Cite this: Chem. Commun., 2012, 48, 6966-6968

## COMMUNICATION

## Visible-light-mediated addition of $\alpha$ -aminoalkyl radicals generated from $\alpha$ -silylamines to $\alpha$ , $\beta$ -unsaturated carbonyl compounds<sup>†</sup>

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Received 18th April 2012, Accepted 16th May 2012 DOI: 10.1039/c2cc32745g

Visible-light-mediated addition of  $\alpha$ -aminoalkyl radicals generated from  $\alpha$ -silylamines to  $\alpha$ , $\beta$ -unsaturated carbonyl compounds using a photoredox catalyst is developed. We also succeeded in the isolation of a silyl enol ether as a primary product of the photochemical reaction.

Oxidative transformation of amines is one of the most important methods for conventional synthesis of nitrogen-containing compounds, which are useful building blocks in various bioactive compounds and electronic materials.<sup>1</sup>  $\alpha$ -Aminoalkyl radicals formed by single electron oxidation of amines are considered to be reactive intermediates,<sup>2–4</sup> but their synthetic utilization has been quite limited because the rapid oxidation of  $\alpha$ -aminoalkyl radicals to iminium ions is more favorable under thermal conditions.<sup>5</sup>

In sharp contrast, single electron oxidation of amines via photoinduced electron transfer is expected to be a suitable method for generation and synthetic use of  $\alpha$ -aminoalkyl radicals.<sup>2a,6-12</sup> Recently we have reported visible-light-mediated addition of a-aminoalkyl radicals to electron deficient alkenes and have also found that this reaction proceeds via a sequential redox pathway.<sup>6</sup> On the other hand, α-silylamines are known to be oxidized readily rather than conventional amines<sup>13</sup> and are alternative candidates for generating *a*-aminoalkyl radicals along with desilylation.<sup>10,14</sup> Since Mariano's group reported addition of  $\alpha$ -aminoalkyl radicals generated from  $\alpha$ -silylamines to  $\alpha,\beta$ -unsaturated ketones under UV irradiation,<sup>10f,g</sup> the utilization of a-silylamines for addition to alkenes has been extensively studied.<sup>10-12</sup> When 9,10-dicyanoanthracene (DCA) and 1,4-dicyanonaphthalene (DCN), which absorb longer UV to visible-light, were used as photosensitizers, addition reactions to alkenes were found to proceed smoothly, but, applicable substrates were limited to trialkylamines<sup>10a,c,d,11</sup> and dialkylamides<sup>12</sup> in these reaction systems. As an extension of our study on the visible-light-mediated utilization of  $\alpha$ -aminoalkyl radicals, we have now envisaged use of  $\alpha$ -silylamines as precursors for



Scheme 1 Photocatalytic addition of  $\alpha$ -aminoalkyl radicals generated from  $\alpha$ -silylamines to  $\alpha$ , $\beta$ -unsaturated carbonyl compounds.

 $\alpha$ -aminoalkyl radicals using a transition metal polypyridyl complex as a photoredox catalyst.<sup>15</sup> In fact, we have found the visible-light-mediated addition of  $\alpha$ -aminoalkyl radicals generated from  $\alpha$ -silylamines to  $\alpha$ , $\beta$ -unsaturated carbonyl compounds and have also succeeded in the isolation of a silyl enol ether as a primary product of the photochemical reaction (Scheme 1). Preliminary results are described here.

At first, we carried out the reaction of diphenyl(trimethylsilylmethyl)amine (1a) with 1.5 equiv. of 2-cyclohexenone (2a) (Scheme 2). When a solution of 1a with 2a in the presence of 1 mol% of the iridium complex [4a][BF<sub>4</sub>] in dichloromethane was illuminated with a 14 W white LED at 25 °C for 18 h, 3-(diphenylaminomethyl)cyclohexanone (3a) was obtained in 90% isolated yield after aqueous work up. Use of similar Ir complex [4b][BF<sub>4</sub>] and [Ru(bpy)<sub>3</sub>][BF<sub>4</sub>]<sub>2</sub> as photocatalysts decreased the yield of 3a. Interestingly, when DCA was used in place of [4a][BF<sub>4</sub>], no formation of 3a was observed.



Scheme 2 Photocatalytic reaction of diphenyl(trimethylsilylmethyl)amine (1a) with 2-cyclohexenone (2a).

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<sup>†</sup> Electronic supplementary information (ESI) available. CCDC 877717. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2cc32745g

It is noteworthy that the alkylated product having a trimethylsilyl group (5) was not observed at all, while the cleavage of a C–H bond at the  $\alpha$ -position in the amines often takes place to give the alkylated products such as 5 in the previously reported system.<sup>10/,g</sup> When methyldiphenylamine was used in place of **1a**, no reaction occurred at all (eqn (1)). These results indicate that C–Si bonds in the amines can be functionalized selectively in this reaction system. Separately, we confirmed that no formation of **3a** was observed in the absence of a photocatalyst or visible light.



Reactions of **1a** with a variety of  $\alpha,\beta$ -unsaturated carbonyl compounds were investigated by using [**4a**][BF<sub>4</sub>] as a photocatalyst. Typical results are shown in Scheme 3. The reactions with 2-cyclopentenone and 2-methyl-2-cyclopentenone in place of **2a** proceeded smoothly to give the corresponding products (**3b** and **3c**) in 79 and 63% yield, respectively. Acyclic ketones were also applicable to this reaction system, giving the corresponding products (**3d-3f**) in good to high yields. Interestingly, the reaction of methyl vinyl ketone also took place to give **3g** in 56% yield. Use of *N*-methyl-*N*-phenylbut-2-enamide as an alkene gave a trace amount of the product, while the reaction of the  $\alpha,\beta$ -unsaturated amide bearing oxazolidinone groups proceeded smoothly to give the corresponding product (**3h**) in a high yield.

Next, we examined the photocatalytic reactions of various  $\alpha$ -silylamines. Typical results are shown in Scheme 4. Introduction of a substituent such as methyl, fluoro or phenyl group at the *para*-position in the benzene ring of **1a** did not affect the yield of **3i–k** much. Dialkyl and trialkyl amines such as *N*-methyl-*N*-trimethylsilylmethylaniline and *N*-trimethylsilylmethylmorpholine were also applicable to this reaction system and the corresponding products **3I** and **3m** were obtained in good yields without the formation of di- and tri-alkylated amines. The reaction of *N*-ethyl-2-trimethylsilylpyrrolidine also proceeded smoothly to give only the corresponding monoalkylated amine **3n** in 48% yield. These results indicate that introduction of a



**Scheme 3** Photocatalytic reactions of diphenyl(trimethylsilylmethyl)amine (1a) with  $\alpha$ , $\beta$ -unsaturated carbonyl compounds (2).



Scheme 4 Photocatalytic reactions of  $\alpha$ -silylamines (1) with 2-cyclohexenone (2a).

silyl group at the  $\alpha$ -position of amines is an effective strategy for generation of  $\alpha$ -aminoalkyl radicals at the desired position of amines to give monoalkylated amines selectively in sharp contrast to the results in the case of direct C–H functionalization of amines, where unselective formation of di- and tri-alkylated amines is usually observed.<sup>3,4,6–9</sup>

To obtain information on the reaction pathway, the isolation of a silyl enol ether was investigated. Treatment of 1a with 1.5 equiv. of 2e under similar reaction conditions afforded the corresponding silvl enol ether (6) in 94% yield without aqueous work up (eqn (2)). This result clearly shows that the silvl enol ether is the primary product in our visible-light-mediated reaction and the corresponding carbonyl compounds 3 should form after hydrolysis. In sharp contrast, Mariano's group reported similar reactions of  $\alpha$ -silvlamines with the  $\alpha$ ,  $\beta$ -unsaturated ketones, where silyl enol ethers were not observed at all.<sup>10f,g</sup> This is due to the contribution of the alcohol solvent assisted desilylation and protonation mechanism, and also use of alcohol solvents is important for providing the corresponding addition products in their reaction systems.<sup>10,13</sup> Additionally, the quantum yield in the reaction of 1a with 2e was estimated to be 0.68, which is less than 1 and is in the common range of molecular transformations via photoinduced electron transfer mediated by transition metal polypyridyl complexes.<sup>16</sup> This result also suggests that the contribution of a photoindependent process such as a radical chain process is negligible in this system.<sup>6</sup>

Considering the experimental results, a plausible reaction pathway is shown in Scheme 5. This functionalization of C–Si bonds in the amines is considered to proceed *via* a sequential redox pathway similar to that of visible-light-mediated C–H alkylation of the amines previously reported by our group.<sup>6</sup> The initial step is the formation of the  $\alpha$ -aminoalkyl radical **A** from a single electron oxidation of **1** by the excited photocatalyst (**\*cat**) and subsequent desilylation. Addition of **A** to **2** results in the formation of the alkyl radical species **B**. The reduction of **B** by the



Scheme 5 Plausible reaction pathway.

one electron reduced form of the photocatalyst (**cat**<sup>-</sup>) affords the corresponding enolate and subsequent silylation occurs to give the silyl enol ether **C** accompanied by regeneration of the photocatalyst (**cat**). The reduction process of **B** is quite feasible according to the reported redox potentials.<sup>17,18</sup> The sequential reduction and silylation step from **B** to **C** is in sharp contrast to the previously reported reaction pathway.<sup>10–13</sup> Finally, the corresponding product (**3**) is obtained after hydrolysis of **C**.

Silyl enol ethers are known to be versatile building blocks in organic synthesis and can be transformed into useful organic compounds.<sup>19,20</sup> We investigated a synthetic application of the produced silyl enol ether **6**. Oxidative transformation of **6** with a stoichiometric amount of palladium acetate successfully proceeded to give the corresponding  $\alpha$ , $\beta$ -unsaturated ketone **7** in 56% yield (eqn (3)).<sup>20</sup>

(3)

In summary, we have developed visible-light-mediated functionalization of C–Si bonds in the  $\alpha$ -silylamines *via*  $\alpha$ -aminoalkyl radicals. The use of visible-light instead of UV-light is also supposed to realize the addition of  $\alpha$ -aminoalkyl radicals generated from  $\alpha$ -silyldiarylamines to alkenes efficiently. The reaction has been found to proceed in an atom economical manner to afford silyl enol ethers in sharp contrast to previously reported UV-light-mediated reactions.<sup>10/,g</sup> We believe that this method described here is an alternative approach to C–H functionalization of amines at the  $\alpha$ -position and provides a useful strategy for the synthesis of nitrogen-containing compounds because  $\alpha$ -silylamines are readily accessible.<sup>21</sup> Further work is now in progress to functionalize C–Si bonds of the  $\alpha$ -silylamines *via* photoinduced electron transfer.

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