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Transformation of RN=CHPh to $R(R'_3Si)NCH_2Ph$ in the Catalytic Desulfurization of Secondary Thioamide with R'_3SiH Promoted by an Iron Complex

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ABSTRACT: *The reaction of imine (RN=CHPh) with hydrosilane (R'_3SiH) in the presence of $CpFe(CO)_2Me$ (**1**) revealed the formation of a hydrosilylation product ($R(R'_3Si)NCH_2Ph$). The findings helped us to understand the reaction mechanism of desulfurization of secondary thioamide catalyzed by* **1** *to give the corresponding imine and amine as a major and minor product, respectively.* © 2014 Wiley Periodicals, Inc. Heteroatom Chem. 25:607–611, 2014; View this article online at wileyonlinelibrary.com. DOI 10.1002/hc.21175

INTRODUCTION

Creation of an effective desulfurization system catalyzed by a transition metal complex is one of the important subjects because sulfur compounds generally serve as catalyst poisons toward transition metal catalysts. Recently, a few desulfurization reactions of thioformamide and thioamide using a transition metal complex have been reported. Sharma and Pannell showed desulfurization of thioformamide ($Me_2NC(S)H$) by hydrosilane (R_3SiH) in the presence of $Mo(CO)_6$ [1], and we reported the desulfurization of thioformamide and thioamide in the presence of $CpFe(CO)_2Me$ (**1**) ($Cp = \eta^5$-C_5H_5) [2] to give amine. In the latter case, the carbene complex of iron with a silylthiolato ligand $CpFe(CO)(SSiR_3)(=CH(NMe_2))$ was isolated as an intermediate in the catalytic cycle. Moreover, we found that secondary thioamides $R^1HNC(S)R^2$ reacted with Et_3SiH in the presence of a catalytic amount of **1** to give imine $R^1N=CHR^2$ as a major product and amine $HR^1NCH_2R^2$ as a minor product [3]. We have proposed the reaction mechanisms for the desulfurization of thioamide (Scheme 1). The thiocarbonyl group coordinates to the $CpFe(CO)(SiEt_3)$ species (**A**) in an η^2-fashion to give **B**. Then, the silyl group migrates from the Fe to the sulfur atom to form **C**, followed by the S—C bond oxidative addition to give the iron–carbene complex **D**. The C=S strong bond cleavage of thioamide is initiated by the silyl migration from Fe to the sulfur atom in thioamide in the coordination sphere. This

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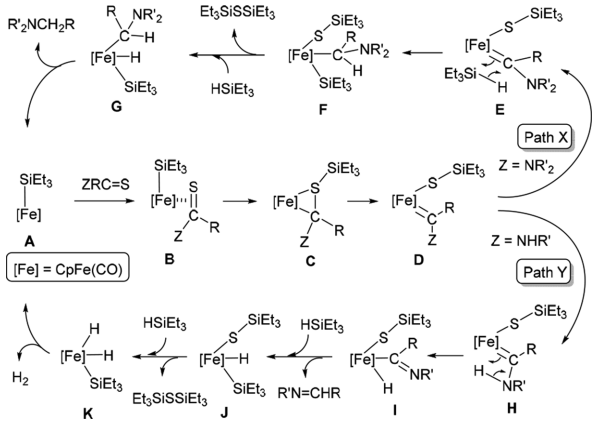


SCHEME 1 Reaction sequences from thioamide to amine and imine.

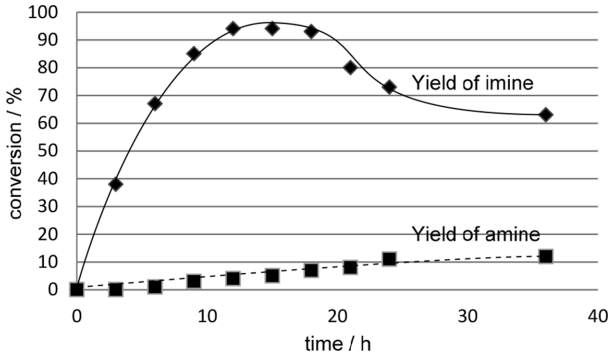


FIGURE 1 Plot of the amounts of PhN=CHPh and $PhHNCH_2Ph$ as a function of time.

type of reaction, that is a *si*lyl-*m*igration–*i*nduced reaction (SiMI reaction), has been applied to achieve the other strong bond cleavage [4]. Next step depends on whether Z is a tertiary amino group (–NR′$_2$) or a secondary amino group (–NHR′). In the former case, an intermolecular addition of the Et_3Si-H bond to the Fe=C bond (**E**) takes place to give **F** (Path X), followed by reductive elimination of $Et_3SiSSiEt_3$, oxidative addition of Et_3Si-H forming **G**, and reductive elimination of amine (R'_2NCH_2R) to regenerate **A**. In the latter case, an intramolecular addition of the H—N bond of the NHR′ group to the Fe=C portion (**H**) occurs to give **I** (Path Y), followed by reductive elimination of imine (R′N=CHR), oxidative addition of Et_3Si-H forming **J**, reductive elimination of $Et_3SiSSiEt_3$, oxidative addition of Et_3Si-H forming **K**, and reductive elimination of H_2 to regenerate **A**. According to the reaction mechanism, it appears that tertiary thioamide gives amine through Path X and secondary thioamide is converted into imine through Path Y. However, our previous results showed that amine in addition to imine was formed in the reaction of secondary thioamide [3]. How is the amine formed? One possible explanation is that parallel reactions (Paths X and Y) proceed to form amine and imine, respectively. Another possibility is that the Path Y is predominant to produce R′N=CHR exclusively and the imine is converted into $R'HNCH_2R$ in this catalytic system. This paper reports the formation mechanism of amine in the desulfurization reaction of secondary thioamide with hydrosilane catalyzed by **1**.

RESULTS AND DISCUSSION

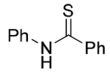
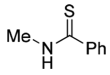
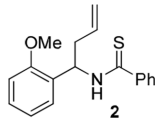
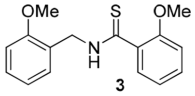
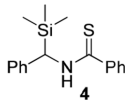
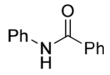
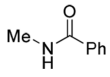
Tetrahydrofuran (THF, 0.43 mL), **1** (0.053 mmol), *N*-phenylbenzothioamide (PhHNC(S)Ph, 0.53 mmol), and triethylsilane (Et_3SiH, 1.6 mmol) were charged in a Schlenk tube, and the solution was heated at 80°C for 24 h (Table 1, entry 1). The ^{1}H NMR spectra and GC-MS analysis of the products demonstrated the formation of *N*-benzylaniline ($PhHNCH_2Ph$, 11% yield based on PhHNC(S)Ph) as a minor product and *N*-benzylideneaniline (PhN=CHPh, 73% yield) as a major product. Similar results were obtained for MeHNC(S)Ph, although conversion yields were low (entry 2). In entries 3–5, no amine and a trace amount of imine were formed, indicating that a bulkier substituent than a phenyl one on the N atom of secondary thioamides reduced the conversion into desulfurization products (amine and imine) presumably due to steric difficulty of the formation of **B** in Scheme 1. Deoxygenation of secondary amide did not occur at all (entries 6–7).

We focused on the reaction shown in entry 1 in Table 1, and followed the reaction with time. A plot of the amounts of PhN=CHPh and that of $PhHNCH_2Ph$ as a function of time is shown in Fig. 1. The imine increased with time and the yield reached 94% at 15 h after the reaction started, and then decreased gradually. In contrast, the amine increased constantly. The results suggest that the imine is converted into the amine in this reaction system.

To confirm the conversion of imine into amine in our reaction conditions, a C_6D_6 solution containing **1**, MeN=CHPh, and Et_3SiH in 1:1:10 molar ratio in a sealed NMR tube was heated for 24 h. The ^{1}H NMR spectrum of the reaction mixture showed the formation of $Me(Et_3Si)NCH_2Ph$ quantitatively (Eq. (1)). When the reaction mixture was exposed to air, $Me(Et_3Si)NCH_2Ph$ disappeared and $MeHNCH_2Ph$ appeared instead. PhN=CHPh showed similar results: it was also converted into $Ph(Et_3Si)NCH_2Ph$ in 77% yield, which was converted into $PhHNCH_2Ph$ upon exposure to air. The results support that desulfurization of secondary thioamide generates imine, which is converted into *N*-silylated amine in the

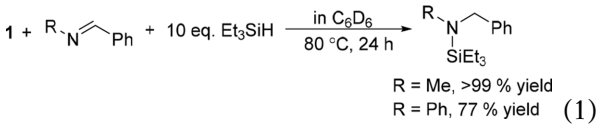
TABLE 1 Desulfurization of Secondary Thioamides with an Iron Catalyst

thioamide + 30 eq. Et_3SiH $\xrightarrow[80\ °C,\ 24\ h]{10\ mol\%\ \mathbf{1}}$ amine + imine

Entry	*Amide*	*Conversion Yield*	*Yield of Amine*	*Yield of Imine*
1[a]		84	11	73
2[a]		26	Trace	24
3	 **2**	Trace	0	Trace
4	 **3**	Trace	0	Trace
5	 **4**	Trace	0	Trace
6		0	0	0
7		0	0	0

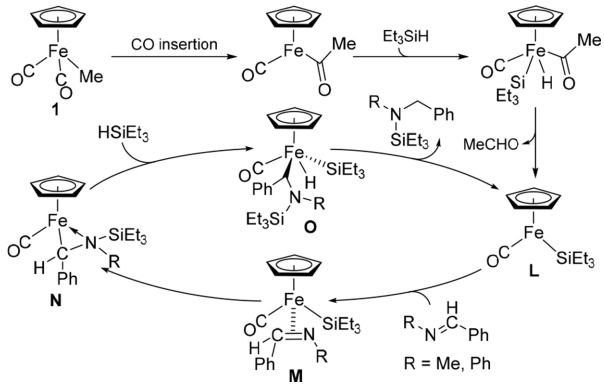
[a]See [3].

reaction with Et_3SiH and then into amine in the reaction with water involved in the reaction system. Several examples concerning hydrosilylation of imines were reported: nickel [5], titanium [6], boron [7], ruthenium [8], iron [9], zinc [10], copper [11], ytterbium [12], iridium [13], rhodium [14], and organo compounds [15, 16].



(1)

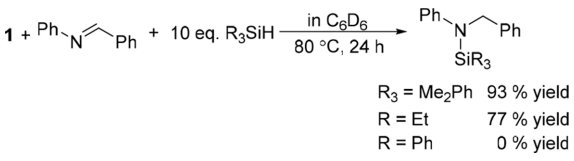
Scheme 2 shows a proposed catalytic cycle for the reaction of imine with Et_3SiH promoted by **1** to form *N*-silyl amine. The 16e species, $CpFe(CO)(C(O)CH_3)$, is formed by CO insertion under heating, followed by the oxidative addition of Et_3Si-H and the reductive elimination of MeCHO to form **L**. Then, RN=CHPh interacts with **L** in the η^2-CN coordination fashion to give **M**. The silyl group migrates from Fe to the N atom to produce the Fe–C–N three-membered ring (**N**). The dissociation of the N coordination and the oxidative addition of Et_3Si-H result in the formation of **O**. Then, the reductive elimination of *N*-silylated amine takes place to regenerate **L**.



SCHEME 2 Proposed catalytic cycle.

Finally, the reactions of PhN=CHPh with Me_2PhSiH and Ph_3SiH in place of Et_3SiH in the presence of **1** were conducted to check the effect of hydrosilane on the hydrosilylation of the imine

(Eq. (2)). The reaction depended on the kind of hydrosilane: Me_2PhSiH resulted in the formation of the corresponding *N*-silylated amine in 93%, whereas Ph_3SiH did not produce $Ph(Ph_3Si)NCH_2Ph$ at all. Our previous paper [3] reported that the reactions of secondary thioamide with Me_2PhSiH and Ph_3SiH produced exclusively the corresponding amine and imine, respectively. The results can be understood reasonably. In the reaction with Me_2PhSiH, the corresponding imine is generated first and then the imine is converted into the *N*-silylated amine rapidly. In contrast, in the reaction with Ph_3SiH, the hydrosilylation of the imine does not proceed. Therefore, the imine is exclusively detected.



(2)

CONCLUSIONS

Secondary thioamide was recently reported to be reduced to the corresponding imine and amine in the reaction with hydrosilane in the presence of a catalytic amount of **1**. However, the formation mechanism of imine and amine remained unclear. This paper brought the mechanism of imine and amine formation to light: Secondary thioamide is converted into the corresponding imine first, and the imine reacts with hydrosilane with the help of an iron catalyst to form the *N*-silylated amine, and finally the *N*-silylated amine is converted into the corresponding amine in the reaction of water existing in the reaction system.

EXPERIMENTAL

General Remarks

All reactions were carried out under an atmosphere of dry nitrogen by using Schlenk tube techniques. THF was distilled from sodium metal. This was stored under a nitrogen atmosphere. Most chemicals were commercially available except thioamides **2**, **3**, and **4**. Thioamides **2** and **4** were synthesized according to the literature methods [17]. IR spectra were recorded on a Perkin-Elmer Spectrum One spectrometer. ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-AL400 spectrometer. All NMR data were referenced to Me_4Si.

Thermal Reaction of Thioamide with Triethylsilane and the Methyl Iron Complex in THF

In catalytic reactions, a solution of **1** (10 mg, 0.053 mmol), Et_3SiH (0.26 mL, 1.6 mmol), and $R^1NHC(S)R^2$ (0.53 mmol) in THF (0.43 mL) was heated at 80°C under a nitrogen atmosphere. Yields of amine and imine of a solution were determined by GC analysis. The reactions of PhNHC(O)Ph and MeNHC(O)Ph were also examined under same conditions.

Hydrosilylation of Imine with Hydrosilane Catalyzed by the Methyl Iron Complex

In catalytic reactions, a solution of **1** (10 mg, 0.053 mmol), R_3SiH (0.53 mmol), and $R^1N{=}CR^2$ (0.053 mmol) in C_6D_6 (0.6 mL) was heated at 80°C for 24 h under a nitrogen atmosphere. Yields of *N*-silylated amine of a solution were determined by ^1H NMR.

Synthesis of 2-Methoxy-N-(2-methoxyphenyl) methlbenzothioamide (**3**)

In a 20-mL two-necked flask, Lawesson's reagent (0.809 g, 2.0 mmol) was added to a toluene solution (6 mL) of 2-methoxy-*N*-(2-methoxyphenyl)methylbenzamide (1.08 g, 4 mmol) at room temperature, and the mixture was stirred at 110–120°C for 1 h. The reaction mixture was concentrated in vacuo. The residue was purified by column chromatography on a silica gel using hexane/EtOAc as eluent to give 2-methoxy-*N*-(2-methoxyphenyl)methylbenzothioamide (1.09 g, 95%) as a yellow solid: mp 86–87°C; IR (KBr) 3320, 3029, 2939, 2837, 1733, 1599, 1531, 1481, 1242, 1021, 941, 757 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.83 (s, 3H), 3.80 (s, 3H), 5.08 (d, J = 5.4 Hz, 2H); 6.8–7.1 (m, 5H), 7.28–7.71 (m, 3H), 9.57(brs, 1H); ^{13}C NMR ($CDCl_3$) δ MS(EI) *m/z* 287 (M^+); HRMS calcd for $C_{16}H_{17}NO_2S$: 287.098, found: 287.096.

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