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An Unusual Chemoselective Hydrogenation of Quinoline Compounds Using Supported Gold Catalysts

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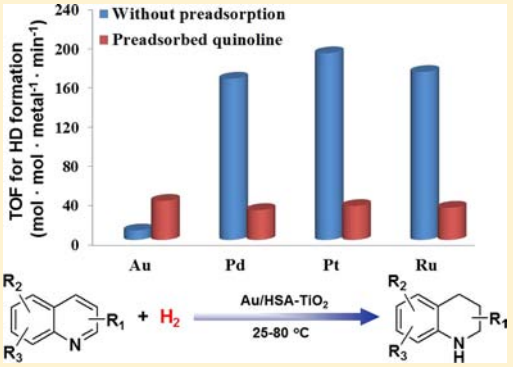
Supporting Information

ABSTRACT: The pursuit of modern sustainable chemistry has stimulated the development of innovative catalytic processes that enable chemical transformations to be performed under mild and clean conditions with high efficiency. Herein, we report that gold nanoparticles supported on TiO_2 catalyze the chemoselective hydrogenation of functionalized quinolines with H_2 under mild reaction conditions. Our results point toward an unexpected role for quinolines in gold-mediated hydrogenation reactions, namely that of promoter; this is in stark contrast to what prevails in the traditional noble metal Pd-, Pt-, and Ru-based catalyst systems, in which quinolines and their derivatives typically act as poisons. As a result of the remarkable promotional effect of quinoline molecules to H_2 activation over supported gold, the transformation can proceed smoothly under very mild conditions (even at temperatures as low as 25 °C). Of practical significance is that various synthetically useful functional groups including halogens, ketone, and olefin remain intact during the hydrogenation of quinolines. Moreover, the protocol also shows promise for the regiospecific hydrogenation of the heterocyclic ring of a variety of other biologically important heteroaromatic nitrogen compounds, such as isoquinoline, acridine, and 7,8-benzoquinoline, in a facile manner. Apart from its importance in catalytic hydrogenation, we believe that this intriguing self-promoted effect by reactant molecules may have fundamental implications for the broad field of gold catalysis and form the basis for development of new catalytic procedures for other key transformations.



INTRODUCTION

Heterogeneous catalytic hydrogenation is a powerful tool for achieving controlled reduction of many types of organic compounds under mild conditions.[1] The importance of this reductive transformation has been originally highlighted by the awarding of the 1912 Nobel Prize in Chemistry to Sabatier for his work on hydrogenation of alkenes over nickel catalysts.[2] Since then, an extensive number of heterogeneous metal catalysts have been introduced. The mostly used ones are the supported Pt and Pd catalysts, along with Raney nickel and a few supported Cu catalysts.[3] These catalysts can hydrogenate many different functional groups with high activity. However, when dealing with multifunctional molecules, the problem often arising is that the classical hydrogenation catalysts reduce sensitive functions simultaneously, leading to an undesired selectivity.[4] In such cases, the use of older, noncatalytic manufacturing processes (by employing stoichiometric reducing agents, such as sodium hydrosulfite, iron, tin, or zinc in ammonium hydroxide), prevails despite the concomitant formation of large quantities of unwanted waste.[5] From both green and synthetic points of view, it is imperative to develop ultraselective and highly efficient heterogeneous catalytic reduction methodologies for clean chemical synthesis.

Catalysts based on supported gold nanoparticles (Au NPs)[6] have attracted considerable attention as a material with a surprising activity and selectivity for a broad array of organic reactions,[7] which is believed to be essential for the chemical industry to move toward sustainability. The pioneering work by Bond et al. in the early 1970s first reported the excellent selectivity of supported Au catalysts prepared by conventional impregnation method for the hydrogenation of unsaturated hydrocarbons,[8] albeit with a very limited activity. Despite such impressive results it was not until almost three decades later, that Claus's and Corma's groups have demonstrated that supported Au NPs with size of 3−5 nm can promote the selective hydrogenation of carbonyl or nitro groups in the presence of other reducible functions even at very high conversion values.[9] These Au-catalyzed hydrogenation processes contributed substantially to catalytic hydrogenation by enhancing the chemoselectivity to an unprecedented level. Nevertheless, they are still not practically useful owing to the lack of sufficient acitvity. In fact, as a consequence of the limited capability of Au toward H_2 activation and dissociation,[10] Au-catalyzed hydrogenation reactions typically occur under demanding conditions (commonly >100 °C), and the hydrogenation delivery rates (mols of substrate converted per mol metal per second) of the Au catalyst are generally 1−2 orders of

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magnitude lower than those of the traditional platinum group metal (PGM)-based catalysts.[9c,11] Hence, the development of new effective Au-based hydrogenation processes that can deliver high activity while preserving high selectivity under mild conditions constitutes a major challenge.

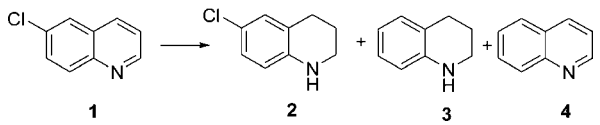
1,2,3,4-Tetrahydroquinolines are ubiquitous in numerous biologically active natural products and pharmacologically relevant therapeutic agents.[12] While Au-catalyzed approaches to tetrahydroquinoline derivatives have been reported,[13] a chemo- and regioselective hydrogenation approach would be superior. The direct hydrogenation of readily available quinolines offers a straightforward and promising approach to access tetrahydroquinolines in terms of its simplicity and high atom efficiency.[14] Unfortunately, the use of this truly green tool has proven extremely difficult, due to the aromatic nature of the quinoline ring and the potential poisoning of the catalysts. Until now, relevant protocols are largely based on several Ir-, Ru- and Rh-based homogeneous systems.[15] Despite their utility, these procedures still suffer from the inherent problems associated with the reusability and/or the indispensable use of cocatalysts. Recently, a handful of heterogeneous catalytic systems based on traditional noble metals (Pd, Pt, Ru etc.) have been developed.[16] These catalysts need to be used with caution because they are vulnerable to the poisoning effect of strongly adsorbed quinolines and/or their hydrogenated derivatives. Moreover, clear drawbacks of these systems are their low tolerance for functional groups and limited substrate scope. Given the vital importance of this type of transformation, the search for new simple, efficient, and general catalytic system that can facilitate selective quinoline hydrogenation under mild and ligand-free conditions remains a challenging but rewarding task.

We report herein an unusual chemoselective hydrogenation of quinolines to the corresponding 1,2,3,4-tetrahydroquinolines using supported Au NPs. As a result of the remarkable reactant-promoted effect of quinoline compounds to hydrogen activation over highly dispersed Au NPs, the transformation can proceed smoothly under mild conditions (even at temperatures as low as 25 °C). Furthermore, a wide range of substituted quinolines can be exclusively hydrogenated to the desired products, keeping various synthetically useful functional groups including halogens, ketone, and olefin intact. The excellent performance of the present catalytic system has allowed us to extend this methodology to the regiospecific hydrogenation of the heterocyclic ring of various other biologically important heteroaromatic nitrogen compounds, such as isoquinoline, acridine, in a facile manner.

RESULTS AND DISCUSSION

In exploratory experiments, we selected the hydrogenation of 6-chloroquinoline (**1**) to corresponding 6-chloro-1,2,3,4-tetrahydroquinoline (**2**) as the model reaction to study the catalytic activity and selectivity of several commercially available noble metal-based catalysts (Table 1, entries 1−5). The hydrogenation of **1** without C−X bond cleavage (X = halogen, by hydrogenolysis) is of critical importance, as the aryl halide products obtained are useful reagents in metal-catalyzed cross-coupling reactions.[17] Under 2 MPa H_2 at 80 °C, the benchmark Au/TiO_2-WGC catalyst (with a Au particle mean diameter of 3.5 nm, supplied by World Gold Council, Figure S3), can afford exclusive formation of **2** with moderate activity (43% conversion) within 4 h (Table 1, entry 1). To our delight, Au/TiO_2-M (supplied by Mintek) catalyst with smaller Au particle size (average size ca. 2.7 nm, Figure S3) facilitated the complete conversion of **1** under identical conditions (Table 1, entry 2). Applying Pd/C, Pt/C, or Ru/Al_2O_3 (provided by Alfa Aesar), the desired halo-substituted 1,2,3,4-tetrahydroquinoline was also formed (Table 1, entries 3−5). Nevertheless, in these cases, an unavoidable concomitant formation of dehalogenation products readily occurs. Given the fact that the rate of nitro or carbonyl group reduction over Au (<5 nm) was significantly lower than those over traditional PGM-based catalysts, the comparable or even superior performance obtained in the present Au-catalyzed hydrogenation of substituted quinolines was remarkable.

Table 1. Hydrogenation of 6-Chloroquinoline to 6-Chloro-1,2,3,4-tetrahydroquinoline under Various Conditions[a]



					select.[g] (%)		
entry	catalysts	T (°C)	t (h)	conv.[g] (%)	2	3	4
1[b]	Au/TiO_2-WGC	80	4	43	100	0	0
2[c]	Au/TiO_2-M	80	4	100	100	0	0
3[d]	Pd/C	80	4	74	61	28	11
4[d]	Pt/C	80	4	81	53	31	16
5[d]	Ru/Al_2O_3	80	4	37	46	30	24
6	Au/HSA-TiO_2	80	1.5	100	100	0	0
7	Au/HSA-TiO_2	60	3	100	100	0	0
8[e]	Au/HSA-TiO_2	25	16	92	100	0	0
9	Pd/HSA-TiO_2	60	3	92	86	12	2
10	Pt/HSA-TiO_2	60	3	97	92	7	1
11	Ru/HSA-TiO_2	60	3	93	88	11	1
12	Pd/HAP	60	3	86	79	17	4
13	HSA-TiO_2	60	3	n.r.	–	–	–
14	$HAuCl_4$	60	3	n.r.	–	–	–
15	Au_2O_3	60	3	n.r.	–	–	–
16	Au^0 powder	60	3	n.r.	–	–	–
17[f]	Au/HSA-TiO_2	60	3	98	100	0	0

[a]6-chloroquinoline (0.5 mmol), toluene (3 mL), catalyst (metal: 1 mol %), 2 MPa H_2; n.r. = no reaction. [b]Au/TiO_2-WGC sample was provided by the World Gold Council. [c]Au/TiO_2-M was supplied by Mintek. [d]Pd/C, Pt/C, and Ru/Al_2O_3 were provided by Alfa Aesar. [e]6-chloroquinoline (0.5 mmol), toluene (3 mL), catalyst (metal: 5 mol %), 2 MPa H_2. [f]Fifth run. [g]Conversion (Conv.) and selectivity (Select.) were based on 6-chloroquinoline consumption (GC analysis).

After these initial promising results, we further examined a series of Au deposited on other mineral supports, such as Al_2O_3, ZnO, CeO_2 and activated carbon. These catalysts, however, were not found to be particularly active, although in all cases the desired chloro-substituted 1,2,3,4-tetrahydroquinoline can be exclusively produced (Table S1, entries 2−5). Considering that TiO_2 (P25) in both Au/TiO_2-WGC and Au/TiO_2-M has rather low surface areas (45 m^2 g^{-1}), we envision that the catalytic performance might be optimized by using higher surface area support materials. Gratifyingly, very small Au NPs (with mean diameter of 2 nm, Figure 1) dispersed on high surface area (HSA) TiO_2 (S_{BET} ∼ 124 m^2 g^{-1}, Figure S1) turned out to give a much more effective catalyst. In particular, over Au/HSA-TiO_2, the quantitative conversion of **1** into **2** was achieved in a very short reaction time (1.5 h) (Table 1, entry 6).[18] When the reaction temperature was lowered to 60 °C, Au/HSA-TiO_2 still produces **2** as the sole product within 3 h

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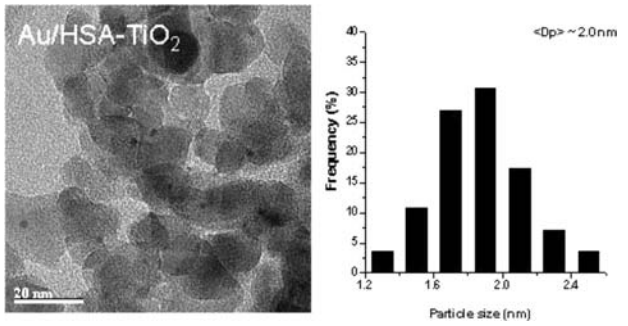


Figure 1. Representative TEM image and size distribution of Au/HSA-TiO_2 (0.5 wt %).

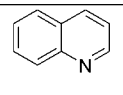
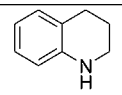
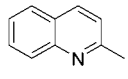
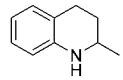
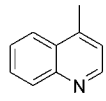
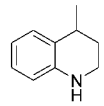
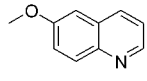
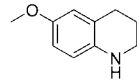
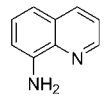
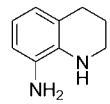
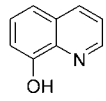
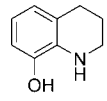
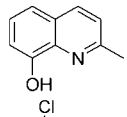
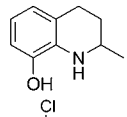
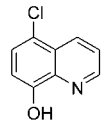
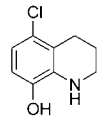
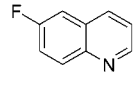
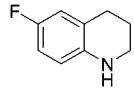
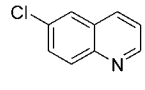
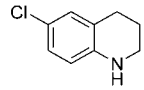
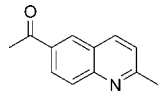
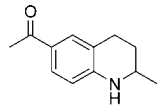
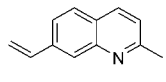
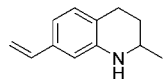
(entry 7). Most remarkably, at temperatures as low as 25 °C, the hydrogenation of **1** proceeds smoothly, although a longer reaction time and relatively larger amounts of the Au catalyst were required (Table 1, entry 8). Nevertheless, the performance is encouraging since it represents the mildest condition in the Au-based hydrogenation process to date.

In subsequent experiments performed under 2 MPa H_2 at 60 °C, a clear advantage of the Au/HSA-TiO_2 catalyst in terms of conversion and selectivity over other noble metals (Pd, Pt, Ru) with identical particle size[19] supported on HSA-TiO_2 was also noticed (Table 1, entries 9−11). Note that previously reported solid catalysts, such as hydroxyapatite (HAP)-supported Pd NPs (Pd/HAP),[16a] showed good activity but much inferior selectivity relative to Au/HSA-TiO_2 under the present reaction conditions (Table 1, entry 12). Blank experiments without catalyst or using the Au-free HSA-TiO_2 gave no conversion, thus further confirming that the highly dispersed Au NPs were indispensable for the desired transformation (Table 1, entry 13). In addition, the use of the catalyst precursor $HAuCl_4$ as well as with other Au compounds, including Au_2O_3 and Au^0 powder (average particle size of ca. 150 nm), did not promote the reaction at all (Table 1, entries 14−16).

To verify whether the observed catalysis is truly heterogeneous or not, the reaction mixture was hot filtered at 40% conversion of **1** at 60 °C. Further stirring of the filtrate under the above reaction conditions did not yield any additional product. An inductively coupled plasma method with detection limit of 0.007 ppm was used to confirm that no Au leached into the filtrate.[20] Furthermore, the recovered Au/HSA-TiO_2 catalyst could be reused at least five runs without appreciable loss of the original catalytic activity (Table 1, entry 17). These results rule out any possible contribution of homogeneous catalysis by leached Au species.

Having established that Au/HSA-TiO_2 was an efficient catalyst for the hydrogenation of quinolines, we extended our studies to various structurally different substituted quinolines. The results were summarized in Table 2. The hydrogenation of quinoline was highly regioselective, producing 1,2,3,4-tetrahydroquinoline exclusively (Table 2, entry 1). No trace of 5,6,7,8-tetrahydroquinoline or decahydroquinoline, byproducts frequently formed under hydrogenation catalysis,[21] was observed. Reactions of quinolines bearing a methyl group at the 2- and 4-position proceeded successfully to give the corresponding 1,2,3,4-tetrahydroquinolines (Table 2, entries 2 and 3). Quinolines with electron-donating groups (−OMe and $-NH_2$) on the benzene ring react smoothly (Table 2, entries 4 and 5). Remarkably, the hydrogenation of 8-hydroxyquinolines afforded the corresponding biologically active 1,2,3,4-tetrahydro-8-hydroxyquinolines (Table 2, entries 6−8), which can inhibit leukotriene formation in macrophages.[22] Furthermore, in the more challenging reactions, where quinolines with other reducible groups (halogens, ketone, and olefin) were employed, the corresponding valuable functional tetrahydroquinolines were obtained in excellent yield (Table 2, entries 9−12), which has no precedent in heterogeneous quinoline hydrogenation.

Table 2. Au/HSA-TiO_2-catalyzed Hydrogenation of Various Quinolines[a]

Entry	Substrate	Product	t (h)	Conv.[c] (%)	Yield by GC[d] (%)
1			3.5	100	100
2			4	100	100
3[b]			9	96	96(91)
4			8	100	100
5[b]			24	99	99(95)
6[b]			10	100	100
7[b]			8	97	97(90)
8[b]			13	96	94(88)
9			7	98	98(93)
10			3	100	100
11			12	97	86(77)
12			9	94	80(71)

[a]Substrate (0.5 mmol), toluene (3 mL), Au/HSA-TiO_2 (Au: 1 mol %), 60 °C, 2 MPa H_2. [b]80 °C. [c]Conversion was based on heteroaromatic nitrogen compounds consumption. [d]Numbers in parentheses refer to yields of isolated products.

Encouraged by these results, we applied this attractive protocol to the regioselective hydrogenation of heterocyclic ring of a series of other biologically important heteroaromatic nitrogen compounds. Isoquinoline, acridine, and 7,8-benzoquinoline were tested. As depicted in Table 3, nearly quantitative

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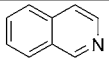
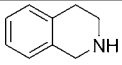
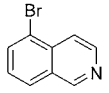
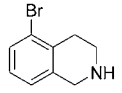
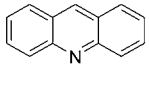
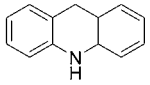
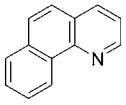
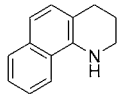
Table 3. Au/HSA-TiO_2-Catalyzed Hydrogenation of Heteroaromatic Nitrogen Compounds[a]

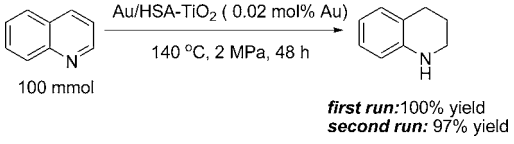
Entry	Substrate	Product	t (h)	Conv.[c] (%)	Yield by GC[d] (%)
1			8.5	100	100
2[b]			10	97	97(93)
3			2.5	100	100
4			7	100	100

[a]Substrate (0.5 mmol), toluene (3 mL), Au/HSA-TiO_2 (Au: 1 mol %), 60 °C, 2 MPa H_2. [b]80 °C. [c]Conversion was based on heteroaromatic nitrogen compounds consumption. [d]Numbers in parentheses refer to yields of isolated products.

yields were obtained in most cases. Isoquinoline was reduced to the corresponding tetrahydroisoquinoline (Table 3, entry 1). 6-bromoisoquinoline was converted to the corresponding 6-bromotetrahydroisoquinoline without any dehalogenation (Table 3, entry 2). More complex fused ring compounds including acridine and 7,8-benzoquinoline were hydrogenated to their corresponding tetrahydroderivatives (Table 3, entries 3 and 4). Note that the order of individual initial rate was acridine > quinoline > 7,8-benzoquinoline > isoquinoline, which reflects both steric and electronic effects. Similar tendencies were observed and explained in the previous reported homogeneous reduction of polynuclear heteroaromatic compounds using $(Ph_3P)_3RhCl$ complexes.[23]

A heterogeneous direct hydrogenation without solvents would be more desirable for practical applications. Notably, this Au/HSA-TiO_2-catalyzed system can facilitate the 100 mmol scale hydrogenation of quinoline under neat conditions at 140 °C (Scheme 1). The hydrogenation was complete within

Scheme 1. Au/HSA-TiO_2-Catalyzed 100 mmol Scale Hydrogenation of Quinoline



48 h with 100% selectivity in the presence of 0.02 mol % Au, in which the turnover number (TON, based on total Au) of the Au catalyst approached 5000 with an excellent average turnover frequency (TOF) of approximately 104 h^{-1}. When the reaction was carried out on this scale, the Au/HSA-TiO_2 catalyst can also be reused without loss of activity.

At this stage, we became interested in elucidation of the nature of active Au in Au/HSA-TiO_2 sample, since the chemical state of Au was generally assumed as one of the key factors in determining the catalytic activity.[24] Detailed spectroscopic characterizations of the Au/HSA-TiO_2 sample were done with X-ray photoelectron spectroscopy (XPS) and diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) as well as X-ray absorption near-edge structure (XANES) studies.[25] From XPS data presented in Figure S5, only metallic Au was identified on the surface of the Au/HSA-TiO_2 catalyst. The fact that no bands for Au^+ or $Au^{\delta+}$ can be seen from the DRIFT spectrum (Figure S6) of adsorbed CO further confirmed the sole presence of metallic Au species in this material. Moreover, Au L_3-edge XANES data (Figure 2) of the Au/HSA-TiO_2 were

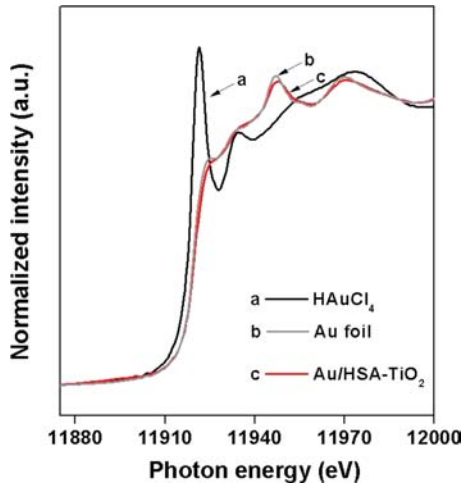


Figure 2. Au L_3-edge XANES spectra of the (a) $HAuCl_4$, (b) Au foil, and (c) Au/HSA-TiO_2.

clearly different from that of $HAuCl_4$ (as a reference compound for ionic Au^{3+} species) but rather similar to that of Au foil, which further indicated that Au species in the Au/HSA-TiO_2 sample exists in its elemental state.

To clarify the origin of the superior activity achieved in present Au^0-mediated hydrogenation system, we studied the H_2–D_2 exchange reaction over a variety of catalysts.[26] For the sake of comparison, the measurements were applied as close to the reaction conditions as possible. Thus, the rates of HD formation in terms of the TOF values were estimated at 60 °C over the samples with and without the presence of preadsorbed quinoline or its hydrogenated derivatives (Figure 3).[27] It is revealed that, as opposed to the case without preadsorption or in presence of preadsorbed tetrahydroquinoline, the H_2–D_2 exchange proceeds much more rapidly over the Au/HSA-TiO_2

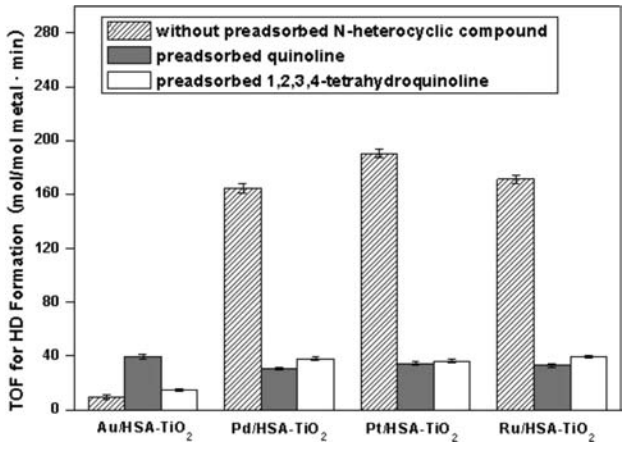


Figure 3. Rate for HD formation over various noble metal-based catalysts. The TOF values were calculated based on the mol of HD molecules formed per mol metal (Au, Pd, Pt, or Ru) per min. The error bars represent the standard deviation of triplicate tests.

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catalyst preadsorbed with quinoline molecules. This is in strong contrast to that occurs with the corresponding traditional Pd-, Pt-, and Ru-based catalysts, in which the rate of HD formation was heavily decreased when the samples were preadsorbed with relevant N-heterocylic compounds. These results unambiguously demonstrate that quinoline, a poison for traditional noble metal-containing hydrogenation catalysts,[3] can act as a promoter for the Au-catalyzed hydrogenation processes via facilitating the activation of H_2.

As for the activation of H_2 for chemoselective reduction of polar bonds (C═O or C═N) with homogeneous metal−ligand bifunctional catalysts, it is widely accepted that the reaction initiates with the heterolytic cleavage of H_2 to yield H^+ in a OH or NH ligand and H^- in metal hydrides, and the resulting H^+/H^- pair preferentially transfers to the polar bonds.[28] This type of ionic mechanism might be applicable also for heterogeneous metal catalysts. Very recently, Garcia and co-workers showed direct IR evidence on heterolytic dissociation of H_2 on ceria-supported Au NPs at 150 °C, leading to a proton bonded to a ceria oxygen and a hydride attached to Au.[29] On the other hand, it is well established that on exposure of H_2 to metal particles dispersed on oxide materials, such as Pt/Al_2O_3 and Rh/Al_2O_3, the formation of additional OH groups on the support via hydrogen spillover will readily occur.[30] Adopting these models, the dissociation of H_2 over Au/HSA-TiO_2 would yield $H^{\delta+}$ on the support and $H^{\delta-}$ species on Au NPs, albeit the characteristic vibrations associated with the Au hydrides were not detected by IR spectroscopy in our case.[31]

To measure the rate of H_2 cleavage step over various Au-based catalysts, H_2-D_2 exchange of D_2 with surface OH groups of the catalysts at 60 °C was monitored by DRIFTS. The results are shown in Figure 4. For Au/HSA-TiO_2, a simultaneous loss and gain in the IR band intensity for the Ti−OH (3686 cm^{-1}) and Ti−OD (2694 cm^{-1}) stretching vibrations were observed.[32] The OD formation rate for Au/HSA-TiO_2 was 3 orders of magnitude higher than that for HSA-TiO_2 (result not shown). This gives direct evidence of the Au NPs-catalyzed cleavage of the H−H bond. From the kinetic curves, the initial rate of the OD formation decreased significantly when Au particle size increased from 2 to 3.5 nm. For the catalysts with the same Au loading (0.5 wt %) and identical mean Au particle size (1.9−2.1 nm), the OH−D_2 exchange reaction rate ranks in the order of Au/HSA-TiO_2 (124 $m^2\ g^{-1}$) > Au/TiO_2−P25 (45 $m^2\ g^{-1}$) > Au/CeO_2 (50 $m^2\ g^{-1}$). This trend is in line with the catalytic data for quinoline hydrogenation, as shown in Tables S1 and S2, suggesting that a high abundance of surface hydroxyl groups on HSA-TiO_2 is beneficial for D_2 dissociation.

Based on the above-mentioned facts and bearing in mind that basic ligands of transition-metal complexes promote heterolytic cleavage of H_2 to give metal-hydride species,[28] we propose a concerted effect between quinoline molecules and the supported Au NPs. As depicted in Scheme 2, the key aspect of quinoline is to facilitate the crucial heterolytic H_2 activation at the Au-support interface. Namely, the quaternizable nitrogen atom of quinoline can serve as a basic ligand to promote the heterolytic H_2 cleavage, providing a favorable situation for provoking hydrogen activation under very mild conditions. Although the precise way by which the quinoline-assisted H_2 cleavage at the Au-support interface occurs remains to be clarified at this stage, it is important to emphasize that the moderate interaction between quinoline and Au could be the key factor accounting for the essential role of quinolines in the present Au-mediated hydrogenation reactions. Recent density functional theory (DFT) calculations have confirmed that flat and tilted orientations of the quinoline ring have lower adsorption energy on Au (7 and 10 kcal·mol^{-1} for flat and tilted species, respectively) compared to adsorption on Pt (ca. 40 kcal·mol^{-1} for flat species).[33] These facts, coupled with the findings in the present study, suggest that self-cooperation of Au surface and functional reactants may open new possibilities for development of new catalytic procedures for other key transformations.

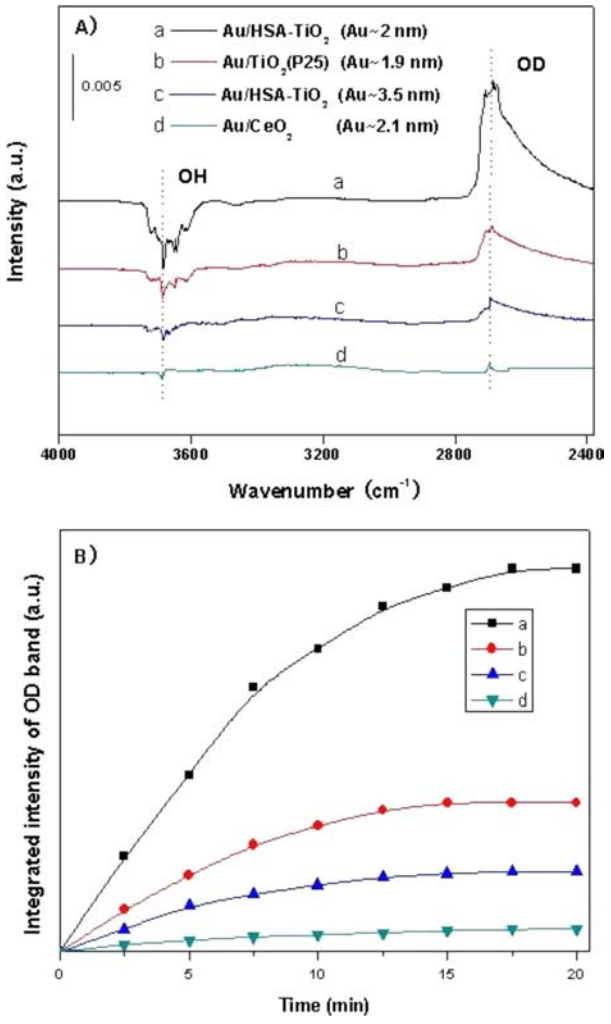
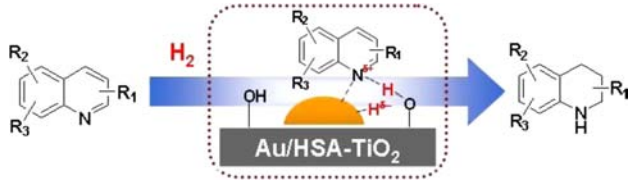


Figure 4. H_2-D_2 exchange of D_2 with surface OH groups of the catalysts at 60 °C. (A) DRIFT spectra recorded after a 20 min exposure to 10% D_2 in He. (B) Integrated intensity of OD band with respect to exposure time.

Scheme 2. Model Explaining the Activation of H_2 by Au and the Substrate through Heterolytic Cleavage



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CONCLUSIONS

In conclusion, we have described an exceedingly efficient approach for mild and clean hydrogenation of a wide range of quinolines and related heteroaromatic nitrogen compounds to the corresponding tetrahydroderivatives using supported Au NPs. Of practical significance is that various synthetically useful functional groups including halogens, ketones, and olefins remain intact during quinoline hydrogenation. Quinoline compounds, a class of well-known poisons for the traditional noble metal-based hydrogenation catalysts, can act as promoters for the Au catalysts, contributing to the superior activity and selectivity achieved with these processes. We believe this intriguing and remarkable promotional effect by reactants may have fundamental implications for the broad field of Au catalysis and be useful to design new powerful catalytic systems for green and sustainable organic synthesis.

EXPERIMENTAL SECTION

Preparation of HSA-TiO_2 Support. HSA nanocrystalline TiO_2 powders predominantly in the anatase phase were prepared by the hydrolysis of tetrabutyl titanate [TTBT, $Ti(OBu)_4$]. Typically, 17.2 g $Ti(OBu)_4$ was dropwise added to 800 mL water under vigorous stirring at room temperature, and then the mixture was further stirred for 2 h. The precipitate obtained was filtered and washed with water. The resultant powder was dried at 100 °C for 12 h and then calcined in a tubular oven at 400 °C in air for 4 h. The BET surface area of the resultant material was 124 $m^2 \cdot g^{-1}$.

Preparation of Au/HSA-TiO_2. Using a routine deposition precipitation (DP) method, 0.5 wt % Au/HSA-TiO_2 catalyst was prepared. An appropriate amount of aqueous solutions of chloroauric acid ($HAuCl_4$) was heated to 80 °C under vigorous stirring. The pH was adjusted to 8.0 by dropwise addition of NaOH (0.2 M), and then 1.0 g of HSA-TiO_2 was dispersed in the solution. The mixture was stirred for 2 h at 80 °C, after which the suspension was cooled to room temperature. Extensive washing with deionized water was then followed until it was free of chloride ions. The samples were dried under vacuum at room temperature for 12 h and calcined in air at 250 °C for 2 h.

General Procedure for Catalytic Hydrogenation of Quinolines. A mixture of substrate (0.5 mmol), catalyst (metal: 1 mol %), and toluene (3 mL) was charged into a Parr autoclave (25 mL capacity, SS-316). Then the autoclave was sealed, and 2 MPa H_2 was charged into it after internal air being degassed completely. The resulting mixture was vigorously stirred (1200 rpm with a magnetic stir bar) at a given temperature. The products were confirmed by the comparison of their GC retention time, mass, and ^1H NMR spectroscopy. The conversion and product selectivity were determined by a GC-17A gas chromatograph equipped with a HP-5 column (30 m × 0.25 mm) and a flame ionization detector (FID). The tetrahydroquinoline products can be isolated by silica gel chromatography (hexanes/ethyl acetate).

Isotope H_2–D_2 Exchange Reaction. The H_2–D_2 exchange reaction was carried out in a fixed bed quartz reactor with an inner diameter of 4 mm at 60 °C. The feed gas containing 20 vol% H_2, 20 vol% D_2, and balancing He is at a total flow rate of 60 $mL \cdot min^{-1}$, corresponding to a gas hourly space velocity (GHSV) of 1.8×10^5 mL h^{-1} g_{cat}^{-1}. Under these conditions, the H_2–D_2 exchange conversions were always kept below 15% to avoid mass-transfer limitations. Reaction products (H_2, HDm and D_2) were analyzed with an online mass spectrometer (Balzers, QMS 200 Omnistar). Trace amounts of HD formed in the experimental setup without catalyst and the product concentrations were corrected for this. Prior to catalytic test, the catalysts were heated in He flow (10 $mL \cdot min^{-1}$) at 200 °C for 0.5 h, followed by cooling to the desired temperature under He flow. For the introduction of quinoline or tetrahydroquinoline to the samples, the liquid compound (25 μmol) was injected under the He flow.

XANES Measurements. The X-ray absorption data at the Au L_3-edge of the samples were recorded at room temperature in transmission mode using ion chambers or in the fluorescent mode with silicon drift fluorescence detector at beamline BL14W1 of the Shanghai Synchrotron Radiation Facility (SSRF), China. The station was operated with a Si (311) double crystal monochromator. During the measurement, the synchrotron was operated at energy of 3.5 GeV and a current between 150 and 210 mA. The photon energy was calibrated with standard Pt metal foil.

DRIFT Spectroscopic Measurements. The DRIFTS experiments were carried out on a Nicolet Magna-IR 760 Fourier transform spectrometer (ThermoNicolet, Madison, WI) using an MCT detector. Prior to the chemisorption (10 vol% D_2/He), the sample (typically 20 mg) was pretreated in a stream of He (35 $mL \cdot min^{-1}$) at 250 °C for 2 h and then cooled under He to 25 °C. Unless stated otherwise, infrared (IR) spectra were recorded against a background of the sample at the reaction temperature under flowing He. IR spectra were recorded with coaddition 64 scans in single-beam spectra or absorbance spectra by applying a resolution of 4 cm^{-1}.

ASSOCIATED CONTENT

Supporting Information

Complete experimental procedures and characterization details. Supporting Information for this article is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(18) The benefit of using Au/HSA-TiO_2 catalyst becomes obvious when comparing its activity with activities of larger Au NPs (with average Au particle size, ca. 3.5 nm,) deposited on HSA-TiO_2 and Au NPs (with average Au particle size, ca. 1.9 nm) supported on conventional TiO_2 (P25, 45 m^2 g^{-1}) (Table S2, entries 1−3).
(19) 0.5 wt% Pd/HSA-TiO_2 (Pd ∼ 2 nm), 0.5 wt% Pt/HSA-TiO_2 (Pt ∼ 2 nm), and 0.5 wt% Ru/HSA-TiO_2 (Ru ∼ 2.3 nm) catalysts were prepared by impregnation technique.
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