

The Isolation of [Pd{OC(O)H}(H)(NHC)(PR₃)] (NHC = N-Heterocyclic Carbene) and Its Role in Alkene and Alkyne Reductions Using Formic Acid

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S Supporting Information

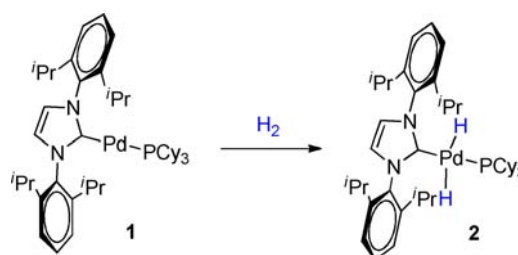
ABSTRACT: The [Pd(SIPr)(PCy₃)] complex efficiently promotes a tandem process involving dehydrogenation of formic acid and hydrogenation of C–C multiple bonds using H₂ formed in situ. The isolation of a key catalytic hydridoformatopalladium species, [Pd{OC(O)H}(H)(IPr)(PCy₃)], is reported. The complex plays a key role in the Pd(0)-mediated formation of hydrogen from formic acid. Mechanistic and computational studies delineate the operational role of the palladium complex in this efficient tandem sequence.

The catalytic hydrogenation of C–C multiple bonds is one of the most important transformations in organic chemistry.¹ Such reactions are usually carried out using molecular hydrogen, with two major drawbacks: H₂ is highly flammable and readily forms explosive mixtures with air,² and the stoichiometry of H₂ is difficult to control, oftentimes leading (when this is possible) to substrate over-reduction. Catalytic transfer hydrogenation represents a viable alternative to the more classical reduction method using molecular hydrogen or metal hydrides.³ Among various possible hydrogen sources, alcohols,^{3d,4} water,⁵ formic acid,⁶ and alkylammonium formates⁷ have found the broadest applications. A Pd(OAc)₂/P^tBu₃ system has been reported to catalyze the reduction of alkenes using formic acid.⁸ The transfer hydrogenation was presumed to occur through the formation of a undefined hydridoformatopalladium species followed by migratory insertion of the substrate into the Pd–H bond. No trace of hydrogen formation was reported.

We recently described the remarkable activity of [Pd(NHC)(PCy₃)] complexes (NHC = N-heterocyclic carbene) in alkene hydrogenation under a hydrogen atmosphere.⁹ Further investigation using a congener permitted the first isolation of monomeric palladium dihydride species, demonstrating the feasibility of direct activation of H₂ by a Pd(0) complex (Scheme 1).¹⁰

The catalytic transfer hydrogenation,⁸ hydrogen activation,¹⁰ and catalytic hydrogenation properties⁹ displayed by Pd(0)–NHC complexes encouraged us to examine [Pd(IPr)(PCy₃)] (1) [IPr = *N,N'*-bis(2,6-diisopropylphenyl)imidazol-2-ylidene]

Scheme 1. Oxidative Addition of H₂ to a Pd(0) Center¹⁰



and its saturated-NHC-bearing relative [Pd(SIPr)(PCy₃)] (3) [SIPr = *N,N'*-bis(2,6-diisopropylphenyl)imidazolidin-2-ylidene] as promising catalysts enabling the hydrogenation of C–C multiple bonds using formic acid as the hydrogen source.

To ascertain the exact role of formic acid in the initial steps of the reported “transfer hydrogenation” process,⁸ 1 was first reacted with formic acid in a J-Young NMR tube at low temperature (Figure 1).¹¹ At –70 °C, conversion of 1 into a hydride-bearing species, 4 [$\delta_{\text{P}} = -43$ ppm, $\delta_{\text{H}} = -18.88$ ppm ($^2J_{\text{H-P}} = 4.5$ Hz)], was observed. Increasing the temperature led

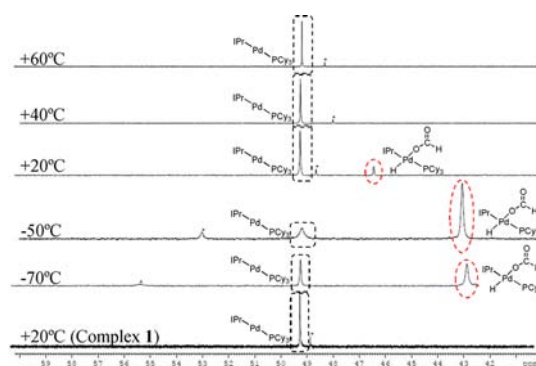


Figure 1. Variable-temperature ³¹P{¹H} NMR experiments on [Pd(IPr)(PCy₃)] (1) in the presence of HCOOH (1.05 equiv) in THF-*d*₈. Peaks labeled with * are due to a minor impurity (see the SI).

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to the disappearance of signals associated with formic acid and the formation of the new complex **4**, which gradually reverted back to **1**. Surprisingly, release of H₂ was observed.¹² At 60 °C, the reaction concluded with complete conversion of the formic acid and quantitative recovery of complex **1** [other minor compounds observed during the reaction were attributed to side products generated by traces of water; see the Supporting Information (SI)]. Interestingly, under these conditions the formation of the *trans*-dihydride complex **2** was never observed spectroscopically.¹⁰ Labeling studies¹³ with selectively deuterated formic acid (DCOOH and HCOOD) allowed the origin of the Pd–H proton to be assigned as the acidic H of formic acid, suggesting the composition [Pd{OC(O)H}(H)(IPr)(PCy₃)] for complex **4**.

To establish the atom connectivity in **4** unequivocally (and in spite of its thermal instability), single crystals were grown at low temperature,¹⁴ and the diffraction data confirmed the structure assigned on the basis of labeling and NMR studies (Figure 2).

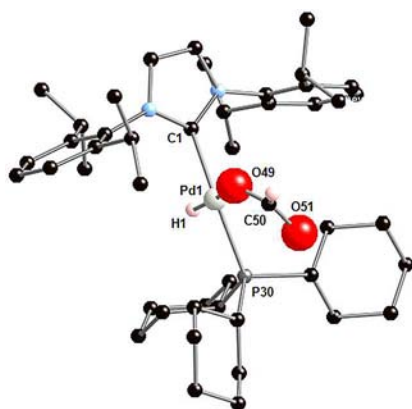


Figure 2. Molecular structure of **4**. Selected bond distances (Å) and angles (deg): Pd–C, 2.064(7); Pd–O, 2.140(5); Pd–P, 2.322(2); Pd–H, 1.76(2); C–Pd–O, 85.9(2); C–Pd–P, 169.91(18); O–Pd–P, 102.89(16); C–Pd–H, 92(3); O–Pd–H, 174(3); P–Pd–H, 80(3).¹⁴

The isolation of such a palladium complex is, to the best of our knowledge, unprecedented. Darendbourg did report the isolation of a greyish [Pd{OC(O)H}(H)(PCy₃)₂] complex, but the reported spectroscopic data suggest the formation of a mixture of isomers under the conditions employed.¹⁵ Achieving such high stability in this architecture may very well be linked to the presence of the NHC, a strategy having precedent in synthetic organometallic chemistry.¹⁶

Because of safety and environmental concerns, the use of formic acid as a hydrogen storage material has received much attention over the past decade (Figure 3).¹⁷ In spite of the efficient reduction of CO₂ to formic acid catalyzed by homogeneous Ru catalysts, which has been extensively studied by the Jessop and Joó groups,¹⁸ the catalytic dehydrogenation of formic acid remains an area of current interest.^{19,20} The

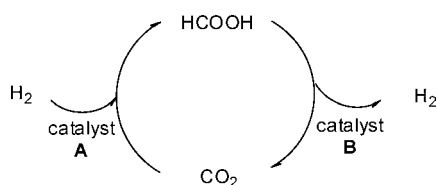
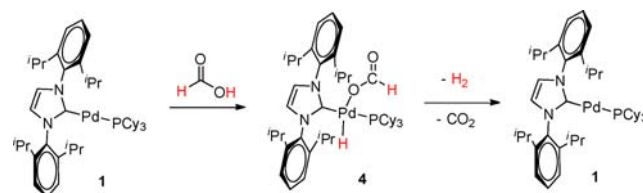


Figure 3. Formic acid as a hydrogen storage material.

ability of a homogeneous complex such as **1** to promote the dehydrogenation of formic acid at low temperature represents, to the best of our knowledge, a true first.²¹

Complex **4** was the only Pd species detected during the mechanistic study and thus is presumed to be a key intermediate or the catalyst resting state involved in this hydrogen formation. The propensity of **4** to convert back into **1** with the generation of H₂ appears to support this hypothesis (Scheme 2). To shed light on the unexpected hydrogen

Scheme 2. Pd(0)-Mediated Dehydrogenation of Formic Acid



production property displayed by **4**, a computational investigation of the individual reaction steps using density functional theory (DFT) was undertaken. The results revealed that dehydrogenation occurs in a stepwise manner without large energy barriers (Figure 4). HCOOH coordination with

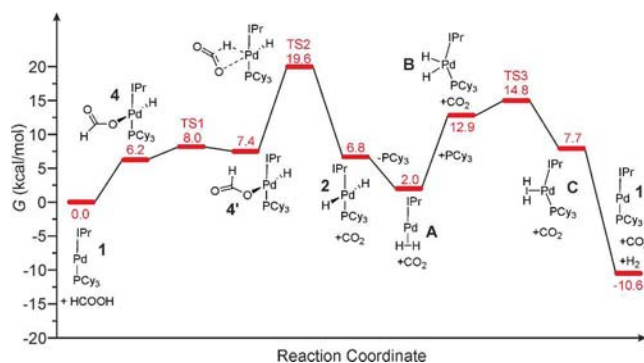


Figure 4. Free energy profile for the dehydrogenation of formic acid.

spontaneous dissociation of the acid proton to form **4** requires 6.2 kcal/mol. Consistent with the crystallographic structure, the DFT-optimized geometry of **4** has the formate H atom pointing away from the metal (see Figures 2 and 4). The first step of the C–H activation involves a conformational rearrangement of **4** to a slightly less stable geometry with the formate H atom pointing toward the metal (structure **4'** in Figure 4). The energy barrier separating **4** from **4'** through transition state **TS1** is only 1.8 kcal/mol. At this point, activation of the C–H bond of the formate ligand by the Pd atom generates **2** through transition state **TS2** with a barrier of 12.2 kcal/mol with liberation of a CO₂ molecule. **TS2** is a very late transition state in which the CO₂ molecule is practically formed and dissociated from the metal center. According to the calculations, concerted isomerization of **2** to its *cis*-H₂ analogue proved to have a very high energy barrier (>30 kcal/mol). Thus, a mechanism involving dissociation of PCy₃ to give intermediate **A**, followed by coordination of PCy₃ to **A** to give Pd dihydride intermediate **B**, and finally formation of intermediate **C** containing a Pd-bound H₂ molecule seems more likely. Dissociation of H₂ from **C** regenerates **1**. Since the total process was computed to release 10.6 kcal/mol, liberation of both CO₂ and H₂ in the medium probably drives the

reaction toward complete consumption of formic acid. The difference in the stabilities of complexes **1**, **4**, and **2** easily explains why no trace of the dihydride species **2** was observed during the experimental study.

We previously reported the excellent catalytic performance of **1** in the hydrogenation of C–C bonds under H₂.⁹ The unique behavior of **1** in the dehydrogenation of formic acid could permit the hydrogenation of C–C bonds using a tandem dehydrogenation/hydrogenation sequence. The ability of Pd(0) species to catalyze such a process was recently reported using NH₃BH₃ as the hydrogen source.²² The release of 1 equiv of H₂ in the reaction medium permitted more selective hydrogenation than classical methodology. To test the efficiency of the tandem process, kinetic profiling of the hydrogenation of *trans*-stilbene (**5**) using HCOOH as the hydrogen source was performed. HCOOH (1.05 equiv) was added to an NMR tube charged with **5** (1 equiv) and **1** (5 mol %) in THF-*d*₈ at –20 °C, and the progress of the reaction was monitored by ¹H NMR spectroscopy at various time intervals at 45 °C (Figure 5). The rapid disappearance of formic acid was

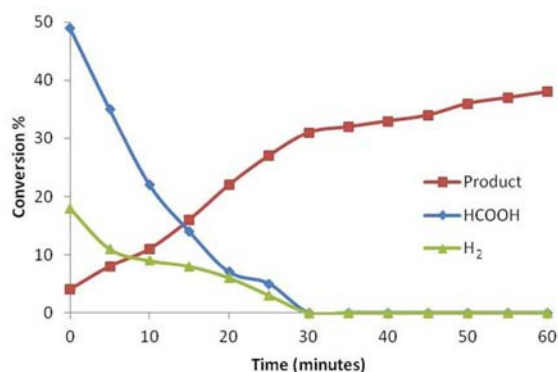
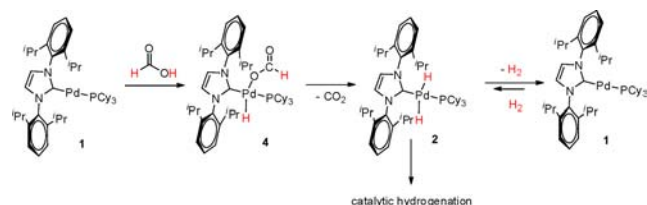


Figure 5. Hydrogenation of *trans*-stilbene using HCOOH as the hydrogen source at 45 °C.

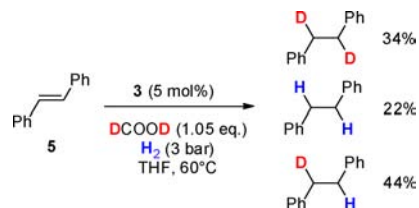
accompanied by the formation of H₂ and fast conversion of **5** to 1,2-diphenylethane. After 30 min at this temperature, no formic acid or hydrogen could be detected by ¹H NMR spectroscopy. Complex **1** was the only organopalladium species observed at the end of the tandem transformation. This suggests initial rapid consumption of formic acid to give formato complex **4** followed by fast conversion of **4** into the catalytically relevant species **2**, which is most likely in equilibrium with precatalyst **1** (Scheme 3).⁹ Computational analysis of this proposed reaction profile indicated that initial displacement of PCy₃ by the alkene and H₂ occurs, followed by conversion of the alkene to an alkyl moiety and then reductive elimination in two low-energy steps. The overall energy profile is provided in the SI.

Scheme 3. Formation of H₂ Starting from Formic Acid Involving Formato Complex **4** and Dihydride Complex **2**



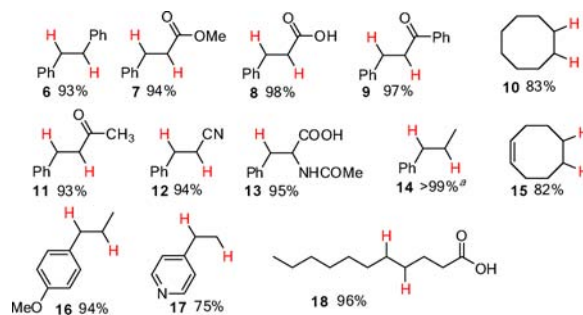
During preliminary labeling studies with complex **1** and deuterated formic acid (DCOOD, DCOOH, or HCOOD), HD and H₂ were observed by ¹H NMR spectroscopy. While the formation of HD using DCOOD could be easily explained by exchange between the acidic D and any labile H, the formation of H₂ observed with DCOOH and HCOOD was more surprising. Those data could be easily related to the isotope exchange reaction observed when complex **1** was reacted with HD.¹⁰ To gain a better understanding of the process, a series of experiments involving hydrogenation of **5** catalyzed by **3** were performed using 1.05 equiv of DCOOD under various pressures of H₂ (see Table S1 in the SI). In addition to the expected incorporation of two or zero deuterium atoms into the final product, the monodeuterated compound was formed in high concentration (Scheme 4). This can be explained by

Scheme 4. Pd(0)-Mediated Dehydrogenation of Formic Acid



scrambling of H₂ and D₂ to form HD mediated by **3**. The high yield of the monodeuterated species formed suggests that under the reaction conditions, the H–D scrambling would be as easily accomplished as the delivery of H to the alkene. Computational analysis of this H₂/D₂ scrambling process mediated by **1** clearly shows it to be energetically facile (see the SI).

A short survey of the substrate scope was performed to highlight the versatility of the tandem reaction. Reduction of a variety of substrates including cyclic and acyclic olefins, α,β -unsaturated aldehydes, α,β -unsaturated ketones, and other α,β -unsaturated carbonyl compounds was investigated. The presence of functional groups such as acids, amides, esters, ketones, or nitriles did not affect the hydrogenation, and excellent isolated yields were generally obtained (Figure 6).



Reaction conditions: catalyst **3** (2 mol%), substrate (0.50 mmol), formic acid (0.53 mmol, 1.05 equiv.), THF (2 mL), 60 °C, 24 h. Isolated yield. ^aYield determined by ¹H NMP using hexamethylbenzene as internal standard.

Figure 6. Hydrogenation of alkenes using **3** and formic acid.

Since the reduction proceeded efficiently without the need to use excess formic acid, we next challenged the economy of this process in the selective semihydrogenation of alkynes (Figure 7). Gratifyingly, using 1.05 equiv of formic acid gave 94% *cis*-stilbene. When the scope was expanded to other substrates, good to excellent *Z* selectivity was achieved with both aromatic

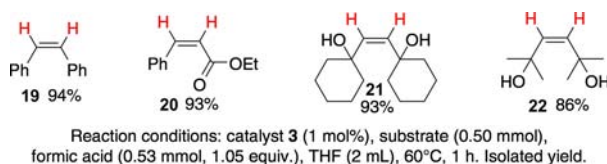


Figure 7. Semireduction of alkynes using **3** and formic acid.

and aliphatic alkynes, and only minor over-reduction to the corresponding alkanes was observed.²³

In summary, the use of a mixed NHC/PR₃ environment about a palladium center has made possible the isolation of a unique hydridoformatopalladium complex, **4**, involved in the dehydrogenation of formic acid. Efficient catalytic hydrogenation of alkenes and alkynes using formic acid proceed via a tandem sequence using **3**. The [Pd(NHC)(PCy₃)] complexes examined play a dual role in catalysis: they facilitate the dehydrogenation of formic acid to generate hydrogen and subsequently make use of the H₂ formed in situ to reduce C–C multiple bonds. DFT calculations support the experimental observations and mechanistic conclusions. The reduction of a variety of cyclic and acyclic olefins bearing diverse functional groups was achieved in very good isolated yields. The system proved to be stereo- and chemoselective for the semi-hydrogenation of aromatic and aliphatic internal alkynes to the corresponding *Z* alkenes under mild conditions. Studies aimed at capitalizing on the fascinating reactivity of these Pd(0) complexes are presently ongoing in our laboratories.

ASSOCIATED CONTENT

Supporting Information

Experimental procedures and details, NMR spectra of stoichiometric reactions and catalytic products, a CIF for **4**, Cartesian coordinates and energies for all species discussed in the text, and computational details. This material 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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- For ¹H and ³¹P{¹H} NMR spectra of reactions between **1** and formic acid in THF-*d*₈ recorded at different temperatures, see the SI.
- Formation of H₂ was clearly observed by ¹H NMR spectroscopy (see the SI).
- Spectra from the labeling studies are available in the SI.
- CCDC-873769 contains the supplementary crystallographic data for **4**. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
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