

Selective Reduction of Terminal Alkynes to Alkenes by Indium Metal

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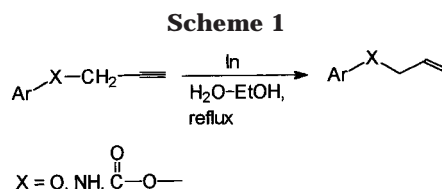
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The selective reduction of alkynes to alkenes is a challenging problem in organic synthesis. Although a number of reagents such as Lindlar's catalyst, sodium in liquid ammonia, and lithium aluminum hydride are commonly used for this purpose,¹ these reductions are not always clean in multifunctional alkynes due to competing reduction of the double bond formed and other reducible groups present in the molecule. Recently, indium has emerged as one of the metals with high synthetic potential.² However, although indium has been used extensively in carbonyl addition reactions,³ its use in other domains has not been explored to any great extent.² Because of the close resemblance of indium to magnesium and zinc in several respects including first ionization potential, we envisioned indium to be a potential reducing agent. Surprisingly, reduction by indium is virtually unexplored except for a few recent examples.⁴ This prompted us to initiate a systematic investigation into the reduction by indium metal.^{4c,d} Although in general organoindium reagents are known to be relatively inert toward unactivated carbon-carbon double and triple bonds,²⁻⁴ we discovered that indium metal reduces a terminal triple bond to a double bond in aryl propargyl ethers, amines, and esters (Scheme 1).

In a typical experimental procedure, an aryl propargyl ether, amine, or ester was heated under reflux with pulverized indium (freshly made by sonication of indium metal in ethanol) in aqueous ethanol for about 40 h. Extraction with ether and usual workup provided the corresponding allyl compound.

A wide range of structurally varied aryl propargyl ethers, amines, and esters underwent reductions by this



procedure to produce the corresponding allyl compounds in high yields. The results are presented in Table 1. As shown in Table 1, although efficient reductions were achieved in phenyl or substituted phenyl ethers, amines, or esters within a reasonable period, benzyl (entry 9), phenyl propyl (entry 10), and other alkyl derivatives (entries 11, 19, 23) were found to be reluctant to undergo reductions. Nonfunctionalized (entry 24) and internal alkynes (entry 25) remained completely inert. On the other hand, phenyl propargyl thioether (entry 26) could not tolerate the reaction condition and led to a mixture of decomposition products within 1 h. However, in general the reactions are very clean and no product other than the reduced one and the starting material were isolated.

Most significantly, no over-reduction beyond alkene was observed in any propargyl ether, amine, or ester under this procedure by indium metal. Moreover, the allyl moiety present in several alkynes (entries 4, 17, 21) remained unaffected. A number of other readily reducible functional groups such as CHO (entry 5), C=O (entry 6), OBn (entry 7), OAc (entry 8), OTs (entry 16), CO₂Me (entry 15), and Cl (entry 22) also did not undergo any change under the present reaction conditions. This is of much synthetic importance as many reducing agents such as LiAlH₄, diborane, and Lindlar's catalyst, which are usually employed for reduction of acetylenes, are not compatible with many of these functionalities. Although the exact mechanism of such a selective reduction of triple bond to double bond by indium metal is not yet clear to us, it is evident from the results that the presence of an aryl moiety, the heteroatom (O and N), and a terminal acetylenic functionality are essential for this reduction to proceed. Probably, the process involves the formation of radical ions, which could be stabilized by such groups.

To conclude, the present procedure using indium metal in aqueous ethanol provides a highly selective reduction of terminal alkynes to alkenes in aryl propargyl ethers, amines, and esters. To the best of our knowledge, this is the first report of reduction of an acetylenic triple bond to an olefinic double bond by indium metal and certainly it broadens the scope of indium-promoted reductions. The significant features of this procedure are as follows: (a) no undesired side reaction including over-reduction of the double bond formed; (b) exclusive compatibility with several easily reducible functionalities; (c) high yields; and (d) green chemistry.

Experimental Section

General Methods. ¹H NMR (300 MHz) and ¹³C NMR (75 MHz) spectra were run in CDCl₃ solutions. IR spectra were taken as thin film. Analyses were done on a Perkin-Elmer 2400 autoanalyzer. Indium metal (Ingot) used was from SRL, India.

General Experimental Procedure. Representative Procedure for Reduction of Phenyl Propargyl Ether. Phenyl

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Table 1. Reduction of Alkynes to Alkenes by Indium Metal

entry	substrate	time(h)	product	yield(%) ^a	entry	substrate	time(h)	product	yield(%) ^a
1		40		90	14		45		90
2		45		90	15		45		95
3		45		95	16		40		95
4		40		95	17		50		40 ^b
5		40		80	18		50		45 ^b
6		45		90	19		40		20 ^b
7		45		85	20		40		95
8		40		90	21		40		95
9		50		45 ^b	22		40		95
10		50		35 ^b	23		50		42 ^b
11		50		18 ^b	24	$C_6H_{13}C\equiv CH$	40	No reaction	
12		40		90	25		40	No reaction	
13		45		95	26		1	Mixture of products	

^a Pure isolated products. ^b Obtained as a mixture with starting material; yields determined by ¹H NMR.

propargyl ether (132 mg, 1 mmol) was heated under reflux with indium (180 mg, 1.5 mmol) (freshly pulverized by sonication in an ultrasonic cleaner for 3 h in ethanol) and aqueous ethanol (1:1) (3 mL) for 40 h. (Use of commercial indium powder makes the reaction slower. The reaction did not proceed at all at room temperature stirring or under sonication without heating.) Ethanol was removed in a vacuum, and the residue was extracted with ether. The extract was washed with brine, dried (Na_2SO_4), and evaporated to leave the crude product. This was then purified by column chromatography over silica gel to furnish the pure phenyl allyl ether (121 mg, 90%), which was identified by comparison of its ¹H NMR spectra with that of an authentic sample.⁵

This procedure was followed for the reduction of all propargyl ethers, amines, and esters listed in Table 1. The known compounds have been identified by comparison of spectral data (IR, ¹H NMR) with those reported.⁵ Spectral (IR, ¹H NMR and ¹³C NMR) and analytical data of isolated pure compounds whose spectral data were not reported earlier are presented below in order of their entries in Table 1.

Allyl (4-methoxyphenyl) ether (entry 3): IR 1649 cm^{-1} ; ¹H NMR δ 6.87–6.80 (m, 4H), 6.09–5.99 (m, 1H), 5.43–5.24 (m, 2H), 4.48 (dt, $J_1 = 5.4$ Hz, $J_2 = 1.2$ Hz, 2H), 3.76 (s, 3H); ¹³C NMR δ 154.3, 153.1, 134.6, 117.8, 116.1 (2), 115.0 (2), 69.9, 56.1. Anal. Calcd for $C_{10}H_{12}O_2$: C, 73.17; H, 7.32. Found: C, 73.05; H, 7.14.

1,2-Diallyl phenyl diether (entry 4): IR 1649 cm^{-1} ; ¹H NMR δ 6.90 (s, 2H), 6.89 (s, 2H), 6.15–6.02 (m, 2H), 5.44 (dd, $J_1 = 3.1$ Hz, $J_2 = 1.5$ Hz, 2H), 5.29–5.25 (m, 2H), 4.62–4.58 (m, 4H); ¹³C NMR δ 148.9 (2), 133.9 (2), 121.6 (2), 117.9 (2), 114.7 (2), 70.3 (2). Anal. Calcd for $C_{12}H_{14}O_2$: C, 75.79; H, 7.37. Found: C, 75.48; H, 7.59.

3-Allyloxybenzaldehyde (entry 5): IR 1649 cm^{-1} ; ¹H NMR δ 9.96 (s, 1H), 7.47–7.39 (m, 3H), 7.21–7.17 (m, 1H), 6.12–5.99 (m, 1H), 5.46–5.29 (m, 2H), 4.60–4.58 (m, 2H); ¹³C NMR δ 192.4, 159.5, 138.2, 133.0, 130.4, 124.0, 122.5, 118.5, 113.5, 69.3. Anal. Calcd for $C_{10}H_{10}O_2$: C, 74.07; H, 6.17. Found: C, 74.28; H, 6.34.

4-Allyloxyacetophenone (entry 6): IR 1647 cm^{-1} ; ¹H NMR δ 7.93–7.89 (m, 2H), 6.95–6.91 (m, 2H), 6.11–5.98 (m, 1H), 5.45–5.29 (m, 2H), 4.60–4.58 (m, 2H), 2.54 (d, $J = 0.9$ Hz, 3H); ¹³C NMR δ 197.1, 162.9, 132.9, 130.9 (2), 130.8, 118.6, 114.8 (2), 69.3, 26.7. Anal. Calcd for $C_{11}H_{12}O_2$: C, 75.00; H, 6.82. Found: C, 74.77; H, 6.87.

Allyl (2-benzyloxyphenyl) ether (entry 7): IR 1647 cm^{-1} ; ¹H NMR δ 7.44–7.26 (m, 5H), 6.91–6.85 (m, 4H), 6.10–6.01 (m, 1H), 5.43–5.36 (m, 1H), 5.24 (dt, $J_1 = 10.53$ Hz, $J_2 = 1.38$ Hz, 1H), 5.11 (s, 2H), 4.58 (dt, $J_1 = 5.22$ Hz, $J_2 = 1.5$ Hz, 2H); ¹³C NMR δ 149.3, 137.9, 134.1, 128.9 (2), 128.2, 127.7 (2), 122.0, 121.8, 121.7, 117.9, 115.5, 115.0, 71.6, 70.4. Anal. Calcd for $C_{16}H_{16}O_2$: C, 80.00; H, 6.67. Found: C, 79.97; H, 6.71.

4-Allyloxybenzyl acetate (entry 8): IR 1647 cm^{-1} ; ¹H NMR δ 7.30–7.26 (m, 2H), 6.93–6.88 (m, 2H), 6.10–6.00 (m, 1H), 5.31–5.27 (m, 2H), 5.04 (s, 2H), 4.54 (d, $J = 5.1$ Hz, 2H), 2.07 (s, 3H); ¹³C NMR δ 171.1, 159.1, 133.5, 130.5 (2), 128.6, 118.2,

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115.2 (2), 66.5, 66.2, 21.5. Anal. Calcd for $C_{12}H_{14}O_3$: C, 69.90; H, 6.79. Found: C, 70.25; H, 7.03.

Allyl(2-methylphenyl)amine (entry 13): IR 1643 cm^{-1} ; 1H NMR δ 7.13–7.04 (m, 2H), 6.68–6.59 (m, 2H), 6.04–5.95 (m, 1H), 5.28 (d, $J = 17.1$ Hz, 1H), 5.17 (d, $J = 10.2$ Hz, 1H), 3.82 (d, $J = 5.1$ Hz, 2H), 3.73 (broad singlet, 1H), 2.15 (s, 3H); ^{13}C NMR δ 146.3, 135.9, 130.5, 127.5, 122.4, 117.5, 116.6, 110.4, 46.9, 17.6. Anal. Calcd for $C_{10}H_{13}N$: C, 81.63; H, 8.84; N, 9.52. Found: C, 82.01; H, 8.76; N, 9.36.

Allyl(4-methoxyphenyl)amine (entry 14): IR 1643 cm^{-1} ; 1H NMR δ 6.80–6.75 (m, 2H), 6.62–6.58 (m, 2H), 6.00–5.91 (m, 1H), 5.30–5.24 (m, 1H), 5.17–5.12 (m, 1H), 3.73–3.70 (m with a singlet at 3.73, total 6H); ^{13}C NMR δ 152.6, 142.6, 136.2, 116.5, 115.2 (2), 114.7 (2), 56.1, 49.9. Anal. Calcd for $C_{10}H_{13}NO$: C, 73.62; H, 7.97. Found: C, 73.37; H, 7.77.

Allyl(2-carbomethoxyphenyl)amine (entry 15): IR 1647 cm^{-1} ; 1H NMR δ 7.91–7.88 (m, 2H), 7.36–7.30 (m, 1H), 6.66–6.55 (m, 2H), 5.99–5.90 (m, 1H), 5.29 (m, 1H), 5.17 (m, 1H), 3.93–3.76 (m with a singlet at 3.85, total 5H); ^{13}C NMR δ 169.5, 151.3, 135.0, 134.9, 132.0, 116.4, 115.0, 111.9, 110.4, 51.8, 45.6. Anal. Calcd for $C_{11}H_{13}NO_2$: C, 69.11; H, 6.81. Found: C, 68.86; H, 6.75.

Allyl(2-*p*-toluenesulfonyloxyphenyl)amine (entry 16): mp 61–62 °C; IR 1645 cm^{-1} ; 1H NMR δ 7.74 (d, $J = 8.26$ Hz, 2H), 7.29 (d, $J = 8.1$ Hz, 2H), 7.08–7.03 (m, 1H), 6.89–6.86 (m, 1H), 6.59–6.51 (m, 2H), 5.77–5.71 (m, 1H), 5.16–5.08 (m, 2H), 4.18 (broad singlet, 1H), 3.62 (d, $J = 5.0$ Hz, 2H), 2.43 (s, 3H); ^{13}C NMR δ 145.4, 140.7, 136.7, 134.5, 132.6, 129.7 (2), 128.4 (2), 127.8, 122.3, 116.3, 116.1, 112.2, 45.6, 21.6. Anal. Calcd for

$C_{16}H_{17}NO_3S$: C, 63.37; H, 5.61; N, 4.62. Found: C, 63.26; H, 5.75; N, 4.73.

Allyl benzoate (entry 20): IR 1649 cm^{-1} ; 1H NMR δ 8.08–7.42 (m, 5H), 6.09–5.98 (m, 1H), 5.45–5.27 (m, 2H), 4.83 (dt, $J_1 = 5.5$ Hz, $J_2 = 1.5$ Hz, 2H); ^{13}C NMR 166.6, 133.4, 132.6, 130.5, 130.0 (2), 128.8 (2), 118.6, 65.9. Anal. Calcd for $C_{10}H_{10}O_2$: C, 74.07; H, 6.17. Found: C, 74.25; H, 6.08.

Diallyl phthalate (entry 21): IR 1649 cm^{-1} ; 1H NMR δ 7.78–7.72 (m, 2H), 7.58–7.53 (m, 2H), 6.05–5.94 (m, 2H), 5.42 (dd, $J_1 = 3$ Hz, $J_2 = 1.5$ Hz, 1H), 5.36 (dd, $J_1 = 3$ Hz, $J_2 = 1.5$ Hz, 1H), 5.30 (dd, $J_1 = 2.3$ Hz, $J_2 = 1.2$ Hz, 1H), 5.27 (dd, $J_1 = 2.4$ Hz, $J_2 = 1.2$ Hz, 1H), 4.79 (dt, $J_1 = 5.7$ Hz, $J_2 = 1.2$ Hz, 4H); ^{13}C NMR δ 167.7 (2), 132.4 (2), 132.2 (2), 131.6 (2), 129.4 (2), 119.1 (2), 66.7 (2). Anal. Calcd for $C_{14}H_{14}O_4$: C, 68.29, H, 5.69. Found: C, 68.45; H, 5.64.

Allyl 2-chlorobenzoate (entry 22): IR 1647 cm^{-1} ; 1H NMR δ 7.86–7.83 (m, 1H), 7.47–7.28 (m, 3H), 6.08–5.99 (m, 1H), 5.47–5.28 (m, 2H), 4.84 (dt, $J_1 = 5.7$ Hz, $J_2 = 1.3$ Hz, 2H); ^{13}C NMR δ 165.7, 134.2, 133.0, 132.2, 131.8, 131.5, 130.4, 127.0, 119.1, 66.5. Anal. Calcd for $C_{10}H_9O_2Cl$: C, 61.08; H, 4.58. Found: C, 61.48; H, 4.23.

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