## Tris(trimethylsilyl)silane-mediated Reductive Decyanation and Cyano Transfer Reactions of Malononitriles

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Reductive decyanation reactions of malononitriles were achieved with tris(trimethylsilyl)silane as a radical mediator. The reaction proceeds via a radical chain mechanism involving a silyl radical addition to the malononitrile to form an imidoyl radical followed by  $\alpha$ -cleavage to give a silyl isocyanide and an  $\alpha$ -cyano radical. The reaction of a 3-butenyl-substituted malononitrile afforded a decyano/cyanosilylation product in good yield through 1,4-cyano transfer.

## Keywords: Radical | Malononitriles | Decyanation

Nitriles can be found in a wide variety of pharmaceuticals, agrochemicals, and optoelectronic materials.<sup>1</sup> They also serve as versatile synthetic intermediates for carboxylic acids, esters, amides, and amines.<sup>2</sup> Accordingly, the development of novel and efficient synthetic methods for nitriles has been a major topic in synthetic organic chemistry.

Malononitrile is the simplest geminal dinitrile. It has a highly acidic proton, thus it is easy to functionalize.<sup>3</sup> Once the dinitrile has served its purpose in the course of a synthesis, it often becomes necessary to replace one of the cyano groups with a hydrogen atom.<sup>4</sup> However, thus far, decyanation reactions of malononitriles are rarely reported.5-7 Tributyltin hydridemediated reductive decyanation of malononitriles were reported in 1991 (Scheme 1, eq 1),<sup>8</sup> but the use of tin hydride is declining due to tin toxicity. Recently, we reported reductive decyanation of malononitriles with N-heterocyclic carbene boranes (e.g. 1,3dimethylimidazol-2-ylidene borane (diMe-Imd-BH<sub>3</sub>)) (eq 2).<sup>9</sup> Other groups reported reductive decyanation of malononitriles via one electron reduction. 5c-5e Here we report radical decyanations of malononitriles with tris(trimethylsilyl)silane (TTMSS).<sup>10</sup> Related decyano/cyanosilylation and decyano/allylation reactions are also presented.

Initially, the reductive decyanation reaction was examined with 2-(4-methoxybenzyl)malononitrile (1a) as a model substrate in the presence of tris(trimethylsilyl)silane (TTMSS, 2 equiv) as reductant and azobisisobutyronitrile (AIBN,



Scheme 1. Radical reductive decyanation of malononitriles.

by flash chromatography, the target decyanation product 2a was obtained in 88% yield.<sup>11</sup>
 Table 1 shows the results of other malononitriles that were reductively decyanated by the same procedure. Substrates

Table 1. TTMSS-mediated reductive decyanation reactions

20 mol%) as initiator (Table 1, Entry 1). The reaction was

conducted in benzene with heating at 80 °C. After purification



<sup>a</sup>Isolated yield after silica gel column chromatography. <sup>b</sup>*t*-BuOO*t*-Bu (1 equiv) was used instead of AIBN and the reaction performed at 120 °C for 4 h. <sup>c</sup>AIBN (40 mol%) was used.

(a) radical probe experiments





Scheme 2. Reactions of 2-phenylcyclopropane-1,1-dicarbonitrile.

having chlorine (**1b** and **1c**) or cyanide (**1d**) substituents on the benzene ring afforded the corresponding decyanation products **2b–2d** in 69–90% yields (Entries 2–4). The reaction of 2phenethylmalononitrile (**1e**) also worked well (Entry 5). The reaction of bis-substituted malononitrile **1f** and **1g** gave decyanation product **2f** and **2g** in 67% and 79% yield with slightly harsh conditions, respectively (Entries 6 and 7). Substrates **1h–1j**, which are easily prepared by Michael reactions of **1a**,<sup>12</sup> gave the corresponding decyanation products **2h–2j** in 65–74% yields (Entries 8–10).

Radical probe experiments were then carried out to offer insights into the reaction mechanism. In the prior tin hydride decyanations, we speculated that the tin radical probably adds to the nitrile nitrogen to give an imidoyl radical, followed by  $\alpha$ -fragmentation.<sup>8</sup> To support this speculation, we conducted reactions of 2-phenylcyclopropane-1,1-dicarbonitrile (**1k**) with TTMSS or Bu<sub>3</sub>SnH, respectively. The reaction with TTMSS under those standard conditions for 16h afforded the ringopening product **1e** in 51% yield (Scheme 2). In the absence of AIBN, starting material **1k** was recovered. The corresponding reaction with Bu<sub>3</sub>SnH also gave dinitrile **1e** in 42% yield along with mononitrile **2e** in 39% yield. Mononitrile **2e** is a secondary product that forms by reductive decyanation of **1e**.

Next we conducted the reaction of 1k with diMe-Imd-BH<sub>3</sub> and this gave decyanation product 2k.

These results show that silyl- and tin-mediated decyanation reactions proceed via an imidoyl radical intermediate such as **A** (Y = Si(SiMe<sub>3</sub>)<sub>3</sub> or SnBu<sub>3</sub>), which usually undergoes an  $\alpha$ -fragmentation to give an  $\alpha$ -cyano radical and isocyanide (:CNSi(SiMe<sub>3</sub>)<sub>3</sub> or :CNSnBu<sub>3</sub>). However, with the radical probe **1k**, scission of the cyclopropane ring to give **B** is more rapid. This leads to product **1e** (and eventually **2e**) by H-transfer reaction and protodesilylation or protodestannylation of the resulting ketene imine. The generating Y• (Y = Si(SiMe<sub>3</sub>)<sub>3</sub> or SnBu<sub>3</sub>) adds to nitrile, thus maintaining the radical chain. In



Scheme 3. Reaction of 3-butenyl substituted malononitrile 11.

a) formation of iminyl radical F



b) fragmentation and hydrogen transfer



Scheme 4. Plausible mechanisms for formation of 31:  $R = CH_2C_6H_4$ -4-OMe,  $Y = Si(SiMe_3)_3$  or SnBu<sub>3</sub>.

contrast, the NHC-borane radical-mediated decyanation reaction proceeds via an iminyl radical intermediate **C** (Y = diMe-Imd-BH<sub>2</sub>). This undergoes a  $\beta$ -fragmentation to form NHC-BH<sub>2</sub>CN and **D**, which in turn abstracts a hydrogen atom from the borane to give **2k**.

Having learned that imidoyl radicals are intermediates in both silyl- and tin-mediated transformations, we wondered whether such intermediates could be trapped by other radical reactions besides cyclopropane cleavage. To address this question, we examined the behavior of 3-butenyl substituted malononitrile **11**, which has an alkene poised to undergo 5-*exo* cyclization with an imidoyl radical (Scheme 3). However, the reaction of **11** with (Me<sub>3</sub>Si)<sub>3</sub>SiH did not give a cyclized product but instead gave decyano/cyanosilylation product **31** in 70% yield. A reaction with Bu<sub>3</sub>SnH gave the corresponding stannylated product **31'** in 66% yield.<sup>13</sup>

Scheme 4 shows possible mechanisms for the cyanosilylation or cyanostannylation reactions of **1**. A key intermediate is iminyl radical **F**, which can form by two routes (Scheme 4a). In the first route, a silyl ( $Y = Si(SiMe_3)_3$ ) or stannyl ( $Y = SnBu_3$ ) radical adds to the terminal alkene of **1** to give **E**, followed by *5-exo* cyclization to give iminyl radical **F**.<sup>14</sup>  $\beta$ -Cleavage of **F** to give  $\alpha$ -cyano radical **I** is followed by hydrogen atom transfer to afford **31** (Scheme 4b). In a second route to **F** (Scheme 4a), the silyl or stannyl radical adds to a nitrile to give an imidoyl radical **G**, which undergoes *5-exo* cyclization to afford **H**. Then **H** undergoes intramolecular homolytic substitution (S<sub>H</sub>i)<sup>15</sup> to give the iminyl radical **F**.

Differentiating the two possible paths to  $\mathbf{F}$  is difficult because additions to both the alkene<sup>9</sup> and the nitrile may be



Scheme 5. Decyano/allylation reaction.

reversible and because the rates of addition (and fragmentation) may be different for tris(trimethylsilyl) and tributylstannyl radicals. However, while intramolecular  $S_{\rm Hi}$  reactions are well known for both silicon and tin,<sup>15</sup> most migration examples involve 1,5- or 1,6-group transfer. The conversion of **H** to **F** is a 1,4-migration, and  $S_{\rm Hi}$  reactions in such settings usually occur not by migration but by displacement of one of the other groups on silicon or tin (SiMe<sub>3</sub> or Bu) to give a silacycle or a stannacycle. Such products are not observed, so the alkene addition pathway probably predominates.

To close the study, we examined a decyano/allylation reaction leading to an  $\alpha$ -allylated quaternary nitrile (Scheme 5). When a mixture of disubstituted malononitrile **1m** and di*tert*-butyl peroxide (*t*-BuOO*t*-Bu) was heated at 140 °C in the presence of allyl tris(trimethylsilyl)silane,<sup>16</sup> the allylated product **4m** was obtained in 21% yield, along with decyanation product **2m** in 34% yield. When allylstannane was used, the yield of **4m** improved to 51%.

In conclusion, we have developed reductive decyanation reactions of malononitriles with tris(trimethylsilyl)silane. A 3butenyl substituted malononitrile gave silylcyano/decyanation product and a reaction with allyl tris(trimethylsilyl)silane gave an allylated product. Mechanistic experiments revealed that both the new silane reaction and the known tin reaction proceed via imidoyl radical intermediates.

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