Homogeneous Catalysis

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Catalytic Activation of N–N Multiple Bonds: A Homogeneous Palladium Catalyst for Mechanistically Unprecedented Reduction of Azo Compounds**

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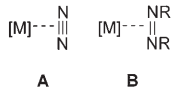
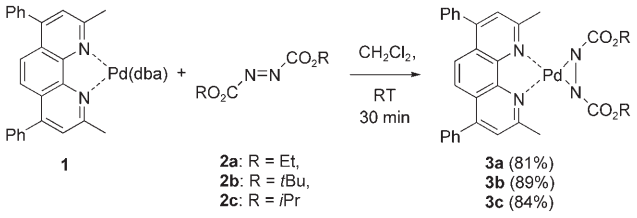
Ready access to nitrogen compounds is of crucial importance, as these molecules are key substances for research in the life sciences. The catalytic reductive transformation of nitrogen–nitrogen multiple bonds at a metal complex constitutes a fundamental endeavor to this end. However, even a century after Haber's pioneering work on the heterogeneously catalyzed synthesis of ammonia from its elements,[1] only limited progress on the activation of N–N multiple bonds has been achieved. For the purpose of dinitrogen activation, nature employs nitrogenase metalloenzymes, which under physiological conditions transform dinitrogen into ammonia.[2] This fascinating process has stimulated interest in transition-metal complexes for dinitrogen reduction under nonbiological conditions.[3,4]

The coordination of dinitrogen to transition metals generates the conceptually simplest complexes with activated N–N multiple bonds. Despite all the progress in nitrogen fixation and in the design of suitable precursor transition-metal complexes,[5] almost all of these systems are limited to stoichiometric reactions. A noteworthy exception is the monomeric molybdenum complex bearing a tetradentate trisanilineamide ligand recently reported by Schrock[6] which was shown to be capable of coordinating dinitrogen and catalyzing consecutive cycles of ammonia formation. The mechanism of this process involves end-on binding of the N_2 molecule through preferential lone-pair coordination and follows the classical Chatt model.[7]

Electronic and structural constraints usually prevent the alternative, η^2-dinitrogen coordination mode **A**. However, these constraints do not necessarily apply to related nitrogen–nitrogen multiple-bond systems. In these cases, the side-on coordination in **B** should allow equal activation of the two nitrogen atoms involved and thus lead to simultaneous reduction. Moreover, the conversion of N–N multiple bonds other than dinitrogen is a promising source of alternative nitrogen-containing products for subsequent organic transformations.[8] In view of the manifold catalytic utility of palladium,[9] the lack of catalytic activation of N–N multiple bonds by this element is notable.[10] Thus, the synthesis and study of palladium compounds resulting from the complexation of N–N multiple bonds is an interesting task.[11]



Herein, we present the synthesis of structurally defined palladium complexes of azo compounds, which originate from an initial η^2-coordination mode (**B**), and report the first catalytic reduction of an N–N double bond at a single palladium center under homogeneous conditions. Our investigation of the potential catalytic reactivity began with the synthesis of palladium complexes with azo ligands, which can be considered to be formal surrogates for the products of the first step in the reduction of dinitrogen. The known (bathocuproine)palladium(0) complex **1**[12] (bathocuproine = 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline) was treated with an equimolar amount of the azodiesters **2a–c** to form in an irreversible reaction the desired monomeric complexes **3a–c** as air- and moisture-stable yellow-to-orange solids (Scheme 1). The coordinated azo ligands in complexes **3a–c** do not dissociate on the NMR time scale, and the products



Scheme 1. Synthesis of palladadiaziridines **3a–c**. The yields of **3a–c** (given in parentheses) refer to isolated material. dba = *trans,trans*-dibenzylideneacetone.

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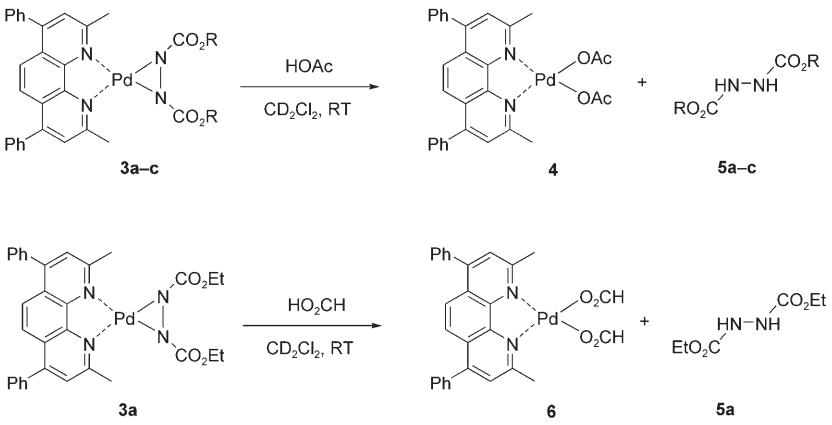
3a–c are inert towards subsequent exchange reactions with alkenes and other azo compounds.[13] For example, treatment of **3a** with an excess of **2b** led to no interconversion of the coordinated azodiester.

The product **3a** was crystallized from a solution in dichloromethane, and the structure obtained from the X-ray diffraction study of **3a**·CH_2Cl_2 is depicted in Figure 1. The expected C_2 symmetry of the complex is distorted as a result of unsymmetrical hydrogen bonding of the cocrystallized solvent molecule to the metal-coordinated azo group. Importantly, rather short Pd–N bond lengths in the range of 2.014–2.043 Å



Scheme 2. Protonolysis of palladadiaziridines **3a–c**. R: see Scheme 1.

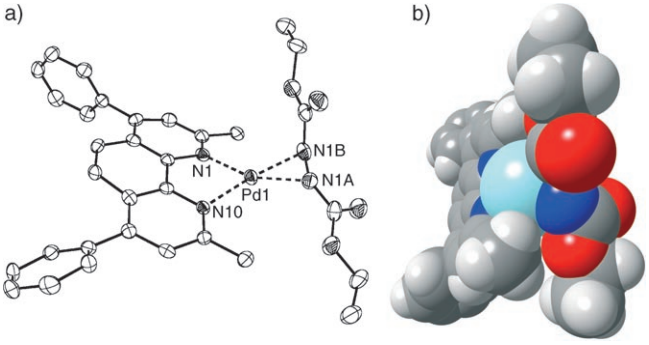


Figure 1. Solid-state structure of **3a**. a) ORTEP plot (thermal ellipsoids are drawn at 50% probability level). The cocrystallized dichloromethane molecule and all hydrogen atoms have been omitted for clarity. Selected bond lengths [Å] and angles [°]: N1A-N1B 1.404(5), Pd-N1A 2.043(3), Pd-N1B 2.014(4); N1B-Pd1-N1A 40.49(14), N1-Pd1-N10 78.93(14), N1B-N1A-Pd1 68.62(19), N1A-N1B-Pd1 70.9(2). b) Space-filling model of **3a**. Pd cyan, C gray, H white, N blue, O red.

are observed together with an N–N bond length of 1.404 Å, which establishes the single-bond character of the N–N bond and leads to the conclusion that a Pd-N-N three-membered ring is the dominating bonding situation. The overall structural composition is therefore best described as a palladadiaziridine. Thus, complexes **3a–c** represent a hitherto-unknown bonding situation within Pd complexes. In other words, the coordinative interaction of the azo compound with the initial Pd^0 center involves a formal redox process between the metal center and the incoming ligand and already entails the desired reduction of the N–N double bond. The space-filling model of **3a** (Figure 1b) illustrates that external electrophiles should be readily able to initiate reactions at the coordinated nitrogen atoms.

These conclusions were supported further by the observation that complexes **3a–c** readily undergo displacement of hydrazines upon protonolysis. For example, the addition of acetic acid to NMR sample solutions of **3a** and **3b** in CD_2Cl_2 led within seconds to clean formation of [(bathocuproine)Pd(OAc)$_2$] (**4**), as well as the *N*,*N*′-di(ethyloxycarbonyl)- and *N*,*N*′-di(*tert*-butyloxycarbonyl)-protected hydrazines **5a** and **5b**, respectively (Scheme 2). Complex **4** was identified on the basis of its NMR data by comparison with an authentic sample.[14] No reversible reaction between the formed palladium(II) complex and the hydrazine was observed, which suggests that hydrazine formation from protonation of complexes **3** represents the desired irreversible process. In an analogous reaction sequence, treatment of **3a** with formic acid led to quantitative production of the corresponding hydrazine **5a** and an unstable palladium formiate complex **6**, which decomposed over a period of two hours at room temperature to palladium black.[15]

The same reactivity of the preformed complexes **3a–c** was observed for reactions on a preparative (1-mmol) scale (Table 1). In this case, protonolysis with acetic acid (2.2 mmol) furnished the corresponding hydrazines **5a–c** in very good yields (88–94%). Also, protonolysis of **3d**, formed in situ by complexation of azobenzene, gave *N*,*N*′-diphenylhydrazine (**5d**) in 90% yield. This result confirms that this reaction is equally efficient for azo ligands with either electron-withdrawing or electron-donating substituents.

Table 1: Protonolysis of palladadiaziridines **3** under homogeneous conditions.[a]

Entry	Compound	Coordinated R_2N_2	Product $R_2(NH)_2$	Yield [%][b]
1	**3a**	R = CO_2Et	**5a**	92
2[c]	**3a**	R = CO_2Et	**5a**	93
3	**3b**	R = CO_2tBu	**5b**	94
4	**3c**	R = CO_2iPr	**5c**	88
5	**3d**[d]	R = Ph	**5d**	90

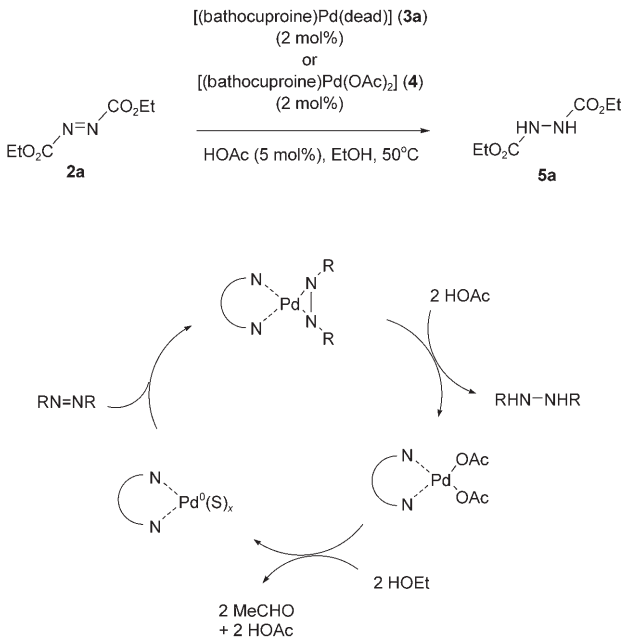
[a] Reaction conditions: 1 mmol **3** (c = 0.25 M solution in CH_2Cl_2, T = 25 °C), addition of 2.2 mmol acetic acid. [b] Yield of product after purification. [c] With formic acid. [d] Complex generated in situ.

In a subsequent experiment, the addition of ethanol to [(bathocuproine)Pd(OAc)$_2$] (**4**) led to facile reduction and regeneration of a formal palladium(0) complex. The reaction was complete within minutes at room temperature and produced a black precipitate. An NMR experiment in [D_6]benzene revealed that the product of the ethanol oxidation is acetaldehyde, which is in agreement with the earlier reports on bathocuproine-based palladium catalysts

for efficient alcohol oxidation.[16] More importantly, when the same reaction was carried out in the presence of an excess of diethyl azodicarboxylate (dead, **2a**), quantitative formation of the initial azo complex **3a** was observed and the deposition of palladium black complex was thus prevented (Scheme 3).

Scheme 3. Reductive regeneration of palladadiaziridine **3a** from diacetate **4**.

On the basis of these three individual stoichiometric reactions, a catalytic cycle could be devised for the catalytic reduction of azo compound **2a** to give hydrazine **5a**. A solution (5 M) of **2a** in ethanol in the presence of palladium catalyst (2 mol%) and acetic acid (5 mol%) was reduced cleanly at 50 °C to yield hydrazine **5a** in excellent yield. Scheme 4 depicts the catalytic cycle. The palladadiaziridine is



Scheme 4. Catalytic cycle for reduction of azo compounds to hydrazines with a bathocuproine–Pd catalyst. The bathocuproine ligand is represented schematically. S = solvent molecule.

protonated and releases the free hydrazine to form a palladium diacetate complex. Oxidation of ethanol to acetaldehyde concomitantly forms a palladium(0) complex and regenerates the catalytic amount of acetic acid. Coordination of the azo substrate to palladium(0) regenerates the palladadiaziridine and completes the catalytic cycle. This proposed overall catalytic cycle is supported by the fact that both the palladadiaziridine **3a** and the palladium diacetate **4** can be employed as the catalyst source with equal efficiency (91 and 89% yield, respectively). In one case, the catalyst loading of isolated **3a** could be further reduced to 0.5 mol% (substrate/catalyst ratio S/C = 200), and hydrazine **5a** was isolated after a reaction time of 36 h in 90% yield, which is equivalent to an average catalyst turnover number of 180. From a mechanistic point of view, the transition-metal catalysis cycles between the two Pd^0 and Pd^{II} oxidation states and involves only three defined catalyst states. Hence, any potential catalyst deactivation is largely avoided.

The observed process is universal. For example, the same reactivity at an S/C ratio of 50 was obtained for the reduction of azobenzene (**2d**) in ethanol (93% yield of hydrazine **5d**) and for **2c** in 2-propanol (87% yield of hydrazine **5c**). The latter catalysis required 3 days to reach completion because palladium reduction with 2-propanol to yield acetone is comparatively slow.[17]

The overall cycle from Scheme 4 is reminiscent of that discovered by EniChem for palladium-catalyzed production of hydrogen peroxide through dioxygen activation.[18] The corresponding (peroxo)palladium catalyst from this reaction was isolated by Stahl.[12] However, the azo activation reported herein has the advantage that it constitutes an irreversible process in which interaction between hydrazines and the palladium catalyst are absent, whereas the production of hydrogen peroxide requires biphasic conditions to prevent disproportionation.

In summary, we have discovered the first homogeneous transition-metal-catalyzed activation of azo compounds, which enables efficient reductive transformation of N–N multiple bonds at a single palladium catalyst site. The catalysis involves an intermediate state displaying a novel azo coordination mode to palladium(0), and the structure was established by independent isolation of a palladadiaziridine.[19] The present process constitutes a novel catalytic reaction and is important for the reduction of N–N multiple bonds.

Experimental Section

3a: A solution of [(bathocuproine)Pd(dba)] (802 mg, 1.14 mmol) in freshly distilled dichloromethane (2 mL) was treated with dead (**2a**, 200 μL, 1.27 mmol), and the resulting mixture was stirred at room temperature for 45 min. The solvent was removed under reduced pressure to a volume of approximately 0.5 mL, and the crude product was precipitated by addition of absolute diethyl ether (20 mL). The yellowish crude product was washed with further portions of diethyl ether, dried under reduced pressure, dissolved in dichloromethane (10 mL), and then filtered through a pad of celite. The remaining solution was evaporated to dryness under reduced pressure to leave the product as a yellow-to-orange solid (592 mg, 0.92 mmol, 81%). Crystals suitable for X-ray analysis were grown from a solution in dichloromethane at −20 °C.

Crystal structure of **3a**: $C_{32}H_{30}N_4O_4Pd \cdot CH_2Cl_2$: yellow crystals, crystal dimensions $0.25 \times 0.15 \times 0.10\ mm^3$; $M = 725.93$; monoclinic, space group $P2_1/c$ (No. 14), $a = 12.3133(4)$, $b = 15.1348(6)$, $c = 16.8231(7)$ Å, $\beta = 97.226(2)°$, $V = 3110.2(2)$ Å^3, $Z = 4$, $\mu(Mo_{K\alpha}) = 0.813\ mm^{-1}$, $T = 123(2)$ K, $F(000) = 1480$. 19374 reflections up to $2\theta_{max} = 50°$ were measured on a Nonius KappaCCD diffractometer with $Mo_{K\alpha}$ radiation, 5469 of which were independent and used for all calculations. The structure was solved by direct methods and refined to F^2 anisotropically; the positions of the H atoms were refined with a riding model. The final quality coefficient $wR2(F^2)$ for all data was

0.0871, with a conventional $R(F) = 0.0425$ for 399 parameters. An empirical absorption correction was applied.

CCDC-288043 contains the supplementary crystallographic data for this paper. 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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[19] The catalytic behavior is not restricted to the bathocuproine ligand. Other 1,10-phenanthroline ligands induce comparable reactivity. Studies of the structural requirements of the ligand constitution are currently under way.

