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Efficient and exceptionally selective semireduction of alkynes using a supported gold catalyst under a CO atmosphere†

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A new efficient method for chemo- and regio-selective semireduction of alkynes using CO/H$_2$O as the hydrogen source catalyzed by gold supported on high surface area TiO$_2$ was developed. A facile and practical synthesis of 1,2-dideuterioalkenes was also realized by using CO/D$_2$O as the reducing agent.

The catalytic semireduction of alkynes to the corresponding alkenes is of great significance in the manufacture of fine chemicals as well as in the polymerization industry.[1] Such reactions are usually carried out using molecular hydrogen in the presence of Pd-based catalysts,[2,3] with two main drawbacks:[4–6] toxic additives are mostly required to improve the selectivity, and hydrogen uptake in these systems should be strictly monitored to prevent over-reduction to alkanes. An attractive alternative is catalysts based on supported gold nanoparticles (NPs), which have shown interesting catalytic properties in the chemoselective transformation of functional groups including partial hydrogenation of carbon–carbon multiple bonds.[7,8] In this connection, a nanoporous gold-catalyzed selective semireduction of alkynes to Z-olefins was recently reported.[9] The hydrogen source used in this process was organosilanes, which however may not be economically suitable and also poses safety concerns. Thus, the development of new alternative Au-based semireduction methods pertaining to the use of safer and more expedient hydrogen sources is highly desirable.

We have recently discovered an excellent Au-catalyzed transfer reduction strategy that can allow rapid and chemoselective reduction of substituted nitro and carbonyl compounds under very mild conditions.[10] This process can circumvent the limited hydrogen delivery capacity that has plagued previously reported Au-catalyzed hydrogenation processes.[11] The reductants used in this green methodology were CO and H$_2$O (rather than H$_2$), where the transient Au$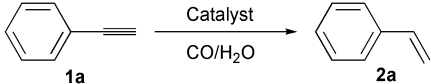^0$–H formed by the CO-induced H$_2$O reduction is believed to be the key active species for selective reduction of unsaturated polar groups. Given the high efficiency and unique chemoselectivity of the Au–CO/H$_2$O-mediated reduction, we were inspired to apply this catalytic methodology to semireduction of alkynes. Herein, we report that Au NPs (mean size *ca.* 2.0 nm) deposited on high surface area TiO$_2$ (Au/HSA-TiO$_2$) efficiently catalyze selective semireduction of alkynes to their corresponding alkenes with CO/H$_2$O as the reductant under mild conditions. To the best of our knowledge, this study also reports semireduction of alkynes to the corresponding 1,2-dideuterioalkenes with the CO/D$_2$O couple in the presence of a gold catalyst for the first time.

Initially, we investigated the catalytic activities of a series of supported Au NPs of approximately 2–3 nm size in the semireduction of phenylacetylene (**1a**) under a mild CO atmosphere (10 atm) at 60 °C. These Au catalysts promoted the semireduction of **1a** to the corresponding styrene (**2a**) with >99% selectivities (Table 1, entries 1–7 and 9–12). Of the Au catalysts tested, the use of high surface area TiO$_2$ as a support gave the highest activity to give **2a** quantitatively within 1 h (entry 1). This result is remarkable, and becomes more relevant as the catalyst can be reused, at least five times, while maintaining a 96% conversion and a yield up to 96% (entry 2). In a gram-scale reaction of **1a** (20-fold scale up) for 19 h, **2a** was obtained in 97% yield (entry 3). Identical gold NPs supported on commercial P25 which has much smaller surface area were also found to be effective but inferior to Au/HSA-TiO$_2$ (entry 1 *vs.* 4), whereas Au/CeO$_2$, Au/ZnO, Au/Al$_2$O$_3$ and Au/ZrO$_2$ gave **2a** in low yields (entries 9–12). Further investigation into the reaction parameters revealed that the catalytic activity was sensitive to the solvent employed in this reaction. Among the solvents tested, ethanol was the best (see Table S1 in ESI†). Notably, without organic solvent, this semireduction can still proceed to end in neat water (Table 1, entry 5). The most noteworthy aspect of the Au/HSA-TiO$_2$–CO/H$_2$O reduction system, however, is that the exclusive selectivity of **2a** can be maintained even after prolonged reaction time following the complete consumption of **1a** (Fig. S3, ESI†). This distinct feature, together with the fact that the semireduction could proceed smoothly even at 25 °C (entry 7), offers practical and real advantages over the existing methods to establish a more sustainable and industrially-viable process.

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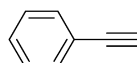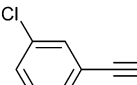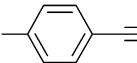**Table 1** Semireduction of phenylacetylene (**1a**) to styrene (**2a**) with CO/ H$_2$O using various catalysts[a]
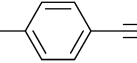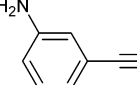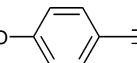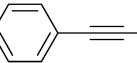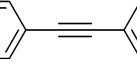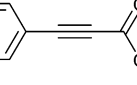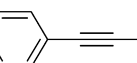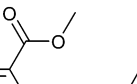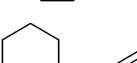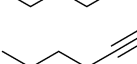

Entry	Catalyst	Temp. (°C)	Time (h)	Conv.[e] (%)	Sel.[e] (%)
1	Au/HSA-TiO$_2$	60	1	>99	>99
2[b]	Au/HSA-TiO$_2$	60	1	96	>99
3[c]	Au/HSA-TiO$_2$	60	19	97	>99
4	Au/TiO$_2$	60	1	72	>99
5[d]	Au/HSA-TiO$_2$	60	9	99	>99
6	Au/HSA-TiO$_2$	40	4	>99	>99
7	Au/HSA-TiO$_2$	25	10	>99	>99
8	HSA-TiO$_2$	60	1	n.r.	—
9	Au/CeO$_2$	60	1	39	>99
10	Au/ZnO	60	1	5	>99
11	Au/Al$_2$O$_3$	60	1	3	>99
12	Au/ZrO$_2$	60	1	24	>99
13	Pd/C	60	1	Trace	—
14	Pt/C	60	1	Trace	—
15	Ru/Al$_2$O$_3$	60	1	Trace	—
16	Ir/TiO$_2$	60	1	Trace	—

[a] Reaction conditions: 0.5 mmol **1a**, metal (1 mol%), CO (10 atm), ethanol (4.5 mL), H$_2$O (0.5 mL). [b] Fifth run. [c] Conditions: substrate (10 mmol), Au (0.1 mol%), CO (20 atm), ethanol (18 mL), H$_2$O (2 mL). [d] H$_2$O (5 mL), no organic solvent. [e] The conversion and selectivity were determined by GC using anisole as the internal standard.

Subsequent studies focusing on the comparison with other noble metals (Table 1, entries 13–16) showed that the presence of gold is essential for exclusive semireduction of **1a** with CO/H$_2$O. To better understand the superior activity and selectivity, we conducted several experiments to gain mechanistic insight into the present Au/HSA-TiO$_2$–CO/H$_2$O semireduction system. First, in a control experiment under identical conditions without **1a**, H$_2$ was not detected. Second, by using H$_2$ as a reducing agent instead of CO/H$_2$O, we observe substantial formation of the over-reduced product of ethylbenzene even at low **1a** conversion levels (Fig. S4, ESI†). These results rule out the participation of H$_2$ in the Au/HSA-TiO$_2$ catalyzed semireduction as described above. Third, in a separate experiment investigating the influence of supports by using O$_2$ as the hydrogen acceptor showed that the liquid phase CO oxidation over Au/HSA-TiO$_2$ occurred with much higher rates than other catalysts (Fig. S5, ESI†), indicating that the CO species adsorbed on the Au–HSA-TiO$_2$ interface could be more active for relevant transformation. Taken together, it is likely that *in situ* gold-hydride species generated from the reaction of CO with H$_2$O over Au/HSA-TiO$_2$ plays a key role in facilitating the desired semireduction in a controlled manner,[8a] although the precise origin of such exceptionally high selectivity remains to be clarified at this stage.

With these findings in hand, we then extended our studies to various kinds of alkynes to establish the scope of this Au/HSA-TiO$_2$–CO/H$_2$O-based semireduction system. The results depicted in Table 2 confirmed that a broad range of sensitive and reducible functional groups, including halide, ketone, ether and ester substituents (Table 2, entries 2, 3, 6 and 9–11), were tolerated in the semireduction process. For terminal alkynes, which are too active to stay in the partially-reduced state in many conventional procedures,[2,12] the corresponding terminal alkenes were obtained in almost

Table 2 Semireduction of various alkynes with CO/H$_2$O[a]

Entry	Substrate	Temp. (°C)	Time (h)	Conv.[b] (%)	Sel.[b] (%)	Z/E[c]
1		60	1	>99	>99	—
2		60	0.5	>99	>99	—
3		60	0.3	>99	>99	—
4		60	1	>99	>99	—
5		60	3	>99	>99	—
6		60	4	>99	>99	—
7		100	16	93	>99	96/4
8		80	14	95	>99	97/3
9		60	2	>99	>99	>99/1
10		60	1	>99	>99	>99/1
11		90	18	92	>99	96/4
12		60	8	>99	>99	91/9
13		80	12	96	>99	—
14		100	12	90	>99	—

[a] Reaction conditions: substrate (0.5 mmol), Au/HSA-TiO$_2$ (Au 1 mol%), CO (10 atm), ethanol (4.5 mL), H$_2$O (0.5 mL). [b] The conversion and selectivity were determined by means of GC using anisole as the internal standard. [c] Z/E ratio was determined by GC and ^{1}H NMR spectroscopy.

quantitative yields without detectable over-reduced alkanes. Furthermore, there seems to be a prominent electronic effect of the substituents in the benzene ring on the overall catalytic efficiencies. For example, a much shorter reaction time is required for reaction completion when *p*-fluorophenyl-acetylene was used as a substrate (entry 3), in sharp contrast to the significantly prolonged reaction time needed for obtaining the desired product in quantitative yield when *p*-methoxy-phenyl-acetylene was used as a substrate (entry 6). The Au/HSA-TiO$_2$–CO/H$_2$O protocol is also
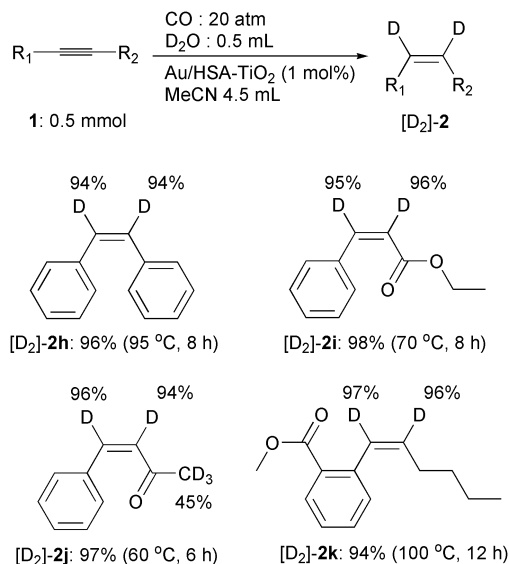
Fig. 1 Syntheses of 1,2-dideuterioalkenes *via* CO/D$_2$O-mediated alkyne semireduction. The yield was determined by GC and deuteration efficiency was confirmed by ^{1}H NMR.

effective for *cis*-selective semireduction of a series of structurally diverse internal alkynes. Owing to the steric hindrance around the triple bond, internal alkynes generally transform much slower than terminal alkynes (entries 7, 8 and 11). Nevertheless, for substrates bearing strong polar groups adjacent to the triple bond, the reaction can still proceed quite smoothly under mild conditions (entries 9, 10 and 12). Moreover, this reduction system was also applicable to aliphatic alkynes at higher temperature to afford the desired aliphatic alkenes in high yields (entries 13 and 14).

Given that CO-mediated H$_2$O activation is a central step in the formation of the key Au-hydride species, we presumed that D$_2$O as the deuterium source should also be amenable to this CO-mediated semireduction, thereby affording a new efficient protocol for the synthesis of 1,2-dideuterioalkenes. Deuterated alkenes are key building blocks for the construction of a variety of deuterated target compounds, which are widely utilized in various scientific fields like biological research and the elucidation of reaction mechanisms.[13] As a result, finding a method that would selectively produce these compounds would be of significant practical utility. Still, direct H/D exchange reactions of unlabeled alkenes with a deuterium source prevail,[14] whereas the site- and regio-selective introduction of deuterium atoms with high deuterium efficiency remains challenging. Several efforts have been devoted to synthesizing deuterated alkenes by site-selective reductive deuteration of alkynes,[15] while most of these previously reported methods suffered from problems like tedious stepwise procedures and/or the necessity of expensive reducing agents. Thus, the development of deuterium-labeling methods with more convenient reagents, simpler procedures, higher deuterium efficiency and better selectivity is highly desired. In view of the fact that D$_2$O is undoubtedly the most inexpensive and easy-to-handle deuterium source, we have performed the alkyne semireduction process using the CO/D$_2$O couple as the reducing agent. As depicted in Fig. 1, it is possible to obtain a range of synthetically useful Z-1,2-dideuterioalkenes with excellent yields and a high deuterium ratio

through this mild and convenient Au–CO/D$_2$O-based catalytic procedure.[16] These preliminary results clearly demonstrate that this Au–CO/D$_2$O protocol is amenable to deuterium-labeled compound synthesis, and work on this topic is ongoing.

In summary, we have developed a new, practical and efficient gold-catalyzed method for highly selective semireduction of a range of alkynes to the corresponding alkenes with CO/H$_2$O as a reducing agent. An essential feature of the present methodology is the exclusive alkene selectivity independent of alkyne conversion. Furthermore, the CO/D$_2$O couple can work as a deuterium transfer reagent in the presence of a gold catalyst, opening up a new avenue for cheap, convenient, and green synthesis of deuterium-labeled alkenes.

Notes and references

1 (a) R. C. Larock, *Comprehensive Organic Transformations*, VCH, New York, 1989; (b) S. Nishimura, *Handbook of Heterogeneous Catalytic Hydrogenation for Organic Synthesis*, Wiley, Chichester, 2001; (c) K. N. Campbell and B. K. Campbell, *Chem. Rev.*, 1942, **31**, 77–175.
2 H. Lindlar, *Helv. Chim. Acta*, 1952, **35**, 446–450.
3 (a) A. Molnár, A. Sárkány and M. Varga, *J. Mol. Catal. A: Chem.*, 2001, **173**, 185–221; (b) A. Borodziński and G. C. Bond, *Catal. Rev.*, 2006, **48**, 91–144; (c) C. Oger, L. Balas, T. Durand and J. M. Galano, *Chem. Rev.*, 2013, **113**, 1313–1350.
4 J. G. Ulan, E. Kuo, W. F. Maier, R. S. Rai and G. Thomas, *J. Org. Chem.*, 1987, **52**, 3126–3132.
5 J. Yu, *Chem. Commun.*, 1998, 1103–1104.
6 M. García-Mota, B. Bridier, J. Pérez-Ramírez and N. López, *J. Catal.*, 2010, **273**, 92–102.
7 (a) M. Stratakis and H. Garcia, *Chem. Rev.*, 2012, **112**, 4469–4506; (b) T. Mitsudomea and K. Kaneda, *Green Chem.*, 2013, **15**, 2636–2654; (c) X. Liu, L. He, Y. M. Liu and Y. Cao, *Acc. Chem. Res.*, 2014, **47**, 793–804.
8 (a) J. Jia, K. Haraki, J. N. Kondo, K. Domen and K. Tamaru, *J. Phys. Chem. B*, 2000, **104**, 11153–11156; (b) J. A. Lopez-Sanches and D. Lennon, *Appl. Catal., A*, 2005, **291**, 230–237; (c) Y. Segura, N. López and J. Pérez-Ramírez, *J. Catal.*, 2007, **247**, 383–386.
9 M. Yan, T. Jin, Y. Ishikawa, T. Minato, T. Fujita, L. Y. Chen, M. Bao, N. Asao, M. W. Chen and Y. Yamamoto, *J. Am. Chem. Soc.*, 2012, **42**, 17536–17542.
10 (a) L. He, L. C. Wang, H. Sun, J. Ni, Y. Cao, H. Y. He and K. N. Fan, *Angew. Chem., Int. Ed.*, 2009, **48**, 9538–9541; (b) L. He, F. J. Yu, X. B. Lou, Y. Cao, H. Y. He and K. N. Fan, *Chem. Commun.*, 2010, **46**, 1553–1555; (c) J. Ni, L. He, Y. M. Liu, Y. Cao, H. Y. He and K. N. Fan, *Chem. Commun.*, 2011, **47**, 812–814; (d) J. Huang, L. Yu, L. He, Y. M. Liu, Y. Cao and K. N. Fan, *Green Chem.*, 2011, **13**, 2672–2677.
11 (a) A. Corma and P. Serna, *Science*, 2006, **313**, 332–334; (b) M. Boronat, P. Concepción, A. Corma, S. González, F. Illas and P. Serna, *J. Am. Chem. Soc.*, 2007, **129**, 16230–16237; (c) A. Corma, P. Serna, P. Concepción and J. J. Calvino, *J. Am. Chem. Soc.*, 2008, **130**, 8748–8753.
12 P. Hauwert, G. Maestri, J. W. Sprengers, M. Catellani and C. J. Elsevier, *Angew. Chem., Int. Ed.*, 2008, **47**, 3223–3226.
13 (a) T. H. Lowry and K. S. Richardson, *Mechanism and Theory in Organic Chemistry*, Harper and Row, New York, 1987; (b) D. J. Porter and F. L. Boyd, *J. Biol. Chem.*, 1991, **266**, 21616–21625.
14 (a) B. Rybtchinski, R. Cohen, Y. Ben-David, J. M. L. Martin and D. Milstein, *J. Am. Chem. Soc.*, 2003, **125**, 11041; (b) G. Erdogan and D. B. Grotjahn, *J. Am. Chem. Soc.*, 2009, **131**, 10354.
15 (a) E. Shirakawa, H. Otsuka and T. Hayashi, *Chem. Commun.*, 2005, 5885–5886; (b) Y. Yabe, Y. Sawama, Y. Monguchi and H. Sajiki, *Chem. – Eur. J.*, 2013, **19**, 484–488.
16 Note that for substrate **1j**, as a result of the rapid reversible keto–enol tautomerism, the acetyl group is partially exchanged with D$_2$O during the semireduction process.