organic chemistry. In those days, the main non-industrial applications of rare-earths in organic chemistry were the cerium(IV) oxidations. Our first approach in that area was connected with oxidation. It was discovered that $(NO_3)_3Yb$ was able to catalyze the oxidation of benzoin to benzil [5]. It is molecular oxygen which is the terminal oxidant, presumably nitrate is involved in the oxidation itself, which was carried out in aqueous DMF. The reaction was not general and could not be extended to monoalcohols. Then, we looked for organic chemistry mediated by Ln(II) species. This chemistry was completely unknown at that time. In the next section are developed the early stages of our investigations.

2. The beginning of the diiodosamarium chemistry

The choice of a new class of reagents is always delicate. We wanted to check the reducing ability of some Ln(II) compounds, if possible soluble in the usual solvents of organic synthesis. How to start this project?

A brief look to the standard redox potential values E^0 (versus NHE) of various lanthanide ions [6] showed the following data (Ln^{2+}/Ln^{3+}): Eu: −0.55 V, Yb: −1.22 V, Sm: −1.55 V, Tm: −2.55 V. We screened europium salts which have been described as able to reduce pyridine carboxylic acid into the corresponding aldehyde [7]. We could not extend this chemistry. We decided to check the reducing properties of other divalent salts. Tm(II) was eliminated because of its price, and we concentrated on Yb(II) and Sm(II). We came across the report of Matignon and Cazes who prepared for the first time samarium diiodide in 1906. SmI_2 was obtained by the reduction of SmI_3 by hydrogen at high temperature [8]. The same reaction was later reinvestigated [9]. We set up a smooth

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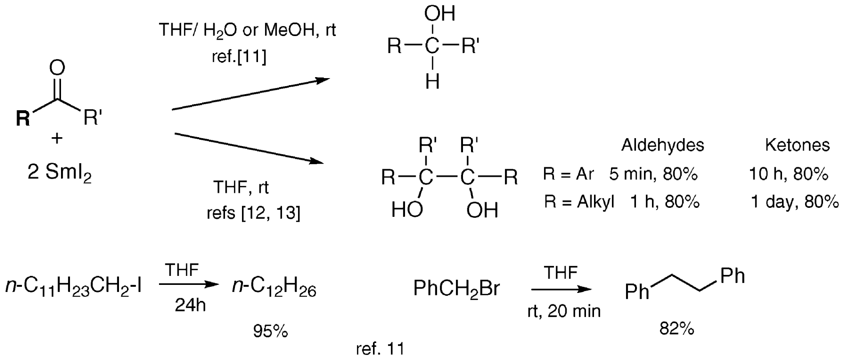


Scheme 1. Some basic reductions induced by samarium diiodide.

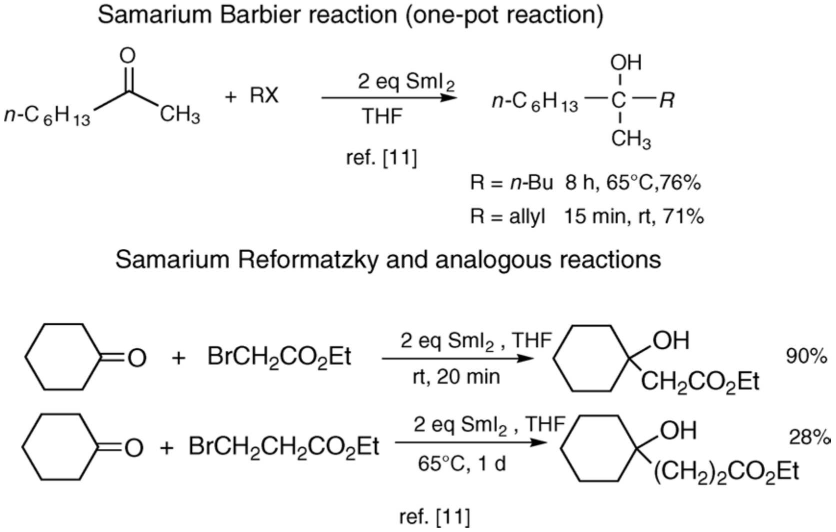
preparation of SmI_2 in THF solution [10,11]. It involves the attack of suspension of samarium metal (powder) by 1,2-diiodoethane (Scheme 1). We identified the composition SmI_2 by various titrations and spectroscopic measurements [12]. The deep blue green THF solution was closed to 0.1 M in SmI_2 and could be stored under inert atmosphere. The passage from Sm^{2+} to Sm^{3+} is easily detected by the change of colour from deep blue green to yellow. A fast screening of the reducing ability of samarium diiodide solutions in THF gave many informations, which are summarized in the next section.

3. Our first results (1977–1983)

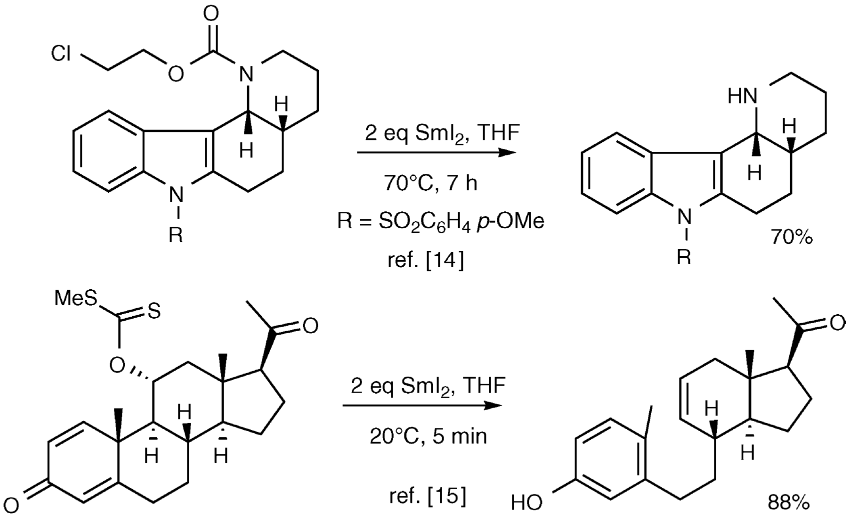
In Scheme 1 are summarized some of the reactions observed with simple organic compounds [11,12]. Aldehydes or ketones were easily transformed into alcohols by SmI_2 when a proton source (alcohol or water) was present in the medium. Competitive reactions showed a much higher reactivity for aldehydes compared to ketones. In aprotic conditions, the pinacol formation occurred, it was especially fast for aromatic aldehydes or ketones.

The activated organic halides (allylic or benzylic) were prone to coupling reactions while aliphatic halides were slowly reduced into the corresponding hydrocarbons. In that case, the THF played the hydrogen donor. The reduction of various acid chlorides unexpectedly led to a coupling into benzoins or ketols [13]. The deoxygenation of some epoxides or sulfoxides was also noticed, but phosphine oxides were not reduced.

Two important classes of C–C bond formation reactions were discovered (Scheme 2): the Barbier-like reaction and the Reformatsky-like reaction, where the usual metal agent (Mg or Zn) is replaced by SmI_2. The Barbier condensation is sluggish with aliphatic halides but could be strongly accelerated by the presence of catalytic amounts of Fe(III) salts. The Reformatsky reaction is very fast and can be runned conveniently. Some mechanistic studies shown indirectly the presence of radical intermediates, for example, in reactions involving organic halides the THF fragment was noticed in the structure of some by-products.



Scheme 2. Some C–C bond formations mediated by samarium diiodide.



Scheme 3. Early examples of cleavage reactions.

4. The developments outside Orsay (1982–1987)

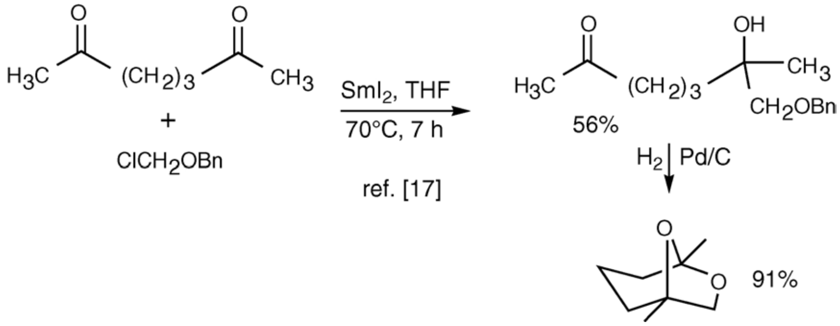
In 1982, it was shown that SmI_2 is a useful selective reagent to induce selective transformations on quite complex molecules (Scheme 3) [14,15]. The cleavage of N–O bond of several isoxazoles was also realized, leading to β-aminoketones [16]. In 1984, Imamoto et al. extended the Barbier reaction by taking $ClCH_2OBn$ as the organic halide (Scheme 4) [17].

In 1986, Molander and Etter published the first papers of an extensive series of investigations on the use of SmI_2 in organic synthesis. They studied the intramolecular version of the samarium Barbier reaction, as examplified in Scheme 5 [18]. These authors also established that a C-heteroatom bond vicinal to a carbonyl group is easily cleaved (Scheme 5) [19]. This is a quite general process, which was used by White et al. in the course of a total synthesis [20].

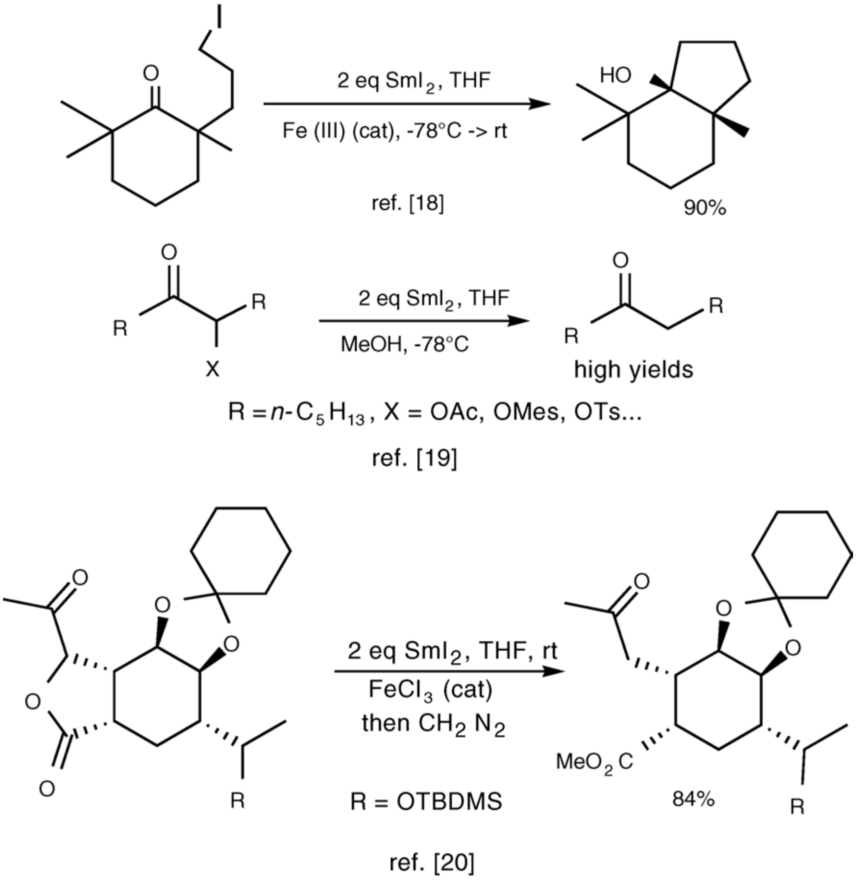
During the years 1986–1987 came some interesting developments in the use of samarium diiodides. It was discovered [21,22] that addition to THF of small amounts of HMPA ($(NMe_2)_3P{=}O$) increased strongly the rate in the lactonization reactions (Scheme 6). This observation was extended by Inanaga et al. to various reactions. For example, alkyl halides are easily reduced [23] as described in Scheme 6. The procedure is now widely used in the literature to accelerate many types of transformations.

These observations stimulated investigations on the mechanistic aspects of the reactions.

Various structural studies on isolated samarium complexes or produced in solution led to some understanding of the coordination chemistry of Sm(II)/HMPA systems. In 1994, Hou et al. described the crystal structure of the isolated complex [SmI_2, 4HMPA] [24]. The discrete molecular entities contain an octahedral Sm with two iodides in axial positions and four equatorial HMPA molecules (O-bonded to Sm). The crystal structure of complex [SmI_2, 5THF] has been studied by Evans [25]. Here, the SmI_2 moiety takes a seven-coordinate pentagonal bipyramidal geometry with iodides in the axial positions. The reducing properties in THF of SmI_2, nHMPA is maximum for $n = 4$ [26]. This has been confirmed by electrochemical measurements (in THF with NBu_4PF_6 as electrolyte) by Flowers and co-workers [27]. The composition of solutions has been investigated by Skrydstrup and co-workers by a combination of spectroscopic and electrochemical methods



Scheme 4. Samarium Barbier reaction with an α-chloroether.



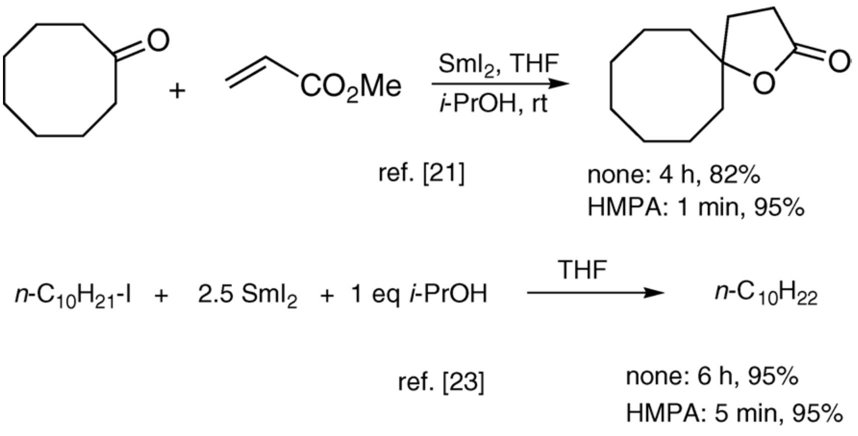
Scheme 5. Various transformations mediated by samarium diiodide.

[28]. They concluded that with four equivalents of HMPA the main species in THF solution is not [SmI_2, 4HMPA] but the ionic cluster $[Sm(HMPA)_4(THF)_2]^{2+}2I^-$ [29]. It is then still difficult to fully understand the mechanistic details of reduction by SmI_2 alone or in presence of various additives. The inner-sphere versus the outer-sphere electron transfer mechanisms is under investigation and discussion (for example, see [29,30]).

5. The developments in the last decade

All the various aspects of the SmI_2 chemistry are impossible to mention here. There are many review articles, which give a general view or are focussed on a specific point [31–43].

Samarium diiodide has been used in the transformations of complex molecules, in some specific families of natural



Scheme 6. Influence of HMPA on the reactivity of samarium diiodide.

products such as carbohydrates and in the total syntheses. For example, several taxoides and taxol syntheses took advantage of SmI_2 chemistry in a cyclization step or in the reductive removal of a functional group [44–46]. Asymmetric synthesis also benefited of samarium diiodide. Tandem reactions with high stereocontrol have been shown to be possible. Catalytic activation of SmI_2 or the catalytic use of SmI_2 thanks to a co-reductant have been studied. In this article, we will just detail these last two points.

6. Catalytic activation of SmI_2

In 1980, we noticed that a standard Barbier reaction between 2-octanone and butyl iodide mediated by Sm_2 needed 1 h reflux in THF or 24 h at room temperature to give 80% yield in the product. We succeeded to get the same yield in only 3 h at room temperature by using a catalytic amount (2%) of a Fe(III) salt [11]. The same reaction runned in THF with 5% HMPA was complete at room temperature in 5 min [23]. It was then interesting to reinvestigate the possibility to optimize the catalytic acceleration of SmI_2 chemistry by transition metal salts. A systematic screening in 1996 established that nickel diiodide is an excellent catalyst for the Barbier reaction [47]. NiI_2 has been widely used to accelerate various types of transformations. For example, the intermolecular nucleophilic acylation of esters by acid chlorides and $SmI_2$was realized [48]. Usually, this is a very slow reaction, which became very easy in the presence of 1% NiI_2. The mechanism of the catalytic effect of NiI_2 remains obscure. Presumably the nickel salt is reduced into a Ni(0) complex which combined to Sm(II) or Sm(III) species.

7. The catalytic use of SmI_2

Samarium diiodide has a large molecular weight (404), in the same range that the organic molecule to transform. The usual stoichiometry needs two equivalents of SmI_2, introducing in weight more of the reagent than the substrate. It is then highly desirable to decrease the amount of the samarium salt by devising a catalytic process. In this process, a co-reducing agent must make the change Sm(III) → Sm(II) and not react with the substrate. Species such as $SmX_3$are easy to reduce at the difference of alkoxides $Sm(OR)_nX_{n-3}$. One solution is to introduce stoichiometric amounts of a silicon reagent, which will provide an exchange reaction such as $Sm(OR)_nX_{n-3} + Me_3SiX \rightarrow Me_3SiOR + SmX_3$. In 1996, Endo and co-workers selected Mg combined to 10 mol% SmI_2 and 1.5 mol eq. of Me_3SiX [49]. This system allowed the pinacol coupling of aromatic ketones in good yield. Corey et al. found that amalgamated zinc is also suitable for the catalytic use of SmI_2 in various transformations, the addition of LiI and Me_3SiOTf enhancing the formation of SmI_3 from the samarium iodoalcoholates intermediates [50].

Helion and Namy proposed in 1999 an alternate solution to the problem of the catalytic use [51]. They selected mischmetall as the co-reducing agent. It is a cheap alloy (≈US$20/kg) of approximate composition La (33%), Ce (50%), Nd (12%), Pr (4%) and other lanthanides (1%). Mischmetall has an average atomic weight of 140. The catalytic samarium Barbier reaction needs the slow addition of a THF solution of SmI_2 containing the organic halide and the ketone to a suspension in THF of mischmetall (1.4 eq.) and 10 mol% SmI_2. The method was applied for the samarium Barbier or samarium Grignard modes [51–53]. It was established that the mischmetall alone is unable to display the above reactions and that there is the in situ formation of a quite stable organosamarium species which can directly react with the substrate or gives a transmetallation with one of the components of the mischmetall.

In principle, an electrochemical regeneration of Ln(II) from Ln(III) should allow to get a catalytic processes, as established by Dunach and co-workers [54].

8. Asymmetric synthesis

Only a limited number of examples are known involving SmI_2 at the key step of an asymmetric synthesis (see, a short review in ref. [42]).

Samarium diiodide is often a useful reagent to release in mild conditions a protecting group after completion of the asymmetric reaction.

9. Natural products, total syntheses

Samarium diiodide has been widely applied to the modification of natural products or in the courses of total syntheses.

Various types of SmI_2 induced cyclizations have been applied in the carbohydrate field. The reductive pinacol coupling of 1,5- and 2,6-diols generates mainly cyclic *cis*-diols [55]. This reaction allowed to make carbocycles from sugars by diol oxidation into dialdehydes followed by a pinacol closure. Reductive eliminations to glycals or C–C couplings between a carbohydrate and a external reactant are some examples of the numerous transformations which have been carried out on carbohydrates (for some references see in ref. [42]).

Many total syntheses of natural products take SmI_2 to induce a transformation at a step of the synthetic scheme. For example, Mukaiyama et al. constructed in 1997 the B ring of taxol by an intramolecular samarium–Reformatsky type [56]. Recently, Nicolaou et al. took advantage of an intramolecular aldehyde–oxime coupling to prepare one of the rings of diazonamide A [57]. Because lack of place, it is impossible to develop more this topic, some additional references can be found in ref. [42].

10. Conclusion

Within a period of 25 years, SmI_2 emerged as a powerful and a major reagent in organic chemistry. The involved reactions are a combination of radical and organosamarium chemistry. An interesting feature is the possibility to perform sequenced reactions, as pioneered by Molander and Etter. A severe limitation for development is the price and the large molecular weight of the reagent. Obviously, catalytic processes are welcomed, especially with low molecular weight and cheap co-reducing agents. Besides organic transformations of middle-size molecules, SmI_2 found some applications in polymer chemistry [58]. A number of analogues of SmI_2 were synthesized and screened for their reducing properties such as $SmBr_2$ [59,60] or $Sm(OTf)_2$ [61–63]. Other divalent lanthanide reagents have been recently prepared and compared to samarium diiodide [64–66]. Promising are the very reactive TmI_2 [64] and DyI_2 [65] derivatives. Another application of SmI_2 is its central position as starting material in the preparation of other divalent samarium derivatives by exchange reactions. The interest generated by SmI_2 is well reflected by an evaluation of the number of papers published by year during the last 25 years. One can anticipate on further exciting developments in the near future.

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