



## Catalytic versus stoichiometric coupling of alkynes with trimethylvinylsilane mediated by zirconocene

Mohamad Soueidan<sup>a</sup>, Florence Héliion<sup>a,\*</sup>, Jean-Louis Namy<sup>a</sup>, Jan Szymoniak<sup>b</sup>

<sup>a</sup> Equipe de Catalyse Moléculaire, CNRS (UMR 8182), ICMO, Bât 420, Université Paris-Sud, 91405 Orsay, France

<sup>b</sup> Institut de Chimie Moléculaire de Reims, CNRS (UMR 6229), Université de Reims, 51687 Reims Cedex 2, France

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### ABSTRACT

Trimethylvinylsilane and disubstituted alkynes underwent coupling reactions in the presence of the lanthanide-originated zirconocene equivalent. Both reactions, stoichiometric and catalytic in zirconium, could be carried out; in the latter case the addition of a stoichiometric amount of AlCl<sub>3</sub> was needed. The catalytic cycle involving bimetallic polarization and a transmetallation step has been proposed.

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Applications of zirconium in organic synthesis since the 1980s<sup>1</sup> have been widely supported by the introduction of a new method for generating a practical zirconocene (Cp<sub>2</sub>Zr) equivalent.<sup>2,3</sup> According to the described procedure, (1-butene)ZrCp<sub>2</sub>, the also called Negishi reagent is formed by treating Cp<sub>2</sub>ZrCl<sub>2</sub> with 2 equiv of *n*-BuLi at –78 °C, followed by warming up to room temperature. By applying this method, Takahashi et al. have described regioselective cross-coupling reactions of alkynes with vinylsilane.<sup>4</sup> By-products arising from alkyne dimerization have also been observed. To the best of our knowledge, cross-coupling reactions between alkynes and trimethylvinylsilane in the presence of a catalytic amount of a zirconium complex have never been reported.

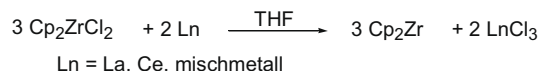
Recently we presented a room-temperature-based protocol for generating of an alkene-free zirconocene equivalent by reducing Cp<sub>2</sub>ZrCl<sub>2</sub> with lanthanum, cerium or mischmetall<sup>5</sup> (Scheme 1).<sup>6</sup>

Dimerization or cyclotrimerization of alkynes catalytic in zirconocene has next been developed, by using this new protocol and AlCl<sub>3</sub> as additive (Scheme 2).<sup>7</sup>

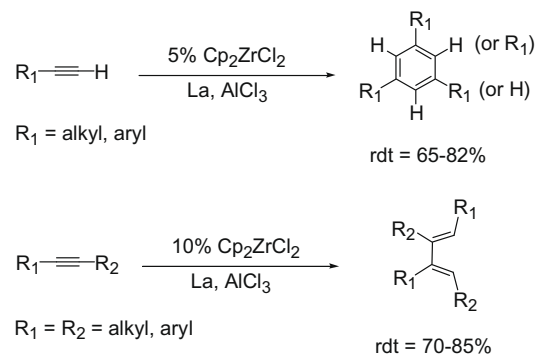
In the pursuit of this work, we have studied herein the coupling of alkynes with vinylsilanes and demonstrated that such reactions can also be performed with a catalytic amount of lanthanide-originated zirconocene equivalent.

Using stoichiometric amounts of Cp<sub>2</sub>ZrCl<sub>2</sub> and La, the coupling of alkynes and vinylsilane could be achieved. The optimized procedure is as follows: a mixture of Cp<sub>2</sub>ZrCl<sub>2</sub> (1 mmol) and the pow-

dered La (0.66 mmol) was stirred at room temperature in 3 mL of THF until a deep red colour appeared. A solution of trimethylvinylsilane (4 mmol) in 2 mL of THF was then added. After 10 min, alkyne (1 mmol) was added at room temperature. The reaction was then carried out at room temperature for an additional 12 h. Finally, hydrolytic workup (HCl 1 M), followed by extraction with



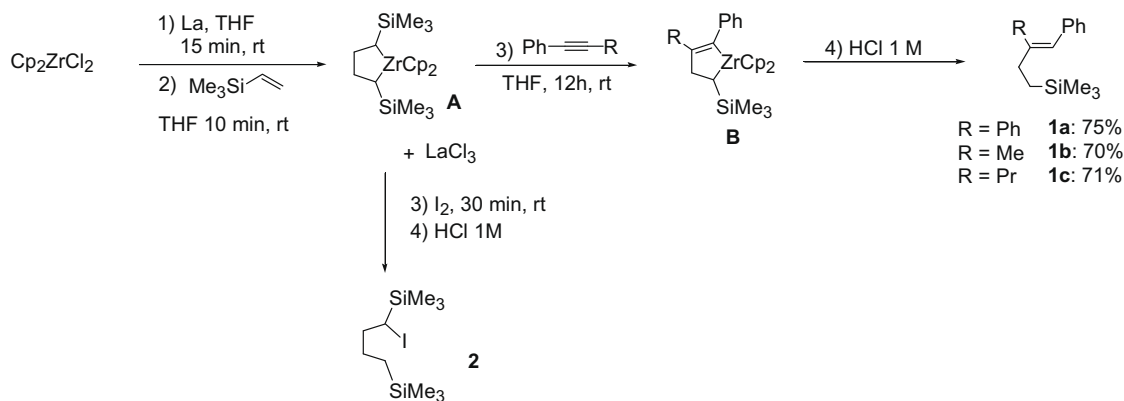
**Scheme 1.** Reduction of Cp<sub>2</sub>ZrCl<sub>2</sub> with lanthanides.



**Scheme 2.** Catalytic dimerization and cyclotrimerization of alkynes.

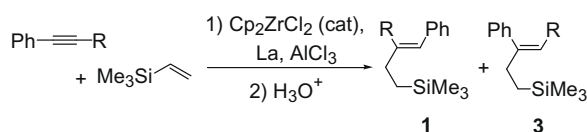
\* Corresponding author.

E-mail address: [flohelion@icmo.u-psud.fr](mailto:flohelion@icmo.u-psud.fr) (F. Héliion).



**Scheme 3.** Stoichiometric coupling of alkynes with trimethylvinylsilane.

**Table 1**  
Catalytic coupling of alkynes with trimethylvinylsilane

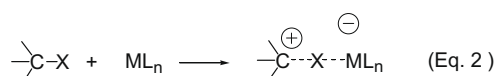
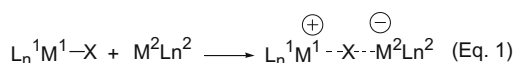


Entry <sup>a</sup>	R	Cp <sub>2</sub> ZrCl <sub>2</sub> <sup>b</sup> (cat) (mol %)	THF (mL)	Combined isolated yield % of <b>1</b> and <b>3</b> <sup>c</sup> ( <b>1</b> : <b>3</b> )
1	Me	20	5	<b>1b</b> : <b>3b</b> 64 (55:45)
2	<i>n</i> -Pr	20	5	<b>1c</b> : <b>3c</b> 61 (68:32)
3	Me	10	2	<b>1b</b> : <b>3b</b> 65 (62:38)
4	<i>n</i> -Pr	10	2	<b>1c</b> : <b>3c</b> 66 (63:37)

<sup>a</sup> Alkyne: 1 mmol, trimethylvinylsilane 4 mmol, La: 0.66 mmol, AlCl<sub>3</sub>: 1 mmol, THF, 12 h, rt.

<sup>b</sup> With respect to alkyne.

<sup>c</sup> Determined by <sup>1</sup>H NMR.



**Scheme 4.** Metal activations.

ether and chromatography purification, afforded trimethyl-(3-alkyl-4-phenyl)-but-3-enyl silanes **1** in good yields (70–75%).<sup>8</sup> No trace of another regioisomer was detected, indicating total double regioselectivity. Furthermore when iodine was added instead of the alkyne, **2** was obtained as a sole product.<sup>8</sup> This result confirms the generation of a common metallacycle intermediate **A** (Scheme 3).

In order to carry out these reactions with a catalytic amount of Cp<sub>2</sub>ZrCl<sub>2</sub>, several conditions were investigated. The influence of some parameters was studied: molar percentage of Cp<sub>2</sub>ZrCl<sub>2</sub> or of AlCl<sub>3</sub> and concentration.

According to the optimized procedure, the reaction was carried out by stirring a mixture of catalytic amount of Cp<sub>2</sub>ZrCl<sub>2</sub> (0.2 mmol; 20 mol %), the powdered La (0.66 mmol) and aluminium chloride (1 mmol) at room temperature in 1 or 3 mL of THF, until the deep red colour appeared. A solution of vinylsilane (4 mmol) in 1 or 2 mL of THF was then added. The following procedure and the workup were identical to those reported for the stoichiometric version. The results are presented in Table 1. With the

use of 20 mol % Cp<sub>2</sub>ZrCl<sub>2</sub> (entries 1 and 2), a complete conversion was observed after a 12-h reaction period, followed by hydrolytic workup. Under the same conditions, the use of 10 mol % Cp<sub>2</sub>ZrCl<sub>2</sub> resulted in an incomplete conversion even after a prolonged (48 h) reaction period. However, the decrease of the amount of THF (entries 3 and 4) led to a complete conversion after 12 h.<sup>8</sup> In all cases, in contrast with the stoichiometric conditions (Scheme 2), two regioisomers (**1** and **3**) were isolated in total yields of 61–66%. It must be noted that in the absence of AlCl<sub>3</sub>, the reaction did not take place (with R: Me, *n*-Pr and Ph).

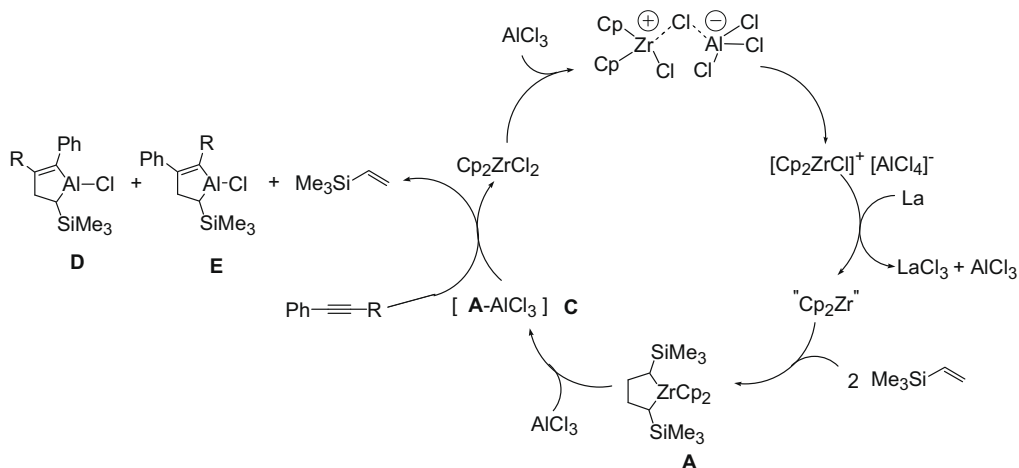
Under stoichiometric conditions, the appearance of the deep red colour is indicative of the formation of zirconocene Cp<sub>2</sub>Zr(II).<sup>6,9</sup> Under the catalytic conditions, we did not observe such a colour change in the absence of AlCl<sub>3</sub>, possibly due to a slow reduction rate and a low concentration in zirconium. In contrast, the deep red colour appeared within a short time (1 min) after the addition of aluminium chloride. Obviously, this compound plays an essential role in the generation of Cp<sub>2</sub>Zr(II) under the catalytic conditions. In both cases, LaCl<sub>3</sub> might be involved as a Lewis acid activator.

A mechanistic pattern involving bimetallic systems, in which one metal activates another via a three-centre two-electron bonding (Scheme 4, Eq. 1), analogously to the mode of carbon activation in the Friedel–Crafts reaction can be proposed<sup>10</sup> (Scheme 4, Eq. 2).

In the catalytic reaction, a bimetallic polarization between Cp<sub>2</sub>ZrCl<sub>2</sub> and AlCl<sub>3</sub>, leads to the formation of [Cp<sub>2</sub>ZrCl]<sup>+</sup>[AlCl<sub>4</sub>]<sup>-</sup>. Its reduction by Ln metal would then be much easier than the reduction of Cp<sub>2</sub>ZrCl<sub>2</sub>. Another mechanistic scenario would involve a bimetallic polarization process through zirconocene-LaCl<sub>3</sub> assemblies.

The decrease of regioselectivity under the catalytic conditions which involves the presence of AlCl<sub>3</sub> is surprising. To puzzle out this problem, we performed the following experiment under stoichiometric conditions (see above) and in the presence of AlCl<sub>3</sub>: La (0.66 mmol), Cp<sub>2</sub>ZrCl<sub>2</sub> (1 mmol) and AlCl<sub>3</sub> (1 mmol) were mixed together in THF at room temperature, after 10 min vinyl silane (4 mmol) was added, after another 10 min 1-phenylpropyne (1 mmol) was added and stirring was maintained for 12 h. After usual workup, the formation of regioisomers **1b** and **3b** in good combined yield (60%) was observed with a **1b**:**3b** ratio very close (69:31) to that measured under catalytic conditions. Thus, it was demonstrated that AlCl<sub>3</sub> influences the regioselectivity of this reaction.

A tentative catalytic cycle is depicted in Scheme 5. The reduction of Cp<sub>2</sub>ZrCl<sub>2</sub> with La in the presence of AlCl<sub>3</sub> gives Cp<sub>2</sub>Zr which further reacts with trimethylvinylsilane to afford disilylzirconacyclopentane **A**. A reaction with AlCl<sub>3</sub> produces the complex **C** which undergoes an insertion reaction to give a mixture of alu-



**Scheme 5.** Mechanistic proposal for catalytic coupling of alkynes with trimethylvinylsilane.

minacyclopentenes **D** and **E** with regeneration of Cp<sub>2</sub>ZrCl<sub>2</sub>. The quenching of **D** and **E** should produce **1** and **3**, respectively. Additional experiments are necessary to define the structure of **C**. However, it must be considered that AlCl<sub>3</sub> is involved in the insertion of the alkyne into the disilylated metallacycle.

The proposed mechanism makes it possible to rationalize the difference of regioselectivity observed between the stoichiometric and catalytic conditions. In the stoichiometric reaction (Scheme 3), the displacement step involves disilylzirconacyclopentane intermediate **A**, which in turn reacts with alkyne to form zirconacyclopentene **B**. In the catalytic reaction, the intermediate **C** is involved in the displacement of the ligand to form a mixture of aluminumacyclopentenes **D** and **E**.

In conclusion, we have carried out cross-coupling reactions between alkynes and trimethylvinylsilane, by using zirconocene (Cp<sub>2</sub>Zr) generated by the reduction of Cp<sub>2</sub>ZrCl<sub>2</sub> with lanthanide metals. The stoichiometric conditions gave coupling products in good yields and with total regioselectivity. The reaction using a catalytic amount of Cp<sub>2</sub>ZrCl<sub>2</sub> and AlCl<sub>3</sub> as an additive was also successful. However, a mixture of regioisomers was formed under these conditions. On this basis, a plausible catalytic cycle has been proposed. It is worth noting that this work is a new example of the use of Cp<sub>2</sub>Zr as a catalyst.

## Acknowledgements

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- Materials and methods. All reactions were performed under an atmosphere of argon using standard Schlenk techniques. Prior to use tetrahydrofuran was distilled under argon from sodium benzophenone ketyl. <sup>1</sup>H NMR spectra were recorded in CDCl<sub>3</sub> on a Bruker 250 DPX or 360 AVANCE. Chemical shifts are reported in delta (δ) units, expressed in parts per million (ppm). <sup>13</sup>C NMR spectra were recorded in CDCl<sub>3</sub> on a Bruker 250 DPX. Chemical shifts are reported in delta (δ) units, expressed in parts per million (ppm). Coupling constants are expressed in hertz (Hz). High-resolution mass spectra (HRMS) were obtained with a MAT-95-S Finnigan. GC-MS were obtained with a DSQ-thermo electron instrument. (*Z*)-(3,4-Diphenyl-but-3-enyl)-trimethylsilane (**1a**): Purification: eluent pentane/EtOAc (95:5). Yellow oil. Yield (75%). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.04 (s, 9H), 0.71 (m, 2H), 2.51 (m, 2H), 6.48 (s, 1H), 6.90–7.40 (m, 10H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ 145.8, 141.5, 137.6, 128.9, 128.6, 128.4, 127.8, 126.8, 126.0, 124.8, 34.8, 15.1, –1.7. HRMS: [M<sup>+</sup>] calcd for C<sub>19</sub>H<sub>24</sub>Si 280.1642; found, 280.1632. (*E*)-Trimethyl-(3-methyl-4-phenyl-but-3-enyl)-silane (**1b**): Purification: eluent pentane/EtOAc (95:5). Yellow oil. Yield (70%). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.05 (s, 9H), 0.80 (m, 2H), 1.90 (s, 3H), 2.12 (m, 2H), 6.34 (s, 1H), 7.30 (m, 5H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ 141.6, 138.8, 128.8, 128.0, 125.7, 123.4, 34.9, 17.6, 15.0, –1.7. HRMS: [M<sup>+</sup>] calcd for C<sub>14</sub>H<sub>22</sub>Si 218.1485; found, 218.1485. (*E*)-Trimethyl-(4-phenyl-propylbut-3-enyl)-silane (**1c**): Purification: eluent pentane/EtOAc (99:1). Yellow oil. Yield (71%). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.04 (s, 9H), 0.75 (m, 2H), 0.92 (t, J = 7.3, 3H), 1.50 (m, 2H), 2.20 (m, 4H), 6.30 (s, 1H), 7.27 (m, 5H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ 145.9, 138.8, 128.6, 128.0, 125.7, 123.7, 32.5, 31.3, 21.5, 15.1, 14.3, –1.7. HRMS: [M<sup>+</sup>] calcd for C<sub>16</sub>H<sub>26</sub>Si 246.1798; found, 246.1792. 1-lodo-1,4-bis-trimethylsilylanyl-butane (**2**): Yellow oil. <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.04 (s, 9H); 0.71 (m, 2H); 1.50 (m, 2H), 1.91 (m, 2H), 3.18 (m, 1H). GC-MS (EI, 70 eV) m/z (%): 329 (17), 328 (100), 313 (11), 285 (14), 273 (34). (*E*)-Trimethyl-(3-methyl-4-phenyl-but-3-enyl)-silane (**1b**) and (*Z*)-trimethyl-(4-methyl-3-phenyl-but-3-enyl) silane (**3b**): Purification: eluent pentane/EtOAc (95:5). Yellow oil. Total yield [64%, (**1b**:**3b**/55:45)] Table 1, entry 1; [65%, (**1b**:**3b**/62:38)] Table 1, entry 3. Regioisomer (**1b**): <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.04 (s, 9H), 0.80 (m, 2H), 1.90 (s, 3H), 2.12 (m, 2H), 6.34 (s, 1H), 7.30 (m, 5H). Regioisomer (**3b**): <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.01 (s, 9H), 0.56 (m, 2H), 1.57 (d, J = 7, 3H), 2.33 (m, 2H), 5.56 (q, 1H, J = 7), 7.30 (m, 5H). (*E*)-Trimethyl-(4-phenyl-3-propyl-but-3-enyl)-silane (**1c**) and (*Z*)-trimethyl-(3-phenyl-hept-3-enyl)-silane (**3c**): Purification: eluent pentane/EtOAc (95:5). Yellow oil. Total yield [61%, (**1c**:**3c**/68:32)] Table 1, entry 3; [66%, (**1c**:**3c**/63:37)] Table 1, entry 4. Regioisomer (**1c**): <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.05 (s, 9H), 0.75 (m, 2H), 0.92 (t, J = 7.3, 3H), 1.50 (m, 2H), 2.20 (m, 4H), 6.30 (s, 1H), 7.27 (m, 5H). Regioisomer (**3c**): <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 0.00 (s, 9H), 0.57 (m, 2H), 0.74 (t, J = 8, 3H), 1.35 (m, 2H), 1.90 (m, 2H), 2.20 (m, 2H), 5.48 (t, J = 8, 1H).
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