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Dichloro(ethylenediamine)platinum(II), a water-soluble analog of the antitumor cisplatin, as a heterogeneous catalyst for a stereoselective hydrosilylation of alkynes under neat conditions

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ABSTRACT

A stereoselective method for the hydrosilylation of internal and terminal alkynes under heterogeneous catalysis by dichloro(ethylenediamine)platinum(II) is discussed. This commercially available platinum complex operates under neat conditions at 90 °C, producing exclusively the (*trans*) Z-isomer with symmetrical internal alkynes, while terminal alkynes produce a mixture of α - and β (*E*)-hydrosilylated products. No β (*Z*)-hydrosilylated product was observed during this study, and the selectivity between the α - and β (*E*)-hydrosilylated products appears to be influenced to a certain degree by the nature of the hydrosilanes. The catalyst was recyclable up to five runs under gram scale conditions without any loss of the catalytic activity.

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Introduction

Metal-catalyzed hydrosilylation of alkynes is arguably one of the most powerful, convenient and atom-efficient method for the synthesis of alkenylsilanes and vinylsilanes [1]. Owing to their unique reactivity, these are valuable intermediates in organic chemistry, with a wide range of applications in a number of important transformations such as Miyaura-type couplings [2], Heck couplings [3], coupling with aldehydes [4], Friedel-Crafts reactions [5], and served as dienophiles in Diels-Alder reactions [6].

Due to their high catalyst turnovers, platinum complexes are by far the most explored catalysts for the hydrosilylation of olefins and acetylenes, with the Speier system ($\text{H}_2\text{PtCl}_6/\text{iPrOH}$) [7] and Karstedt complex ($[\text{Pt}_2(\text{dvtms})_3]$, dvtms = 1,3-divinyl-1,1,3,3-tetramethyldisiloxane) [8] being the most commonly used in industrial settings. These latter catalysts are well known to form colloidal platinum particles during the course of the reaction, and to address these shortcomings, a number of platinum complexes bearing a wide range of ligands including bulky phosphines, *N*-heterocyclic carbenes or chelating acyclic aminocarbenes have been explored [9]. In addition, less reactive but highly selective ruthenium complexes [6,10], as well as some rhodium(I) [11]

and palladium complexes [12] are also reported in the chemical literature.

The constant need for more selective, robust and recyclable catalysts has resulted in the development of heterogeneous hydrosilylation methods, primarily based on metal nanoparticles [1d,13]. This includes super-microporous silica-supported platinum nanoparticles [1d,13h], ligand-free Pt_3 clusters [13e,i], polysiloxane stabilized platinum nanoparticles, as well as platinum nanodispersed in organically modified silicates from our research group [13g], all used as heterogeneous catalysts for the hydrosilylation of olefins and acetylenes. In our continuous effort to develop heterogeneous catalytic systems for the hydrosilylation of olefins and acetylenes, we here report the stereoselective hydrosilylation of internal and terminal alkynes under neat conditions using dichloro(ethylenediamine)platinum(II). Unlike many discrete metal complexes which operate preferentially under homogeneous catalysis, this commercially available platinum complex proceeds via heterogeneous catalysis. Furthermore, despite platinum complexes being well explored for their catalytic activities in hydrosilylation reactions [9], this water-soluble analog of the antitumor cisplatin has been investigated primarily for its anticancer properties [14], which is the result of its DNA-damaging effects via a selective binding mechanism [15]. As such, its catalytic capability remains unexplored. This work represents a rare and to the best of our knowledge, unprecedented glimpse into its potential as a catalyst in

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chemical transformations. In addition, the catalytic system developed during the course of this study works equally well with internal and terminal alkynes, producing exclusively the (*trans*) *Z*-isomer with symmetrical internal alkynes, while terminal alkynes produce a mixture of α - and $\beta(E)$ -hydrosilylated products. The nature of the hydrosilanes seems to influence somewhat the selectivity between the α - and $\beta(E)$ -hydrosilylated products, and with no $\beta(Z)$ -vinylsilane observed.

Results and discussion

As part of our continue efforts to develop more efficient and sustainable hydrosilylation methods [13g,16], we noticed that dichloro(ethylenediamine)platinum(II), Pt(en)Cl₂, was able to catalyze the hydrosilylation of diphenylacetylene in the presence of diphenylsilane in refluxing toluene in 18 h as illustrated in Scheme 1. These initial reaction conditions were adapted from a previous study from our research group [13g], and a quick optimization was undertaken as summarized in Table 1. It appears that the reaction goes to completion in toluene at 100 °C, in presence of 1 mol% of Pt(en)Cl₂ (entry 3), but not when refluxed in either CH₃CN or THF (entries 4 and 5) with the same catalyst load.

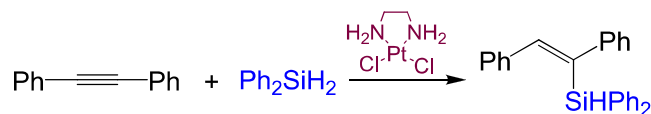
All these reactions were performed under a nitrogen atmosphere, and when neat conditions were implemented with a similar catalyst load and 1.2 eq. of hydrosilane at 90 °C for 18 h, no starting material was observed in the reaction mixture as indicated by GC–MS (entry 6). The increase of the equivalence of diphenylsilane from 1.2 to 2.0 did not have any noticeable impact on the reaction outcome (entry 7). However, any decrease in the equivalence of diphenylsilane (entry 8), catalyst load (entry 9), temperature (entry 11) or reaction time (entry 13) appear to negatively impact the reaction, with no product observed in the absence of the catalyst (entry 12). It should be mentioned that the reaction proceeds at room temperature, although only a modest yield was

obtained in 18 h (entry 10). As a result, the conditions in entry 6 were selected for the exploration of the scope of the reaction.

Diphenylacetylene was thus reacted with a number of hydrosilanes, including triethoxysilane, benzyldimethylsilane, triethylsilane and triphenylsilane, in the presence of 1 mol% of Pt(en)Cl₂ at 90 °C for 18 h under neat conditions, to produce compounds 2–5 respectively, in good to excellent yields (Fig 1). The reaction also works well with hex-3-yne in the presence of either diphenylsilane or triethoxysilane to produce compounds 6 and 7 respectively.

All these reactions with symmetrical alkynes produced exclusively a single isomer of the expected product as indicated by the GC–MS and NMR spectra. A careful analysis of the ¹H, ¹³C NMR, HSQC, HMBC and NOESY spectra of 4, used as an example, indicated that this compound is the *Z*-isomer (*trans*). In fact, no NOESY correlation was observed between the vinylic proton of the alkene and any of the protons of the triethylsilane group, indicating that this proton was not spatially close to the triethylsilane group. Instead, this proton shows correlations only with the protons from the benzenes rings, confirming that the vinylic proton and the triethylsilane group are not on the same side of the double bond (see supplementary information). The same pattern was observed in the NMR data of all the other compounds.

A number of terminal alkynes with various electronic features, including phenylacetylene, trimethylsilylacetylene, *p*-tolylacetylene, 4-ethynylanisole, 1-bromo-4-ethynylbenzene and 1-ethynyl-4-(trifluoro)benzene were also explored under this catalytic system, and the reaction appears to work equally well as summarized in Table 2. However, unlike symmetrical internal



Scheme 1. Hydrosilylation of diphenylacetylene by diphenylsilane in the presence of dichloro(ethylenediamine)platinum(II).

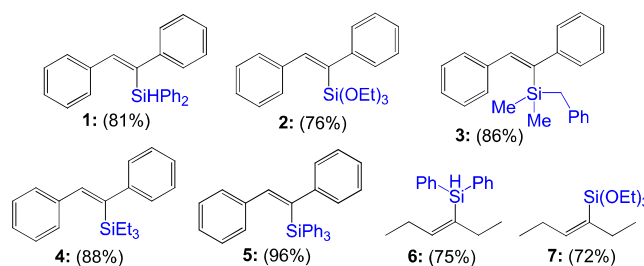


Fig. 1. Dichloro(ethylenediamine)platinum(II) catalyzed hydrosilylation of diphenylacetylene and hex-3-yne using a range of hydrosilanes (isolated yields from 200 mg reactions).

Table 1
Exploration of the reaction conditions using diphenylacetylene and diphenylsilane.

Entries	Ph ₂ SiH ₂ (eq. ^a)	Pt(en)Cl ₂ (mol%)	Solvent	Temperature °C	Time (h)	Percent conversion (%) ^b
1	1.2	0.5	Toluene	reflux	18	65
2	1.2	1.0	Toluene	60	18	78
3	1.2	1.0	Toluene	100	18	98 ^c
4	1.2	1.0	CH ₃ CN	reflux	18	37
5	1.2	1.0	THF	reflux	18	84
6	1.2	1.0	neat	90	18	97 ^c
7	2.0	1.0	neat	90	18	98 ^c
8	1.0	1.0	neat	90	18	80
9	1.2	0.5	neat	90	18	63
10	1.2	1.0	neat	rt	18	32
11	1.2	1.0	neat	60	18	76
12	1.2	none	neat	90	18	N.R. ^d
13	1.2	1.0	neat	90	6	73

Reactions were performed under a nitrogen atmosphere, using 100 mg of diphenylacetylene.

^aIn relationship to the number of moles of diphenylacetylene.

^bPercent conversions determined by GC–MS, using tridecane as an internal standard.

^cNo starting material was present upon reaction completion as indicated by GC–MS.

^dN.R. = No Reaction.

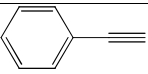
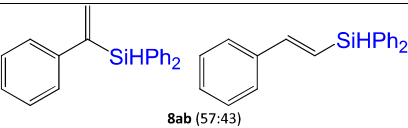
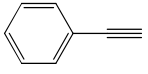
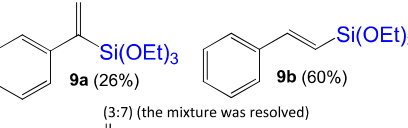
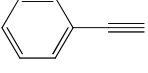
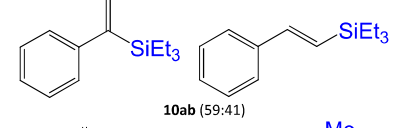
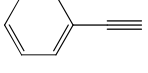
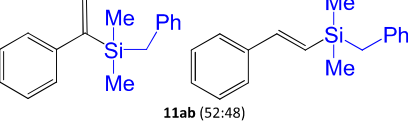
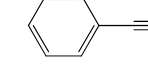
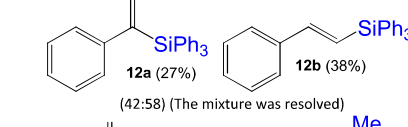
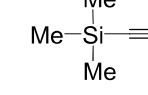
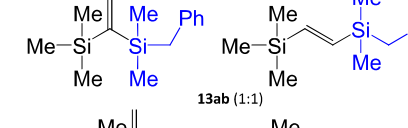
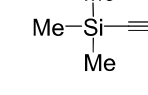
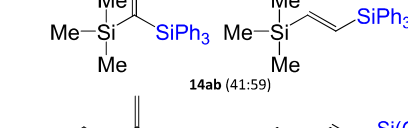
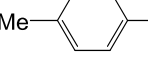
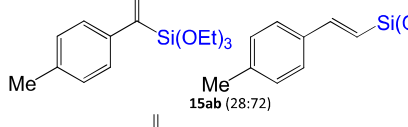
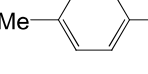
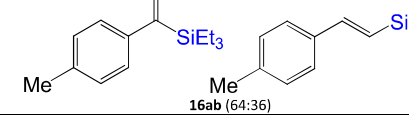
alkynes that produced exclusively the (*trans*) *Z*-isomer, terminal alkynes produce a mixture of α - and β (*E*)-hydrosilylated products, with no β (*Z*)-vinylsilane observed during this study. Although many of these mixtures were inseparable by conventional column chromatography, their constituents, namely α -vinylsilane and β (*E*)-vinylsilane isomers were rather easily characterized by ^1H NMR and GC–MS. In fact, the large coupling constant ($J = 19.2$ Hz) between the *trans* vinylic protons in the β (*E*)-vinylsilane isomer in the ^1H NMR of the mixture stands in clear contrast to the small coupling constant ($J = 3.2$ Hz) between the two germinal protons of the α -vinylsilane isomer. These four distinguishable doublets of 1H each (2 from each isomer) consistently appeared at different chemical shifts, thus enabling an easy determination of the α : β isomeric ratio.

Furthermore, the two isomers also appeared to have different retention times on the gas chromatographs, allowing to record a separate mass spectrometry spectrum for each isomer (see [supplemental data](#)). The combination of ^1H and ^{13}C NMR on one hand and

GC–MS on the other permit a full characterization of the components within each mixture. More importantly, the resolution of three of these mixtures by column chromatography resulting in the isolation and full characterization of pure isomers in each case, namely **9a**, **9b**, **12a**, **12b**, **18a** and **18b**, provides additional data to support these observations. The structure of **12b**, obtained as a clear crystalline material, was further confirmed by single crystal X-ray diffraction, and the molecular structure with thermal ellipsoid representation at 50% probability level is shown in [Fig. 2](#).

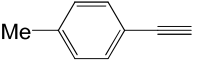
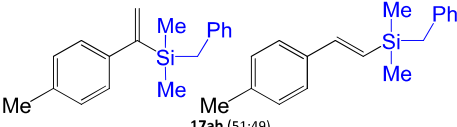
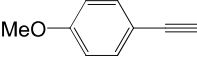
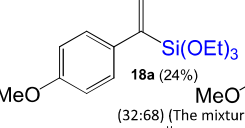
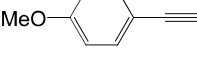

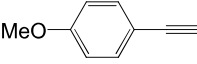
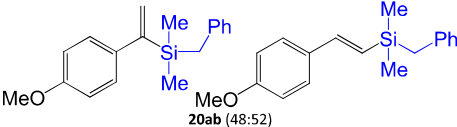
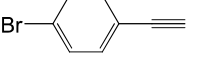
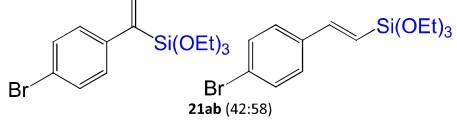
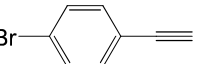
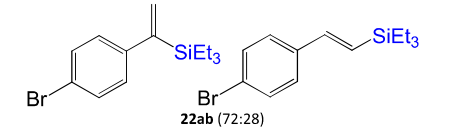
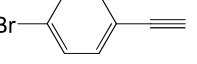
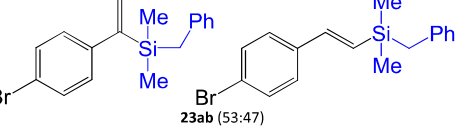
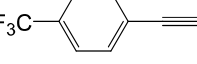
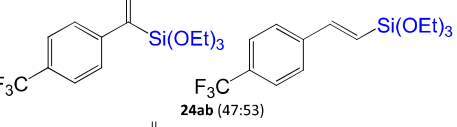
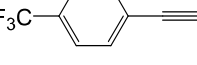

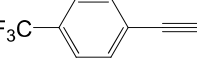
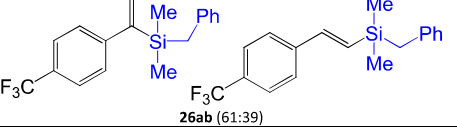
While the nature and the electronic profile of alkynes and hydrosilanes do not appear to significantly affect the overall yield of the reaction, they do have some impact on the α : β isomeric ratio. For example, triphenylsilane produced similar isomeric ratios with both with phenylacetylene (**12ab**, 42:58) and trimethylsilylacetylene (**14ab**, 41:59), with an excess of the β -(*E*) isomer, while benzyldimethylsilane produced a 1:1 isomeric ratio with every alkyne tested regardless of their electronic profile; phenylacetylene (**11ab**, 52:48), trimethylsilylacetylene (**13ab**, 50:50),

Table 2
Summary of reactions with terminal alkynes (isolated yields from 200 mg reactions).

Starting material	Silane	Products (α : β ratio)	% yield
	H_2SiPh_2	 8ab (57:43)	88
	$\text{HSi}(\text{OEt})_3$	 9a (26%) 9b (60%) (3:7) (the mixture was resolved)	86
	HSiEt_3	 10ab (59:41)	75
	$\text{HSi}(\text{Me})_2\text{Bn}$	 11ab (52:48)	73
	HSiPh_3	 12a (27%) 12b (38%) (42:58) (The mixture was resolved)	65
	$\text{HSi}(\text{Me})_2\text{Bn}$	 13ab (1:1)	88
	HSiPh_3	 14ab (41:59)	70
	$\text{HSi}(\text{OEt})_3$	 15ab (28:72)	79
	HSiEt_3	 16ab (64:36)	73

(continued on next page)

Table 2 (continued)

	HSi(Me) ₂ Bn		79
	HSi(OEt) ₃		75
	HSiEt ₃		76
	HSi(Me) ₂ Bn		84
	HSi(OEt) ₃		71
	HSiEt ₃		72
	HSi(Me) ₂ Bn		87
	HSi(OEt) ₃		81
	HSiEt ₃		75
	HSi(Me) ₂ Bn		84

p-tolylacetylene (**17ab**, 51:49), 4-ethynylanisole (**20ab**, 48:52) and 1-bromo-4-ethynylbenzene (**23ab**, 53:47), except for 1-ethynyl-4-(trifluoromethyl)benzene (**26ab**, 61:39) that produced a larger excess of the α -isomer. Interestingly, while triethoxysilane produced mixtures with an excess of the β -(*E*)-isomer, which appears to be more pronounced with alkynes with an electron-donating groups, triethylsilane does exactly the opposite by producing mixtures with an excess of the α -isomer, which appeared to be more pronounced with alkynes with electron-withdrawing groups.

From a mechanistic perspective, the presence of the Markovnikov (α -isomer) and the anti-Markovnikov (β -isomer) in the product mixtures implies two competitive pathways well accepted for the hydrosilylation of alkynes and alkenes. As such, the key step that determines the regioselectivity of the reaction is the migratory insertion, which proceeds either through hydroplatination to

produce the β -isomer or through silylplatination resulting in the α -isomer [9a,c,17], following a Chalk–Harrod mechanism recently modified by Corma and coworkers [13e], as illustrated in Scheme 2. According to this recent study, the Pt species formed in situ determines the observed selectivity, with Pt nanoparticles inducing the production of β -vinylsilanes, while small Pt clusters of 3–4 atoms control the formation of α -vinylsilanes [13e]. These observations are consistent with a previous study from our research group in which Pt nanoparticles dispersed and stabilized in organically modified silicates produced exclusively the β -vinylsilane products during the hydrosilylation of alkenes and alkynes, with no α -isomer observed [13g]. The study from the Corma's research group clearly showed that small Pt clusters preferably produced the α -isomer, and also enable the identification of alternative intermediates, labelled in Scheme 2

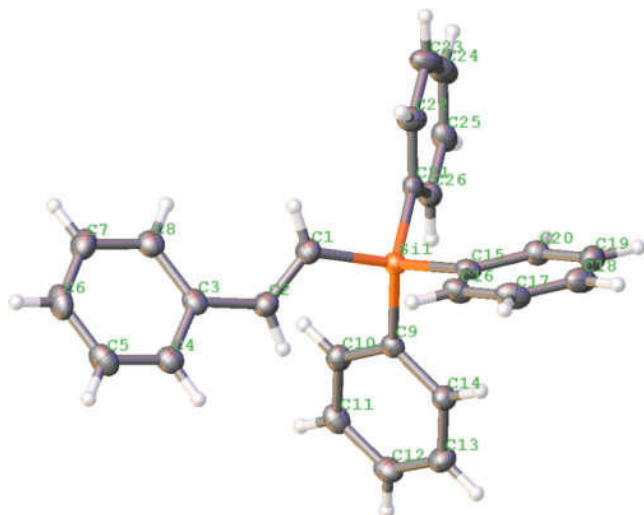


Fig. 2. The molecular structure of **12b**, showing 50% probability ellipsoids. The single crystal X-ray data for **12b** (CCDC 2007037) is deposited in the Cambridge database, and copies of these materials can be obtained free of charge from CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, <https://www.ccdc.cam.ac.uk/>.

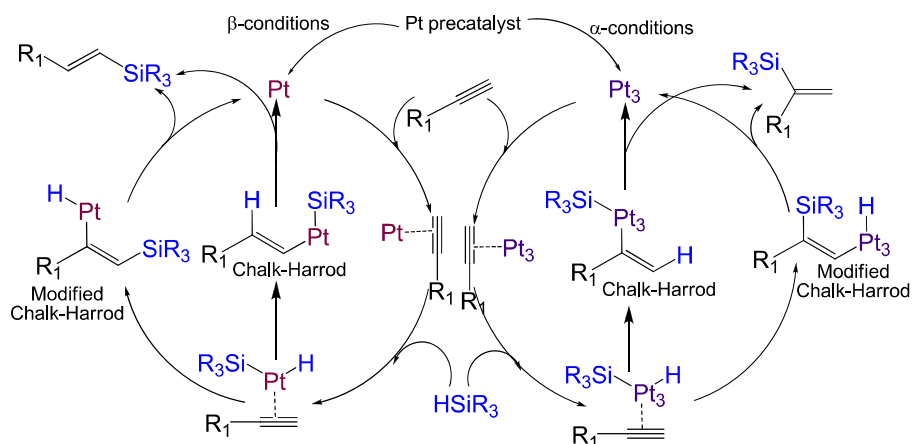
as modified Chalk-Harrod species [13e]. Taken together, these studies suggest that the presence of both the α -isomer and the β -isomer within the same reaction mixture implies the formation

of two different Pt catalytic species, namely Pt nanoparticles (which exclusively produces β -vinylsilanes) and small Pt clusters (which exclusively produces α -vinylsilanes), from the same initial Pt precatalyst (Scheme 2). It is still unclear how the electronic profile of the alkyne starting materials and the nature of hydrosilanes contribute to the formation of either of these catalytic species, if at all. One thing for sure is that they have some influence on the selectivity observed during the course of this study, indicating that further investigations are still needed.

Nevertheless, since the reaction proceeds via heterogeneous catalysis, it was necessary to investigate the reusability of the catalyst. This study was carried out at a gram scale, using hex-3-yne and triethoxysilane as the starting materials. Not only the yield of the reaction was similar at a larger scale, the same catalyst was recycled up to five runs with no loss of catalytic activities, as illustrated in Fig. 3. However, it should be mentioned that the reaction proceeded via homogeneous catalysis whenever a solvent such as toluene, CH_3CN or THF was used.

Conclusion

Dichloro(ethylenediamine)platinum(II), a water-soluble analog of the antitumor cisplatin, has been proven to be a catalyst precursor for an efficient and robust hydrosilylation of acetylenes. Unlike many discrete metal complexes which operate preferentially under homogeneous catalysis, this commercially available platinum com-



Scheme 2. Possible pathways for the hydrosilylation of alkynes leading to either the α -isomer (right) or the β -isomer (left) through both Chalk-Harrod and modified Chalk-Harrod mechanisms [13e].

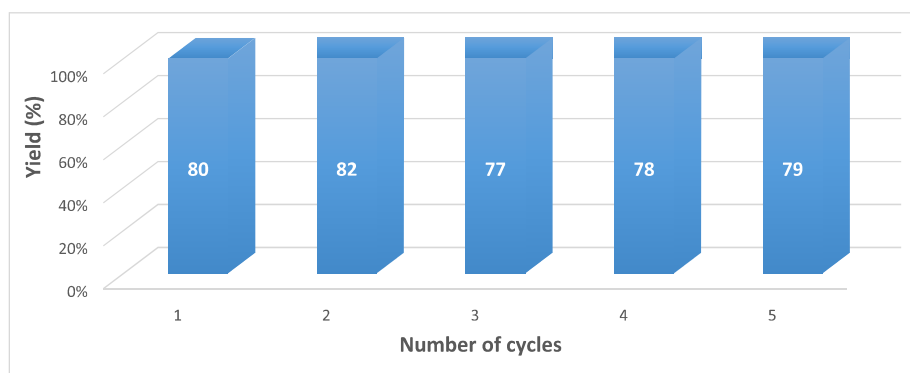


Fig. 3. Study of the reusability of dichloro(ethylenediamine)platinum(II) using hex-3-yne and triethoxysilane in the preparation of **7** (these are isolated yields from 1 g scale reactions).

plex proceeds via heterogeneous catalysis under neat conditions, and works well with both internal and terminal alkynes. While symmetrical internal alkynes produced exclusively the (*trans*) Z-isomer, terminal alkynes produced a mixture of α - and β (E)-vinylsilanes, with no β (Z)-hydrosilylated product observed during this study. The electronic profile of the alkynes as well as the nature of the hydrosilanes also appeared to have some influence on the observed selectivity. As for possible mechanistic pathways, the presence of both the α -isomer and the β -isomer within the same reaction mixture suggests the creation of two different Pt catalytic species; the Pt nanoparticles enabling the formation of β -vinylsilanes and small Pt clusters allowing for the production of α -vinylsilanes, both from the same initial Pt precatalyst. This catalyst was recyclable up to 5 runs under a gram scale conditions without any loss of the catalytic activity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data (experimental data, ^1H and ^{13}C NMR, and the GC–MS spectra featuring the isomeric ratios in each of the mixtures reported) to this article can be found online at <https://doi.org/10.1016/j.tetlet.2020.152300>.

References

- [1] (a) D. Troegel, J. Stohrer, *Coord. Chem. Rev.* 255 (2011) 1440–1459; (b) S.-L. Shi, Z.L. Wong, S.L. Buchwald, *Nature* 532 (2016) 353–356; (c) Z. Mo, J. Xiao, Y. Gao, L. Deng, *J. Am. Chem. Soc.* 136 (2014) 17414–17417; (d) M. Planellas, W. Guo, F. Alonso, M. Yus, A. Shafir, R. Pleixats, T. Parella, *Adv. Synth. Catal.* 356 (2014) 179–188; (e) A. Garcia-Rubia, J.A. Romero-Revilla, P. Mauleon, R. Gomez Arrayas, J.C. Carretero, *J. Am. Chem. Soc.* 137 (2015) 6857–6865; (f) A. Simonneau, M. Oestreich, *Nat. Chem.* 7 (2015) 816–822; (g) A. Rivera-Hernandez, B.J. Fallon, S. Ventre, C. Simon, M.-H. Tremblay, G. Gontard, E. Derat, M. Amatore, C. Aubert, *Org. Lett.* 18 (2016) 4242–4245; (h) J. Guo, Z. Lu, *Angew. Chem. Int. Ed.* 55 (2016) 10835–10838.
- [2] (a) Y. Hatanaka, T. Hiyama, *Synlett* 12 (1991) 845–853; (b) T. Hiyama, *J. Organomet. Chem.* 653 (2002) 58–61; (c) L. Cornelissen, V. Cirriez, S. Vercruysse, O. Riant, *Chem. Commun.* 50 (2014) 8018–8020; (d) L. Cornelissen, M. Lefrancq, O. Riant, *Org. Lett.* 16 (2014) 3024–3027.
- [3] (a) K. Itami, Y. Ushioji, T. Nokami, Y. Ohashi, J.-I. Yoshida, *Org. Lett.* 6 (2004) 3695–3698; (b) A. Battace, T. Zair, H. Doucet, M. Santelli, *J. Organomet. Chem.* 690 (2005) 3790–3802.
- [4] M.C. McIntosh, S.M. Weinreb, *J. Org. Chem.* 56 (1991) 5010–5012.
- [5] L.A. Paquette, W.E. Fristad, D.S. Dime, T.R. Bailey, *J. Org. Chem.* 45 (1980) 3017–3028.
- [6] B.M. Trost, Z.T. Ball, *J. Am. Chem. Soc.* 127 (2005) 17644–17655.
- [7] (a) J.L. Speier, J.A. Webster, G.H. Barnes, *J. Am. Chem. Soc.* 79 (1957) 974–979; (b) J.L. Speier, R. Zimmerman, J. Webster, *J. Am. Chem. Soc.* 78 (1956) 2278–2281.
- [8] (a) B.D. Karstedt, DE2307085A1, 1973. (b) B.D. Karstedt, DE1941411A, 1970. (c) B.D. Karstedt, FR1548775, 1968.
- [9] (a) G. Berthon-Gelloz, J.-M. Schumers, G. De Bo, I.E. Marko, *J. Org. Chem.* 73 (2008) 4190–4197; (b) M. Blug, X.-F. Le Goff, N. Mezailles, P. Le Floch, *Organometallics* 28 (2009) 2360–2362; (c) J.-X. Xu, M.-Y. Chen, Z.-J. Zheng, J. Cao, Z. Xu, Y.-M. Cui, L.-W. Xu, *ChemCatChem* 9 (2017) 3111–3116; (d) G.F. Silbestri, J.C. Flores, E. de Jesus, *Organometallics* 31 (2012) 3355–3360; (e) P. Zak, M. Bolt, M. Kubicki, C. Pietraszuk, *Dalton Trans.* 47 (2018) 1903–1910; (f) R.S. Chay, B.G.M. Rocha, A.J.L. Pombeiro, V.Y. Kukushkin, K.V. Luznyanin, *ACS Omega* 3 (2018) 863–871; (g) L. Ortega-Moreno, R. Peloso, C. Maya, A. Suarez, E. Carmona, *Chem. Commun.* 51 (2015) 17008–17011.
- [10] (a) Y. Na, S. Chang, *Org. Lett.* 2 (2000) 1887–1889; (b) C. Menozzi, P.I. Dalko, J. Cossy, *J. Org. Chem.* 70 (2005) 10717–10719; (c) B.M. Trost, Z.T. Ball, *J. Am. Chem. Soc.* 123 (2001) 12726–12727.
- [11] A. Sato, H. Kinoshita, H. Shinokubo, K. Oshima, *Org. Lett.* 6 (2004) 2217–2220.
- [12] (a) Y. Sumida, T. Kato, S. Yoshida, T. Hosoya, *Org. Lett.* 14 (2012) 1552–1555; (b) H. Zhou, C. Moberg, *Org. Lett.* 15 (2013) 1444–1447.
- [13] (a) H. Miura, K. Endo, R. Ogawa, T. Shishido, *ACS Catal.* 7 (2017) 1543–1553; (b) R.C. Bal, A.K. Shil, N.R. Guha, D. Sharma, P. Das, *Catal. Lett.* 144 (2014) 1530–1536; (c) W.A. Solomonsz, G.A. Rance, B.J. Harris, A.N. Khlobystov, *Nanoscale* 5 (2013) 12200–12205; (d) W. Hu, H. Xie, H. Yue, P. Prinsen, R. Luque, *Catal. Commun.* 97 (2017) 51–55; (e) M.A. Rivero-Crespo, A. Leyva-Perez, A. Corma, *Chem. Eur. J.* 23 (2017) 1702–1708; (f) B.P.S. Chauhan, A. Sarkar, *Dalton Trans.* 46 (2017) 8709–8715; (g) B.J. Duke, E.N. Akeroyd, S.V. Bhatt, C.I. Onyeagusi, S.V. Bhatt, B.R. Adolph, J. Fotie, *New J. Chem.* 42 (2018) 11782–11795; (h) G. Fernandez, R. Pleixats, *ChemistrySelect* 3 (2018) 11486–11493; (i) U. Diaz, D. Brunel, A. Corma, *Chem. Soc. Rev.* 42 (2013) 4083–4097.
- [14] (a) A.P. Jekunen, D.K. Hom, J.E. Alcaraz, A. Eastman, S.B. Howell, *Cancer Res.* 54 (1994) 2680–2687; (b) E.F. McClay, K.D. Albright, J.A. Jones, A. Eastman, R. Christen, S.B. Howell, *Cancer Res.* 52 (1992) 6790–6796.
- [15] (a) T. Ohmori, T. Morikage, H. Sugimoto, Y. Fujiwara, K. Kasahara, K. Nishio, S. Ohta, Y. Sasaki, T. Takahashi, N. Saijo, *Jpn. J. Cancer Res.* 84 (1993) 83–92; (b) V. Murray, H. Motyka, P.R. England, G. Wickham, H.H. Lee, W.A. Denny, W. D. McFadyen, *Biochemistry* 31 (1992) (1817) 11812–11821; (c) A. Eastman, *Anal. Biochem.* 197 (1991) 311–315; (d) A. Eastman, *Chem. Biol. Interact.* 61 (1987) 241–248; (e) A. Eastman, *Biochemistry* 25 (1986) 3912–3915; (f) A. Eastman, *Biochemistry* 24 (1985) 5027–5032.
- [16] (a) S.V. Bhatt, S.V. Bhatt, J. Fotie, *Am. Chem. Soc.* (2018); (b) S.V. Bhatt, S.V. Bhatt, J. Fotie, *Tetrahedron Lett.* 60 (2019) 1636–1639.
- [17] (a) A.J. Chalk, J.F. Harrod, *J. Am. Chem. Soc.* 87 (1965) 16–21; (b) S. Sakaki, N. Mizoe, M. Sugimoto, *Organometallics* 17 (1998) 2510–2523.