

Recyclable palladium(0)-catalysed silylstannation of terminal alkynes in ionic liquids

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Abstract

The palladium(0)-catalysed addition of silylstannanes $\text{Bu}_3\text{SnSiMe}_3$ and $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ to terminal alkynes has been shown to proceed in the ionic liquids 1-*n*-butyl-3-methylimidazolium hexafluorophosphate ($[\text{bmim}]\text{PF}_6$) and 1-*n*-butyl-3-methylimidazolium tetrafluoroborate ($[\text{bmim}]\text{BF}_4$). These reactions generally proceed in excellent yields to give 1-trialkylsilyl-2-tributylstannyl-1*Z*-alkenes regio- and stereoselectively as a single product with reaction times comparable to those reported for reactions performed in tetrahydrofuran (THF). The reaction has been shown to tolerate remote functionality on the alkyne. Each of the ionic liquids containing the immobilised palladium catalyst has been recycled up to 10 times without loss of activity, allowing extensive reuse of the expensive solvent/catalyst system. A catalyst activation stage involving mild heating of the palladium catalyst in the ionic liquid/diethyl ether solvent system decreased reaction time in the first cycle once all reagents were added, indicating the formation of a catalytically active palladium species other than tetrakis(triphenylphosphine)palladium(0). © 2004 Elsevier B.V. All rights reserved.

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1. Introduction

Ionic liquids have recently attracted much attention from many areas of chemistry. The increasing level of interest in these compounds arises from the fact that they are ionic compounds that are liquids at or near room temperature. As such, they have many unique properties that are currently being utilised in a number of varied applications. There are many different types of known ionic liquids based on various cations and anions. The most commonly used ionic liquid cations are based on *N,N'*-dialkylimidazolium species. These liquids have remarkably different properties that depend on their associated anion [1]. Ionic liquids typically have wide liquid temperature ranges, are immiscible with a number of organic solvents, and exhibit no measurable vapour pressure. Their inertness toward many reagents makes them ideal for use as a new class of polar [2,3], non-co-ordinating, ionic solvents.

Many different reactions have been performed in ionic liquids, often affording greater yields, product selectivity

and rate enhancement. While these reactions have been both catalytic and non-catalytic [4–7], ionic liquids are being used increasingly in transition metal-catalysed reactions as they often allow easy recycling of the catalyst and offer greater catalyst stability [8–11]. Several metal catalysts have been immobilised in ionic liquids, using the ionic liquid both as a solvent and as a support for the catalyst. The polar, ionic nature of the solvent allows easy dissolution of metal complexes and its non-co-ordinating nature allows the catalyst to remain active. While the exact nature of the interactions between ionic liquids and their solutes remains unclear, ionic liquids are capable of supporting catalysts and retaining them after reaction products have been extracted from the solvent. This allows catalyst to be reused due to the non-volatile nature of ionic liquids.

Trialkyl(trialkylstannyl)silanes are versatile organometallic reagents that contain a silicon–tin bond. These compounds are easily synthesised by generating a trialkyltin anion through various methods (e.g. deprotonation of trialkyltin hydride with lithium diisopropylamide, LDA) and quenching this with a trialkylsilyl chloride [12]. As well, some are commercially available. Trialkyl(trialkylstannyl)silanes are particularly interesting in that there is potential to incorporate both the trialkylstannyl and trialkylsilyl

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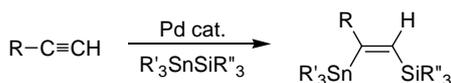


Fig. 1. Palladium-catalysed silylstannation of terminal alkynes.

moieties into organic products providing two new reactive centres for further manipulation. Perhaps the most useful reaction involving trialkyl(trialkylstannyl)silanes is their palladium-catalysed addition across unsaturated systems such as terminal alkynes (Fig. 1) [13–17]. These reactions afford a bifunctional organic dianion equivalent containing both carbon–tin and carbon–silicon bonds. These functionalised products can then undergo a number of organic transformations including selective protodesilylation or protodestannylation, tin–lithium exchange via treatment with alkyllithium reagents, substitution of the trialkyltin and/or trialkylsilyl groups, and palladium-mediated Stille couplings [13–17]. Drawbacks to the addition of trialkyl(trialkylstannyl)silanes to alkynes include the expense of the palladium catalyst that is necessary for the reaction to proceed and the inability to recycle the catalyst.

We have recently reported that the ionic liquid 1-*n*-butyl-3-methylimidazolium hexafluorophosphate ([bmim]PF₆) (Fig. 2) can be used to immobilise a palladium(0) catalyst and act as a co-solvent with diethyl ether in the palladium-catalysed silylstannation of selected terminal alkynes using trimethyl(tributylstannyl)silane Bu₃SnSiMe₃ [18]. This reaction proceeds in a similar fashion as in tetrahydrofuran (THF) with excellent yields to afford 1-trimethylsilyl-2-tributylstannyl-1Z-alkenes as single isomers (Fig. 1) [13,14]. Use of the ionic liquid allowed recycling of the costly palladium(0) catalyst without loss of activity. This reaction might be considered a “greener” reaction as it exhibits total atom economy, incorporating all atoms of the starting materials into the product with no by-product formation [19]. Ionic liquids have been proposed as ideal reaction media for green chemistry due to their non-volatile nature and ease of reuse. The use of ionic liquids as solvents for the silylstannation of alkynes thus increases the overall “greenness” of the process. Also, the use of a silylstannane expands the scope of organometallic reagents used in ionic liquids since to date most organometallic reagents used in ionic liquids have been part of a transition metal complex.

We report herein a full account of our investigations into the palladium(0)-catalysed silylstannation reactions of terminal alkynes in ionic liquids. Reactions between a variety of terminal alkynes with two silylstannane reagents in two different ionic liquids have been demonstrated. The robust nature of this system regarding the recyclability of the immobilised catalyst has also been shown.

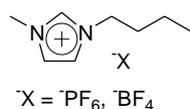


Fig. 2. Ionic liquids used in this study [bmim]PF₆ and [bmim]BF₄.

2. Experimental

2.1. General details

Synthesis and reactions of trialkyl(trialkylstannyl)silanes were performed in oven-dried glassware that was cooled under vacuum and released to a nitrogen atmosphere. THF and Et₂O that were used in the synthesis and reactions of trialkyl(trialkylstannyl)silanes were dried and distilled over potassium/benzophenone immediately prior to use. Dichloromethane was dried and distilled over calcium hydride. Pyridine and diisopropylamine were dried over and distilled onto potassium hydroxide pellets. Thionyl chloride was distilled from quinoline. Ionic liquids [20,21], Bu₃SnSiMe₂Ph [12,15], 6-chlorohex-1-yne [22], and 2-(5-hexynyloxy)tetrahydro-2H-pyran [23] were synthesised and purified before use according to literature procedures. All other reagents were used as received from Aldrich. Column chromatography was performed using Kieselgel 60, 230–400 mesh silica gel. Thin-layer chromatography was performed using aluminium-backed plates coated with Kieselgel 60 F254; plates were visualised under ultraviolet lamp and/or using 5% phosphomolybdic acid in ethanol. Silylstannation reactions were heated on a Mirak Thermolyne temperature controlled hotplate. Low temperatures for trialkyl(trialkylstannyl)silane syntheses were maintained by an FTS Systems cooling apparatus. Gas chromatography (GC)–mass spectrometry was performed using a Varian 3800 gas chromatograph equipped with a flame ionisation detector and a Varian Saturn 2000 electron impact/ion trap spectrometer. Nuclear magnetic resonance spectra were recorded on a Bruker 250 MHz spectrometer at the Atlantic Regional Magnetic Resonance Centre. These spectra were recorded using CDCl₃ solutions and chemical shifts are reported in parts per million referenced to tetramethylsilane unless otherwise stated. The melting point of 1-*n*-butyl-3-methylimidazolium chloride ([bmim]Cl) was measured using a Mettler FP85 differential scanning calorimetry cell in conjunction with a Mettler FP80 central processing unit at 2 °C/min between 50 and 100 °C.

2.2. Synthesis of ionic liquids

2.2.1. 1-*n*-Butyl-3-methylimidazolium chloride

1-Methylimidazole (40 ml, 0.50 mol) and 1-chlorobutane (90 ml, 0.86 mol) were refluxed for 18 h, after which time excess 1-chlorobutane was decanted off of the newly-formed viscous tan-coloured lower layer. This lower layer was washed with ethyl acetate (EtOAc, 3 × 100 ml) then heated under vacuum at 80 °C for 6 h. An off-white solid formed upon cooling, mp 68.6 °C (81.43 g, 0.466 mol, 93%). ¹H NMR: δ 0.75 (t, 3H, N–CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.17 (sextet, 2H, N–CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.70 (quintet, 2H, N–CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 3.93 (s, 3H, N–CH₃), 4.14 (t, 2H, N–CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 7.41 (br s, 1H, H4/H5), 7.58 (br s, 1H, H4/H5),

10.36 (s, 1H, H₂). ¹³C NMR: δ 13.3, 19.3, 32.0, 36.4, 49.5, 122.0, 123.7, 137.5.

2.2.2. 1-*n*-Butyl-3-methylimidazolium hexafluorophosphate

[bmim]Cl (87.95 g, 0.504 mol) was dissolved in water (150 ml) and cooled in an ice bath. A 60% aqueous solution of HPF₆ (74.5 ml, 0.506 mol) was added dropwise over 20 min as a lower tan-coloured layer formed exothermically. The mixture was stirred for 24 h, after which time the upper aqueous phase was decanted. The lower ionic liquid phase was washed with water (10 × 100 ml) after which the washings were pH neutral. After heating under vacuum at 70 °C for 6 h the ionic liquid was obtained as a clear tan oil (96.26 g, 0.339 mol, 67%). ¹H NMR (acetone-*d*₆): δ 0.94 (t, 3H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.38 (sextet, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.92 (quintet, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 4.03 (s, 3H, N-CH₃), 4.34 (t, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 7.67 (br s, 1H, H₄/H₅), 7.72 (br s, 1H, H₄/H₅), 8.91 (s, 1H, H₂). ¹³C NMR (acetone-*d*₆): δ 13.7, 19.9, 32.7, 36.6, 50.2, 123.4, 124.8, 137.3.

2.2.3. 1-*n*-Butyl-3-methylimidazolium tetrafluoroborate ([bmim]BF₄)

[bmim]Cl (30.76 g, 0.176 mol) was dissolved in water (150 ml) to which a 48% aqueous solution of HBF₄ (23.0 ml, 0.176 mol) was added. The solution stirred for 72 h after which time the water was evaporated under reduced pressure. Heating under vacuum at 70 °C for 6 h afforded the ionic liquid as a clear tan oil (38.87 g, 0.172 mol, 98%). ¹H NMR (acetone-*d*₆): δ 0.93 (t, 3H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.37 (sextet, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 1.91 (quintet, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.32 Hz), 4.03 (s, 3H, N-CH₃), 4.34 (t, 2H, N-CH₂CH₂CH₂CH₃, ³J = 7.3 Hz), 7.69 (br s, 1H, H₄/H₅), 7.75 (br s, 1H, H₄/H₅), 9.01 (s, 1H, H₂). ¹³C NMR (acetone-*d*₆): δ 13.7, 19.9, 32.8, 36.5, 50.1, 123.4, 124.7, 137.6.

2.3. Synthesis of dimethylphenyl(tributylstannyl)silane

Dry THF (50 ml) was injected into a dry flask followed by freshly distilled diisopropylamine (3.08 ml, 22.0 mmol). This was cooled to -10 °C and a 1.6 M hexanes solution of butyllithium (13.75 ml, 22.0 mmol) was injected dropwise. After stirring for 10 min, Bu₃SnH (5.38 ml, 20.0 mmol) was injected dropwise. This stirred at 0 °C for 45 min, after which time chlorodimethylphenylsilane (3.69 ml, 22.0 mmol) was injected dropwise. The solution was allowed to warm to room temperature and stir for 1 h, after which time GC-FID analysis of a water-quenched aliquot showed almost complete reaction. The solvent was evaporated under reduced pressure and the resulting cloudy white oil was filtered through celite and washed with Et₂O. After evaporating the Et₂O under reduced pressure, the yellow oil was purified via short-path distillation under vacuum (~0.1 mmHg), the

product coming over at 160–165 °C as a clear colourless oil (5.93 g, 13.9 mmol, 70%). ¹H NMR: δ 0.54 (s, 6H, Si(CH₃)₂), 0.85–0.92 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.23–1.49 (m, 12H, Sn(CH₂CH₂CH₂CH₃)₃), 7.34–7.51 (m, 5H, ArH). ¹³C NMR: δ -0.2, 8.3, 13.8, 27.7, 30.3, 128.0, 128.5, 133.7, 141.5. MS (EI) *m/z* (rel. int. %): 369 (11), 311 (19), 255 (100), 177 (15), 135 (68), 75 (9), 43 (14).

2.4. Synthesis of 6-chlorohex-1-yne

5-Hexyn-1-ol (1.00 ml, 9.1 mmol) was injected into a flask containing dry Et₂O (15 ml) followed by dry pyridine (0.74 ml, 9.1 mmol) and stirred in an ice bath for 30 min. Thionyl chloride (0.80 ml, 11.0 mmol) was injected dropwise; the flask was fitted with a dry condenser and the cloudy white mixture heated to reflux under nitrogen overnight. GC-FID analysis of a reaction aliquot confirmed complete reaction, at which time the brown solution was poured into water (50 ml). The mixture was extracted with Et₂O (30 ml). The Et₂O layer was washed with water (2 × 50 ml), dried over anhydrous MgSO₄, filtered and concentrated to afford a dark oil. This was purified via flash chromatography (10:1 hexanes/EtOAc) to afford the product as a volatile clear light brown oil (0.436 g, 3.7 mmol, 41%). ¹H NMR: δ 1.68 (quintet, 2H, H₄/H₅, ³J = 6.5 Hz), 1.91 (quintet, 2H, H₄/H₅, ³J = 6.5 Hz), 1.97 (t, 1H, H₁, ⁴J = 2.6 Hz), 2.25 (dt, 2H, H₃, ³J = 6.5 Hz, ⁴J = 2.6 Hz), 3.57 (t, 2H, H₆, ³J = 6.5 Hz). ¹³C NMR: δ 17.7, 25.6, 31.4, 44.5, 68.9, 83.7. MS (EI) *m/z* (rel. int. %): 115 (2), 90 (33), 88 (100), 81 (59), 79 (97), 65 (33), 53 (65), 41 (50).

2.5. Synthesis of (±)-2-(5-hexynyloxy)tetrahydro-2H-pyran

p-Toluenesulphonic acid (0.13 g, 0.68 mmol) was dissolved in dry dichloromethane (10 ml). 5-Hexyn-1-ol (1.50 ml, 13.6 mmol) was injected to the solution, followed by 3,4-dihydro-2H-pyran (2.50 ml, 27.4 mmol). The pink solution was stirred at room temperature and turned dark green after 10 min. When the reaction was complete by TLC analysis, the solvent was evaporated and the resulting dark green oil was purified via flash chromatography (10:1 hexanes/EtOAc), affording the product as a clear colourless oil (2.10 g, 11.5 mmol, 85%). ¹H NMR: δ 1.48–1.80 (m, 10H, H_b, H_c, H_d, H_e, H_f), 1.91 (s, 1H, H_j), 2.23 (t, 2H, H_i), 3.37–3.51, 3.71–3.87 (m, 4H, H_a, H_f), 4.56 (t, 1H, H_e). ¹³C NMR: δ 18.4, 19.8, 25.6, 25.7, 29.0, 30.9, 62.5, 67.1, 68.6, 84.6, 99.0. MS (EI) *m/z* (rel. int. %): 181 (1), 125 (3), 111 (4), 101 (12), 85 (100), 79 (29), 67 (29), 55 (20), 41 (27).

2.6. Silylstannation of terminal alkynes

2.6.1. (*Z*)-1-Phenyl-1-(tributylstannyl)-2-(trimethylsilyl)ethene (representative procedure)

Ionic liquid ([bmim]PF₆ or [bmim]BF₄, 1.0 ml) was heated in a dry flask under vacuum at 70 °C for 4 h. After

releasing the vacuum to nitrogen, the flask was transferred to an argon glove box where Pd(PPh₃)₄ (0.058 g, 0.05 mmol for 5%, 0.012 g, 0.01 mmol for 1%) was weighed and added. After stirring to suspend the palladium, the reaction vessel was removed from the glove box. Bu₃SnSiMe₃ (0.42 ml, 1.2 mmol) was injected via needle and syringe, followed by phenylacetylene (0.11 ml, 1.0 mmol) and dry Et₂O (5.0 ml). A dry reflux condenser was connected and the reaction was heated under nitrogen in a 70 °C oil bath for 36 h. Once the reaction was complete by GC–FID analysis of a reaction aliquot, the reaction was cooled and the upper Et₂O phase was removed via needle and syringe. The ionic liquid was washed with dry Et₂O (8 × 8 ml) under nitrogen using needles and syringes. The Et₂O extracts were combined and solvent was evaporated under reduced pressure. The resulting oil was purified via flash chromatography (hexanes) to afford the product as a clear colourless oil (0.46 g, 0.99 mmol, 99%). ¹H NMR: δ 0.32 (s, 9H, Si(CH₃)₃), 0.98–1.10 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.34–1.65 (m, 12H, Sn(CH₂CH₂CH₂CH₃)₃), 6.71 (s, 1H, C=C–H, ^{sat}J_{SnH} = 160, 168 Hz), 7.13–7.16 (m, 2H, ArH), 7.26–7.32 (m, 1H, ArH), 7.38–7.41 (m, 2H, ArH). ¹³C NMR: δ 0.3, 12.1, 13.8, 27.5, 29.2, 125.6, 126.0, 128.0, 148.5, 152.0, 166.2. MS (EI) *m/z* (rel. int. %): 451 (6), 409 (96), 353 (49), 295 (15), 235 (31), 175 (43), 121 (13), 73 (100), 45 (23).

2.6.2. (Z)-2-(Tributylstannyl)-1-(trimethylsilyl)dec-1-ene

Prepared as above, clear yellow oil (0.484 g, 0.97 mmol, 97%). ¹H NMR: δ 0.09 (s, 9H, Si(CH₃)₃), 0.79–1.58 (m, 42H, SnBu₃, C₇H₁₅CH₂–C=C), 2.20–2.33 (m, 2H, C₇H₁₅CH₂–C=C), 6.32 (s, 1H, C=C–H, ^{sat}J_{SnH} = 176, 184 Hz). ¹³C NMR: δ 0.4, 8.0, 11.4, 13.8, 14.3, 22.8, 27.7, 29.4, 29.7, 30.2, 30.5, 32.1, 47.8, 143.3, 166.0. MS (EI) *m/z* (rel. int. %): 488 (7), 444 (86), 390 (57), 334 (17), 291 (3), 235 (28), 179 (36), 121 (9), 73 (100).

2.6.3. (Z)-5-(Tributylstannyl)-6-(trimethylsilyl)hex-5-en-1-ol

Prepared as above, cloudy white oil (0.412 g, 0.89 mmol, 89%). ¹H NMR: δ 0.09 (s, 9H, Si(CH₃)₃), 0.87–0.99 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.25–1.68 (m, 17H, Sn(CH₂CH₂CH₂CH₃)₃, HOCH₂CH₂CH₂CH₂–C=), 2.30 (t, 2H, HOCH₂CH₂CH₂CH₂–C=C), 3.64 (m, 2H, HOCH₂CH₂CH₂CH₂–C=C), 6.34 (s, 1H, C=C–H, ^{sat}J_{SnH} = 172, 180 Hz). ¹³C NMR: δ 0.2, 11.2, 13.6, 25.9, 27.5, 29.2, 32.3, 47.1, 62.9, 143.7, 165.1. MS (EI) *m/z* (rel. int. %): 447 (2), 405 (100), 347 (5), 291 (4), 235 (14), 193 (39), 135 (10), 73 (56), 44 (24).

2.6.4. (±)-(Z)-2-(5-(Tributylstannyl)-6-(trimethylsilyl)-5-hexenyloxy)tetrahydro-2H-pyran

Prepared as above, clear colourless oil (0.538 g, 0.99 mmol, 99%). ¹H NMR: δ 0.08 (s, 9H, Si(CH₃)₃), 0.86–0.95 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.27–1.65 (m, 22H, Sn(CH₂CH₂CH₂CH₃)₃, H_b, H_c, H_d, H_e, H_f), 2.29 (t, 2H, H_i), 3.30–3.90 (m, 4H, H_a, H_f), 4.58 (t, 1H, H_e), 6.33

(s, 1H, C=C–H, ^{sat}J_{SnH} = 175, 183 Hz). ¹³C NMR: δ 0.22, 11.2, 13.6, 19.6, 25.5, 26.6, 27.5, 29.2, 29.3, 30.8, 47.5, 62.3, 67.6, 98.9, 143.7, 165.5.

2.6.5. (Z)-6-Chloro-2-(tributylstannyl)-1-(trimethylsilyl)hex-1-ene

Prepared as above, clear colourless oil (0.327 g, 0.68 mmol, 68%). ¹H NMR: δ 0.09 (s, 9H, Si(CH₃)₃), 0.86–0.96 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.24–1.50, 1.71–1.77 (m, 16H, Sn(CH₂CH₂CH₂CH₃)₃, ClCH₂CH₂CH₂CH₂–C=C), 2.28 (t, 2H, ClCH₂CH₂CH₂CH₂–C=C, ³J = 6.7 Hz), 3.52 (t, 2H, ClCH₂CH₂CH₂CH₂–C=C, ³J = 6.7 Hz), 6.33 (s, 1H, C=C–H, ^{sat}J_{SnH} = 172, 180 Hz). ¹³C NMR: δ 0.2, 11.2, 13.7, 27.0, 27.5, 29.2, 32.1, 45.0, 46.6, 144.1, 164.8. MS (EI) *m/z* (rel. int. %): 465 (1), 423 (37), 387 (67), 331 (12), 269 (100), 233 (24), 177 (27), 121 (13), 73 (73), 45 (23).

2.6.6. (Z)-2-(Dimethylphenylsilyl)-1-phenyl-1-(tributylstannyl)ethene

Prepared as above using Bu₃SnSiMe₂Ph (0.510 g, 1.2 mmol) instead of Bu₃SnSiMe₃, product obtained as a clear colourless oil (0.516 g, 0.98 mmol, 98%). ¹H NMR: δ 0.11 (s, 6H, Si(CH₃)₂), 0.33–0.50 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 0.78–0.99 (m, 12H, Sn(CH₂CH₂CH₂CH₃)₃), 6.41 (s, 1H, C=C–H, ^{sat}J_{SnH} = 156, 164 Hz), 6.70–7.04, 7.24–7.28 (m, 10H, ArH). ¹³C NMR: δ –0.5, 12.0, 13.7, 27.4, 29.1, 125.8, 126.0, 127.9, 128.1, 129.1, 134.2, 139.6, 146.0, 152.0, 169.0. MS (EI) *m/z* (rel. int. %): 513 (1), 471 (100), 414 (7), 357 (3), 291 (2), 233 (6), 177 (15), 135 (40).

2.6.7. (Z)-1-(Dimethylphenylsilyl)-2-(tributylstannyl)dec-1-ene

Prepared as above, clear colourless oil (0.439 g, 0.78 mmol, 78%). ¹H NMR: δ 0.34 (s, 6H, Si(CH₃)₂), 0.73–0.88, 1.18–1.41 (m, 42H, SnBu₃, C₇H₁₅CH₂–C=C), 2.29–2.35 (m, 2H, C₇H₁₅CH₂–C=C), 6.50 (s, 1H, C=C–H, ^{sat}J_{SnH} = 170, 176 Hz), 7.30–7.35 (m, 3H, ArH), 7.49–7.54 (m, 2H, ArH). ¹³C NMR: δ –0.6, 11.1, 13.7, 14.2, 22.7, 27.5, 28.0, 29.2, 29.4, 29.6, 31.0, 31.9, 47.8, 127.7, 128.8, 134.0, 140.1, 140.7, 168.9. MS (EI) *m/z* (rel. int. %): 550 (1), 508 (100), 452 (8), 394 (3), 233 (7), 177 (17), 135 (37).

2.6.8. (Z)-6-(Dimethylphenylsilyl)-5-(tributylstannyl)hex-5-en-1-ol

Prepared as above, cloudy oil (0.325 g, 0.62 mmol, 62%). ¹H NMR: δ 0.36 (s, 6H, Si(CH₃)₂), 0.81–0.90 (m, 15H, Sn(CH₂CH₂CH₂CH₃)₃), 1.19–1.64 (m, 17H, Sn(CH₂CH₂CH₂CH₃)₃, HOCH₂CH₂CH₂CH₂–C=C), 2.37 (t, 2H, HOCH₂CH₂CH₂CH₂–C=C), 3.65–3.67 (m, 2H, HOCH₂CH₂CH₂CH₂–C=C), 6.53 (s, 1H, C=C–H, ^{sat}J_{SnH} = 170, 178 Hz), 7.31–7.55 (m, 5H, ArH). ¹³C NMR: δ –0.4, 11.4, 13.8, 26.2, 27.6, 29.5, 32.6, 47.4, 63.0, 127.9, 129.0, 134.4, 139.6, 141.5, 168.4.

2.6.9. (\pm)-(Z)-2-(6-(Dimethylphenylsilyl)-5-(tributylstannyl)-5-hexenyloxy)tetrahydro-2H-pyran

Prepared as above, clear colourless oil (0.492 g, 0.83 mmol, 83%). ^1H NMR: δ 0.36 (s, 6H, $\text{Si}(\text{CH}_3)_2$), 0.77–0.93 (m, 15H, $\text{Sn}(\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3)_3$), 1.18–1.72 (m, 22H, $\text{Sn}(\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3)_3$, H_b , H_c , H_d , H_g , H_h), 2.37 (t, 2H, H_i), 3.38–3.90 (m, 4H, H_a , H_f), 4.58 (t, 1H, H_e), 6.53 (s, 1H, $\text{C}=\text{C}-\text{H}$, $^{\text{sat}}J_{\text{SnH}} = 177, 185$ Hz), 7.26–7.55 (m, 5H, ArH). ^{13}C NMR: δ -0.5, 11.2, 13.8, 19.8, 25.7, 26.7, 27.6, 29.3, 29.5, 30.9, 47.6, 62.3, 67.5, 98.9, 127.8, 128.9, 134.1, 140.0, 141.2, 168.6.

3. Results and discussion

3.1. Addition of $\text{Bu}_3\text{SnSiMe}_3$ to terminal alkynes in ionic liquids

The ionic liquid 1-*n*-butyl-3-methylimidazolium hexafluorophosphate was investigated as a solvent during the initial stages of our study of addition reactions of trialkyl(trialkylstannyl)silanes to terminal alkynes due to its prevalent use in a variety of palladium-catalysed reactions. 1-*n*-Butyl-3-methylimidazolium tetrafluoroborate was also used in the course of our studies of this reaction. These ionic liquids are perhaps the two most widely used in current literature. They are liquids below room temperature, they have a wide liquid temperature range, they are moisture- and heat-stable, and they are immiscible with a number of organic solvents. They are commercially available but can be easily synthesised for a small fraction of the cost [20,21]. For example, 1 l of 1-methylimidazole cost \$251, 1 l of 1-chlorobutane cost \$88, and 500 g of 60% HPF_6 cost \$70 from Aldrich in the 2003–2004 catalogue, allowing $[\text{bmim}]\text{PF}_6$ to be synthesised for less than 5% of the cost of its purchase (\$93 for 5 g), based on raw material price. Several research groups, including our own, have investigated various methods of ionic liquid preparation for product purity, especially with regard to halide contamination [24,25]. The methods used in this paper appear to provide some of the cleanest ionic liquids.

The catalyst tetrakis(triphenylphosphine)palladium(0) $\text{Pd}(\text{PPh}_3)_4$ was chosen based on previous studies by Chenard and van Zyl [13] demonstrating its activity in the addition of trialkyl(trialkylstannyl)silanes to terminal alkynes. This group attempted reactions using different palladium(0) and palladium(II) catalysts as well as molybdenum-, rhodium- and platinum-containing catalysts and concluded that $\text{Pd}(\text{PPh}_3)_4$ was by far the superior catalyst. These results on catalyst activity with terminal alkynes were supported by the work of other groups [14,15] as well by a reaction we performed using a palladium(II) catalyst with no success as will be discussed further on.

The trialkyl(trialkylstannyl)silane used in our original investigation of these reactions in $[\text{bmim}]\text{PF}_6$, trimethyl-(tributylstannyl)silane ($\text{Bu}_3\text{SnSiMe}_3$) was chosen due to its

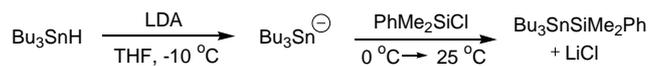


Fig. 3. Synthesis of dimethylphenyl(tributylstannyl)silane [12].

commercial availability and its general use in the literature. To increase the scope of our methodology, further investigations using an additional trialkyl(trialkylstannyl)silane were conducted. Dimethylphenyl(tributylstannyl)silane ($\text{Bu}_3\text{SnSiMe}_2\text{Ph}$) was easily synthesised via generation of a tributyltin anion followed by a quench with chlorodimethylphenylsilane (Fig. 3). This trialkyl(trialkylstannyl)silane has been used in addition reactions with alkynes to generate products more easily protodesilylated than their trimethylsilyl counterparts [15].

Our initial attempts at coupling phenylacetylene with excess $\text{Bu}_3\text{SnSiMe}_3$ were performed in neat $[\text{bmim}]\text{PF}_6$ at 70°C without the addition of a co-solvent. While gas chromatographic analysis showed no phenylacetylene present after 18 h, isolated yields were less than quantitative (i.e. 66%). It was observed that material was condensing on the walls of the flask during the reaction and was not coming in contact with the palladium/ionic liquid phase. For subsequent reactions the flask was fitted with a dry reflux condenser and diethyl ether was used as a co-solvent to “wash” the reagents down into the ionic liquid phase as the ether refluxed in the 70°C oil bath. Diethyl ether was chosen due to its immiscibility with the ionic liquid and its ability to dissolve the starting materials and products. This resulted in more favourable isolated yields. $\text{Bu}_3\text{SnSiMe}_3$ was added to five terminal alkynes of differing functionality in the presence of 5 or 1 mol% $\text{Pd}(\text{PPh}_3)_4$ in $[\text{bmim}]\text{PF}_6$ and $[\text{bmim}]\text{BF}_4$ ionic liquids with diethyl ether as a co-solvent in a 70°C oil bath, the results of which are presented in Table 1. All reactions were monitored by gas chromatography and were deemed complete after the disappearance of the alkyne starting material peak.

Table 1
Results of $\text{Bu}_3\text{SnSiMe}_3$ addition to terminal alkynes $\text{R}-\text{C}\equiv\text{CH}$ in $[\text{bmim}]\text{PF}_6/\text{Et}_2\text{O}$ and $[\text{bmim}]\text{BF}_4/\text{Et}_2\text{O}$ in the presence of $\text{Pd}(\text{PPh}_3)_4$ heating at 70°C

Entry	R-group of alkyne	Ionic liquid	Pd (mol%)	Reaction time (h)	Isolated yield (%)
1	Ph	$[\text{bmim}]\text{PF}_6$	5	36	100
2	Ph	$[\text{bmim}]\text{PF}_6$	1	17	99
3	Ph	$[\text{bmim}]\text{BF}_4$	5	36	100
4	$(\text{CH}_2)_7\text{CH}_3$	$[\text{bmim}]\text{PF}_6$	5	15	97
5	$(\text{CH}_2)_7\text{CH}_3$	$[\text{bmim}]\text{PF}_6$	1	72	100
6	$(\text{CH}_2)_7\text{CH}_3$	$[\text{bmim}]\text{BF}_4$	5	120	82
7	$(\text{CH}_2)_4\text{OH}$	$[\text{bmim}]\text{PF}_6$	5	18	89
8	$(\text{CH}_2)_4\text{OH}$	$[\text{bmim}]\text{PF}_6$	1	24	87
9	$(\text{CH}_2)_4\text{OH}$	$[\text{bmim}]\text{BF}_4$	5	24	61
10	$(\text{CH}_2)_4\text{OTHP}$	$[\text{bmim}]\text{PF}_6$	5	84	99
11	$(\text{CH}_2)_4\text{Cl}$	$[\text{bmim}]\text{PF}_6$	5	120	68
12	$(\text{CH}_2)_4\text{Cl}$	$[\text{bmim}]\text{PF}_6$	1	144	22

Reaction conditions: 1 mmol alkyne, 1.2 mmol $\text{Bu}_3\text{SnSiMe}_3$, 1.0 ml ionic liquid, 5.0 ml Et_2O , 70°C oil bath; THP: tetrahydropyranyl.

As can be seen from the data presented, the addition of $\text{Bu}_3\text{SnSiMe}_3$ to the five terminal alkynes proceeded in good to excellent yields under all conditions tested. All reactions proceeded in excellent yield (i.e. >95%) when reaction aliquots were assessed by gas chromatography as evidenced by the complete disappearance of the alkyne substrate peak. The GC analyses were supported in most cases by equally high isolated yields after column chromatography, separating the product from excess $\text{Bu}_3\text{SnSiMe}_3$. All reactions proceeded to give only a single product isomer, the 1,2-bismetallated *Z*-alkene containing the trimethylsilyl group on the terminal carbon and the tributylstannyl group on the internal carbon (Fig. 2). This was confirmed by the value of the coupling constant between the tin atom and the terminal vinylic proton. This three-bond coupling constant (3J) occurs from coupling between the vinylic proton and the two abundant NMR-active isotopes of tin, ^{117}Sn and ^{119}Sn , both of which have a spin of 1/2 and are 7.68 and 8.59% abundant, respectively [26]. ^{115}Sn also has a spin of 1/2 but is not abundant enough to be easily detected (0.34%). The coupling constant is known to be around 180 Hz for *trans*-coupling and around 100 Hz for *cis*- and geminal-coupling [13]. The products from the reactions described in Table 1 all have 3J coupling constants between 160 and 184 Hz.

The isolated yields of these reactions compare well with literature values, being slightly higher in most cases [13–15]. In many cases the reaction times are somewhat lengthy, being more than 24 h; however, this is typical of these reactions. As well, these reactions were allowed to proceed to completion, based on absence of starting material, as monitored by gas chromatography before products were isolated. Phenylacetylene afforded quantitative yields of product after 17 h with 1% Pd (Table 1, Entry 2), somewhat longer than the 3 h required to obtain a 91% yield in refluxing THF [13]. 1-Decyne gave a 97% yield after 15 h with 5% Pd (Table 1, Entry 4), while a 52% yield had previously been obtained with the analogous alkyne 1-hexyne after 20 h under solventless conditions at 80 °C [14]. The 5-hexyn-1-ol addition product was isolated in 89% yield after 18 h (Table 1, Entry 7) with 5% Pd while the adduct from the analogous alkyne 4-pentyn-1-ol was previously obtained in 88% yield after refluxing in THF for 72 h [13]. The tetrahydropyranyl (THP) ether prepared from 5-hexyn-1-ol and 2,3-dihydro-2*H*-pyran [23] (2-(5-hexynyloxy)tetrahydro-2*H*-pyran) was coupled with $\text{Bu}_3\text{SnSiMe}_3$ to afford the product in 99% yield after 84 h (Table 1, Entry 10). For comparison, a 92% yield had previously been obtained with the THP ether of the analogous alkyne 3-butyn-1-ol after 48 h in refluxing THF [13]. 5-Hexyn-1-ol was also used as a starting material to generate 6-chlorohex-1-yne using thionyl chloride and pyridine [22]. 6-Chlorohex-1-yne gave the addition product in somewhat lower yield, 68% after 120 h (Table 1, Entry 11). This is comparable to the 80% isolated yield using the analogous alkyne 5-chloropent-1-yne after 72 h in refluxing

THF, indicating that these chloroalkynes are less reactive [13].

As can be seen from the results in Table 1, the reactions proceed better with 5 mol% Pd than they do with 1 mol% Pd. Although this may be the intuitive result of increasing the amount of catalyst, it demonstrates that in general the reaction proceeds smoothly with 1 mol% Pd to give comparable yields to those obtained from reactions using 5 mol% Pd. The reactions with less catalyst simply require longer reaction times. It may be that the observed differences in yields between the two catalyst loadings are results of catalyst poisoning or deactivation.

As mentioned earlier, $\text{Pd}(\text{PPh}_3)_4$ was chosen as the catalyst as a result of previous studies by other groups showing it to display optimal activity [13,14]. We tried using bis(acetonitrile)palladium(II) chloride ($(\text{CH}_3\text{CN})_2\text{PdCl}_2$) as a palladium(II) catalyst for the reaction with phenylacetylene. After 24 h at room temperature in a [bmim]PF₆/Et₂O system with 5 mol% catalyst very little reaction had occurred. After heating for 48 h in a 70 °C oil bath very little product had formed. A large amount of $\text{Bu}_3\text{SnSiMe}_3$ remained in addition to an appreciable amount of hexabutyliditin, $\text{Bu}_3\text{SnSnBu}_3$, having been formed after extended reaction times. This by-product is likely the result of a palladium-catalysed disproportionation reaction known to occur with trimethyl(trimethylstannyl)silane during reaction with unreactive alkynes resulting in the formation of hexamethyldisilane and hexamethyldistannane [13].

The reaction between phenylacetylene and $\text{Bu}_3\text{SnSiMe}_3$ catalysed by $\text{Pd}(\text{PPh}_3)_4$ has previously been shown to proceed at room temperature in THF [13]. When we performed the same reaction in [bmim]PF₆ at room temperature without Et₂O as a co-solvent, no reaction was observed after 18 h (our initial results showed that these reactions proceed smoothly in neat [bmim]PF₆ at 70 °C and that Et₂O is not necessary to promote the reaction [18]). After the addition of Et₂O and heating in a 70 °C oil bath, complete reaction was observed overnight. The ionic liquid phase was a light yellow colour, showing no deposition of palladium black. The reactions in THF started with the light orange colour of the starting palladium catalyst and quickly turned black, suggesting that palladium black deposited. These reactions are thus very slow in ionic liquids alone at room temperature and require heating to increase the rate; however, the catalyst appears to be more stable demonstrating potential recyclability. A kinetic study was undertaken to measure the initial reaction rate between phenylacetylene and $\text{Bu}_3\text{SnSiMe}_3$ in [bmim]PF₆ in the presence of 5 mol% $\text{Pd}(\text{PPh}_3)_4$ heating in a 70 °C oil bath. After 8 h, however, the reaction had only proceeded to 4.5% completion. It was evident from this that there was no rate enhancement of the reaction resulting from the use of ionic liquids as the same reaction was complete in 3 h in refluxing THF; hence, no further kinetic measurements were performed on the ionic liquid systems used in our study.

Table 2

Results of $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ addition to terminal alkynes $\text{R}-\text{C}\equiv\text{CH}$ in $[\text{bmim}]\text{PF}_6/\text{Et}_2\text{O}$ and $[\text{bmim}]\text{BF}_4/\text{Et}_2\text{O}$ in the presence of 5% $\text{Pd}(\text{PPh}_3)_4$ heating at 70°C

Entry	R-group on alkyne	Ionic liquid	Reaction time (h)	Isolated yield (%)
1	Ph	$[\text{bmim}]\text{PF}_6$	96	98
2	Ph	$[\text{bmim}]\text{BF}_4$	96	97
3	$(\text{CH}_2)_7\text{CH}_3$	$[\text{bmim}]\text{PF}_6$	108	78
4	$(\text{CH}_2)_7\text{CH}_3$	$[\text{bmim}]\text{BF}_4$	144	62
5	$(\text{CH}_2)_4\text{OH}$	$[\text{bmim}]\text{PF}_6$	19	62
6	$(\text{CH}_2)_4\text{OTHP}$	$[\text{bmim}]\text{PF}_6$	168	83

Reaction conditions: 1.0 mmol alkyne, 1.2 mmol $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$, 1.0 ml ionic liquid, 5.0 ml Et_2O , 70°C oil bath; THP: tetrahydropyranyl.

3.2. Addition of $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ to terminal alkynes in ionic liquids

The slightly larger silylstannane $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ was also used in these reactions in both ionic liquids. The results of the addition of $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ to four alkynes in the presence of 5% Pd are presented in Table 2. As with the less bulky trimethyl(tributylstannyl)silane, the majority of the reactions proceeded in good to excellent yields. These reactions were also monitored by gas chromatography for the disappearance of the alkyne substrate peak. As well the reaction proceeded regio- and stereoselectively, giving the 1,2-bismetallated *Z*-alkene containing the trialkylsilyl group on the terminal carbon and the tributylstannyl group on the internal carbon. The isomeric natures of the products were again confirmed by the values of the tin–vinyl proton 3J coupling constants corresponding with *trans*-coupling, the values being between 156 and 185 Hz.

As with the products from the coupling of $\text{Bu}_3\text{SnSiMe}_3$, the isolated yields of products from reactions with $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ were generally similar to those obtained by other researchers who used THF as a solvent [15]. A 98% yield of the addition product from phenylacetylene was obtained in the ionic liquid after 96 h (Table 2, Entry 1), while a 95% yield had previously been obtained after only 3 h in refluxing THF [15]. A 78% yield of the addition product from 1-decyne was obtained from the ionic liquid after 108 h (Table 2, Entry 3), which is comparable to the 80% yield obtained previously with 1-hexyne, an analogous alkyne, after 120 h [15]. The 5-hexyn-1-ol addition product was obtained in 62% yield after only 19 h in the ionic liquid (Table 2, Entry 5) while an 81% yield of product was reported with the analogous alkyne 3-butyne-1-ol after 120 h in refluxing THF [15]. 2-(5-Hexynyloxy)tetrahydro-2*H*-pyran reacted to produce an 83% yield of addition product after 168 h in the ionic liquid (Table 2, Entry 6), which was similar to the 82% yield reported with the analogous THP ether of 3-butyne-1-ol after 120 h in refluxing THF [15]. It appears as though the reactions using $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ are slower than those using $\text{Bu}_3\text{SnSiMe}_3$ as the product yields are slightly lower and the reaction times are longer. This is likely not due to the use of an ionic liquid since the same trend is

observed using THF as a solvent [13–15]. Lower yields using $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ may be due to steric factors influencing reactions with the larger dimethylphenylsilyl moiety.

When studying the results in terms of which ionic liquid is a better solvent for the addition of trialkyl(trialkylstannyl)silanes to alkynes, the data shows that $[\text{bmim}]\text{PF}_6$ affords somewhat better yields of products in less time than $[\text{bmim}]\text{BF}_4$. This trend is observed regardless of which trialkyl(trialkylstannyl)silane or alkyne is employed, with the exception of phenylacetylene which has been shown to be exceptionally reactive in these reactions [13]. It thus appears as though the reaction in $[\text{bmim}]\text{BF}_4$ is slower than that in $[\text{bmim}]\text{PF}_6$. The reason for this does not immediately present itself, as these two ionic liquids are very similar in terms of their physical properties. Viscosity differences may be proposed as a factor in the rates of these reactions. If $[\text{bmim}]\text{BF}_4$ were more viscous than $[\text{bmim}]\text{PF}_6$, this may explain the longer reaction times as molecules would take longer to move through the solvent to reach one another to react. However, several groups have measured the viscosities of these ionic liquids (albeit with each obtaining slightly different results), showing them to range from both ionic liquids having almost the same viscosity to $[\text{bmim}]\text{PF}_6$ being about twice as viscous as $[\text{bmim}]\text{BF}_4$ [1]. In addition, ionic liquids generally become much less viscous once organic materials such as reagents or co-solvents are added. Chloride impurities have been shown to increase the viscosity of ionic liquids [24]. These impurities result from incomplete reaction of $[\text{bmim}]\text{Cl}$ with the PF_6^- or BF_4^- source (e.g. NaBF_4 versus HBF_4). Studies have been performed to determine which method of ionic liquid preparation results in the lowest amount of chloride contamination. The acid/base neutralisation method used in this study involving HBF_4 and HPF_6 provides ionic liquid with some of the lowest levels of chloride contamination [24,25]. It is thus unlikely that viscosity differences are responsible for the differences in efficiency of each ionic liquid for these reactions.

Since the $[\text{bmim}]\text{PF}_6$ ionic liquid is “hydrophobic” and $[\text{bmim}]\text{BF}_4$ is water-soluble, it follows that $[\text{bmim}]\text{PF}_6$ would have a lower water content. Although the ionic liquids were dried by heating under vacuum for several hours before use, they still contain a certain amount of water as evidenced by Rogers and co-workers [1]. This group showed that after heating under vacuum for 4 h at 70°C $[\text{bmim}]\text{BF}_4$ contained 4530 ppm water, about 7.5 times the amount held by $[\text{bmim}]\text{PF}_6$ with 590 ppm, showing that $[\text{bmim}]\text{PF}_6$ is not strictly “hydrophobic” as is commonly claimed. The presence of water in both ionic liquids could account for some of the longer reaction times when compared to THF and would also account for the longer reaction time required for $[\text{bmim}]\text{BF}_4$ since it has substantially more bound water than $[\text{bmim}]\text{PF}_6$. Indeed, a silylstannation reaction was performed in $[\text{bmim}]\text{BF}_4$ that had only been dried for 3 h, which after 24 h showed mainly decomposition of $\text{Bu}_3\text{SnSiMe}_3$ (which is moisture-sensitive).

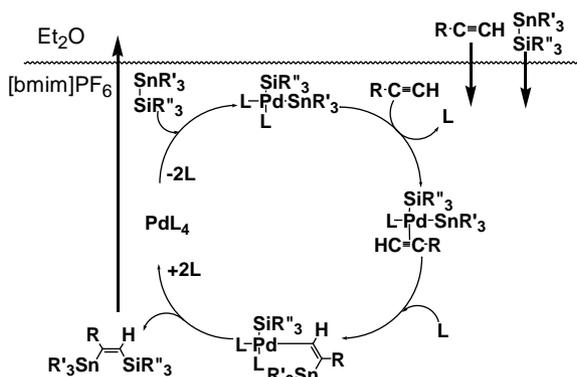


Fig. 4. Proposed reaction sequence and mechanism for palladium-catalysed trialkyl(trialkylstannyl)silane addition to terminal alkynes in ionic liquid/ Et_2O biphasic systems.

3.3. Catalytic cycle

Under biphasic conditions, the trialkyl(trialkylstannyl)silane and alkyne are dissolved in the upper Et_2O phase from which they partition into the lower ionic liquid phase containing the palladium catalyst. The reaction proceeds in the ionic liquid, after which the products partition back into the Et_2O phase. The starting materials and products are very soluble in Et_2O and are extracted quite easily from the ionic liquid. The final washings of the ionic liquids are always devoid of products or starting materials by gas chromatography. As well, the palladium catalyst resides in the ionic liquid phase preferentially and is likely not extracted during product isolation with Et_2O , as evidenced by several researchers [27–29]. It may be that the reaction products are more soluble in $[\text{bmim}]\text{BF}_4$ than in $[\text{bmim}]\text{PF}_6$ and reside in the $[\text{bmim}]\text{BF}_4$ phase preferentially. If the reactions were inhibited by the build-up of products in the catalytic phase, impeding further reaction and lowering the rate, the reactions would take longer to proceed using the ionic liquid in which the products were more soluble. It is likely that the catalytic reaction proceeds in the ionic liquid phase since the palladium catalyst resides there (Fig. 4).

The mechanism of the catalytic cycle depicted in Fig. 4 has been developed based on experimental evidence, on the proposed mechanism of the closely related bis-silylation of unsaturated molecules, and on a theoretical study using *ab initio* Hartree–Fock calculations to determine the energies of steps during the reaction of the hypothetical silyl-stannane H_3SnSiH_3 catalysed by the hypothetical catalyst $\text{Pd}(\text{PH}_3)_2$ [17,30]. After the silyl-stannane and alkyne partition into the ionic liquid phase, the first step in the cycle is oxidative addition of the silyl-stannane to the palladium(0) species, followed by co-ordination of the alkyne. The next step, regioselective insertion of the alkyne into the palladium–tin bond, is presumed to be the rate-determining step based on calculations. The final step is then reductive elimination of the product to regenerate the palladium(0) species and give the product as a single isomer, which would then dissolve in the upper Et_2O phase.

Chenard and van Zyl [13] have stated that less reactive alkynes give poorer yields of addition product because they are poor ligands for palladium due to steric bulk. This would explain the lower yields obtained with $\text{Bu}_3\text{SnSiMe}_2\text{Ph}$ as this silyl-stannane imposes even more steric bulk around the palladium atom. However, relatively high yields were obtained from reactions using 2-(5-hexyloxy)tetrahydro-2H-pyran and 1-decyne while lower yields were obtained from reactions using 5-hexyn-1-ol and 6-chlorohex-1-yne. 1-Decyne and 2-(5-hexyloxy)tetrahydro-2H-pyran have the largest substituents but are also the least volatile, giving the highest yields. In fact, 6-chlorohex-1-yne was observed to have a relatively high volatility that may have contributed to low isolated yields of its addition products. It may also be that the addition products of 5-hexyn-1-ol and 6-chlorohex-1-yne had greater affinity for the silica gel used during chromatography, complicating purification. The fact that alkynes with variable functionality can be coupled with trialkyl(trialkylstannyl)silanes shows some tolerance of this reaction for different functional groups. Aromatic alkynes, saturated alkynes, and hydroxy-, ether- and chloride-bearing alkynes all coupled with two different trialkyl(trialkylstannyl)silanes in two different ionic liquids in the presence of $\text{Pd}(\text{PPh}_3)_4$.

3.4. Recyclability studies

The ionic liquid/catalyst system was extensively investigated regarding recyclability. In studies performed by other groups using palladium(0) catalysts for allylation reactions, their $[\text{bmim}]\text{PF}_6$ /catalyst systems were processed between successive reactions using a complex purification procedure [31,32]. This process involved washing the ionic liquid with water, dissolving it in ethyl acetate, drying it over sodium sulphate, and evaporating the ethyl acetate to recover the ionic liquid that still contained palladium. The ionic liquid/catalyst system recovered in this manner continuously lost activity over successive cycles. When working with a palladacycle palladium(II) source for the Heck reaction in ionic liquids, Bohm and Herrmann [28] noted that extremely careful drying procedures had to be undertaken in order to obtain optimal activity. They also saw that addition of small amounts of water lowered the catalyst's turnover number and lifetime, indicating that washing the ionic liquid/catalyst system with water as a purification method between successive reactions may be responsible for loss of catalyst activity. Mathews et al. [27], however, found that washing their ionic liquid/ $\text{Pd}(\text{PPh}_3)_4$ catalyst system had no effect on its activity in Suzuki couplings. In fact, Hagiwara et al. [33] found that a water wash was necessary to remove ionic impurities that built up from Heck reactions catalysed by Pd/C that was suspended in the ionic liquid. When they performed a water wash after the fifth cycle, the yield that had been steadily decreasing increased back to a value comparable to that obtained after the first cycle. Many other groups have also found that palladium catalysts can be re-

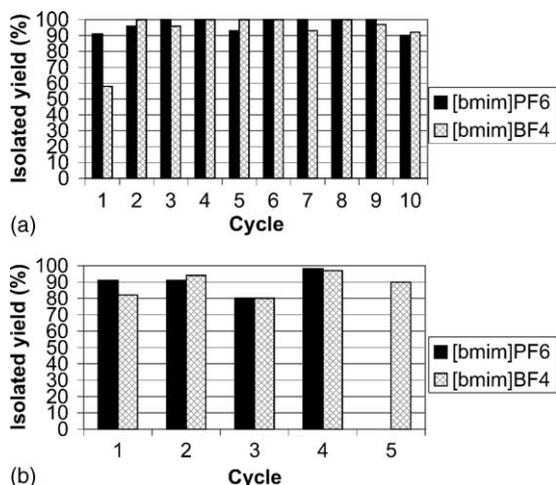


Fig. 5. Recyclability studies on [bmim]PF₆ and [bmim]BF₄ containing 5 mol% Pd(PPh₃)₄ in the coupling of phenylacetylene with (a) Bu₃SnSiMe₃ and (b) Bu₃SnSiMe₂Ph, both heating in a 70 °C oil bath.

cycled in ionic liquids with little loss in activity simply by extracting the reaction products from the ionic liquid with an organic solvent such as Et₂O. Generally, this does not result in leaching of palladium species from the ionic liquid [20,29,34,35].

We have previously reported that Pd(PPh₃)₄ could be recycled in [bmim]PF₆ four times in the coupling of Bu₃SnSiMe₃ and phenylacetylene without loss of activity [18]. Here, we report that the same reaction can be performed at least 10 times with the same ionic liquid/catalyst system without loss of activity; the same has been shown for [bmim]BF₄, as well (Fig. 5a). These reactions were monitored by gas chromatography and were generally complete

after 48 h as evidenced by the complete disappearance of the alkyne substrate peak. In addition, the reaction between Bu₃SnSiMe₂Ph and phenylacetylene was performed four times in a [bmim]PF₆/Pd(PPh₃)₄ system and five times in a [bmim]BF₄/Pd(PPh₃)₄ system, also without loss of activity (Fig. 5b). These reactions were also monitored by gas chromatography and were generally complete in 72 h.

As can be seen from the results presented in Fig. 5, the ionic liquid/palladium catalyst systems are highly recyclable. The results presented in Fig. 5 represent isolated yields, obtained after the reaction was deemed complete by gas chromatography. The reaction conditions for the recyclability studies were the same as before, employing 5 mol% Pd(PPh₃)₄ in a biphasic ionic liquid/Et₂O system heated in a 70 °C oil bath under nitrogen. Products were isolated by washing the ionic liquid/catalyst under nitrogen with dry Et₂O, which was then removed via needle and syringe. Fresh trialkyl(trialkylstannyl)silane and alkyne were then injected along with dry Et₂O and the reaction repeated. Fig. 6 depicts the process used to recycle the ionic liquid/catalyst systems.

The ionic liquid/catalyst system is very robust and amenable to continuous recycling. Recycling of the system using 1-decyne and 5-hexyn-1-ol was possible, also without activity loss. On one occasion, the ionic liquid/catalyst system previously used for 5-hexyn-1-ol was recycled using 1-decyne and vice versa. These systems provided their expected addition products, showing that the ionic liquid/catalyst system can be recycled with any alkyne regardless of which alkyne was used previously. Most of the ionic liquid/catalyst systems investigated for recyclability contained 5 mol% palladium, but recycling was also performed on occasion with systems containing 1 mol% palladium, which also showed no loss of activity. In general, the next

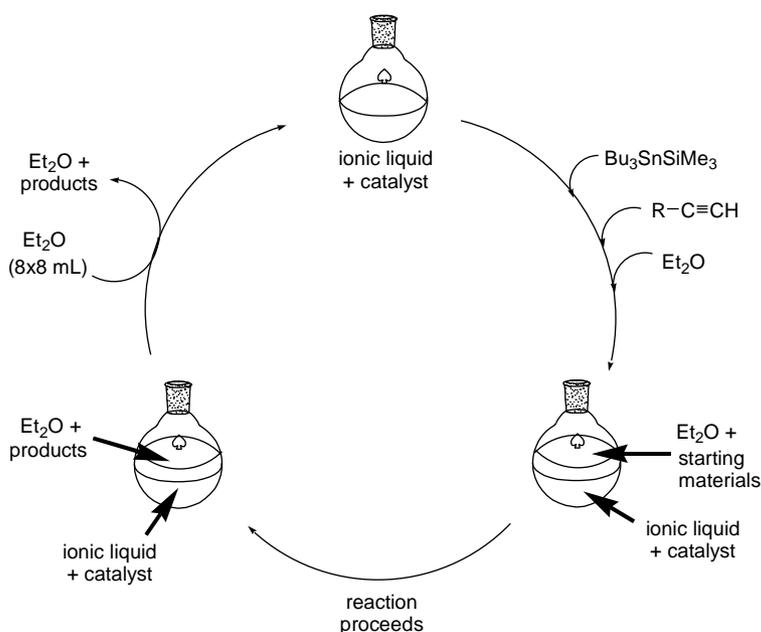


Fig. 6. Ionic liquid/catalyst recycling process.

reaction during recycling was performed immediately after the product was isolated from the previous reaction. However, the ionic liquid/catalyst system has been left for up to 10 days without special precautions, after which the catalyst displayed no loss of activity in subsequent reactions.

3.5. Catalyst activation

Interestingly, the first reaction performed in both ionic liquids using both trialkyl(trialkylstannyl)silanes required longer reaction times than subsequent reactions that went to completion much faster. In fact, after 144 h the reaction of $\text{Bu}_3\text{SnSiMe}_3$ with phenylacetylene in $[\text{bmim}]\text{BF}_4$ was only ~85% complete by GC and an isolated yield of 58% was obtained. In the second cycle for this system, however, 100% GC and isolated yields were obtained after only 36 h. This seems to indicate that some time may be required for “catalyst activation” as has been observed for other palladium-catalysed reactions in ionic liquids that require pre-heating of the ionic liquid/catalyst system to obtain optimal activity [27,36–38].

We investigated the necessity of catalyst activation by performing the coupling of $\text{Bu}_3\text{SnSiMe}_3$ and phenylacetylene under various conditions, the results of which are presented in Table 3. In the case of Suzuki reactions, other groups heated their palladium catalyst in an ionic liquid along with the aryl halide substrate at high temperatures, after which they added the boronic acid substrate and carbonate base to promote the cross-coupling reaction [27,36]. We heated 5 mol% $\text{Pd}(\text{PPh}_3)_4$ in $[\text{bmim}]\text{PF}_6$ at 70 °C which was black after 20 h. The silylstannation reaction performed in this system proceeded to give a 97% isolated yield but required 120 h to reach completion (Table 3, Entry 1). We obtained more favourable results heating the catalyst in the biphasic ionic liquid/ Et_2O systems. $\text{Pd}(\text{PPh}_3)_4$ (5 mol%) was heated in $[\text{bmim}]\text{PF}_6/\text{Et}_2\text{O}$ and in $[\text{bmim}]\text{BF}_4/\text{Et}_2\text{O}$ in a 70 °C oil bath along with $\text{Bu}_3\text{SnSiMe}_3$. After 20 h, phenylacetylene was added to the bright yellow reagent mix and coupled to provide 100 and 92% yields after 19 and 20 h in $[\text{bmim}]\text{PF}_6/\text{Et}_2\text{O}$ and $[\text{bmim}]\text{BF}_4/\text{Et}_2\text{O}$, respectively (Table 3, Entries 4 and 5). In fact, GC analyses of these

Table 3

Catalyst activation studies performed on the addition of $\text{Bu}_3\text{SnSiMe}_3$ to phenylacetylene in the presence of 5 mol% $\text{Pd}(\text{PPh}_3)_4$ under various conditions, heating in a 70 °C oil bath

Entry	Ionic liquid	Reagents present during activation	Reaction time (h)	Isolated yield (%)
1	$[\text{bmim}]\text{PF}_6$	None	120	97
2	$[\text{bmim}]\text{PF}_6$	Et_2O	20	100
3 ^a	$[\text{bmim}]\text{PF}_6$	Et_2O	16	100
4	$[\text{bmim}]\text{PF}_6$	$\text{Bu}_3\text{SnSiMe}_3$, Et_2O	19	100
5	$[\text{bmim}]\text{BF}_4$	$\text{Bu}_3\text{SnSiMe}_3$, Et_2O	20	92
6 ^a	$[\text{bmim}]\text{BF}_4$	$\text{Bu}_3\text{SnSiMe}_3$, Et_2O	16	97

Reaction conditions: 1.0 mmol phenylacetylene, 1.2 mmol $\text{Bu}_3\text{SnSiMe}_3$, 1.0 ml ionic liquid, 5.0 ml Et_2O , 70 °C oil bath, 20 h activation period.

^a Second cycle with same ionic liquid/catalyst system.

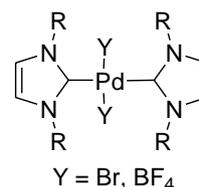


Fig. 7. Palladium(0)–dialkylimidazolylidene carbene complex isolated from Heck reactions performed in $[\text{bmim}]\text{BF}_4$ and $[\text{bmim}]\text{Br}$ ionic liquids [41].

reactions indicated they had proceeded ~65 and ~90% to completion after only 3 h, respectively. The catalyst was also heated in a 70 °C oil bath in a biphasic system consisting of $[\text{bmim}]\text{PF}_6/\text{Et}_2\text{O}$ without any additional reagents. After 20 h, $\text{Bu}_3\text{SnSiMe}_3$ and phenylacetylene were added to the bright orange catalytic mixture, coupling to give 100% yield after 20 h (Table 3, Entry 2). This result shows that it is not necessary to have silylstannane present at the activation stage and that the formation of any other catalytic species in the ionic liquid is not a result of reagent addition to the palladium(0) centre. It seems that mild heating of the catalyst in the ionic liquid is sufficient to activate the catalyst. Heating $\text{Pd}(\text{PPh}_3)_4$ in neat ionic liquid at 70 °C does not provide active catalyst species, as evidenced by the long time required to achieve complete addition of $\text{Bu}_3\text{SnSiMe}_3$ to phenylacetylene. This may be a result of the high temperature. Temperature measurements of the reaction mixture rather than the oil bath made while heating 1.0 ml of ionic liquid with 5.0 ml Et_2O in a 70 °C oil bath show that the temperature of the ionic liquid does not exceed 40 °C. Presumably the temperature of the ionic liquid is being regulated by the boiling point of Et_2O (35 °C). It therefore seems that the catalyst is activated simply with gentle heating in the ionic liquid. Furthermore, these pre-activated systems were recyclable, giving comparable results on their second cycles (Table 3, Entries 3 and 6).

Some researchers ascribe these catalyst activation effects to the possible formation of a palladium–imidazolylidene carbene complex (Fig. 7). These types of complexes, prepared independently of ionic liquid research, have been shown to be very active in Heck and Suzuki couplings in conventional solvents [39], showing excellent stabilities and reaction rates [40].

Several groups have been able to observe and in some cases isolate palladium–imidazolylidene carbene complexes from Suzuki and Heck reactions in ionic liquids. The proton on carbon 2 of the imidazolium ring is acidic and can be removed with a base to generate a carbene. Xu et al. [41] observed the formation of such a complex during a Heck reaction in $[\text{bmim}]\text{Br}$ as the reaction colour changed from dark brown to red to yellow, similar to the colour of reactions performed in our studies. The palladium complex was isolated from a reaction performed in a mixture of $[\text{bmim}]\text{Br}$ and THF, then characterised. The isolated carbene complex was then used in a subsequent

Heck reaction and shown to be highly active. The carbene complex was not observed in [bmim]BF₄, indicating that a halide was required to deprotonate imidazolium. Mathews et al. [42] also observed and isolated a palladium–carbene complex in a Suzuki reaction in [bmim]BF₄ but added a halide source such as NaCl to induce its formation. Indeed, it has been shown that in Heck reactions performed in non-imidazolium-based ionic liquids palladium black deposition slowly decreases catalyst activity, inhibiting its recyclability [28]. In fact, density functional analysis has shown that oxidative C–H addition of the proton–carbon 2 bond of an imidazolium cation across closely related platinum(0) is exothermic, supported experimentally by the reaction of the 1,3-dimethylimidazolium cation with Pt(PPh₃)₄ to produce the carbene complex [43]. Hamill et al. [44] have performed investigations using X-ray absorption fine structure (XAFS) to determine the speciation of the palladium catalyst during a Heck reaction in several ionic liquids. These studies showed the formation of a bis-carbene–palladium complex in *N,N*-dialkylimidazolium chloride ionic liquids while in *N,N*-dialkylimidazolium tetrafluoroborate and hexafluorophosphate ionic liquids palladium nanoclusters were observed. The addition of triphenylphosphine to the systems increased the induction time required for nanocluster formation but showed that they were more stable and resistant to palladium black deposition in ionic liquids. Deshmukh et al. [45] claimed to have isolated a Pd–bis-carbene complex from both 1,3-di-*n*-butylimidazolium bromide, [bmim]Br and [bmim]BF₄. Through transmission electron microscopy they observed the conversion of this complex to palladium nanoparticles using sonication. Isolated palladium nanoclusters have been shown to be active in the Heck reaction. Reactions performed in our studies also required an induction time and were similar in colour to reactions in which palladium-imidazolylidene complexes and/or palladium nanoparticles were observed. It therefore seems likely that the active palladium species in the silylstannation of alkynes in ionic liquids is not Pd(PPh₃)₄, a possibility requiring further study.

The exact nature of the active catalytic species in the silylstannation of alkynes in imidazolium based ionic liquids is topic of a current study in our laboratory and will be reported in due course. An aspect of this study involves analysis of catalytic leaching into the organic extract using ICP-MS. Furthermore, we have used ICP-MS to determine residual halide content in various ionic liquids, including [bmim]BF₄ and [bmim]PF₆, prepared via various methods [25]. This study will give insight into the effect of halide ions (residual or added) to the systems described here.

4. Conclusions

We have shown that it is possible to perform addition reactions between trialkyl(trialkylstannyl)silanes and terminal alkynes in two different ionic liquids. Two tri-

alkyl(trialkylstannyl)silanes and five alkynes containing differing functionalities were successfully coupled in good to excellent isolated yields. Although acceptable yields were obtained from both ionic liquids, it appears as though the reactions proceed slightly faster in [bmim]PF₆ than they do in [bmim]BF₄, perhaps due to catalyst inactivation resulting from higher water content of [bmim]BF₄ or better stabilisation of the active catalytic palladium species by [bmim]PF₆. All reactions proceeded with complete stereo- and regioselectivity. These results add to the growing repertoire of organometallic reactions that can be performed in ionic liquids in which the organometallic reagent is not part of a transition metal complex.

Perhaps more significantly, we have also shown that the ionic liquid/catalyst system is extensively recyclable, being reused 10 times without loss of activity in both ionic liquids. The requirement of an induction time for optimal catalyst activity, coupled with the colours of the reactions, seems to suggest that Pd(PPh₃)₄ is not the active catalytic species. Based on our results and previous studies, it seems likely that either a palladium–imidazolylidene carbene complex or palladium metal nanoclusters are the active species. This requires further study through NMR and/or XAFS analysis of the reaction during its course. We also intend to investigate tandem reactions in our systems, performing further reactions with the silylstannylated alkenes in the same reaction vessel after their formation. Such reactions include palladium-catalysed Stille couplings with aryl halides and protodesilylations.

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