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Versatile Synthesis of $P^R_2N^{R'}_2$ Ligands for Molecular Electrocatalysts with Pendant Bases in the Second Coordination Sphere

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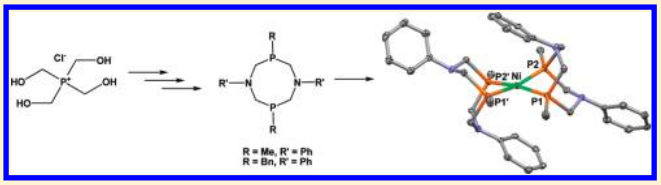
Supporting Information

ABSTRACT: Two 1,5-diaza-3,7-diphosphacyclooctane (P_2N_2) ligands with alkyl-substituted phosphines have been synthesized via a versatile method that allows for improved control of the phosphine substituent. The methyl- and benzyl-substituted phosphine P_2N_2 ligands ($P^{Me}_2N^{Ph}_2$ and $P^{Bn}_2N^{Ph}_2$) were synthesized and characterized by $^{31}P\{^1H\}$ NMR, ^1H NMR, and elemental analysis, and their corresponding $[Ni(P^R_2N^{Ph}_2)_2](BF_4)_2$ complexes were synthesized and characterized by $^{31}P\{^1H\}$ NMR, ^1H NMR, and electrochemistry. The structure of the complex $[Ni(P^{Me}_2N^{Ph}_2)_2](CF_3SO_3)_2$ was characterized by X-ray crystallography.



The catalytic reductions of protons to H_2 and of small molecules such as CO_2 and N_2 pose significant chemical challenges. Transformations of these molecules are often hindered by high kinetic barriers for the formation of key intermediates; however, these reactions can be facilitated by proton-coupled electron transfer (PCET) reduction processes.[1] Many enzymes take advantage of PCET to manage electron transfers at low overpotentials.[2] One particularly interesting example is the [FeFe]hydrogenase enzyme (**A**), which contains an azadithiolate ligand whose nitrogen base is poised to deliver or accept a proton during the reversible oxidation of H_2, as shown in Figure 1.[3] Many groups have developed both

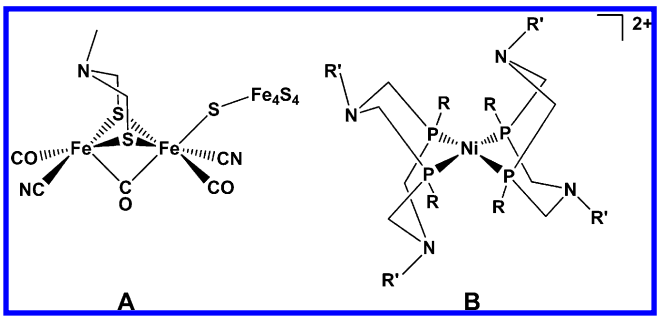


Figure 1. Structures of the [FeFe]hydrogenase active site (**A**) and the $[Ni(P^R_2N^{R'}_2)_2]^{2+}$ cation (**B**).

structural and functional mimics of this active site, incorporating various pendant bases and studying their ability to support hydrogen transfer and bonding in H_2 activation and other reactions.[4] One of the most successful functional models of the hydrogenase enzyme to date is the $[Ni(P^R_2N^{R'}_2)_2]^{2+}$ system (**B**), also shown in Figure 1. Different variants have shown excellent electrocatalytic rates for the proton-coupled processes of H_2 oxidation,[5] proton reduction to H_2,[6] O_2 reduction,[7] and more recently the oxidation of formate.[8]

One reason $P^R_2N^{R'}_2$ systems exhibit high electrocatalytic performances lies in their ability to take on multiple conformations that orient the nitrogen bases in ideal positions for assisting proton-coupled processes.[9] The utility of these complexes is additionally expanded by the fact that both the phosphine and amine substituents of the ligand can be varied in order to tune the thermodynamic properties and reactivity of the complexes. The basicity of the pendant amine can be tuned via substitution at R′,[10] while the redox potentials of the metal center can be modified via substitution at R and to a lesser extent at R′. More donating substituents at R generally lead to more negative reduction potentials for the metal complexes. The steric properties of R also affect the bite angles and dihedral angles of the two ligands on the metal center, which have a substantial effect on the hydricities (hydride donation abilities) of the corresponding $[NiH(P^R_2N^{R'}_2)_2]^+$ species and the reduction potentials of the metal complexes.[11] The development of new $P^R_2N^{R'}_2$ catalysts has been hampered by the limited availability of starting materials for the ligand synthesis. This arises from the fact that the first step in the literature synthesis is the dihydroxymethylation of a primary phosphine (Scheme 1).[12]

Primary phosphines are highly air-sensitive, noxious, toxic, and often pyrophoric chemicals whose commercial availability in bulk quantities is limited to cyclohexyl- and phenylphosphine. While some primary phosphines can be synthesized via alkylation of PH_3 or via the Arbuzov reaction followed by reduction, these routes require that the primary phosphine be isolated from the reactions prior to use in the synthesis of P_2N_2

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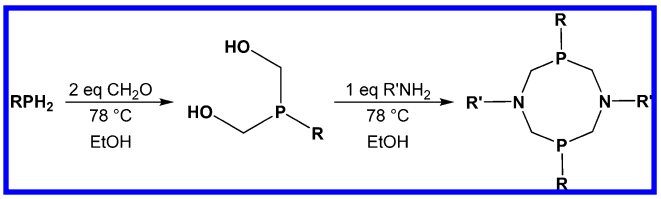
Scheme 1. Traditional $P^R_2N^{R'}_2$ Ligand Synthesis



ligands.[13] Ideally, ligand syntheses should use stable and commercially available reactants, be concise, and be scalable for the production of large quantities.

Here, we report a new synthetic route to P_2N_2 ligands that meets the criteria above for convenience, cost, simplicity, and scalability. A report by Griffiths and co-workers indicates that alkylbis(hydroxymethyl)phosphines (**4**) can be synthesized utilizing a cheap, commercially available, and air-stable reagent: tetrakis(hydroxymethyl)phosphonium chloride (THPCl, **1**).[14] This route removes the need to synthesize or utilize a primary phosphine. We demonstrate its use in the synthesis of $P^R_2N^{Ph}_2$ ligands with methyl and benzyl substituents on the phosphine (Scheme 2).

Dehydroxymethylation of THPCl (**1**) under basic conditions in neat triethylamine or KOH in ethanol yields tris(hydroxymethyl)phosphine (THP, **2**).[15] This phosphine reacts with alkyl halides, yielding the alkyltris(hydroxymethyl)phosphonium halide salt (**3**). Methyl iodide and benzyl chloride were successfully used as alkylating agents for this reaction. This selection of compounds demonstrates the versatility of the synthesis: alkylating agents can be chosen irrespective of the halide leaving group and with concern for safety, utility, and expense. After alkylation, the compound is once more dehydroxymethylated in neat triethylamine to form **4**. From here the synthesis of the $P^R_2N^{Ph}_2$ ligands **5** and **6** proceeds in the same fashion as the traditional ligand synthesis, as **4** is treated with 1 equiv of a primary amine ($R'NH_2$; aniline for **5** and **6**) to form the corresponding $P^R_2N^{R'}_2$. The overall synthesis from **1** gave yields of 63% for **5** and 13% for **6** (Figure 2).

Ligands **5** and **6** were isolated and characterized by elemental analysis, ^{1}H NMR, and ^{31}P{^{1}H} NMR.[16] We have used these ligands to prepare their homoleptic nickel complexes, and their cyclic voltammograms were examined to study how these P-alkyl-substituted P_2N_2 ligands affect the reduction potentials of the associated $[Ni(P^R_2N^{Ph}_2)_2]^{2+}$ complexes. The electrochemical properties of such complexes with R = Ph, Cy are well documented in the literature.[5−9] The nickel complexes $[Ni(P^R_2N^{Ph}_2)_2(CH_3CN)_n](BF_4)_2$ (R = Me, n = 0, **7**; R = Bn, n = 1, **8**) were synthesized analogously to the previously reported complexes (Scheme 3).

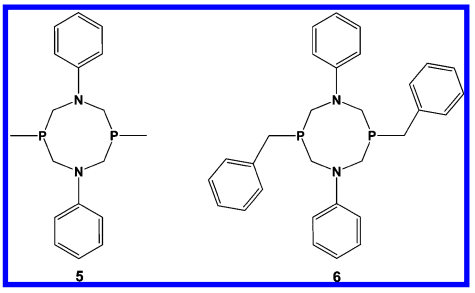
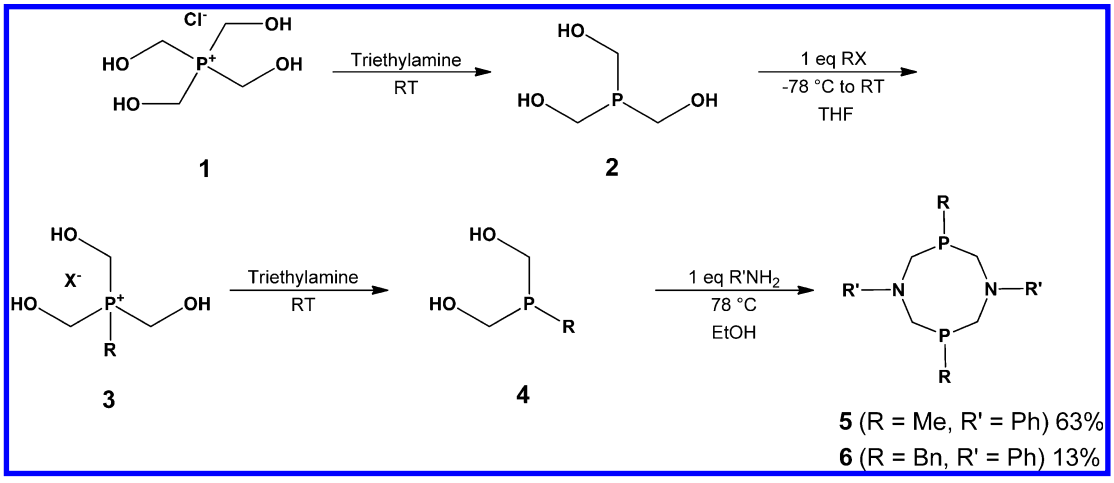


Figure 2. $P^R_2N^{Ph}_2$ ligands with methyl (**5**) and benzyl (**6**) phosphine substituents synthesized from THPCl.

These complexes typically give cyclic voltammograms consisting of two reversible one-electron redox processes associated with $E°(Ni^{II/I})$ and $E°(Ni^{I/0})$, exemplified by the CV of $[Ni(P^{Me}_2N^{Ph}_2)_2](BF_4)_2$ (**7**) shown in Figure 3.[8] Table 1 compares the reduction potentials in benzonitrile for previously reported complexes with those synthesized in this work. The methyl-substituted phosphine ligands on $[Ni(P^{Me}_2N^{Ph}_2)_2]^{2+}$ (**7**) shift both reduction potentials of the nickel complex more negative against the $FeCp_2^{+/0}$ reference in comparison to $[Ni(P^{Ph}_2N^{Ph}_2)_2]^{2+}$ (**9**) and the previously reported $[Ni(P^{Cy}_2N^{Ph}_2)_2]^{2+}$ (**10**).[8] The electron-donating character of the alkylphosphines (R = Me, Bn) is expected to be greater than that of the aryl phosphine (R = Ph). However, it is notable that the the benzyl-substituted P_2N_2 complex **8** is reduced at nearly the same potential as the phenyl-substituted complex **9**. The decrease in steric bulk at R as compared to the cyclohexylphosphine-substituted P_2N_2 ligands may have the effect of reducing the distortion toward a tetrahedral geometry in the Ni(II) state. The partial tetrahedral distortion in complexes ligated with the bulky cyclohexylphosphine P_2N_2 ligands lowers the $Ni^{II/I}$ reduction potential and stabilizes the Ni(I) state. Less bulky alkyl substituents may favor a square-planar geometry in the Ni(II) state, which raises the $Ni^{II/I}$ reduction potential and

Scheme 2. $P^R_2N^{R'}_2$ Synthesis via Dehydroxymethylation and Alkylation of THPCl (1)



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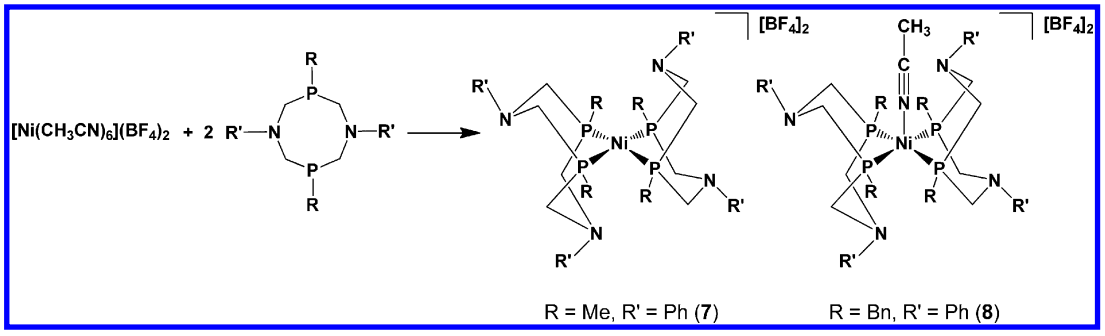
Scheme 3. Synthesis of Homoleptic Nickel Complexes of $P^{R}_{2}N^{R'}_{2}$ Ligands



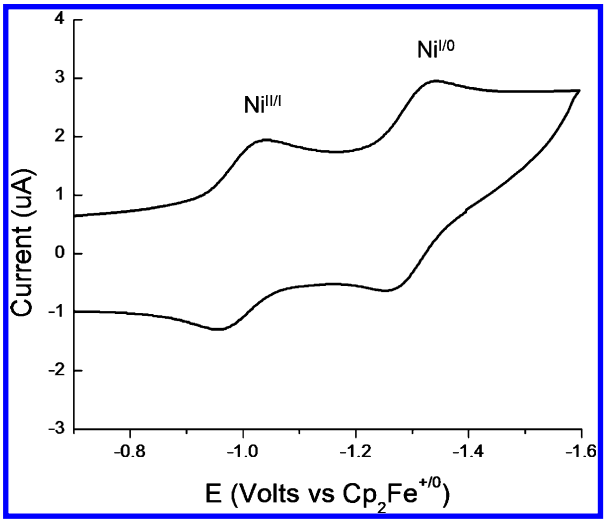


Figure 3. Cyclic voltammogram of 2.0 mM $[Ni(P^{Me}_{2}N^{Ph}_{2})_2](BF_4)_2$ (**7**) in benzonitrile/0.2 M Bu_4NPF_6 with a 1 mm glassy-carbon working electrode. Scan rate: 0.1 V s^{-1}.

Table 1. Reduction Potentials for the Series of Complexes $[Ni(P^{R}_{2}N^{Ph}_{2})_2(CH_3CN)](BF_4)_2$ in Benzonitrile

Complex	$E°(Ni^{II/I})$ (V vs $Cp_2Fe^{+/0}$)	$E°(Ni^{I/0})$ (V vs $Cp_2Fe^{+/0}$)
7 (Me, Ph)[a]	−1.01[b]	−1.30[b]
8 (Bn, Ph)	−0.78[b]	−1.16[b]
9 (Ph, Ph)	−0.79[b]	−1.00[b]
10 (Cy, Ph)	−0.60[c]	−1.10[c]

[a]**7** does not bear a CH_3CN ligand. [b]This work. [c]Reference 8.

destabilizes the Ni(I) state.[10] Indeed, from Table 1 it can be seen that as the steric bulk of the phosphine groups increases (Me < Ph < Bn < Cy), the reduction potential $E°(Ni^{II/I})$ becomes less negative (Me < Ph < Bn < Cy).

The importance of the steric effect exerted by the phosphine substituent is illustrated by the X-ray crystal structure of the $[Ni(P^{Me}_{2}N^{Ph}_{2})_2]^{2+}$ complex. X-ray-quality crystals were obtained for $[Ni(P^{Me}_{2}N^{Ph}_{2})_2](CF_3SO_3)_2$ (**11**) (Figure 4) by vapor diffusion of diethyl ether into acetonitrile. The noncoordinative nature of both the $[BF_4]^-$ and $[CF_3SO_3]^-$ anions allow for reasonable comparisons between the $[Ni(P^{R}_{2}N^{R'}_{2})]^{2+}$ cations. This structure differs from most previous $[Ni(P^{R}_{2}N^{R'}_{2})_2]^{2+}$ complexes in that acetonitrile is not coordinated to the metal center in the crystal structure;[8−10] this was previously observed only for the $[Ni(P^{Cy}_{2}N^{Bz}_{2})_2]^{2+}$ complex.[9] The reduced steric influence exerted by the methyl substituent yields a distorted-square-planar structure for the $[Ni(P^{Me}_{2}N^{Ph}_{2})_2]^{2+}$ cation, which

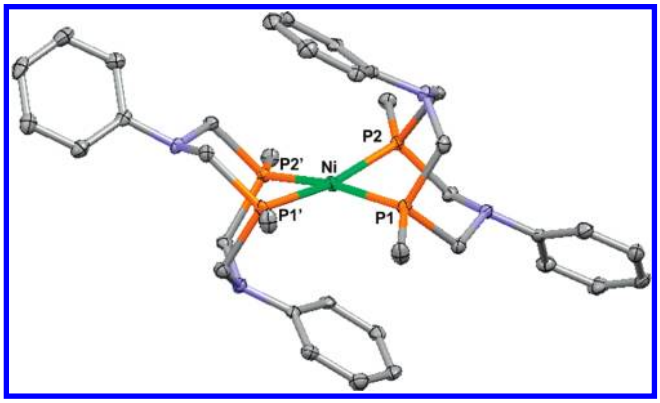


Figure 4. X-ray crystal structure of $[Ni(P^{Me}_{2}N^{Ph}_{2})_2](CF_3SO_3)_2$ (**11**) with protons, cocrystallized solvent, and counterions excluded for clarity. Ellipsoids are shown at the 50% probability level. Selected bond distances (Å) and angles (deg): Ni−P1 = 2.2393(11), Ni−P1′ = 2.2393(11), Ni−P2 = 2.2088(12), Ni−P2′ = 2.2089(12); P1−Ni−P2 = 83.16(4), P1−Ni−P1′ = 99.64(6), P1′−Ni−P2′ = 83.16(5), P2−Ni−P2′ = 96.06(6). P1 and P1′ and P2 and P2′ are related by symmetry.

differs significantly from the reported structures of the $[Ni(P^{Bn}_{2}N^{Ph}_{2})_2(CH_3CN)]^{2+}$ and $[Ni(P^{n\text{-}Bu}_{2}N^{Ph}_{2})_2(CH_3CN)]^{2+}$ cations, both of which exhibit distorted-trigonal-bipyramidal structures.[15b] The structure of **11** deviates slightly from a square-planar geometry, with the Ni center lying on a crystallographic 2-fold axis and displaying a dihedral angle of 16.16° between the two P−Ni−P planes.

We have demonstrated a versatile synthetic route for the production of P-alkyl P_2N_2-type ligands that avoids the use of primary phosphines. This synthesis gives unprecedented control over the substitution at the phosphorus atoms in the ligand, which directly modifies the donating character of the ligand and the redox potentials of the associated metal complexes. The homoleptic nickel complexes of the $P^{Me}_{2}N^{Ph}_{2}$ and $P^{Bn}_{2}N^{Ph}_{2}$ ligands have been synthesized and characterized, and the reduction potentials of the two complexes have been compared with previously reported $P^{R}_{2}N^{Ph}_{2}$ complexes (R = Ph, Cy). A homoleptic nickel $P^{Me}_{2}N^{Ph}_{2}$ complex has also been characterized by X-ray crystallography.

This new route to P_2N_2 ligands invites the synthesis of P_2N_2 ligands with a multitude of substituents on the phosphine. We are in the process of employing this control to impart further functionality on P_2N_2 ligands and their metal complexes. While previous studies have attempted to attach P_2N_2 catalysts to electrode surfaces, they have been limited by the traditional synthesis, which has largely restricted ligand functionalization to the amine.[17] Attaching the amine to a surface limits the flexibility of the pendant base, which has been shown to be

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critical to the electrocatalytic activity of the P_2N_2 complexes.[10] By combining the synthesis described in this report with electrode surface modification techniques, the freedom of the pendant base should be preserved while attachment of an appropriate functional group to the phosphine substituent will enable a direct connection between the electrode and the catalytic site.

In addition, we are using this synthesis to modify the electrocatalytic activity of $P^R_2N^{R'}_2$ complexes of nickel and other metals. By increasing the electron-donating character of the phosphine substituent, the redox potentials of the metal $P^R_2N^{R'}_2$ complexes can be pushed to more negative values, and the hydricities of the corresponding $[NiH(P^R_2N^{R'}_2)]^+$ complexes should also increase.[18] This thermodynamic property can be used to predict whether a complex will oxidize H_2 or reduce protons under the given reaction conditions.[19] Our goal is to find a similar balance in the new complexes with regard to formate oxidation and carbon dioxide reduction.[8] Adding more electronically donating and less sterically bulky substituents increases the hydride donation ability and should push formate oxidation catalysis toward its microscopic reverse, the single proton-coupled two-electron reduction of carbon dioxide to formate or further reduction products. Further studies of P_2N_2 ligands synthesized by this method and their corresponding metal complexes will be reported in due course.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Text and figures giving experimental details and cyclic voltammograms for compounds prepared in this paper and a CIF file giving X-ray crystal data for **11**. 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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