

Heteropoly acids: a green and efficient heterogeneous Brønsted acidic catalyst for the intermolecular hydroamination of olefins

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Abstract

Intermolecular hydroamination of non-activated olefins with amides and benzyl carbamate proceeds efficiently in the presence of environmentally benign silicotungstic acid (HSiW) catalyst under mild conditions in air to afford addition products in good to excellent yields.

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Keywords: Heteropoly acids; Intermolecular hydroamination; Amides; Olefins

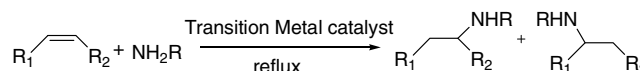
In recent years, Keggin type heteropoly acids (HPAs) catalysts have received much attentions in both academic and industrial applications due to their unique properties, which offers several advantages in terms of catalytic performance, strong acidic, and redox site and selectivity to particular reaction product by selective stabilization of reaction intermediate.¹ HPAs are non-corrosive, environmentally benign, and economically feasible solid acid catalysts compared to conventional homogeneous acids, such as H₂SO₄ or TfOH. Furthermore, they can be reused and recycled easily in most cases after the reaction and hence they are regarded as green catalysts. As a consequence, a variety of synthetically useful transformations have been developed using HPAs as catalysts, such as oxidation of alcohols,² esterification,³ Friedel–Crafts reactions,⁴ Mannich reactions,⁵ cyanosilylation,⁶ ring-opening of epoxides,⁷ and dehydration.⁸

Hydroamination, the simple addition of an N–H bond across C–C unsaturated organic fragment, has attracted much attention in the past decades. Intermolecular hydroamination of olefins is one of the most important and challenging topics in this area.⁹ Despite significant efforts that have been devoted into the intermolecular hydroamination of olefins with alkylamines and arylamines, only a few reports of the intermolecular hydroamination of non-activated alkenes with weakly basic amine nucleophiles such as sulfonamides, carbamates, and carboxamides are known (Scheme 1).

Recently, efficient platinum(II),¹⁰ gold(I),¹¹ Cu(II),¹² Fe(III),¹³ and other metal salts¹⁴ catalyzed hydroaminations of amides and carbamates were reported. Along with the metal catalysts, there also have been examples using metal-free catalysts for the hydroaminations of olefins and amides.¹⁵ Although some notable progress has been made on the hydroamination reactions of alkenes with

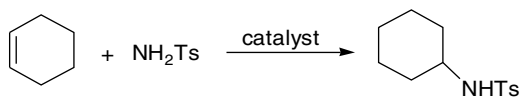
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Scheme 1. Hydroamination reaction.

Table 1
Hydroamination between toluenesulfonamide and cyclohexene under different reaction conditions



| Entry ^a | Catalyst | Solvent | Yield ^b (%) |
|--------------------|---|--------------------|------------------------|
| 1 | H ₃ PW ₁₂ O ₄₀ ·nH ₂ O | DCE | 63 |
| 2 | H ₃ PMo ₁₂ O ₄₀ ·nH ₂ O | DCE | 82 |
| 3 | H ₃ SiW ₁₂ O ₄₀ ·nH ₂ O | DCE | 95 |
| 4 | Na ₃ PMo ₁₂ O ₄₀ | DCE | NR |
| 5 | (NH ₄) ₃ PW ₁₂ O ₄₀ | DCE | Trace |
| 6 | Ag ₃ PW ₁₂ O ₄₀ | DCE | Trace |
| 7 | H ₂ MoO ₄ | DCE | NR ^c |
| 8 | NH ₂ SO ₃ H | DCE | NR ^c |
| 9 | H ₃ SiW ₁₂ O ₄₀ ·nH ₂ O | CH ₃ CN | Trace |
| 10 | H ₃ SiW ₁₂ O ₄₀ ·nH ₂ O | <i>n</i> -Heptane | 86 |
| 11 | H ₃ SiW ₁₂ O ₄₀ ·nH ₂ O | CH ₃ Ph | 92 |
| 12 | H ₃ SiW ₁₂ O ₄₀ ·nH ₂ O | 1,2-Dioxane | 75 |

^a Reaction conditions: cyclohexene (2 mmol), NH₂Ts (1 mmol), catalyst (100 mg), solvent (2 ml), 85 °C, 18 h, sealed tube, in air.

^b GC yield.

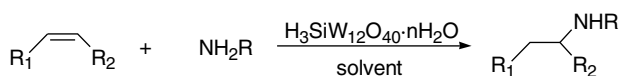
^c Using 0.1 mmol of solid acid as catalyst.

amides in the past two years, there are also some drawbacks on the reported methods, such as using expensive and toxic metals, higher reaction temperature, large excess amounts of olefins, and tedious reaction procedures. *Additionally, most of the reported methods must be carried out under inert atmosphere.* Therefore, the development of a novel, green, and simple catalyst for addition reactions of non-activated alkenes with sulfonamides, carboxamides and carbamates remains an intriguing challenge.

Although silver-exchanged tungstophosphoric acid¹⁶ or using HPAs as acid additive¹⁷ have been examined for intermolecular hydroamination of alkynes with aromatic amines, to the best of our knowledge, there are no studies and reports of HPAs-catalyzed intermolecular hydroamination of olefins with amides. In the present letter, we report an efficiently, easy operational, and reusable heteropoly acids catalyst for the intermolecular hydroamination of various olefins with both amides and carbamates.

In order to study the feasibility of HPAs-catalyzed hydroamination of amides, hydroamination of cyclohexene with *p*-toluenesulfonamide (TsNH₂) was selected as a model reaction (Table 1). Under our reaction conditions,


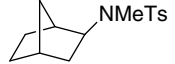

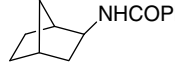

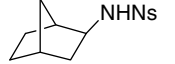

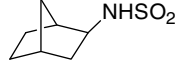

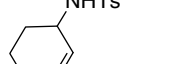

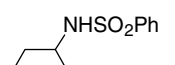

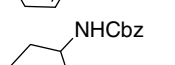
Table 2
Hydroamination of unactivated olefins with nitrogen nucleophiles¹⁸



| Entry ^a | Olefin | Nucleophile | Time (h)/Temp (°C) | Solvent | Product | Yield ^b (%) |
|--------------------|--------|-----------------------------------|--------------------|---------|---------|------------------------|
| 1 | | NH ₂ Ts | 23/85 | DCE | | 78 |
| 2 | | NH ₂ Ts | 18/85 | DCE | | 91 |
| 3 | | PhSO ₂ NH ₂ | 18/85 | DCE | | 54 |
| 4 | | NH ₂ Ts | 24/45 | DCE | | 78 |
| 5 | | NH ₂ Ts | 24/rt | DCE | | 64 |
| 6 | | NH ₂ Ts | 24/45 | DCE | | 68 |
| 7 | | NH ₂ Ts | 24/85 | DCE | | 88 |

(continued on next page)

Table 2 (continued)

| Entry ^a | Olefin | Nucleophile | Time (h)/Temp (°C) | Solvent | Product | Yield ^b (%) |
|--------------------|---|-----------------------------------|--------------------|---------|---|------------------------|
| 8 |  | CH ₃ NHTs | 24/85 | DCE |  | 60 |
| 9 |  | PhCONH ₂ | 28/85 | Dioxane |  | 67 |
| 10 |  | NH ₂ Ns | 28/85 | Dioxane |  | 85 |
| 11 |  | PhSO ₂ NH ₂ | 28/85 | DCE |  | 86 |
| 12 |  | NH ₂ Ts | 24/50 | DCE |  | 62 |
| 13 |  | PhSO ₂ NH ₂ | 24/50 | DCE |  | 48 |
| 14 |  | NH ₂ COOBn | 26/50 | DCE |  | 71 |

^a Reaction conditions: olefin (2 mmol), NH₂Ts (1 mmol), H₃SiW₁₂O₄₀·*n*H₂O (100 mg), solvent (2 ml), sealed tube, in air.

^b Isolated yield.

among the HPAs tested, H₃SiW₁₂O₄₀·*n*H₂O was found to be the most efficient catalyst compared to H₃PW₁₂O₄₀·*n*H₂O and H₃PMo₁₂O₄₀·*n*H₂O. Solid acids such as NH₂SO₃H and H₂MoO₄ could not furnish the desired products. No or only trace products were found when using the HPAs salts such as Na₃PMo₁₂O₄₀, (NH₄)₃PW₁₂O₄₀, and Ag₃PW₁₂O₄₀ as catalysts. Using H₃SiW₁₂O₄₀·*n*H₂O as catalyst, various solvents were then examined. Among the solvents examined, non-polar DCE was found to give better results in terms of chemical yields. Polar solvent 1,4-dioxane tended to shut down the reacting system and afforded the addition product in lower yield.

To investigate the scope of the H₃SiW₁₂O₄₀·*n*H₂O catalyzed hydroamination reaction, several selected olefins and amides were then examined under given reaction conditions and the results are summarized in Table 2.¹⁷ Cyclopentene and cyclohexene were successfully converted to the corresponding *N*-cyclopentenyl *p*-toluenesulfonamide and *N*-cyclohexyl *p*-toluenesulfonamide. PhSO₂NH₂ gave lower yield of the addition products. The hydroamination reactions of NH₂Ts with various vinyl arenes gave fast and high-yielding reactions under mild reaction conditions. Interestingly, addition of NH₂Ts to *p*-methylphenylene catalyzed by H₃SiW₁₂O₄₀·*n*H₂O occurred even at room temperature in good yield. Similarly, the additions of various amides to the more strained norbornene furnished the hydroamination products in good to excellent yields under modified reaction conditions.

To further extend the scope of the substrate, 1,3-cyclohexadiene was investigated in the reaction of amides and

NH₂Cbz. All the nitrogen donors underwent hydroamination with good yields at 50 °C within 24–26 h. The possibility of the recycling of the catalyst was also examined. For this reaction, the hydroamination of NH₂Ts and styrene in DCE at 45 °C in the presence of catalytic H₃SiW₁₂O₄₀·*n*H₂O was selected as a model. When the reaction completed, the catalyst could be recycled after simple filtration and washed with DCE. The obtained powder was dried under vacuum, and then directly reused in subsequently recycled reaction. After two runs, the yield of the corresponding addition compound was somewhat decreased (74%, 62%).

In conclusion, we have developed a commercially available and reusable HPAs catalyzed intermolecular hydroamination of unactivated alkenes with weakly basic amine nucleophiles such as sulfonamides, benzyl carbamate, and benzamide, which can be used successfully and environmentally friendly to afford good to excellent yields of addition products. Furthermore, this methodology offers significant improvements with regard to the scope of this transformation, simplicity in operation, and green aspects by avoiding toxic metals or corrosive catalysts.

Acknowledgments

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- A typical procedure for intermolecular addition reactions of amides or carbamates to olefins:* Into a test tube were placed H₃SiW₁₂O₄₀·nH₂O (100 mg), NH₂Ts (1 mmol), CH₂ClCH₂Cl (2 ml), and cyclohexene (2 mmol). After sealing, the reaction mixture was heated at 85 °C and stirred vigorously for 18 h. After the reaction completed, the mixture was concentrated in vacuo to remove the DCE. The product was purified by column chromatography (ethyl acetate/petroleum = 1/10–1/5) to gain the analytically pure product (91% isolated yield). All the known compounds were determined by GC–MS or NMR. The spectral data of some representative products are given below.
N-Cyclohexyl p-toluenesulfonamide (Table 2, entry 2): ¹H NMR (400 MHz) δ 7.77 (d, *J* = 8.0 Hz, 2H), 7.28–7.26 (d, *J* = 8.0 Hz, 2H), 4.55 (d, *J* = 6.4 Hz, 1H), 3.10–3.07 (m, 1H), 2.40 (s, 3H), 1.73–1.70 (m, 2H), 1.62–1.58 (m, 2H), 1.50–1.46 (m, 1H), 1.29–1.06 (m, 5H). ¹³C NMR (100 MHz) δ 143.09, 138.40, 129.60, 126.90, 52.53, 33.89, 25.10, 24.60, 21.51. GC–MS, *m/z* 253.
N-Cyclopentyl p-toluenesulfonamide (Table 2, entry 1): ¹H NMR (400 MHz) δ 7.75 (d, *J* = 8.0 Hz, 2H), 7.26 (d, *J* = 15.6 Hz, 2H), 4.96 (s, 1H), 3.56–3.51 (m, 1H), 2.44 (s, 3H), 1.73–1.70 (m, 2H), 1.64–1.59 (m, 2H), 1.52–1.46 (m, 1H), 1.25–1.08 (m, 5H). ¹³C NMR (100 MHz) δ 143.15, 137.77, 129.59, 127.06, 55.06, 33.30, 23.05, 21.47. GC–MS, *m/z* 239.
N-exo-bicyclo[2.2.1]hept-2-yl-p-toluenesulfonamide (Table 2, entry 7): ¹H NMR (400 MHz) δ 7.73 (d, *J* = 7.2 Hz, 2H), 7.28 (d, *J* = 7.6 Hz, 2H), 4.61 (d, *J* = 6.4 Hz, 1H), 3.10 (s, 1H), 2.41 (s, 3H), 2.16 (s, 1H), 2.07 (s, 1H), 1.59–1.54 (m, 1H), 1.43–1.38 (m, 2H), 1.31–1.29 (m, 2H), 1.15–1.03 (m, 2H), 0.99–0.87 (m, 2H). ¹³C NMR (100 MHz) δ 143.19, 137.84, 129.63, 127.06, 56.61, 42.44, 40.74, 35.54, 35.14, 27.96, 26.27, 21.51. GC–MS, *m/z* 265.
Cyclohex-2-enyl-p-toluenesulfonamide (Table 2, entry 12): ¹H NMR (400 MHz) δ 7.75 (d, *J* = 7.6 Hz, 2H), 7.27 (d, *J* = 8.0 Hz, 2H), 5.71 (d, *J* = 10 Hz, 1H), 5.31 (d, *J* = 10.4 Hz, 1H), 4.84 (d, *J* = 8.4 Hz, 1H), 3.765 (s, 1H), 2.39 (s, 3H), 1.94–1.77 (m, 2H), 1.74–1.61 (m, 1H), 1.57–1.50 (m, 3H). ¹³C NMR (100 MHz) δ 143.14, 138.24, 131.39, 129.60, 126.95, 126.91, 48.89, 30.12, 24.38, 21.45, 19.22. GC–MS, *m/z* 251.