Supported Au Nanoparticles with \(N\)-Heterocyclic Carbene Ligands as Active and Stable Heterogeneous Catalysts for Lactonization

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Supporting Information

ABSTRACT: Attachment of \(N\)-heterocyclic carbenes (NHCs) on the surface of metal nanoparticle (NP) catalysts permits fine-tuning of catalytic activity and product selectivity. Yet, NHC-coated Au NPs have been seldom used in catalysis beyond hydrogenation chemistry. One challenge in this field has been to develop a platform that permits arbitrary ligand modification without having to compromise NP stability toward aggregation or leaching. Herein, we exploit the strategy of supported dendrimer-encapsulated metal clusters (DEMCs) to achieve aggregation-stable yet active heterogeneous Au NP catalysts with NHC ligands. Dendrimers function as aggregation-inhibitors during the NP synthesis, and NHCs, well-known for their strong attachment to the gold surface, provide a handle to modify the stereochemistry, stereoelectronics, and chemical functionality of the NP surface. Indeed, compared to “ligandless” Au NPs which are virtually inactive below 80 °C, the NHC-ligated Au NP catalysts enable a model lactonization reaction to proceed at 20 °C on the same time scale (hours). Based on Eyring analysis, proto-deauration is the turnover-limiting step accelerated by the NHC ligands. Furthermore, the use of chiral NHCs led to asymmetric induction (up to 16% enantiomeric excess) in the lactonization transformations, which demonstrates the potential of supported DEMCs with ancillary ligands in enantioselective catalysis.

INTRODUCTION

Supported dendrimer-encapsulated metal clusters (DEMCs) are highly active and easily recyclable catalysts, which have enabled new supported catalysis methodology.1 However, despite its broad utility, this catalyst platform presently lacks a modular handle to tune reaction outcomes. Yet, rapid optimization of catalyst performance metrics such as reactivity, enantio-, diastereo-, regio-, and chemo-selectivity would greatly advance the sophistication and scope of transformations catalyzed by DEMCs. Ancillary ligands, commonly utilized in transition metal catalysis to tune catalyst selectivity, were a logical choice of the desired modular handles to be added to DEMCs. Among a broad array of ligands, persistent carbenes (PCs, also known as stable carbenes;2 e.g., N-heterocyclic carbenes, or NHCs3) offer numerous advantages: (1) strong binding to a broad array of elements,4 which in many cases has enabled the stabilization and isolation of highly reactive chemical species,5 (2) improved oxidative stability compared to ligands like phosphines and thiolates,6 and (3) synthetic accessibility and modularity.5 In addition, the judicious choice of NHCs as ligands on metal nanoparticle (NP) surfaces has been shown as a versatile strategy to enable selective heterogeneous catalysis,8 with pioneering work by Glorius5a,b,8f and Chaudret.8g So far, most examples of NHC-ligated NP catalysis focused on Pd, Pt, and Ru, and with the exceptions of three reports (enantioselective ketone arylation8b and aldehyde allylation;8c Buchwald–Hartwig amination8f) nearly all of the examples describe hydrogenation catalysis.8k,8f Despite the broad scope of known gold-catalyzed transformations8 and the growing body of work on NHC-Au surface chemistry,5b,10 catalysis by NHC-ligated Au NPs has been scarcely explored, and to our knowledge, only been applied to hydrogenation chemistry or electrochemical \(\text{CO}_2\) reduction.8k,11 A main challenge has been to systematically vary the ligand structure without perturbing Au NP stability to Au complex leaching and/or NP aggregation. Work in our laboratories on supported dendrimer encapsulated Au NPs1d provided a platform for overcoming this challenge.

Herein, we combine the strategies of supported DEMCs and NHC-ligated nanoparticles for the facile synthesis of catalytically active yet stable heterogeneous gold catalysts for a model
lactonization reaction with the possibility of ligand-derived enantioinduction (Figure 1). To the best of our knowledge, this is the first report of DEMCs with NHC ligands, as well as of NHC-ligated Au NP catalysis extended beyond hydrogenation or CO₂ reduction, namely, lactonization of allene-carboxylic acids. This model lactonization reaction was chosen because gold complexes, homogeneous⁻¹² or loaded in molecular form onto silica, have been previously shown to successfully catalyze this transformation in enantioselective fashion. Given the often ambiguous oxidation state, as well as distinct coordination environment and ligand presentation at a Au NP surface compared to molecular Au(I) species, translation of homogeneous reactivity to Au NPs is a known challenge. However, this challenge is also an opportunity to utilize the distinctly nanoparticle-derived handles (e.g., under-coordinated surface sites) on reactivity and selectivity. The synthesis, characterization, and proof-of-principle reaction studies of these catalysts will be discussed in detail.

Experimental Section

Synthesis of Cat-0. The synthesis of NHC-free Au NP catalyst, stabilized with the fourth generation hydroxyl-terminated polyamidoamine dendrimer (PAMAM G4OH, or G4OH for short) is utilized in this work.

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Table 1. Sample Codes and the Corresponding Compositions of the Gold Samples

<table>
<thead>
<tr>
<th>Codes</th>
<th>Composition</th>
</tr>
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<tbody>
<tr>
<td>Cat-0</td>
<td>Au₄/G4OH/SBA-15</td>
</tr>
<tr>
<td>Au/G4OH-NP-0</td>
<td>Au₄/G4OH (aqueous solution) before loading onto SBA-15</td>
</tr>
<tr>
<td>1</td>
<td>NH₄Au(I)-Cl complex as the precursor for Au NPs, see Figure 1 for the chemical structure</td>
</tr>
<tr>
<td>Au/G4OH-NP-1</td>
<td>Au NPs (methanol/chloroform solution) prepared from the reduction of 1 in the presence of G4OH</td>
</tr>
<tr>
<td>Cat-1</td>
<td>Au/G4OH-NP-1 loaded onto SBA-15</td>
</tr>
<tr>
<td>AuNP-1</td>
<td>Au NPs (methanol/chloroform solution) prepared from the reduction of 1 in the absence of G4OH</td>
</tr>
<tr>
<td>AuNP-1/SBA-15</td>
<td>AuNP-1 loaded onto SBA-15 as a solid</td>
</tr>
<tr>
<td>IS-1</td>
<td>the precursor imidazolium salt of 1</td>
</tr>
</tbody>
</table>

The codes containing 2, 3, ..., 11 are used in the same way as the codes containing 1, which is illustrated in Figure 4.
previously demonstrated success in forming NHC-ligated gold nanoparticles.\textsuperscript{10c,18} The average sizes of both as-synthesized NPs were comparable (ca. 3 nm in diameter). However, NPs in Cat-1 were still growing during the loading process due to continued reduction of 1, ultimately reaching a diameter of ~4.7 nm; meanwhile, the NPs in Cat-0 remained the same average size as before loading (Figure 2A,B). The observed size NP difference between Cat-0 and Cat-1 proved inconsequential with regard to their activity, given the results for other catalysts described herein (vide infra; Tables S1 and S2).

The use of dendrimer enhances the stability of the NPs to addition of the dendrimer resolved this issue. Thus, the dendrimers functioned as a stabilizer of the NPs.

Besides the reduction of structurally well-defined NHC-Au(I) complexes, e.g. Au-1, to prepare Cat-1, another method was attempted to attach the NHC to the Au surface,\textsuperscript{6a,10d,h} namely, via CO, adducts of N-heterocyclic carbenes (NHC-CO). However, the surface modification method led to the aggregation of Au particles under the conditions we tested (Figure S2). Thus, this method was not used further in this work.

**Au Oxidation State Analysis.** X-ray photoelectron spectroscopy (XPS) analysis shed light on the oxidation state differences at the Au NP surfaces (Figure 2C). The Au 4f/2 binding energy of Cat-0 was 83.4 eV, consistent with nanoparticulate Au(0): Kruse and Chenakin\textsuperscript{19} previously observed that the charge-corrected Au 4f/2 binding energy in Au NP/TiO\textsubscript{2} catalysts was 0.15–0.45 eV lower than that in the pure bulk Au. In contrast, the Au 4f/2 binding energy observed for Cat-1 was 84.9 eV, similar to that of the Au(I) complex 1 (84.7 eV). This difference of ~1.5 eV between Cat-1 and Cat-0 reflected the prevalence of Au(I) species at the surface of the former and Au(0) at the surface of the latter. To understand how far beyond the very surface the oxidation state differences persisted, we turned to X-ray absorption near edge structure (XANES), a bulk analysis technique. XANES of complex 1 was analogous to that of another NHC-Au(I) chloride reported by Silb斯特ri and colleagues,\textsuperscript{20} whereas the spectra of both Cat-1 and Cat-0 where quite different, and nearly identical to that of a gold foil (Figure 2E). Linear combination analyses using the spectra of Au-1 and the Au foil as the basis set indicated that over 95% of Au atoms in Cat-1 and Cat-0 are in the Au(0) phase. In addition, in situ XANES spectra of Cat-1 under the catalytic reaction conditions, i.e., in the presence of the reactant and solvent (vide infra), remain the same as the ex situ spectra (Figure S5). Thus, the particles do not undergo oxidative degradation (e.g., to Au(I) complexes) on the time scale of the reaction. Based on XPS and XANES, we can therefore conclude that the Au NPs of Cat-1 are coated with a ~ monolayer of Au(I) species, presumably NHC-Au(I) complexes. Such monolayers of NHC-oxidized metal species at metal NP and bulk metal surfaces have a number of recent precendents.\textsuperscript{8b,21}

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) provided additional evidence for the presence of NHC-Au complexes at the surfaces of AuNP-1 and Au/G4OH-NP-1. (Cat-1 was not directly analyzed because ToF-SIMS typically cannot probe below the very surface of the given material). Namely, both samples exhibited a mass-to-charge ratio (m/z) of 769.294 (Figure 2D) and associated isotope pattern (Figure S4), attributable to the corresponding (NHC)\textsubscript{2}Au\textsuperscript{+} ion (theoretical m/z = 769.375, Figure 2D inset). Furthermore, when the as-synthesized sample was purifed via dialysis against methanol, dried and redispersed in CD\textsubscript{2}OD, the \textsuperscript{1}H NMR spectrum revealed the presence of two sets of broadened NHC-derived aromatic resonances; meanwhile, other reaction components (e.g., 1 and 15BuN\textsubscript{2}H\textsubscript{2}B\textsubscript{3} hydropyrids) were absent (Figure S35). The presence of two sets instead of one suggests the presence of multiple NHC-Au species at the Au NP surface. Together, TEM, XPS, XANES, ToF-SIMS, and \textsuperscript{1}H NMR analyses allow us to infer that Cat-1 is composed of ~4.7 nm-diameter nanoparticles whose core of Au\textsuperscript{0} is coated with NHC-Au(I) complexes such as (NHC)\textsubscript{2}Au\textsuperscript{+} and (NHC)\textsubscript{2}Au\textsuperscript{+}. Whereas the latter coordinately saturated Au(I) species is unlikely to be active in our transformation, the under-
coordinated surface gold atoms, including (NHC)Au⁺ were considered plausible catalytically active sites.

**Catalytic Studies.** Intramolecular lactonizations of allenes (Figure 1) were chosen as model reactions to evaluate the effect of Au NP surface composition on its performance under a diverse set of conditions. Note that while molecular Au(I) complexes dispersed in mesoporous silica were previously found to be active catalysts for this reaction, formation of Au NPs under reaction conditions actually led to reduced activity over time. Indeed, Au NP-catalyzed lactonization of allenes remains a challenge, and we address this limitation herein. Cat-1 readily catalyzes the lactonization of reactant A at room temperature in predeuterated dichloromethane (CD₂Cl₂), benzene (C₆D₆), and chloroform (CDCl₃) (Table 2), and CD₂Cl₂ provided the highest reaction rate. Notably, though Cat-1 can achieve full conversion of A within 22 h at room temperature (20 °C), Cat-0 shows no reactivity under the same conditions. Even at 80 °C (in toluene-d₆), Cat-0 shows little activity and requires 100 °C to reach full conversion of A within 22 h. Thus, the presence of NHC complexes on the surface of Cat-1 is critical to engender the catalyst with high activity even at room temperature.

The reaction stops immediately upon the filtration of Cat-1, which confirms that the catalysis is truly heterogeneous. The heterogeneity of the catalyst was also confirmed by the inductively coupled plasma optical emission spectroscopy (ICP-OES) tests of the filtrate of the reaction mixture after reaction, where the Au concentration was below the 0.1 ppm detection limit of the instrument. The analysis procedure is included in the SI (TEM images see Figure S7 and statistics analyses in Table S2). Generally, Au NPs in Cat-2–Cat-8 have relatively uniform size distributions, ranging from 2 to 7 nm in diameter. Cat-9–Cat-11, however, contain Au NPs larger than 10 nm. XPS analysis of these new catalysts indicated that the surface Au 4f 7/2 binding energy varied considerably with the NHC: Cat-5 (85.7 eV) > Cat-1 (84.7 eV) > Cat-2–Cat-4, Cat-10 (83.8–84.3 eV) > Cat-6–Cat-8 (83.5–83.7 eV) > Cat-0 (83.4), Cat-11 (82.9 eV) (Figure S8). This variation indicated that the distribution of Au oxidation states at the NP surface could be tuned using different NHCs.

As in the case of Cat-1, for most new catalysts, A’ underwent lactonization faster than A at 20 °C. Cat-1–Cat-8 all catalyze full conversion of A’ in 22 h, although Cat-8 cannot accomplish the same for A. The turnover frequencies (TOF, normalized to the total amount of Au) based on the 2 h reactions of A under the same conditions reflect the catalytic activity of each catalyst. Several valuable conclusions were derived from these results. First, the presence of one mesityl N-substituent on the NHC ligand led to an elevated TOF per Au (cf. Cat-1 vs Cat-6, and Cat-4 vs Cat-7). This observation is consistent with the activating influence of an aryl-surface interaction recently

![Figure 3. Kinetics studies of the lactonization reaction catalyzed by Cat-1. (A) Reaction scheme. (B) Plot of ln[A] vs time showing first-order kinetics. The reaction was performed in an NMR tube with constant shaking at room temperature. (C) Eyring plot of A and A’ along with the corresponding ΔH° and ΔS°. Each reaction was run for 2 h.](image_url)
The attachment of NHC on the surface of Au NPs not only activates the catalysts, but also installs a handle to control uncontrolled decomposition of the cationic complex, with the precipitaton of Au. The Au species that remain in solution are active catalysts, but afford only 2% ee (entry 3 of Table S1 and Figure S70), indicating that NHC anchoring at the NP surface is crucial for enantioselectivity in our transformation. Although 16% ee is the highest that could be attained for our system at present, this result is, to our knowledge, the first demonstration of enantioselective catalysis by NHC-ligated Au NPs, as well as by Au DEMCs.

**CONCLUSIONS**

In this work, we present a novel synthesis of dendrimer-encapsulated persistent carbene-ligated Au NPs in silica. The dendrimer encapsulation and silica support rendered the NPs resistant to aggregation, which allowed us to systematically modify the NHCs with little impact on NP aggregation and complex leaching. In turn, NHCs as ligands alter the oxidation state distribution of the surface Au atoms and significantly increase the activity of the Au NPs toward a model complex transformation that is typically challenging for Au NPs—allene-carboxylic acid lactonization. Note that prior to this report, NHC-Au NP catalysis was limited to hydrogenation or CO2 electroreduction chemistry. Moreover, beyond enhanced activity and stability, ligand-derived enantioselectivity has been demonstrated in this system. The truly modular synthesis of NHC-ligated Au NPs in the presence of dendrimers, the vast array of available NHCs with excellent performance as ancillary ligands in Au catalysis, and the superb recyclability of silica-loaded NPs combine to make for a powerful new heterogeneous catalyst system that can address challenges in both heterogeneous and homogeneous Au catalysis.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.8b01017.

General synthetic protocol, characterization method, and spectroscopy data (PDF)

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Notes

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