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In Situ Generation of Catalytically Relevant Nanoparticles from a Molecular Pincer Iridium Precatalyst during Polyol Deoxygenation

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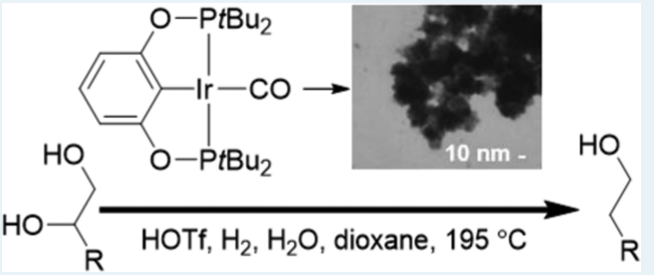
ABSTRACT: Pincer complexes such as (^{R}POCOP)Ir-based species (^{R}POCOP = κ^3-C_6H_3-1,3-[OP(R)$_2$]$_2$) are widely used as precatalysts for organic transformations with many mechanistic studies of these transformations based on the assumption that the precatalysts retain their molecular nature under catalytic conditions. We demonstrate that even (^{tBu}POCOP)IrCO (^{tBu}POCOP = κ^3-C_6H_3-1,3-[OP(tBu)$_2$]$_2$), a precatalyst valued for its stability, can be susceptible to the formation of nanoparticles at elevated temperatures under the acidic reducing conditions required for polyol deoxygenation and that the nanoparticles formed in situ can contribute to the observed hydrogenation activity. The iridium nanoparticles isolated from reaction mixtures by centrifugation and detected on glass and polytetrafluoroethylene (PTFE) reactor liners exhibit a high degree of aggregation and resist common cleaning protocols.



KEYWORDS: *iridium, hydrogenation, deoxygenation, catalyst speciation, pincer, nanoparticles*

INTRODUCTION

Tridentate pincer ligands are widely used in catalytic reactions involving homogeneous transition metal catalysts.[1] Pincer ligands are valued for their strong binding and chelating abilities, while their modular design allows for significant steric and electronic variation in the service of catalyst tunability.[2]

Although in situ generation of nanoparticles that are catalytically relevant, either as precatalysts or as active catalytic species, from molecular species is a known phenomenon,[3,4] reports on nanoparticle formation from pincer complexes are less common. Previous reports of metallic nanoparticle catalyst or precatalyst formation from precious metal pincer species under catalytic conditions include a rhodium-based pincer complex in an arene dehalogenation−hydrogenation system,[5] a palladium-catalyzed alkyne hydrogenation system,[6] and several palladium-based complexes employed as precatalysts in coupling reactions.[7−21] To our knowledge, the formation of catalytically relevant nanoparticles from a third-row metal pincer precatalyst has not been reported.

(POCOP)Ir-based pincer[22] complexes ((^{R}POCOP = κ^3-C_6H_3-1,3-[OP(R)$_2$]$_2$)), in particular, have been used as precatalysts in a wide range of transformations including transfer dehydrogenation of alkanes,[23−30] heterocycles,[31] alcohols,[32] amines,[33] amine borane[34−36] and hydrazine borane,[37] the electrocatalytic reduction of CO_2,[38,39] the reduction of amides,[40,41] esters,[42] and alkyl halides,[43,44] olefin isomerization,[45,46] C−H functionalization,[47−49] the hydrosilylation of carbonyls[50,51] and CO_2,[52] silane dehydrocoupling,[53] ether C−O cleavage,[54,55] formal epoxide hydrogenation,[56] and most relevant to the present work, polyol deoxygenation.[57−59]

Polyol deoxygenation is significant in several schemes to convert biomass into value-added chemicals.[60] The ability of (POCOP)Ir species to catalyze the hydrogenation step of polyol deoxygenation reactions has been attributed to the stability of the complexes to high temperature, an acidic/aqueous environment, and harsh reducing conditions that are often required for such transformations.[57,58]

Here, we demonstrate that the robust pincer (^{tBu}POCOP)-IrCO precatalyst (^{tBu}POCOP = κ^3-C_6H_3-1,3-[OP(tBu)$_2$]$_2$) can generate nanoparticles under the reaction conditions required for polyol deoxygenation and that even the portion of the resulting nanoparticles that is deposited on the reactor liner is a sufficient precatalyst for the hydrogenation step of the polyol deoxygenation reaction. While the results presented here do not exclude the possibility of a molecular (POCOP)Ir-based catalyst in polyol deoxygenation,[61] they do suggest that the speciation of the active iridium is more complicated than previously recognized.

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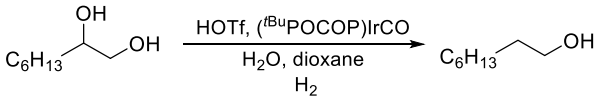
RESULTS AND DISCUSSION

Deoxygenation of 1,2-octanediol to 1-octanol was used as a model reaction in this study. As with previously reported polyol deoxygenation reactions involving ($^{t\text{Bu}}$POCOP)-IrCO,[57,58] the deoxygenation of 1,2-octanediol to 1-octanol in the presence of acid and ($^{t\text{Bu}}$POCOP)IrCO likely proceeds by a dehydration−hydrogenation mechanism consisting of initial acid-catalyzed dehydration to form an aldehyde intermediate followed by iridium-catalyzed hydrogenation. In the absence of iridium, the quantity of 1-octanol obtained is minimal indicating limited background hydrogenation activity in the reactor when a liner is in place (Table 1, entry 1), and

Table 1. Conversion of 1,2-Octanediol to 1-Octanol Using a ($^{t\text{Bu}}$POCOP)IrCO Precatalyst



entry[a]	Ir (mol %)	HOTf (mol %)	1-octanol (%)[b]	1,2-octanediol (%)
1	0	0.26	11	<1
2	0.6	0.26	70	4
3[c]	0.6	0.26	71	10
4	0.2	0.26	73	9
5	0.2	0.13	60	33

[a]Reactions were carried out in a stainless-steel reactor with a covered polytetrafluoroethylene (PTFE) liner (see the Supporting Information for a detailed description). Reaction conditions: 1,2-octanediol (1.2 mmol), dioxane (0.7 mL), HOTf (added as 0.17 M aq stock solution), water (180 μL), ($^{t\text{Bu}}$POCOP)IrCO (quantity varies by entry), decane (25 μL), H_2 (charged to 600 psi at 25 °C), then heated at 195 °C for 15 h. [b]Yields (relative to the initial quantity of 1,2-octanediol) measured by gas chromatography-flame ionization detection (GC-FID) using decane as an internal standard. [c]With 990 mg Hg and stirred.

confirming that the presence of iridium is essential.[62] Note that mass balance is often not obtained in dehydration−hydrogenation reactions under acidic conditions because a variety of side products can form. While none is individually present in more than 10% in our system, collectively they are nontrivial. Ahmed Foskey and co-workers characterized and quantified these minor species in the dehydration−hydrogenation of 1,2-propanediol.[58]

Changing the loading of ($^{t\text{Bu}}$POCOP)IrCO had an insignificant impact on the yield of 1-octanol formed (Table 1, entries 2 and 4) suggesting that under the conditions studied the yield of 1-octanol does not depend on the concentration of iridium. In contrast, decreasing the loading of triflic acid (Table 1, entries 4 and 5) resulted in a decreased yield of 1-octanol along with a notable increase in the quantity of 1,2-octanediol starting material remaining.

After the reactions, ^{31}P NMR signals consistent with ($^{t\text{Bu}}$POCOP)IrCO and *trans*-($^{t\text{Bu}}$POCOP)IrCO(H)$_2$ were observed, indicating the same postreaction molecular iridium speciation as was previously reported in diol deoxygenation reactions with a ($^{t\text{Bu}}$POCOP)IrCO precatalyst.[58] The purity of the ($^{t\text{Bu}}$POCOP)IrCO synthesized in our lab was confirmed by elemental analysis, and after the catalytic reactions, the reaction mixtures appeared clear to the naked eye.

After several reactions, however, a black residue was observed on the PTFE reactor liner. Examining a PTFE liner by SEM after a single reaction confirmed the presence of clusters of particles (Figure 1). EDS analysis (see the Supporting Information) confirmed the presence of iridium

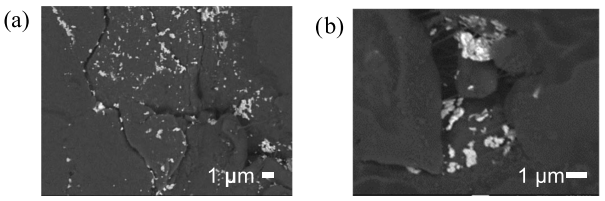


Figure 1. Backscatter electron images of a PTFE reactor liner after use in a polyol deoxygenation reaction. The bright spots indicate regions where Ir has been deposited.

along with the expected fluorine signal from the PTFE (Table S1). The presence of Ir was corroborated by LA-ICP-MS (Figure S1). LA-ICP-MS analysis of a piece of PTFE not exposed to the reaction conditions confirmed the absence of iridium.

We then investigated whether this residue could be relevant to the hydrogenation step of the diol deoxygenation reaction. An initial control experiment in the absence of iridium was performed to establish the extent of background reactivity in our reactor and liner. This established that the contribution from the steel reactor[62] and impurities on the PTFE from polymerization or machining were minimal compared to the yields when the iridium catalyst was present (Figure 2a,

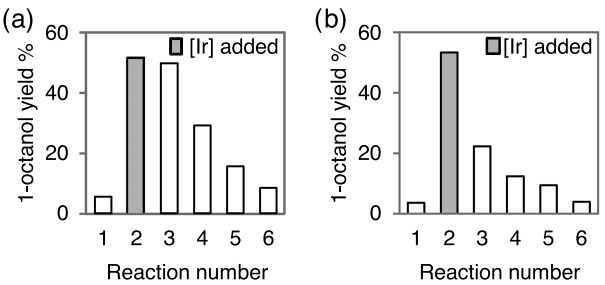


Figure 2. Catalytic performance of the ($^{t\text{Bu}}$POCOP)IrCO precatalyst and the Ir residue remaining in (a) a PTFE liner and (b) a glass liner. In both graphs, reaction 1 represents a control experiment in a new liner. Reaction conditions: 1,2-octanediol (0.19 g, 1.3 mmol), dioxane (0.7 mL), HOTf (0.52 mol % added as 0.34 M aq stock solution), water (180 μL), H_2 (charged to 600 psi at 25 °C), then heated (without stirring) at 195 °C for 15 h. Reaction 2 also included ($^{t\text{Bu}}$POCOP)IrCO (0.0050 g, 0.0081 mmol, 0.62 mol %). Yields measured by GC-FID using a decane (25 μL) internal standard added after the reaction.

reaction 1). This control experiment is in addition to the one described in Table 1, entry 1, and the two were not performed consecutively. This second control experiment then also confirms that if any Ir is depositing outside the covered liner on the stainless steel reactor, the catalytic contribution of this material is minimal. We then performed a reaction in the presence of the iridium catalyst. Following the reaction, the liner was cleaned with THF and acetone, two solvents in which ($^{t\text{Bu}}$POCOP)IrCO is soluble. The liner was then used for a control experiment (Figure 2a, reaction 3) with all of the catalytic conditions kept constant except for the ($^{t\text{Bu}}$POCOP)-IrCO, which was omitted. The product yield remained nearly identical. The rinsing procedure and control reaction steps were repeated several times and the product yields diminished

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ACS Catal. 2021, 11, 495−501

on each subsequent cycle (Figure 2a). We have not confirmed whether the diminished yields are explained by mechanical loss/leaching, changes in the nature of the heterogeneous precatalyst, or both.

Because PTFE is polymeric, we considered the possibility of molecular species becoming embedded in the polymer and thus resistant to removal by rinsing. Although this would not explain the observation of clusters of nanoparticles, molecular species could in theory explain the residual reactivity shown in Figure 2a. To control for the possibility of molecular species embedded in the polymer, we repeated the same series of experiments using glass liners. When reactions were performed in glass liners, the black residue build-up was also observed and the residue was imaged using SEM (Figure 3). LA-ICP-MS

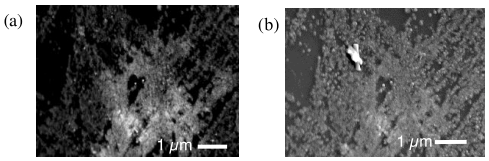

Figure 3. SEM images of a glass reactor liner after use in a polyol deoxygenation reaction. (a) Backscatter electron image, where the brighter regions indicate areas where elements of high atomic masses are present. (b) Secondary electron image showing the topography of the surface.

and EDS analyses (see the Supporting Information Figure S2 and Table S2, respectively) confirm that the residue is iridium-containing and that iridium-containing particles adhere to the glass surface. The residual reactivity declines more rapidly with glass compared to PTFE (Figure 2b), perhaps because particles adhere less effectively to the smoother glass surface.

Nanoparticles were isolated from the reaction mixture by centrifugation followed by washing with excess THF to remove organic impurities. The resulting solid was dispersed in ethanol, deposited on a copper grid, and characterized by STEM imaging (Figure 4a) and EDS (Table S3). Deposition

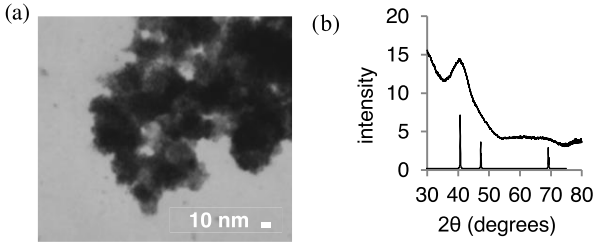

Figure 4. (a) Brightfield STEM image of aggregated nanoparticles isolated from a catalytic reaction mixture by centrifugation. (b) Powder X-ray diffraction pattern of the aggregated nanoparticles (top) and Ir(0) (ICDD 06-0598, bottom).

of the isolated and purified particles onto a copper grid allowed for higher magnification than could be obtained with the carbon-coated PTFE and glass samples or with samples of the crude reaction mixture deposited onto copper grids. A sample of the centrifuged solid was also characterized by powder X-ray diffraction (Figure 4b). Powder X-ray diffraction revealed a diffraction pattern consistent with metallic iridium.[63] Similar broadness has been observed in diffraction patterns of 2.5 nm Ir nanoparticles by other researchers.[64]

Efforts to quantify the extent of particle formation were hindered by the small quantity of samples involved. The quantity of nanoparticles isolated from a typical reaction mixture was less than 0.1 mg, the resolution of a laboratory balance, compared to 5.0 mg of ($^{t\text{Bu}}$POCOP)IrCO added at the beginning of the reaction. No change in mass of the liners could be detected at the 0.1 mg level of precision. We attempted to quantify the isolated particles by analyzing suspensions of the particles by ICP-MS,[65] but the results were found to be highly sensitive to variables in manipulation such as how the particles were transferred from the reactor to the centrifuge to the instrument and how quickly the samples could be drawn into the plasma after sonication.

Finke and co-workers have previously demonstrated the involvement of minimally ligated, unsupported, nonalloyed iridium nanoparticles generated in situ from $[(\text{cod})\text{IrCl}]_2$ (cod = cyclooctadiene) in the hydrogenation of carbon−oxygen double bonds.[66] In light of our evidence that nanoparticles may be relevant, either as precatalysts spawning smaller active clusters or as an active catalyst, we briefly investigated whether the ($^{t\text{Bu}}$POCOP)IrCO complex and its multistep synthesis were necessary. Several commercially available iridium precursors demonstrated some catalytic activity under the same conditions as the ($^{t\text{Bu}}$POCOP)IrCO precursor (Table 2). The resulting residues were characterized by SEM and their catalytic performance was assessed (Table S5).

Table 2. Deoxygenation of 1,2-Octanediol Using Molecular Ir Precatalysts

entry[a]	iridium precursor	1-octanol (%)[b]
1	($^{t\text{Bu}}$POCOP)IrCO	71
2	$[(\text{cod})\text{Ir}(\text{OMe})]_2$	55
3	$[\text{Cp}^*\text{IrCl}_2]_2$	62
4	$[(\text{cod})\text{IrCl}]_2$	53

[a]Reactions were carried out in a stainless steel reactor with a glass liner. Reaction conditions: 1,2-octanediol (0.19 g, 1.3 mmol), dioxane (0.7 mL), HOTf (0.26 mol % added as 0.17 M aq stock solution), water (180 μL), iridium source (0.0081 mmol Ir, 0.62 mol % Ir loading), decane (25 μL), H_2 (charged to 600 psi at 25 °C), then heated without stirring at 195 °C for 15 h. [b]Yields measured by GC-FID using decane as an internal standard.

The detection of nanoparticles generated from ($^{t\text{Bu}}$POCOP)IrCO under these acidic reducing conditions may have important implications for selective biomass deoxygenation, in particular, the longstanding challenge of converting glycerol to 1,3-propanediol.[67,68] A commonly invoked mechanism for this process is the dehydration−hydrogenation mechanism,[69] which has been suggested in previous deoxygenation studies involving ($^{t\text{Bu}}$POCOP)IrCO under acidic conditions.[56−58] Schlaf and co-workers have noted that heterogeneous catalysts for glycerol deoxygenation by dehydration−hydrogenation mechanism strongly favor the formation of 1-propanol rather than the more valuable 1,3-propanediol and suggest that this can be explained by the surface of the heterogeneous transition metal particle acting as an acid catalyst that promotes dehydration of the sterically favored terminal position.[70] They then propose that an effective catalyst for the deoxygenation of glycerol to 1,3-propanediol by a dehydration−hydrogenation mechanism will need to be homogeneous so that the dehydration step will occur at the electronically favored internal site.

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ACS Catal. 2021, 11, 495−501

When ($^{t\text{Bu}}$POCOP)IrCO was previously investigated as a catalyst for glycerol deoxygenation, it was found that the ratio of 1-propanol to 1,3-propanediol increases over time.[57] The authors of that work suggested that a change in the nature of the catalyst could be responsible. Our results along with Schlaf and co-workers' analysis suggest that the increase in 1-propanol could be the result of the formation of nanoparticles, which then promote dehydration at the sterically preferred terminal carbon.

The observation of nanoparticle formation during the conversion of 1,2-octanediol to 1-octanol is also relevant to our previous report of the formal hydrogenation of terminal epoxides to primary alcohols.[56] The formal epoxide hydrogenation occurred under similar conditions to the present study and diols were observed to be rapidly formed intermediates on the pathway between the epoxides and primary alcohols.

Besides suggesting that the ($^{t\text{Bu}}$POCOP)IrCO is less stable under polyol deoxygenation conditions than was previously thought, our results also emphasize the need to perform control experiments in the middle of catalytic studies if labware is used repeatedly.[71] In addition to performing control experiments in the middle of catalytic studies, the community would benefit if the timing of these control experiments was reported as a routine detail in publications or their Supporting Information.

As shown in Figure 2, simply rinsing with an organic solvent may not be sufficient to remove insoluble microscopic deposits of iridium nanoparticles from glass or PTFE labware. With more aggressive cleaning solutions such as base bath and aqua regia, the catalytic activity of the liners declines but the reactivity remained above the baseline level in all cases after one cleaning treatment (Table 3). These observations are consistent with previous reports that complete dissolution of iridium metal is nontrivial.[72−76]

Further, our observations suggest that systematic reuse of labware could provide a quick way to identify systems where further time- and resource-intensive[3,4] investigations of potential nanoparticle involvement are appropriate.

Table 3. Effect of Common Cleaning Treatments on Residual Catalytic Activity

entry[a]	cleaning treatment	1-octanol obtained from treated PTFE liner (%)[b]	1-octanol obtained from treated glass liner (%)[b]
1	new liner	6	3
2	THF and acetone rinses	50	22
3	base bath soak (48 h)	25	14
4	aqua regia soak (48 h)	10	16

[a]For each entry, a new liner in a stainless-steel reactor was charged with 1,2-octanediol (0.19 g, 1.3 mmol), dioxane (0.7 mL), HOTf (0.52 mol % added as 0.34 M aq stock solution), water (180 μL), ($^{t\text{Bu}}$POCOP)IrCO (0.0081 mmol, 0.62 mol % Ir loading), and H_2 (charged to 600 psi at 25 °C), and then heated without stirring at 195 °C for 15 h. The liner was then subjected to the cleaning treatment at room temperature. After the cleaning treatment, the liner was recharged with 1,2-octanediol (0.19 g, 1.3 mmol), dioxane (0.7 mL), HOTf (0.26 mol % added as 0.17 M aq stock solution), water (180 μL), and H_2 (charged to 600 psi at 25 °C), and then heated without stirring at 195 °C for 15 h. [b]Yields of this second reaction were measured by GC-FID using a decane (25 μL) internal standard added after the reaction.

CONCLUSIONS

The data presented here demonstrate that even pincer complexes, often regarded as robust, are not immune to the formation of nanoparticles in catalytically relevant quantities. The nanoparticles can adhere to reaction vessels made of glass and PTFE; thus, performing control reactions after catalytic reactions can be a useful means of screening for the potential relevance of nanoparticles in catalytic reactions. Finally, we presented data supporting the assertion that completely removing some iridium residues from labware is difficult.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acscatal.0c03180.

Detailed experimental procedures and data (PDF)

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Author Contributions

All authors have given approval to the final version of the manuscript.

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Notes

The authors declare no competing financial interest.

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