A general method for the rapid reduction of alkenes and alkynes using sodium borohydride, acetic acid, and palladium

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ABSTRACT

Alkenes and alkynes are rapidly reduced to the corresponding alkanes using sodium borohydride and acetic acid in the presence of a small amount of palladium catalyst. The heterogeneous reaction is conducted in open air at room temperature. Reactions typically afford conversions to the alkane product of 98% or more within 15 min. The best solvent system was determined to be isopropyl alcohol, though reduction also takes place in solvents such as tetrahydrofuran, chloroform and, with some substrates, even in water. The method described is a convenient alternative to hydrogenations that require an external supply of hydrogen gas.

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The reduction of unsaturated hydrocarbons is a fundamental synthetic transformation. Over the last hundred years, the ubiquity of alkenes and alkynes in synthetic, petroleum, and natural products chemistry has led to the development of numerous methods for their reduction. Today, alkenes and alkynes can be reduced to the corresponding alkanes using several principal approaches, each of which offers certain advantages.[1,2] The most common of these approaches is direct hydrogenation using an external source of molecular hydrogen and, typically, a finely divided metal catalyst. As an alternative, catalytic transfer hydrogen methods that make use of solvent or an additional reagent as the hydrogen source have also been widely employed for the reduction of alkenes and alkynes. Recently, several enzymatic, biochemical methods have been described for the reduction of alkenes,[3–6] though this approach is somewhat limited by the generally poor water solubility of most hydrocarbons. Another approach to the reduction of unsaturated hydrocarbons is the application of hydride reagents such as lithium aluminum hydride ($LiAlH_4$), triethylsilane (Et_3SiH), and sodium borohydride ($NaBH_4$).

Generally speaking, unmodified borohydride reagents are, without additional catalysts, not useful for reducing alkenes and alkynes. Instead, borohydrides are ordinarily used for the reduction of polar functional groups, especially carbonyl-containing groups such as ketones, aldehydes, and esters. Over the last few decades, a great number of specially modified borohydrides such as sodium cyanoborohydride ($NaBH_3CN$) and lithium triethylborohydride ($LiEt_3BH$) have been prepared and applied for highly selective reductions.[7]

Among the borohydride reagents, sodium borohydride in particular is valued for its low cost, mild nature, and ease of handling. Surprisingly, however, it has found only limited use in the reduction

of alkenes and alkynes. Brown first described the use of sodium borohydride for reduction of simple unsaturated hydrocarbons in 1962, using the borohydride to reduce metal salts to active metals that in turn catalyzed the hydrolysis of the borohydride to produce hydrogen gas. In the presence of the thusly generated hydrogen gas, these reduced metals were also found to catalyze the hydrogenation of simple alkenes.[8,9]

Subsequent related work by Brown and others focused largely on modification of the procedure to produce selective reductions through combination of sodium borohydride with various simple metal salts.[10–19] Other researchers expanded this general approach to the selective reduction of alkenes and alkynes by using a variety of hydride reagents combined with both simple and complex salts of palladium, rhodium, nickel, indium, and other metals.[20–26] While a considerable amount of work has been done to explore the selectivity of borohydride–metal hydrogenations, little has been done to expand the broad applicability of sodium borohydride to the general reduction of alkenes and alkynes.
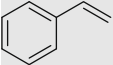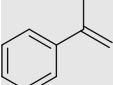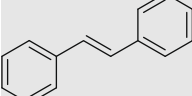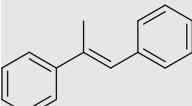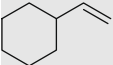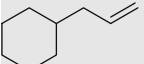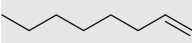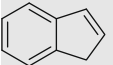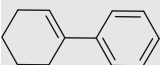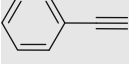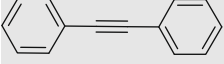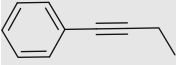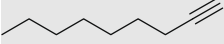
Here, we describe a modification of Brown's original work that serves as a robust, mild, yet general method for the nearly quantitative reduction of a wide variety of alkenes and alkynes using sodium borohydride. Our modifications include the direct use of palladium metal in place of metal salts and the addition of acetic acid. We found that the use of palladium metal in place of metal salts allowed the reaction to proceed in a wider range of solvents and with a broader group of substrates. Addition of acetic acid dramatically improved reaction times and yields for unsaturated substrates that were resistant to Brown's original method. So far as we are aware, the method allows for an unprecedentedly broad application of borohydride chemistry to the reduction of unsaturated hydrocarbons.

The method relies on the reaction of $NaBH_4$ and acetic acid in the presence of a catalytic amount of palladium metal. In our opti-

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Table 1
Catalyst loadings and % conversion for reduction of alkynes and alkenes to the corresponding alkanes. Reactions conducted at a 10 mmol scale

$$\text{ALKENE or ALKYNE} \xrightarrow[\text{IPA, RT, 15 min, open air}]{\text{NaBH}_4 \text{ (4 equiv), CH}_3\text{COOH (2 equiv), cat. Pd/C}} \text{ALKANE}$$

Substrate	(mol % Pd/C)	Conversion[a]
styrene	1%	>99% (99)
α-methylstyrene	1%	>99% (89)
stilbene	5%	98% (98)
α-methylstilbene	5%	>99% (92)
cyclooctene	1%	>99% (98)
vinylcyclohexane	1%	>99% (90)
allylcyclohexane	1%	>99% (92)
1-heptene	1%	>99% (83)
indene	1%	>99% (91)
phenylcyclohexene	1%	98% (96)
norbornene	1%	>99% (88)
phenylacetylene	2.5%	>99% (91)
diphenylacetylene	5%	>99% (87)
1-phenyl-1-butyne	5%	>99% (86)
3-heptyne	5%	>99% (99)
1-octyne	5%	98% (84)

[a] Determined by GC/MS analysis (isolated yields).

mized general procedure,[27] the alkene is allowed to stir with a Pd/C catalyst suspended in isopropyl alcohol (IPA) or other solvent. Acetic acid (2 equiv) is then added, followed by NaBH$_4$ (4 equiv), the addition of which causes the rapid evolution of hydrogen gas bubbles.[28] Depending on the substrate, reduction is rapid and largely complete in as little as 15 min. Product alkanes are obtained in fairly pure form by acid-base workup, extraction with pentane or ether, drying, and evaporation of the solvent under reduced pressure. For the substrates we examined, all of the reductions were more than 98% complete within 15 min. The procedure is extremely convenient; the reduction takes place at room temperature in open air, and requires no special equipment besides a stirrer, flask, and stir bar. Typical results are given in Table 1.

The amount of palladium catalyst used was based on achieving rapid reduction within 15 min of reaction time. We generally observed that reaction progress would slow after 15 min and usually stop entirely by 30 min of reaction time. The reported Pd/C catalyst loadings were successful with both anhydrous catalyst and catalyst containing 50% water by weight.

We found that the method also works well in other solvents. Experiments conducted on the reduction of styrene using tetrahydrofuran (THF), chloroform, acetonitrile, and toluene gave results similar to those obtained using IPA, although the catalyst loading had to be adjusted appropriately in certain other solvents. Significantly, we also found that this procedure worked well even when water was used as a solvent (see Table 2).

The robust and rapid nature of the reduction is intriguing. While little is known of the mechanistic details of metal-catalyzed hydrogenations, studies on the reduction of alkenes using borohydrides and metal salts suggest that the reaction takes place by catalytic hydrogenation on the metal surface.[29,30] It is known that palladium and platinum metals catalyze the hydrolysis of sodium borohydride at the metal surface to release hydrogen gas.[31–34] As the alkene or alkyne will also be adsorbed on the metal surface, this would help to explain the extraordinarily rapid nature of the reduction. Additional hydrogen is produced from reaction of the borohydride with acetic acid, a combination known to produce an acetoxyborohydride (Scheme 1).[35,36]
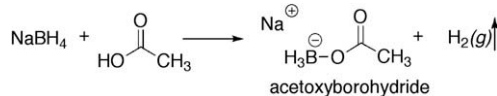
Combined with hydrogen released from hydrolysis on the metal surface, the additional hydrogen produced through acetoxyborohydride formation would create very high effective concentrations of molecular hydrogen at the metal surface. Alternatively, the reduction may occur, at least partly, through an ionic hydrogenation mechanism, whereby the acid generates a carbocation that is in turn reduced with the nucleophilic hydride reagent to yield the reduced product. Such ionic hydrogenation is known to occur, to various degrees, with substrates that can form stable carboca-

Table 2
Reduction of styrene (1 mmol) to ethylbenzene using NaBH$_4$ (4 mmol), acetic acid (2 mmol), and Pd/C catalyst in various solvents with 15-min reaction time

Solvent	Pd/C (mol %)	% Conversion[a]
Isopropyl alcohol	1	99
Water	1	99
Chloroform	1	99
Toluene	1	98
Tetrahydrofuran	5	99
Acetonitrile	5	99
Ethyl lactate	5	86

[a] Determined by GC/MS analysis.

$$\text{NaBH}_4 + \text{HO-C(=O)CH}_3 \longrightarrow \text{Na}^{\oplus} \; \text{H}_3\text{B}^{\ominus}\text{-O-C(=O)CH}_3 + \text{H}_2(g)\uparrow$$

acetoxyborohydride

Scheme 1.

tions.[37] We are pursuing studies to determine the mechanisms at work in this reduction method.

In summary, we have developed a very simple and robust, general method for the reduction of alkenes and alkynes. The method is convenient, and does not require an external source of hydrogen gas. Significantly, the procedure works well in a variety of solvents and with a broad range of unsaturated hydrocarbons. We are currently conducting studies to determine the general applicability of this reaction to other functional groups in various solvents.

Acknowledgments

References and notes

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27. *Isolation scale procedure*: A 250 mL round-bottomed flask with stir bar is charged in open air with the Pd/C catalyst, the alkene (10 mmol), and 50 mL of isopropyl alcohol (IPA). The flask is clamped over a mechanical stirrer, and the contents are stirred. Acetic acid (20 mmol) is added in a single portion via pipette. Powdered NaBH$_4$ (40 mmol) is added in a single portion directly to the stirring heterogeneous solution (*Note*: Addition of the NaBH$_4$ causes the rapid evolution of small hydrogen gas bubbles). The contents of the reaction flask are left to stir in open air at room temperature for 15 min. Workup is conducted by quenching the reaction mixture with several mLs of 0.1 M HCl until no further hydrogen evolution is observed (*Note*: Quenching produces considerable heat; it is advisable to cool the contents with an ice bath during quenching). The solution is then adjusted to a pH of approximately 10 using NaOH and filtered to remove the Pd/C catalyst. *n*-Pentane (40 mL) is added to the filtrate, which is then extracted with DI water (3 × 40 mL). The aqueous portions are then combined and reextracted with *n*-pentane (1 × 40 mL). The organic portions are combined, dried over MgSO$_4$, and filtered. The product alkanes are obtained in pure form by removal of the solvent under reduced pressure. Reactions are typically analyzed by GC/MS and/or ^{1}H NMR.
28. Under solvent-free, open-air conditions, the combination of sodium borohydride and palladium catalyst produces rapid hydrolysis of the borohydride with release of hydrogen gas. In the absence of solvent, the heat evolved from the hydrolysis is sufficient to cause combustion of the hydrogen gas. Thus, the procedure described above should only be performed following the indicated order of addition and with the catalyst suspended in the selected solvent. In our experience with laboratory scale experiments, the palladium catalyst could be safely filtered from the reaction mixture after quenching the reaction with aqueous HCl.
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