C−H Activation

C−H Activation of Benzene by a Photoactivated NiII(azide): Formation of a Transient Nickel Nitrido Complex**

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In memory of Greg Hillhouse

Abstract: *Photochemical activation of nickel-azido complex **2** [Ni(N₃)(PNP)] (PNᴴP = 2,2′-di(isopropylphosphino)-4,4′-ditolylamine) in neat benzene produces diamagnetic complex **3** [Ni(Ph)(PNᴾNᴴ)], which is crystallographically characterized. DFT calculations support photoinitiated N₂-loss of the azido complex to generate a rare, transient Niᴵⱽ nitrido species, which bears significant nitridyl radical character. Subsequent trapping of this nitrido through insertion into the Ni−P bond generates a coordinatively unsaturated Niᴵᴵ imidophosphorane P=N donor. This species shows unprecedented reactivity toward 1,2-addition of a C−H bond of benzene to form **3**. The structurally characterized chlorido complex **4** [Ni(Cl)-(PNᴾNᴴ)] is generated by reaction of **3** with HCl or by direct photolysis of **2** in chlorobenzene. This is the first report of aromatic C−H bond activation by a trapped transient nitrido species of a late transition metal.*

Transition metal complexes with terminal multiple bonds to main-group elements (e.g. C, O, N) play critical roles in various chemical and biological processes, including but not limited to nitrogen fixation, water splitting, and metathesis.[1] However, ligands based on multiple-bonded heteroatoms (e.g. imido or nitrido) typically exhibit strong π-donor character. For stable multiple bonding to occur between a transition metal and a strong π-donor main-group element, one or more empty metal d-orbitals of suitable symmetry and matching energy levels should be available on the metal center to accommodate the additional π-electron density.[2] Hence, complexes with Group 9–11 metals featuring multiple-bonded E-fragments are either rare or elusive, a situation sometimes referred to as "the oxo-wall dilemma".[3] Notwithstanding the challenges associated with the preparation of these species, their potential application in for example, C−N bond formation[4] or as intermediates in alternative routes for N₂ fixation warrant continued investigation, even when using "abiological" non-Group 8 metals.

Metal azides offer access to the interesting chemistry of nitrido complexes, as thermal, photolytic, or oxidative activation may result in the expulsion of N₂. Progress in the generation of Group 9 nitrides and open-shell nitridyl radical analogues demonstrate the feasibility of this approach.[5] However, these studies are dominated by the use of the second- and third-row transition metals. Only very recently the first low-temperature characterization of a cobalt nitrido intermediate was reported, which highlights the potential for late first-row transition metal nitrido chemistry.[6]

Studies on the activation of terminal metal azides to generate M≡N species with Group 10 metals are very scarce, particularly for nickel[7–9] and no bona fide (transient) nickel nitrido has been reported to date. Photo-, thermal, or redox-induced release of N₂ would convert the monoanionic azido ligand into a trivalent nitrido (N³⁻) ligand, which raises the formal oxidation state of the metal platform by two (Figure 1). Hence, stabilization of such (transient) species could potentially benefit from electron-donating or redox-active ligands. Terminal nitrido ligands on Group 9 metals are often too reactive to be isolated, and "trapping" these sought-after transient species by insertion into ligand C−H[10] or

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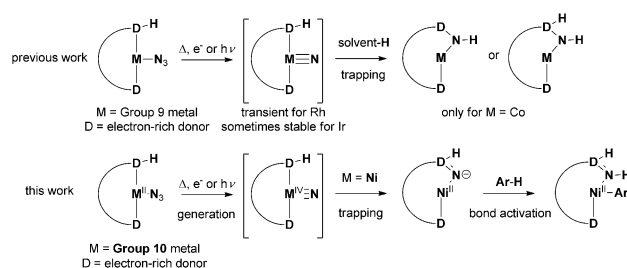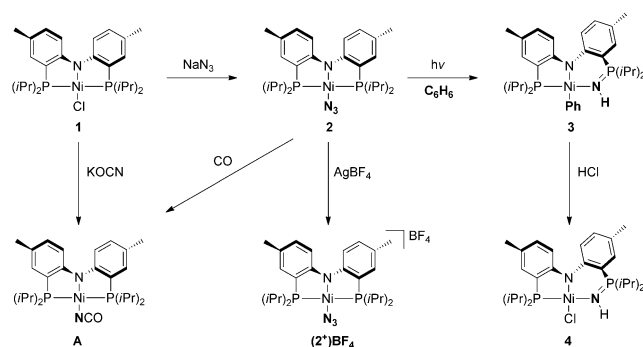3400 N Charles Street, Baltimore, MD 21218 (USA)

Figure 1. Strategies toward and reactivity with "trapped" transient nitrido species of Group 9 (previous work) and Group 10 metals (Ni, this work; arene C−H).

metal–ligand[5,11] bonds is an attractive strategy. However, to the best of our knowledge, well-defined reactivity of a "trapped" nitrido species toward intermolecular arene C−H bond activation has not been reported to date.

As part of our ongoing program to utilize reactive ligands with (first-row) late transition metals for bond activation,[12] we became interested in the preparation of nitrido species for nonligand C−H bond functionalization. Inspired by the recent examples with Group 9 metals,[5,6] we set out to explore this chemistry with Group 10 congeners. Herein, we report on the photolytic activation of a $Ni(N_3)(PNP)$ complex, which results in a transient nitrido species that is trapped as parent imidophosphorane by an intramolecular insertion reaction. This species facilitates unexpected follow-up aromatic C−H bond activation of benzene. DFT calculations on the mechanism and reactivity of the photolysis product are presented. The combined data provide insight into the chemical reactivity of a transient Ni-bound "nitrido" ligand.

Our starting point was the previously reported chlorido complex $Ni(Cl)(PNP)$ (**1**; PNP = 2,2′-di(isopropylphosphino)-4,4′-ditolylamide).[13] This species cleanly reacted through salt metathesis with excess NaN_3 in THF to generate azido complex $Ni(N_3)(PNP)$ (**2**, Scheme 1) in high yield, as con-

intact azide fragment as deduced from IR spectroscopy. Surprisingly, the azide band of the oxidized species was found at the same wavenumber as for its neutral analogue (ν 2051 cm^{-1}). Species **2** also proved thermally stable up to 200 °C as a solid and no sign of decomposition was observed after five days in refluxing toluene. The azide fragment cleanly converted to the corresponding isocyanate under five bars of CO, as confirmed by NMR (^{31}P: singlet δ 37.7) and IR spectroscopy (ν 2240 cm^{-1}) and by independent synthesis of the isocyanate species **A** [Ni(NCO)(PNP)] (Scheme 1; for details, see the Supporting Information, SI). This reaction occurred both in the absence and presence of light, implying the direct (intramolecular) attack of CO onto the azide with expulsion of N_2.[15] Addition of PMe_3 or PPh_3 to a solution of **2** in THF did not result in any appreciable reactivity.

Interestingly, in contrast to the thermal and oxidative stability of species **2**, photolysis of a [D$_6$]benzene solution of **2** (10.4 mM) using a 500 W Hg/Xe lamp with a cut-off filter at 305 nm resulted in a clear color change from green to yellow and complete conversion of the azide complex, according to IR spectroscopy. Multinuclear NMR spectroscopy suggested the quantitative formation of one well-defined diamagnetic species. The ^{1}H NMR spectrum (Figure 2) showed complete preservation of all hydrogen atoms within the ligand scaffold,
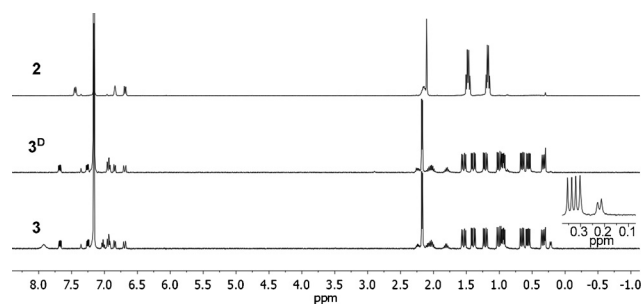

Scheme 1. Synthesis and reactivity of complex **2**, (PNP)Ni(N$_3$), including reaction with CO to generate **A**, photolytic activation to species **3**, and subsequent reaction with HCl to product **4**.

Figure 2. ^{1}H NMR spectra before (top), after irradiation of **2** in C$_6$D$_6$ (middle), and after irradiation in C$_6$H$_6$ (bottom). The insert is showing an additional (-NH) doublet at 0.22 ppm for the irradiation in C$_6$H$_6$.

firmed by multinuclear NMR (^{31}P: singlet δ 36.3) and IR spectroscopy (ν 2051 cm^{-1}; ^{15}N-labeled isotopomer: ν 2040 cm^{-1}). The compound absorbs strongly at λ 345 nm (ε = 32 000 L mol^{-1} cm^{-1}) and at λ 316 nm (ε = 24 000 L mol^{-1} cm^{-1}), as deduced from UV/Vis spectroscopy. Complex **2** exhibits local C$_2$-symmetry according to ^{1}H NMR spectroscopy. The X-ray structure of **2** was determined by X-ray diffraction on single crystals grown from toluene/pentane.

To establish the stability of species **2** and in particular the robustness of the azide group, we conducted a series of experiments. The azide complex exhibited fully reversible one-electron oxidation chemistry in cyclic voltammetry, with a $E_{1/2}$ of 0.03 V versus Fc^0/Fc$^+$ (in THF). Oxidation of precursor **1** has been shown by DFT calculations to occur predominantly at the nitrogen of the PNP backbone (ΔE = −0.10 V vs. **2**), making this a redox-active ligand.[14] Chemical oxidation with AgBF$_4$ in acetone resulted in the blue cationic derivative [Ni(N$_3$)(PNP)]BF$_4$ (**2$^+$)BF$_4$, which contained an

hence excluding ligand-based intramolecular C−H activation as a potential reaction pathway. Furthermore, complete loss of the C$_2$ symmetry is observed, with two signals for the -CH$_3$ groups of the ditolylamine backbone and eight non-equivalent -CH$_3$ signals from the PiPr$_2$ groups present. Notably, the ^{31}P NMR spectrum contains two doublets at δ 45.9 and 48.5 with a small coupling constant J_{PP} of 6.4 Hz, excluding a direct *trans*-coordination of the P moieties. Irradiation of the corresponding ^{15}N-labeled isotopomer of **2** resulted in two new doublets-of-doublets in the ^{31}P NMR spectrum. Remarkably, both J_{PN} coupling constants are almost identical at 29.2 and 30.5 Hz, whereas the J_{PP} coupling is 6.5 Hz. This confirmed the presence of the azide Nα-atom and suggested that the two P-atoms are chemically inequivalent, but both couple to the ^{15}N nucleus. Further analysis of the species by cold-spray ionization (CSI) MS spectrometry revealed the presence of a perdeuterophenyl fragment in the generated complex.

Based on the latter observation, we decided to switch to C_6H_6 as the solvent for the photolysis reaction. In line with the MS data, this resulted in the appearance of additional aromatic signals in the ${}^1H$ NMR spectrum and, markedly, also a doublet at δ 0.22, coupled to a ${}^{31}P$ nucleus (confirmed by selective ${}^{31}P$ decoupling of the ${}^1H$ NMR spectrum). The ${}^{15}N$-enriched material gave an additional splitting of the doublet with a large coupling constant (J_{NH} 73.2 Hz), which suggests a direct bond between a hydrogen of the activated benzene and a nitrogen originating from the decomposed azide group. The existence of an N−H fragment was additionally confirmed by the appearance of a weak N−H vibration (ν 3365 cm^{-1}) in the IR spectrum. Closer inspection of the IR spectrum of 3^D (product from photolysis in C_6D_6) revealed the presence of an N−D vibration at ν 2493 cm^{-1}. In the corresponding ${}^{15}N$ HSQC NMR spectrum a triplet was observed at δ −365.

Yellow-colored single crystals, suitable for X-ray diffraction, were obtained by slow evaporation of a dichloromethane/cyclopentane mixture. The X-ray structure of square-planar Ni^{II}-complex **3** (Figure 3) confirms the formal insertion of an -NH fragment into the Ni${}_1$−P${}_1$ bond, thus creating a parent iminophosphorane, with a P${}_1$–N${}_2$ bond length of 1.5970(20) Å, which is typical for a P=N double bond.[17] The angles $\angle$N${}_1$-Ni${}_1$-N${}_2$ (93.98(8)°) vs. (83.83(4)° for $\angle$N${}_1$-Ni${}_1$-P${}_1$ in **2**) and $\angle$N${}_2$-Ni${}_1$-P${}_2$ (177.48(7)°) vs. 167.38(1)° for $\angle$P${}_1$-Ni${}_1$-P${}_2$ in **2**) illustrate the expanded coordination sphere around Ni upon transformation of the PNP-donor into a 5,6′-chelating PN^{P}N^H donor in **3**. Furthermore, C−H bond activation of benzene has resulted in the introduction of a phenyl ligand, with hydrogen transfer to the nitrogen originating from the azide precursor.[18] Variable temperature NMR studies suggest that the phenyl ligand exhibits hindered rotation at room temperature, causing the broadening of the *ortho*- and *meta*-H signals in the ${}^1H$ NMR spectrum (Figure 2). Decreasing the temperature of a sample in [D${}_8$]toluene to −20°C gave rise to splitting of these broad signals into four well-defined peaks. Species **3** still displays well-behaved redox chemistry, as illustrated by cyclic voltammetry, with a reversible one-electron oxidation event occurring at $E_{1/2}$ −0.34 V, which is significantly more negative (ΔE −0.41 V) than that for azide **2**.

To gain more insight into the mechanism of the formation of complex **3**, DFT calculations were performed. For computational ease, a simplified model of complex **2** was used, with phenyl instead of tolyl rings for the backbone and Me-substituents at the phosphorus atoms. We investigated routes at different (excited-state) spin states, both at the hybrid b3-lyp level (Scheme 2) and the pure GGA BP86 DFT functional (Scheme S3, SI). Open-shell singlet
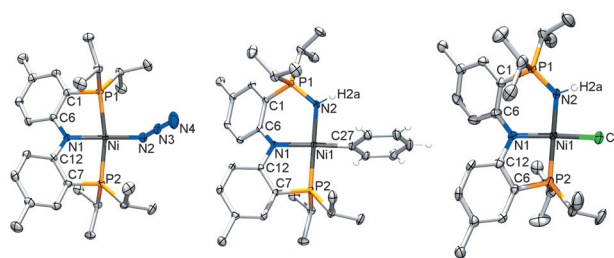

Figure 3. ORTEP plots (50% probability level) for **2** (left), **3** (middle), and **4** (right). Hydrogen atoms are omitted for clarity, except for hydrogen on N${}_2$ and hydrogens on exogenous phenyl ring.[16] Selected bond lengths [Å] and angles [°], for **2**: Ni${}_1$−P${}_1$ 2.1956(4); Ni${}_1$−N${}_1$ 1.8970(8); Ni${}_1$−P${}_2$ 2.1988(4); Ni${}_1$−N${}_2$ 1.9004(10); N${}_2$−N${}_3$ 1.1826(17); P${}_1$-Ni${}_1$-P${}_2$ 167.376(11); P${}_1$-Ni${}_1$-N${}_1$ 83.82(4); P${}_1$-Ni${}_1$-N${}_2$ 96.63(5); N${}_1$-Ni${}_1$-N${}_2$ 177.08(6); Ni${}_1$-N${}_2$-N${}_3$ 120.59(10); C${}_6$-N${}_1$-C${}_{12}$ 121.97(9). For **3**: Ni${}_1$−N${}_1$ 1.9770(17); Ni${}_1$−P${}_2$ 2.1259(6); Ni${}_1$−N${}_2$ 1.8923(18); Ni${}_1$−C${}_{27}$ 1.893(2); N${}_2$−P${}_1$ 1.597(2); P${}_2$-Ni${}_1$-N${}_2$ 177.48(7); N${}_1$-Ni${}_1$-N${}_2$ 93.98(8); N${}_1$-Ni${}_1$-P${}_2$ 85.92(5); N${}_1$-Ni${}_1$-C${}_{27}$ 177.74(8); Ni${}_1$-N${}_2$-P${}_1$ 123.39(11); C${}_6$-N${}_1$-C${}_{12}$ 117.99(17). For **4**: Ni${}_1$−N${}_1$ 1.930(3); Ni${}_1$−P${}_2$ 2.112(2); Ni${}_1$−N${}_2$ 1.893(3); Ni${}_1$−Cl${}_1$ 2.1951(11); N${}_2$−P${}_1$ 1.587(3); P${}_2$-Ni${}_1$-N${}_2$ 176.80(13); N${}_1$-Ni${}_1$-N${}_2$ 94.05(13); N${}_1$-Ni${}_1$-P${}_2$ 86.03(11); N${}_1$-Ni${}_1$-Cl${}_1$ 173.74(9); Ni${}_1$-N${}_2$-P${}_1$ 129.7(2); C${}_6$-N${}_1$-C${}_{12}$ 116.8(3).

(OSS) configurations for all investigated stationary points could only be located at the hybrid b3-lyp level. At the BP86 level only closed-shell singlet (CSS) configurations were found. As a starting point the activation of the azide was investigated. The release of N${}_2$ proceeds via a high-energy transition state **TS1** on all calculated surfaces and is therefore considered as a nonthermal, photochemical step. The reaction pathway after N${}_2$ loss from **2** can either follow photochemical or thermal steps or a combination thereof. The *meta*-stable "Ni^{IV}-nitrido" intermediate **B** is most stable in its triplet configuration (^{3}**B**), both at the BP86 and at the b3-lyp level.
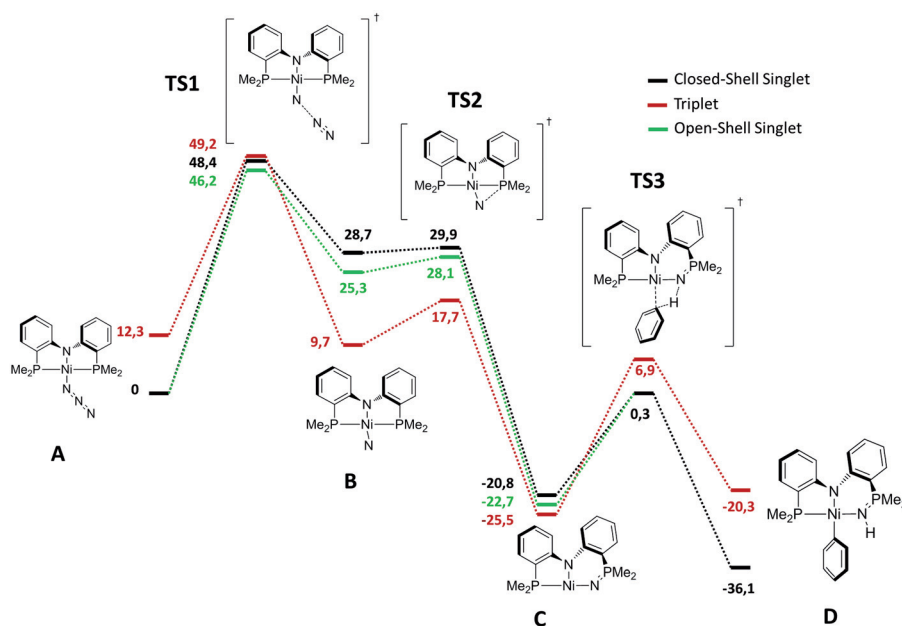
Scheme 2. Proposed pathway for the formation of **3** upon irradiation of **2** in C_6H_6 based on DFT calculations (b3-lyp, def2-TZVP). Energies in kcal mol^{-1} relative to CSS state of compound **A**.
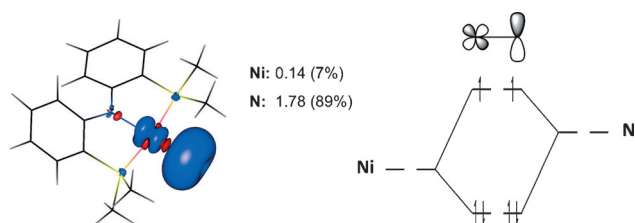
Ni: 0.14 (7%)
N: 1.78 (89%)

Figure 4. Spin density plot of triplet intermediate ^{3}**B** (b3-lyp, def2-TZVP) and a schematic representation of the metal–nitrido π-bonding scheme.

The spin density predominantly resides on the N-atom (b3-lyp: 89%, BP86: 81%), resulting in significant nitridyl radical character (Figure 4), similar to previously reported systems.[5b,d,f,6] The unusual electronic structure of ^{3}**B** is perhaps best described with contributions from the following resonance structures: $Ni^{IV}(N^{3-}) \leftrightarrow Ni^{III}(N^{\cdot 2-}) \leftrightarrow Ni^{II}(^{\cdot}N^{\cdot -})$. The CSS and the OSS configurations of singlet ^{1}**B** collapse via a virtually barrierless transition state **TS2** to the coordinatively unsaturated $Ni^{II}(PN^PN)$ intermediate **C**, featuring two anionic N-donor atoms (i.e. the PNP-nitrogen and the "nitrido" nitrogen). In fact, the barrier from ^{1}**B** to ^{1}**C** at the closed-shell singlet BP86 configuration is so low that ^{1}**B** converges spontaneously to ^{1}**C**. Conversion of ^{3}**B** to ^{3}**C** on the triplet surface also has quite a low barrier (both at the BP86 and the b3-lyp level) and thus might well proceed thermally (although photoexcitation to the singlet surface cannot be excluded).

The relative spin-state energies of intermediate **C** at the CSS, OSS, and triplet surface are quite similar. While the triplet configuration of **C** is most stable at the b3-lyp level, the CSS configuration of **C** is most stable at the BP86 level. The reaction from **C** via **TS3** to **D** may follow a thermal or photochemical pathway. Thermal conversion at the triplet surface has a prohibitively high barrier at room temperature, but spin cross-over from the triplet to the CSS surface might facilitate the overall process. A pathway involving H-atom abstraction from benzene followed by a radical rebound reaction was found to be less likely, due to a higher energy barrier. At the CSS and OSS surfaces, direct thermal conversion from ^{1}**C** to ^{1}**D** is energetically possible at room temperature. The alternative scenarios of outer-sphere C–H activation prior to the N-insertion step, with formation of a five-coordinate Ni(PNP)(NH)(Ph) imido-species intermediate, were also investigated but found to be less favorable.

Based on these computational data, several attempts to trap the postulated intermediate **B** were undertaken. Photolysis of **2** in benzene in the presence of Me$_3$NO, 50 equiv PMe$_3$, or in pure 1,4-cyclohexadiene did not generate Ni(NO)(PNP), Ni(N=PMe$_3$)(PNP), or Ni(NH$_2$)(PNP), respectively, based on IR and NMR spectroscopic analysis. The use of H$_2$ as trapping agent did not lead to the parent Ni-amido species, but instead the known Ni(H)(PNP) complex[13] was observed. NH$_3$ was detected by ^{15}N NMR spectroscopy and spectrophotometric assay analysis (SI). Use of D$_2$ resulted in ND$_3$. The NH$_3$ and the Ni-hydride may originate from reaction of H$_2$ with the transient nitrido, but other pathways for their formation cannot be excluded at this

point.[19] Initial experiments to broaden the reactivity "scope" of the trapped nitrido species **C** were also performed. Photolysis of **2** in toluene led to four sets of doublets by in situ ^{31}P NMR spectroscopy, suggesting that C_{sp^2}–H and C_{sp^3}–H bond activation may be competitive processes. Photolysis of **2** in neat cyclohexane or heptane resulted in a myriad of unidentified species in the ^{31}P NMR spectrum. Photolysis in 1,3,5-trideuterobenzene was thwarted by trace amounts of chlorobenzene (detected by MS), culminating in the presence of two doublets at δ 46.8 and 45.3 in the ^{31}P NMR spectrum, attributed to be the chlorido derivative of **3**, NiCl(PN^{P}N^H) (**4**).[20] Complex **4** was also prepared independently by reaction of **3** with HCl (Scheme 1) and fully characterized by NMR spectroscopy, mass spectrometry, and X-ray crystallography (see Figure 3 for X-ray structure). The structural parameters for **4** are very similar to those observed for **3** (Figure 3). Deprotonation of **4** with lithium diisopropylamide (LDA) in the presence of benzene did not result in arene C–H activation. We are currently exploring the reactivity of **3** and **4**, both to understand the unique structural features of these species and to deduce whether the parent iminophosphorane P=NH unit shows promising ligand reactivity.

In summary, we herein report the first example of a trapped transient nickel nitrido species, making use of a well-defined Ni^{II}(PNP) platform. Irradiation of the nickel-azido precursor generates a nickel nitrido, which has significant nitridyl radical character, that is efficiently trapped by insertion of the nitrogen into a Ni–P bond. This trapped intermediate undergoes follow-up intermolecular C–H bond activation of aromatic solvent, with the activated exogenous phenyl fragment incorporated in the final complex **3**, which bears a unique tridentate phosphino-amido-iminophosphorane PN^{P}N^H ligand in the coordination sphere of Ni^{II}. DFT calculations support the intermediacy of a rare transient formal Ni^{IV} nitrido species and subsequent 1,2-addition of the C–H bond. Substitution of the Ph-ligand for Cl is facile, generating **4**, which is likely amenable to follow-up chemistry.

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