Molecular titanium nitrides: nucleophiles unleashed†

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In this contribution we present reaction studies of a rare example of a titanium salt, in the form of [μ2-K(OEt)2][μ2-PN]2TiN2 (1) (PN = N-[2-(disopropyphosphino)-4-methylphenyl]-2,4,6-trimethylanilido) to produce a series of imide moieties including rare examples such as methylimido, borylimido, phosphonylimido, and a parent imido. For the latter, using various weak acids allowed us to narrow the pkₐ range of the NH group in (PN)₂Ti=NH to be between 26–36. Complex 1 could be produced by a reductively promoted elimination of N₂ from the azide precursor (PN)₂TiN₃, whereas reductive splitting of N₂ could not be achieved using the complex (PN)₂Ti=NN=N=Ti(PN)₂ (2) and a strong reductant. Complete N-atom transfer reactions could also be observed when 1 was treated with CIC(O)Bu and OCOCPh₂ to form NCtBu and KNCCPh₂, respectively, along with the terminal oxo complex (PN)₂Ti=O, which was also characterized. A combination of solid state ¹⁵N NMR (MAS) and theoretical studies allowed us to understand the shielding effect of the counter cation in dimer 1, the monomer [K(18-crown-6)][(PN)₂Ti=NN=N=Ti(PN)₂] and the discrete salt [K(2,2,2-Kryptofix)][(PN)₂Ti=NN=N=Ti(PN)₂] as well as the origin of the highly downfield ¹⁵N NMR resonance when shifting from dimer to monomer to a terminal nitride (discrete salt). The upfield shift of ¹⁵N nitride resonance in the ¹⁵N NMR spectrum was found to be linked to the K⁺ induced electronic structural change of the titanium-nitride functionality by using a combination of MO analysis and quantum chemical analysis of the corresponding shielding tensors.

Introduction

Investigation of transition metal nitrides by synthetic and physical chemists alike over the past several decades has revealed the relevance of this ubiquitous functional group to industrial and biological processes, as well as their applications in materials and surface chemistry.¹–⁷ Nitride reactivity can be tuned with the appropriate transition metal ion to render this site either nucleophilic or electrophilic. High oxidation states, generally, can be stabilized with this type of motif and are known to participate in reactivity spanning various transformations⁸ such as N-atom transfer reactions and nitrile-alkyne cross-metathesis,⁹,¹⁰ and also to act as surface supports that engage in important industrial processes such as Haber–Bosch¹¹–¹⁴ and hydrodenitrogenation and hydrodesulfurization.¹⁵–¹⁷ The nitride ligand can also provide a realistic snapshot of the active site of nitrogenases through molecular platforms modeling N₂ reductive splitting reactions.⁶–²⁰ Additionally, nitride-based materials are investigated for use in thin films, often derived via chemical vapor deposition and by direct current electron sputtering.²¹–²⁵ Consequentially, the nitride group is extremely important in small molecule activation, in modeling and performing N₂ to ammonia synthesis, and in producing new materials with important electronic properties or applications.

While the synthesis of both terminally bound as well as bridging metal nitrides are rather routine for groups 6–7 transition metals,⁷,²⁶–²⁹ a convergent synthesis of these highly nucleophilic terminal transition metal nitrides for groups 4 or 5 metals has not been documented until recently, and hence, their reactivity has been rather unexplored when compared to groups 6 and 7 derivatives.³⁰–⁴¹ Of particular interest are group 4 terminally bound Ti nitrides, expected to be highly ionic given the disparity in Pauling electronegativities between Ti (1.5) and N (3.0). Only in certain cases could the nitride ligand be installed with protecting Lewis acidic groups (Fig. 1).³²–³⁴ However, examples of well-defined group 4 nitrides are indeed known, and can be isolated as dinuclear (Fig. 1), trinuclear (Fig. 1), tetrannuclear, and even hexanuclear species.³⁵–⁵¹ Thus, we focused our attention on group 4, especially on Ti, since reactivity studies of mononuclear nitrides in this group have largely evaded the reach of the synthetic chemist until
The fact that mononuclear titanium nitrides are exceedingly rare is rather surprising since group 4 nitrides have been proposed in N₂ activation and reductive splitting reactions, and the nitride group is often generated in route to the deposition of thin metal nitride films. The elusive nature of terminal titanium nitrides, adjunct with the wealth of useful reactivity established in mid-transition metal nitrides, calls for the attention to probe the nature of this highly polarized bond and to determine the degree of nucleophilicity in this rather uncharacterized motif.

Recently, we reported the synthesis of a dinuclear titanium-nitride complex supported by a sterically encumbering β-diketiminate (BDI) ligand (Fig. 2). However, due to degradation in this ligand scaffold, as well as other decomposition pathways, reactivity studies of this system were quite restricted. We turned instead to new titanium nitrides supported by two PN/C₀ ligands (PN/C₀ = N-(2-(diisopropylphosphino)-4-methylphenyl)-2,4,6-trimethylanilide, Fig. 2), derived from a more direct route via reduction of the corresponding azide precursor. This ligand framework was selected as it was speculated to be more robust, lacking vulnerable protons in the ligand backbone, as well as the imine group present in β-diketimimates, which can be split under reducing conditions. Inspired by Parkin and Woo’s five coordinate L₂Ti=X complexes (L₂ = meso-substituted porphyrin, octamethyldibenzotetraaza[14]annulene; X = chalcogen or imide group), we hypothesized that two PN⁻ ligands could enforce a pseudo tetragonal ligand field environment suitable for the construction of a terminally bound nitride or other isoelectronic atoms or groups. Fig. 3 depicts a simplified d-orbital splitting diagram for a square planar Ti⁴⁺ fragment supported by four σ donor nitrogen ligands, two of which could also serve as π donors in a transoid orientation, akin to the ubiquitous porphyrin scaffold. For a d⁰ fragment, the empty and hybridized dₓz as well as π-like dₓ and dᵧ orbitals are available to form a triple bond with an incoming axial ligand. Further evidence that a chelating ligand such as PN⁻ could enable a more robust Ti-X multiple bond (such as a nitride) derived from the fact that terminally bound chalcogenido complexes of the Ti⁴⁺ ion supported by two monoanionic benzimidinate ligands could be isolated as demonstrated in the work by Arnold. However, unlike the highly constrained porphyrin or octamethyldibenzotetraaza[14]annulene dianion ligands, the use of two chelating ligands allows for a more flexible geometric interplay between trigonal bipyramidal and
square pyramidal scaffolds when such a system is confronted by a fifth ligand.

Isolation of the dinuclear, or mononuclear titanium nitride complexes having the anionic core \([\text{[PN]}_2\text{Ti}‰\text{N}]^-\), presents an exciting opportunity to exploit such functionality, either by salt elimination followed by complete and incomplete N-atom transfer. Herein, we report reactivity of the dinuclear nitride elimination followed by complete and incomplete N-atom transfer. In conjunction with solution-state spectroscopic studies of these species we also report salt elimination reactions, some of which result in complete N-atom transfer. This opportunity to exploit such functionality, either by salt elimination followed by complete and incomplete N-atom transfer. In conjunction with solution-state spectroscopic studies of these species we also report salt elimination reactions, some of which result in complete N-atom transfer.

**Experimental section**

**General procedures**

Unless otherwise stated, all operations were performed in a M. Braun Lab Master double-dry box under an atmosphere of purified dinitrogen or using high vacuum standard Schlenk techniques under an argon atmosphere. NMR spectra were recorded on a Bruker AV-II 500 MHz spectrometer for \(^{13}\)C spectra, and a Bruker AVIII 400 MHz spectrometer for \(^{1}\)H and \(^{31}\)P\(^{(1)}\)H spectra. \(^{1}\)H NMR spectra are reported with reference to residual proteo solvent resonances of benzene-d\(_6\) at 7.16 ppm. \(^{13}\)C\(^{(1)}\)H NMR spectra were referenced to solvent resonances of benzene-d\(_6\) at 128.06 ppm. \(^{31}\)P\(^{(1)}\)H NMR spectra were referenced to external H\(_3\)PO\(_4\) (0 ppm). Pentane, hexanes, benzene, and toluene were purchased from Fisher Scientific and stabilizer-free diethylether (Et\(_2\)O) and tetrahydrofuran (THF) were purchased from Sigma Aldrich. Solvents were sparged with argon for 20 minutes and dried using a two-column solvent purification system where columns designated for pentane, hexanes, benzene, and toluene were packed with Q5 and alumina respectively, and columns designated for Et\(_2\)O and THF were packed with alumina. Deuterated benzene and deuterated toluene were purchased from Cambridge Isotope Laboratories (CIL) and were dried over 4 Å sieves, and degassed by freeze–pump–thaw cycles. All solvents were transferred into a dry box and were stored over 4 Å sieves. All sieves were heated to 200 °C under vacuum overnight prior to use. Celite used for filtrations was also heated to 200 °C under vacuum overnight prior to use. Compounds 1, 1-\(^{15}\)N, [K\(2\),\(2\),\(2\)-Kryptofix] \([\text{[PN]}_2\text{Ti}‰\text{N}]\)' and \([\text{[PN]}_2\text{Ti}‰\text{N}]\) were prepared following published procedures.\(^{3}5\) The UV-Vis absorption spectra were obtained in a J-Young valve 1 cm quartz cell on a Cary 5000 UV-Vis-NIR. Elemental analyses were performed at a FLASH EA 1112 Series CHN analyzer (Thermo Finnigan). \([\text{[PN]}_2\text{Ti}‰\text{N}]=\text{[Ti}‰\text{PN}]_2\) (2). In a 20 mL scintillation vial, \([\text{[PN]}_2\text{Ti}‰\text{Cl}700\text{mg, 0.916 mmol, 1 equiv.}]\) dissolved in 5 mL toluene as a dark brown solution. To this solution was added a 5 mL slurry of KC\(_8\) (123.8 mg, 0.916 mmol, 1 equiv.) while stirring with a glass coated metal stirbar. The mixture was stirred overnight at room temperature, during which time it became a deep red color. This solution was filtered over a thick pad of celite. The product is highly insoluble, so the celite pad was washed with 80 mL of toluene in order to extract the product free from the salt. The filtrate solution was concentrated to 50 mL, and then layered with 20 mL of hexane. Storage at −35 °C overnight resulted in the formation of a magenta powder, which was isolated over a frit, followed by washing with 10 mL cold toluene (673 mg, 0.458 mmol, 49%). Single crystals suitable for X-ray diffraction could be grown from a concentrated benzene solution after one week at room temperature. \(^{1}\)H NMR (400 MHz, 25 °C, benzene-d\(_6\)): \(\delta\:7.04\) (br, \(\Delta r_{1/2} = 8\) Hz, 2H, \(\text{meta-}Ar_\text{Mesityl}\)), 6.85 (dd, \(J_{H-H} = 4.12\) Hz, 1H, \(\text{meta-}Ar_\text{H(Tolyl)}\)), 6.73 (s, 1H, \(\text{meta-}Ar_\text{H(Tolyl)}\)), 5.85 (dd, \(J_{H-H} = 4.10\) Hz, 1H, \(\text{ortho-}Ar_\text{H(Tolyl)}\)), 2.87 (s, 3H, \(\text{CH}_3\text{Tolyl}\)), 2.73 (br, 1H, P-CH=CH\(_2\)), 2.23 (s, 3H, \(\text{ortho-CH}_2\text{Mesityl}\)), 1.87 (s, 3H, \(\text{para-}CH_2\text{Mesityl}\)), 1.40 (d, \(J_{H-H} = 4.16\) Hz, 3H, P-CH=CH\(_2\)), 0.54 (br, 3H, P-CH=CH\(_2\)), 0.29 (sept, \(J_{H-H} = 4.13\) Hz, 1H, P-CH=CH\(_2\)). \(^{31}\)P\(^{(1)}\)H NMR (162 MHz, 25 °C, benzene-d\(_6\)): \(\delta\:18.98\) (s, 2P, \(\text{PN}\)). Unfortunately, the poor solubility of this complex prevented us from obtaining reliable \(^{13}\)C NMR spectra. Anal. calcd for C\(_94\)H\(_{130}\)N\(_6\)P\(_4\)Ti\(_2\) (including 1 benzene per dinuclear complex): C: 72.20, H: 8.38, N: 5.37. Found: C: 73.18, H: 9.19, N: 3.96. The loss of N\(_2\) in the complex resulted in a lower % of nitrogen.
(PN)₂Ti=NMe (3). In a 20 mL scintillation vial, compound 1 (200 mg, 0.105 mmol, 1 equiv.) was dissolved in 5 mL toluene. To this light orange solution was added methyl iodide dropwise by microsyringe (13.3 μL, 0.210 mmol, 2 equiv.) while stirring at room temperature. The color of the solution changed during addition of methyl iodide from light orange to dark red. The solution was stirred at room temperature for 15 minutes. Volatiles were removed under vacuum, resulting in a dark red residue. The residue was triturated three times with five mL of pentane. The resulting powder was dissolved in 5 mL pentane and filtered through celite to remove the salt. Crystallization from the 5 mL filtrate solution overnight at −35 °C resulted in the isolation of red crystals (149.9 mg, 0.198 mmol, 94.6%), which were suitable for X-ray diffraction studies.

¹H NMR (400 MHz, 25 °C, benzene-d₆): δ 6.91 (br, 2H, meta-ArH₃mes), 6.78 (s, 1H, meta-ArH₃tol), 6.89 (br, J=14.0 Hz, 1H, meta-ArH₃tol), 5.84 (dd, J=4.9 Hz, 1H, ortho-ArH₃tol), 2.63 (s, 3H, NCH₃), 2.69 (br, J=14.2 Hz, 2H, P–C–CH₃), 2.17 (s, 3H, para-CH₃mes), 2.47 (br, 3H, P–CH–CH₃), 0.81 (br, 3H, P–CH–CH₃), 0.34 (br, 1H, P–CH–CH₃), 31P{¹H} NMR (162 MHz, 25 °C, benzene-d₆): δ 12.48 (s, 2P, PN). ¹³C{¹H} NMR (125.8 MHz, 25 °C, benzene-d₆): δ 161.8 (Ar–C), 147.3 (Ar–C), 133.4 (Ar–C), 131.9 (Ar–C), 123.8 (Ar–C), 112.9 (Ar–C), 112.8 (Ar–C), 57.44 (NCH₃), 20.9 (P(CH₃)₂), 20.7 (P(CH₃)₂), 18.4 (Ar–CH₃). We were unable to obtain satisfactorily elemental analysis due to the thermal sensitivity of this complex.

(PN)₂Ti=N=PPr₂ (5). In a 20 mL scintillation vial, compound 1 (166 mg, 0.088 mmol, 1 equiv.) was dissolved in 3 mL toluene as a light orange solution. To this solution, was added trimethylsilylazide dropwise via a microsyringe (23 μL, 0.175 mmol, 2 equiv.) while stirring. The solution rapidly turned to a deep red, along with precipitation of a solid that deposited on the walls of the vial. The volatiles were taken dryness after 5 minutes of stirring, and the resulting red residue was triturated with 5 mL pentane resulting in a dark red powder. This powder was dissolved in 5 mL pentane, filtered through celite, and the filtrate concentrated to 3 mL. Cooling to −35 °C overnight resulted in the isolation of dark red crystals suitable for X-ray diffraction (128.1 mg, 0.157 mmol, 90.2%). ¹H NMR (400 MHz, 25 °C, benzene-d₆): δ 7.00 (s, 1H, meta-ArH₃tol), 6.89 (br, J=13.7 Hz, 2H, meta- ArH₃mes), 6.80 (dd, J=4.2 Hz, 1H, meta- ArH₃mes), 5.81 (dd, J=4.5 Hz, 1H, ortho- ArH₃tol), 2.53 (br, 3H, P–CH–CH₃), 2.23 (s, 3H, CH₃tol), 2.14 (s, 3H, para-CH₃mes), 1.02 (s, 6H, ortho-CH₃mes), 0.217 (s, 9H, NSiMe₃). ³¹P{¹H} NMR (162 MHz, 25 °C, benzene-d₆): δ 13.33 (s, 2P, PN). ¹³C{¹H} NMR (125.8 MHz, 25 °C, benzene-d₆): δ 161.7 (Ar–C), 147.6 (Ar–C), 133.9 (Ar–C), 133.6 (Ar–C), 124.2 (Ar–C), 113.4 (Ar–C), 20.9 (P(CH₃)₂), 20.6 (P(CH₃)₂), 5.3 (TMS). We were unable to obtain satisfactorily elemental analysis due to the thermal sensitivity of this complex.

(PN)₂Ti=N=NH (7). Experimental note: synthesis of 7 must be conducted in the absence of light; further chemical
transformations proceed in ambient light. Compound 1 (300 mg, 0.16 mmol, 1 equiv.) was dissolved in 6 mL toluene in a 20 mL vial. To this light orange solution was added a 5 mL colorless toluene solution of hexamethyldisilazane (66.3 µL, 0.32 mmol, 2 equiv.) at room temperature. Immediate color change to a magenta color was observed, and the solution was stirred for 15 minutes at ambient temperature. The solution was then taken to dryness and the deep red oil was triturated with 5 mL of pentane three times. This red powder was then dissolved in 7 mL pentane, filtered over celite, and concentrated to 4 mL. Cooling overnight to $-35 \, ^\circ C$ resulted in the formation of dark red microcrystals (198 mg, 0.267 mmol, 83.6%). Crystals suitable for X-ray diffraction were grown from a dilution solution of 7 in THF/pentane after 2 nights at $-35 \, ^\circ C$. $^1H$ NMR (400 MHz, 25 °C, benzene-d$_6$): $\delta$ 7.01 (dd, $^3$J$_{H-H}$ = 4.53 Hz, 1H, meta- ArHMesityl), 6.88 (br, 2H, meta-ArH$_{Mesityl}$), 6.80 (s, 1H, meta-ArH$_{Mesityl}$), 5.81 (dd, $^3$J$_{H-H}$ = 4.14 Hz, 1H, ortho-ArH$_{Mesityl}$), 5.07 (s, 1H, Ti=NH), 2.41 (sept, $^3$J$_{H-H}$ = 16.0 Hz, 1H, P–CH–CH$_2$), 2.26 (s, 3H, CH$_3$S$_{Tolyl}$), 2.22 (s, 3H, ortho-CH$_3$S$_{Mesityl}$), 2.15 (s, 3H, para-CH$_3$S$_{Mesityl}$), 0.79 (br, 3H, P–CH–CH$_2$), 0.29 (sept, $^3$J$_{H-H}$ = 8.11 Hz, 1H, P–CH–CH$_2$). $^{31}$P{$^1$H} NMR (162 MHz, 25 °C, benzene-d$_6$): $\delta$ 15.66 (s, 2P, PN). $^{13}$C{$^1$H} NMR (125.8 MHz, 25 °C, benzene-d$_6$): $\delta$ 13.33 (s, 2P, PN). $^{13}$C{$^1$H} NMR (125.8 MHz, 25 °C, benzene-d$_6$): $\delta$ 161.9 (Ar–C), 145.3 (Ar–C), 138.3 (Ar–C), 134.2 (Ar–C), 133.7 (Ar–C), 131.7 (Ar–C), 130.5 (Ar–C), 124.7 (Ar–C), 113.1 (Ar–C), 20.9 (P(CH$_2$)$_3$)$_2$, 19.6 (P(CH$_2$)$_3$)$_2$, 15.6 (Ar–CH$_3$), 15.9 (Ar–CH$_3$). We were unable to obtain satisfactorily elemental analysis for this complex.

Results and discussion

Recently, we reported that the azide complex (PN)$_2$Ti(N$_3$)$_2$, readily prepared from (PN)$_2$TiCl and NaN$_3$, could undergo reductive extrusion of N$_2$ with KC$_8$ in Et$_2$O to form the nitride salt [M$_2$K(OEt)$_3$][(PN)$_2$Ti=N=N$_2$] (1) along with graphite (Scheme 1). This route circumvents a radical mechanism commonly observed in the formation of the parent imido (thBDI) Ti=NH(N(tolyl)$_2$)$_2$, which results in much lower yield due to the sacrificial H-atom source deriving from the ligand scaffold. In addition, the introduction of the nitride group directly from the azide skips an additional deprotonation step involving the parent imido. To our surprise however, we found that the dinitrogen complex (PN)$_2$Ti=N=N=Ti(PN)$_2$ (2), a species prepared in 49% yield from KC$_8$ reduction of (PN)$_2$TiCl under N$_2$, cannot be fragmented with excess reductant (such as KC$_8$) to form two equivalents of complex 1. This route would undoubtedly provide a more atom economical route to 1 using a vast resource such as atmospheric N$_2$. Complex 2 is a diamagnetic species, displaying one single PN chemical environment by both $^1$H and $^{31}$P NMR spectra, and as shown in Fig. 4, its solid state structure reveals a topologically linear TiN$_2$Ti moiety where the N–N bond has been partially reduced by $2e^-$ ($1.252(8) \, \text{Å} \, \text{versus} \, 1.0976 \, \text{Å} \, \text{in free N}_2$). Although a formal N$_2$ ligand would intuitively account for its diamagnetic nature, the observed N–N and Ti–N distances and computed bond orders argue for 2 possessing two Ti(m) centers that strongly antiferromagnetically couple, i.e. its core can be best

Scheme 1 Synthesis of complex 1 from reductive splitting of an azide with KC$_8$. Also shown is the attempted synthesis of 1 from reductive splitting of N$_2$ in 2 with excess KC$_8$. 

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characterized formally as Ti\(=\)N\(=\)N\(=\)Ti. In stark contrast to 2, Fryzuk and co-workers have observed \(\text{N}_2\) splitting reactions with low-valent titanium reagents, via reduction of \([\text{NPN}]\text{TiCl}_2\) \([\text{NPN}^2 = \text{PhP(CH}_2\text{SiMe}_2\text{NPh})_2]\), to produce transient titanium nitrides which then undergo insertion into the Ti\(–\)P linkages of the ligand.\(^{61}\) For us, we attribute the lack of reactivity in 2 to being reduced is likely to be kinetic as well as thermodynamic in nature. Akin to vanadium(n) dinitrogen complexes prepared in our group, we propose the rigid PN ligands in a putative species such as 2\(^{2-}\) (2\(^{2-}\) represents 2 being reduced by two electrons) to disfavor the mixing of triplet and singlet subspaces that is critical for the dinitrogen cleavage process.\(^{62}\) In addition, the reactive nature of 1 suggests the formation of a nitride from \(\text{N}_2\) to be thermodynamically less stable than 2\(^{2-}\), a common trait also observed in vanadium nitrides versus dinitrogen complexes. Compound 2 is remarkably stable, failing to react with electrophiles as well as reductants, and further attempts to functionalize the \(\text{N}_2\) have been unsuccessful. Arnold and co-workers have observed formation of a similar complex to 2 using benzamidinate ligands.\(^{59}\)

**Reactivity studies of the titanium nitride with electrophiles**

Although bridging derivatives of group 4 methyl imides have been reported,\(^{63,64}\) terminal bound examples are unknown. Accordingly, we treated compound 1 with \(\text{MeI}\) in toluene at 25 °C causing an immediate color change from orange to dark red. Workup of the reaction mixture and recrystallization of the solid from pentane at \(-35\) °C allowed for the isolation of the methyl-imide complex \([\text{PN}]_2\text{Ti}^\text{NMe}\) (3) in \(\sim 95\%\) yield (Scheme 2). The \(^{31}\text{P}\) NMR spectrum of 3 features a singlet at 12.45 ppm, shifted slightly upfield from 1 (7.23 ppm), while the methyl imide resonance is observed at 2.63 ppm in the \(^1\text{H}\) NMR spectrum and correlated to a resonance at 57.4 ppm in the \(^{13}\text{C}\) NMR spectrum. A solid state structural analysis confirmed the monomeric nature of 3 (Fig. 6), and revealed a short Ti–N distance of 1.709(3) Å with a linear Ti–N–Me angle of 178.5(4)° (Table 1). While the geometry of 1 (\(\tau_5 = 0.529\)) is between idealized trigonal bipyramidal (\(\tau_5 = 1\)) and square pyramidal (\(\tau_5 = 0\)), conversion to the imide species 3 (\(\tau_5 = 0.721\)) alters the geometry more towards a trigonal bipyramidal environment.

Treatment of 1 with certain azide reagents can also result in salt elimination. For example, combining 1 with \(\text{N}_3\text{SiMe}_3\) yields \(\text{KN}_3\) along with the trimethylsilylimide \([\text{PN}]_2\text{Ti}^\text{N}\{\text{SiMe}_3\}\) in \(\sim 90\%\) yield as a deep red colored material (Scheme 2).

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**Scheme 2** Synthesis of compounds 3–7 from 1 and various electrophiles. All reactions were performed in toluene at 25 °C due to the insolubility of 1 in aliphatic solvents.
Table 1  Selected metrical parameters for complexes 1–7 showing bond distances in Å and angles in degrees. X represents the substituent on the nitride or formal nitride ligand. For 1, X = K; 2, X = N; 3, X = C; 4, X = Si; 5, X = P; 6, X = B; 7, X = H. \(\tau_5\) represents \((\beta - a)/60\) where \(\beta > a\) are the two greatest valence angles of the coordination center.\(^5\)

<table>
<thead>
<tr>
<th>Complex</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti–N</td>
<td>1.674(2)</td>
<td>1.832(3)</td>
<td>1.709(3)</td>
<td>1.730(2)</td>
<td>1.753(3)</td>
<td>1.7312(2)</td>
<td>1.747(2)</td>
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<tr>
<td>Ti–N(_{PN})</td>
<td>2.173(2)</td>
<td>2.107(3)</td>
<td>2.093(3)</td>
<td>2.095(2)</td>
<td>2.0695(2)</td>
<td>2.0521(1)</td>
<td>2.0605(1)</td>
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<tr>
<td>Ti–N(_{PN})</td>
<td>2.170(2)</td>
<td>2.091(2)</td>
<td>2.096(3)</td>
<td>2.0736(2)</td>
<td>2.0695(2)</td>
<td>2.0685(1)</td>
<td>2.0987(2)</td>
</tr>
<tr>
<td>Ti–P</td>
<td>2.6779(6)</td>
<td>2.6763(8)</td>
<td>2.6777(1)</td>
<td>2.6917(7)</td>
<td>2.7041(6)</td>
<td>2.6718(5)</td>
<td>2.6810(5)</td>
</tr>
<tr>
<td>Ti–P</td>
<td>2.683(8)</td>
<td>2.7306(8)</td>
<td>2.6824(1)</td>
<td>2.7094(7)</td>
<td>2.7041(6)</td>
<td>2.6532(6)</td>
<td>2.6566(1)</td>
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<tr>
<td>N–X</td>
<td>2.729(2)</td>
<td>1.250(4)</td>
<td>1.431(5)</td>
<td>1.737(2)</td>
<td>1.732(3)</td>
<td>1.395(2)</td>
<td>0.860(0)</td>
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<tr>
<td>P–Ti–P</td>
<td>167.42(3)</td>
<td>166.03(4)</td>
<td>173.14(3)</td>
<td>167.14(3)</td>
<td>171.16(3)</td>
<td>175.289(2)</td>
<td>177.16(3)</td>
</tr>
<tr>
<td>Ti–N(_{X})</td>
<td>135.40(1)</td>
<td>1.250(4)</td>
<td>178.5(4)</td>
<td>168.06(1)</td>
<td>162.21(6)</td>
<td>175.00(1)</td>
<td>180.0(0)</td>
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<tr>
<td>N(<em>{PN})=Ti–N(</em>{PN})</td>
<td>135.67(8)</td>
<td>128.79(1)</td>
<td>129.87(1)</td>
<td>134.35(8)</td>
<td>130.02(1)</td>
<td>131.33(6)</td>
<td>130.99(6)</td>
</tr>
<tr>
<td>P–Ti–N(_{PN})</td>
<td>74.88(6)</td>
<td>76.30(7)</td>
<td>75.24(8)</td>
<td>73.77(6)</td>
<td>75.88(5)</td>
<td>75.27(4)</td>
<td>74.94(4)</td>
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<tr>
<td>P–Ti–N(_{PN})</td>
<td>75.11(6)</td>
<td>75.18(7)</td>
<td>75.13(8)</td>
<td>75.46(5)</td>
<td>75.88(5)</td>
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<td>P–Ti–N</td>
<td>95.83(8)</td>
<td>96.99(2)</td>
<td>93.46(1)</td>
<td>99.59(2)</td>
<td>94.14(2)</td>
<td>92.67(5)</td>
<td>92.52(6)</td>
</tr>
<tr>
<td>P–Ti–N</td>
<td>96.75(8)</td>
<td>98.31(2)</td>
<td>93.37(1)</td>
<td>96.25(7)</td>
<td>94.14(2)</td>
<td>91.96(5)</td>
<td>90.22(7)</td>
</tr>
<tr>
<td>(\tau_5)</td>
<td>0.529</td>
<td>0.621</td>
<td>0.721</td>
<td>0.557</td>
<td>0.686</td>
<td>0.733</td>
<td>0.769</td>
</tr>
</tbody>
</table>
Terminal bound imides with a hydrogen substituent (referred to as a parent imide) are exceptionally rare in early transition metals, with the only documented examples for group 4 being (BDI)Ti=NH[Ntolyl2] and (BDI·Cl=C(O)tBu in toluene. Immediate formation of a purple transient, non-isolable intermediates. Not surprisingly, pKa information on parent imides is unknown, but one would expect the imide moiety to be a weak acid given the highly polarized nature of the nitride group. Conversely, the basicity of terminal nitride anions is also unknown. While these species have rarely been reported, it has been hypothesized that some parent imide complexes exist as transient, non-isolable intermediates. Since formation of 1 does not traverse through a parent imide, we treated this species with a weak acid not only to allow us entry to this rare moiety but also to provide some information about the basicity of the nitride ligand in 1. Hence, exploring various sources of a proton established HN[SiMe3]2 (pKa = 25.8, THF) to cleanly yield the parent imide (PN)2Ti=NH (7) in ~84% isolated yield (Scheme 2). The imide resonance was observed in the 1H NMR spectrum as a broad feature at 5.07 ppm (ΔJ1/2 = 9.1 Hz) while the 31P NMR spectrum displayed a singlet at 15.66 ppm (ΔJff = 0.769), which contrasts the geometry observed for the few known group 4 transition metal parent imides having coordination numbers of four and five. One notable feature is the nearly linear orientation of the phosphine groups (P–Ti–P, 177.16(3)° when associated to other (PN)2Ti scaffolds (Table 1). It is also noted that single X-ray diffraction revealed that the molecule also co-crystallizes in a 4 : 1 ratio with a secondary product in which the N atom of the imide has inserted into the phosphorous arm of the PN ligand, and the H atom of the parent imide has formed a bond to titanium, namely the compound “(PN)2(NPN)Ti(H)” (see ESI† for an explanation of these co-crystals). The metal-hydride bond that is observed as a result of this transformation is under further investigation with regard to the implications this rearrangement has on reactivity of the parent imide. While the ylide Ph3PCH2 (pKa = –22, DMSO) failed to deprotonate the imide, attempts to use stronger bases resulted in decomposition products presumably due to the reactivity of the titanium nitride product. It was found independently that complex 7 gradually decomposes over time thus precluding reactivity with stronger bases. However, attempts to protonate the nitride with disopropylamine, HN[Pr2 (pKa = 36, THF), resulted in no reaction. This observation allowed us to narrow the pKa range of the parent imide to be within 26–36 based on this set of control experiments. Given these pKa ranges for the parent imide, we are able to estimate the pKa of 1 on the order of –20, in accord with such a moiety being a strong base and nucleophile as demonstrated through our reactivity.

Complete N-atom transfer of the titanium nitride

A salt elimination reaction concurrent with complete N-atom transfer could be accomplished when complex 1 was treated with CIC(O)3Bu in toluene. Immediate formation of a purple...
solution is evidenced upon addition of the acid chloride, and workup of the reaction mixture followed by NMR spectroscopic characterization confirmed this purple species to be the oxo complex (PN)₂Ti=O (8) (Scheme 3) in near quantitative yield, ~96%. Examination of the reaction mixture also revealed the formation of another product, which was identified as the organic nitride NC₅Bu based on NMR spectroscopic comparison to an authentic sample. The formation of the nitride was monitored in ¹H NMR spectroscopy to be formed in the same ratio as 8 via integration. A similar transformation involving N for O/Cl exchange was originally reported by Cummins using nitride complexes such as N≡W[N(²Pr)₂Ar]₃ (Ar = 3,5-Me₂C₆H₃) or the salt [Na[N≡Nb(N(²Pr)₂Ar)]₂] (Np = CH₃C≡Bu). Likewise, Veige more recently reported N for O atom transfer to various acid chlorides using [[BuOCON][Mo≡N][Na(DMF)]₂ [BuOCON]⁻ = 2,6-C₆H₃(6-ButC₆H₄O)₂]. In their studies the authors were able to isolate the acylimido intermediate [BuOCON]Mo≡NC(O)Ce₂Bu and mechanistically probe for an azametallacylobutene species en route to N for O exchange.

Complex 8 was characterized by ¹H and ³¹P NMR spectroscopy and the latter displayed a sharp singlet at 13.3 ppm. Although there are no clear diagnostic signatures for 8 in the ¹H NMR spectrum, monitoring the reaction mixture by ¹H NMR spectroscopy revealed clean formation of a resonance at 0.8 ppm consistent with the pivaylil nitrile (NC₅Bu). Single crystal X-ray diffraction studies of 8 are in accord with a five-coordinate, mononuclear complex having a terminal oxo group, with a Ti=O length of 1.644(2) Å (Fig. 7), well within the range of many reported terminal titanium oxo moieties. Rather unsurprisingly, the o xo complex closely parallels the molecular geometry of the parent imide, complex 7, with a τ₂ value of 0.769 and very similar P-Ti-P angle of 179.08(3)°. Furthermore, we explored the unusual purple color of this Ti(iv) complex via UV-vis analysis. The extremely low intensity absorption observed at 550 nm (ε = 174.8 M⁻¹ cm⁻¹) possibly corresponds to a similar phenomenon like that observed in MnO₄⁻, where the complex absorbs yellow light to promote a LMCT band.

Complex 1 can also transfer the nitride atom to other carbon containing groups such as the ketene O=C=CPh₂ (Scheme 3). Accordingly, addition of the ketene to 1 rapidly produces the signature purple color indicative in formation of 8, as confirmed by both ¹H and ³¹P NMR spectroscopy. However, upon addition of the ketene a salt is also produced which could be readily separated from the mixture via filtration. Given the insoluble nature of this yellow solid (presumably KN=≡C=CPh), we proceeded to treat it with Me₃SiCl, immediately forming a salt (KCl) and a neutral species which was unequivocally identified to be the azamellallene Me₃Si=N≡C=CPh₂ based on ¹H NMR spectroscopic comparison to a literature report.⁹⁹

**Solid state ¹⁵N NMR spectroscopic studies of titanium nitrides**

Isolation of dinuclear and mononuclear nitrides of titanium presented us with a rare opportunity to investigate their axial symmetry. Hence, we prepared the 50% ¹⁵N enriched complex ¹⁵N≡N and converted it to the terminal nitride [K(2,2,2-Kryptofix)][(PN)₂Ti≡¹⁵N] by addition of the cryptand (2,2,2-Kryptofix = 4,7,13,16,21,24-hexaaxa-1,10-diazabicyclo[8.8.8]hexacosane). We were able to analyze this discrete salt by magic angle spinning (MAS) ¹⁵N NMR spectroscopy. In accord with our expectations, this species reveals a significantly downfield chemical shift (δiso = 902 ppm), which is attributable to a highly deshielded terminal nitride species (Fig. 8). As presented in Fig. 8, the simulated ¹⁵N NMR solid state spectrum agrees well with experimentally collected values in both solid and solution state phases (δ = 958 ppm).¹¹ Tensor components span a large chemical shift anisotropy (CSA) of nearly 1500 ppm, with δ₁₁ = 1392 ± 50 and δ₁₂ = 22 ± 50 ppm. Such anisotropy has been similarly observed in other mononuclear metal nitride species, namely ¹⁵N≡Mo(N≡Bu)Ar)₃ (Ar = 3,5-Me₂C₆H₃) and [K(OEt₂)][¹⁵N≡C≡N] in [¹⁵N≡C≡N]₂ [¹⁵N≡C≡N]$^-$ = [ArNC₅Bu]₃CH; Ar = 2,6-(C₆H₅), which also have a range of several hundred ppm for CSA in their tensor components.¹⁵N NMR chemical shift tensors were then used to compute the axial symmetry component, κ = 3(δ₁₂ - δ₁₃)/(δ₁₁ - δ₁₃) = 1 ± 0.2. Gratifyingly, the κ value close to unity supports the triply bound nature of the Ti-nitride moieties in [K(2,2,2-Kryptofix)] [(PN)₂Ti≡¹⁵N], and which is the favorable bonding due to
a pseudo-tetragonal environment shown in Fig. 3 (vide supra). The $\kappa$ value observed here deviates notably from that reported previously for a less symmetrical Ti-nitride containing the BDI ligand, which has $\kappa = 0.64$.

Computational studies scrutinizing the titanium nitride functionality

To understand the observed characteristic reactivity and some of the measured physicochemical properties of the titanium nitride functionality we carried out a comprehensive computational and theoretical study on the putative anion $[[\text{PN}]_2\text{Ti}≡\text{N}]^-$ as well as complexes 1 and $[\text{K}(18\text{-crown-6})][[\text{PN}]_2\text{Ti}≡\text{N}]$, that we recently characterized. Using the X-ray structures as guiding geometries, the slightly truncated models were fully optimized using the BLYP functional$^{93,94}$ in combination with the Def2-TZVP(-f) basis set.$^{95}$ The structural modifications included only the replacement of two para-methyl substituents to hydrogens in each PN ligand and were introduced to facilitate an all-electron DFT investigation for systems of the size of 3, which still consists of 232 atoms after truncation. Dispersion has been also taken into account during optimizations using Grimme’s D3 method.$^{96}$ Dispersion turned out to be a critical component of our computational practice as it significantly contributed to finding accurate equilibrium geometries for both the dimer species, 1 and 2, and for monometallic systems, that is $[[\text{PN}]_2\text{Ti}≡\text{N}]^-$, $[\text{K}(18\text{-crown-6})][[\text{PN}]_2\text{Ti}≡\text{N}]$. It is important to note that we observed a substantial improvement in the computed distances of weak Ti–P and K$^+⋅⋅⋅\text{N}$ interactions for the latter systems when compared to our earlier simulations without dispersion.$^{93}$ As a matter of fact, the computational protocol outlined in the ESI† might offer useful practical solutions to few of the inborn weaknesses of standard DFT for such very extended transition-metal- and alkali-metal-containing systems. For example, one might obtain more realistic results for the notoriously overestimated bond lengths of weak metal–ligand interactions when taking into account inter ligand dispersion. One might be able to discard the surreal behavior of alkali-metal(s) in simulations, which was recently noted by Holland and co-workers to be detrimental for a systematic computational study on the alkali metal effect on Fe$≡\text{N}≡\text{N}≡\text{Fe}$ functionalities.$^{97}$ As Fig. 9 reveals, the computed equilibrium structures are very similar to the experimentally determined molecular geometries established by single crystal X-ray diffraction studies. Also, in excellent agreement with our experiments, calculations predict the $^{15}\text{N}$ NMR spectroscopic chemical shifts to be 913 ppm, 970 ppm and 878 ppm using the slightly truncated models of $[[\text{PN}]_2\text{Ti}≡\text{N}]^-$, $[\text{K}(18\text{-crown-6})][[\text{PN}]_2\text{Ti}≡\text{N}]$, and 1, respectively. These two benchmarks convincingly imply that our computer models capture the most salient features of the electronic structure of these molecular systems reasonably well and that the introduced structural simplification is acceptable. In particular, the agreement between the computed and experimentally observed effect of alkali-metal coordination on $^{15}\text{N}$ NMR spectroscopic resonances supports the notion that the corresponding electronic structural changes are captured computationally in at least a plausible fashion.

![Fig. 8](image1.png)

Fig. 8 Simulated (top) and observed (bottom) solid state MAS $^{15}\text{N}$ NMR spectrum of $[\text{K}(2,2,2\text{-Kryptofix})][[\text{PN}]_2\text{Ti}≡\text{N}]$.

![Fig. 9](image2.png)

Fig. 9 Equilibrium geometries for $[[\text{PN}]_2\text{Ti}≡\text{N}]^-$, $[\text{K}(18\text{-crown-6})][[\text{PN}]_2\text{Ti}≡\text{N}]$ and 1 together with the most important structural metrics computed and determined by single crystal X-ray diffraction (grey). Also given are the computed and measured $^{15}\text{N}$ NMR chemical shifts of the nitride centers as well as Mulliken charges of titanium, $q(\text{Ti})$, and the nitride center, $q(\text{N})$ together with the Mayer bond order (BO) index of the Ti≡N interaction.
As noted in our earlier communication,31 various computed electronic structure descriptors imply that the main difference in the Ti–N\textsubscript{nitr}
 bonding is the different covalent/ionic character of the bond in the monomeric species [K(18-crown-6)]\((\text{PN})_2\text{Ti}=\text{N}\) and \([\text{PN}]_2\text{Ti}=\text{N}\). Namely, the Ti=N bond in \([\text{PN}]_2\text{Ti}=\text{N}\) exhibits a greater degree of covalent character than in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\). In the case of the latter, the proximity of the K\textsuperscript{+} ion electrostatically stabilizes the highly charged nitride center and, concomitantly, induces a density shift from the Ti center towards the N\textsubscript{nitr}
. This electron density shift induced by the proximity of K\textsuperscript{+} renders the titanium-nitride bond more ionic in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) than in \([\text{PN}]_2\text{Ti}=\text{N}\). As a matter of fact, the different ionic character can be clearly witnessed in the computed atomic charges of Ti (0.53 e in \([\text{PN}]_2\text{Ti}=\text{N}\) and 0.87 e in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) and N (−0.63 e in \([\text{PN}]_2\text{Ti}=\text{N}\) vs. −0.88 e in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) (Fig. 10). The reduced bond order in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) (2.36 vs. 2.54 in \([\text{PN}]_2\text{Ti}=\text{N}\)) also conforms to a lower degree of covalent character of the Ti=N bond in this structure. These pronounced differences in Ti–N\textsubscript{nitr}
 bonding are further enhanced with the presence of two potassium ions in 1. In particular, atomic charges \(q(\text{Ti}) = 1.02 e\) and \(q(\text{N}) = −0.975 e\) as well as the reduced bond order of 2.27 indicate the higher ionic and lower covalent character of the Ti=N bond in 1 to either \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) or \([\text{PN}]_2\text{Ti}=\text{N}\) (Fig. 9).

More thorough insights into the electronic structure changes induced by the alkali-metal ion are gained through a close inspection of the molecular orbitals (MOs) that describe the bonding of the titanium-nitride functionality. A conceptual MO diagram that highlights the most relevant molecular orbitals of the metal–nitr
 interactions is given in Fig. 3, implying one σ- and two π-bonds and a lone pair at N\textsubscript{nitr}
. Instead of the expected four MOs representing these functions, however, Fig. 10 depicts six occupied orbitals for each Ti=\text{N} functionality merely because the σ-bond as well as one of the Ti=N π-bonds can be defined by two MOs. In detail, the Ti–N\textsubscript{nitr}
 σ-interaction of each Ti=N functionality in Fig. 10 is represented by two MOs, \(\sigma^\text{d}\) and \(\sigma^\text{p}\), which evolve due to the formation of a bonding (b) and an anti-bonding (a) combination with a π-type orbital of the PN\textsuperscript{−} ligand(s). Similarly, orbitals \(\pi_1^\text{a}\) and \(\pi_1^\text{b}\), which appear again as a bonding/anti-bonding pair with a PN\textsuperscript{−} ligand orbital, together characterize one of the Ti–N\textsubscript{nitr}
 π-interactions. In addition, \(\pi_2\) represents the other π-type interaction which lies about in the P–Ti–P plane whereas, as hypothesized in Fig. 3, the lone pair at N\textsubscript{nitr}
 has a strong component of s atomic orbital character and it is of low energy.

Although the crown ether-encapsulated K\textsuperscript{+} breaks the symmetry in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) as well as it alters the ordering of the orbitals, the computed MOs characterize the same Ti–N\textsubscript{nitr}
 interactions as for \([\text{PN}]_2\text{Ti}=\text{N}\). Moreover, the analogous MOs can also be intuitively recognized for the dimer species 1 (Fig. 10), for which only the symmetric combinations are illustrated for clarity. The side-by-side comparison of the corresponding MOs reveal that the σ-interaction, mostly \(\sigma^\text{d}\), as well as \(\pi_1\) experiences a significant change in character when being confronted by the alkali metal ion(s); the atomic contribution of Ti decreases whereas that of N\textsubscript{nitr}
 increases in these MOs when going from \([\text{PN}]_2\text{Ti}=\text{N}\) to \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) or 1. This difference in corresponding MOs conforms to the additional polarization of the Ti–N\textsubscript{nitr}
 bond that was discussed above and which was supported with charge distribution measures and bond descriptors. Finally, the stabilization effect of the nearby cation on the electron rich N\textsubscript{nitr}
 can be clearly witnessed in the computed orbital energies, which are much more negative in 1 and in \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) than in \([\text{PN}]_2\text{Ti}=\text{N}\).

The observed and computed \(\text{^15N}\) NMR chemical shift of N\textsubscript{nitr}
 is not only useful for precisely determining the identity of these species in solution, but can also be utilized as a diagnostic tool that gives direct information on the chemical environment about N\textsubscript{nitr}
 and, as such, on the Ti–N\textsubscript{nitr}
 interaction. In particular, the gradual upfield shift of 50–30 ppm when going from \([\text{PN}]_2\text{Ti}=\text{N}\) to \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) and 1 suggests a subtle change in the electronic structure due to the nearby cation(s). In order to put this trend of \(\text{^15N}\) chemical shift into context with the underlying electronic structures it is critical to realize that magnetic shielding of heavy nuclei does not directly correlate with the electron density at the nucleus. Rather, heavy nuclei, such as \(\text{^15N}\), have access to low-energy molecular orbitals of p and d-type atomic contributions that make the electron density around these nuclei very dynamic in the sense that local fluctuations of the electron cloud become more prevalent in an external magnetic field. The magnetic shielding that results from these electron density fluctuations is conventionally referred to as paramagnetic shielding, \(\sigma^p\), and is typically more sensitive to the changes in chemical bonding than the diamagnetic shielding, \(\sigma^d\), which originates from tightly-bound electron density at the nucleus. In a recent study we discussed the basic relationships of such density fluctuations with MOs, shielding tensors and chemical shifts and, by scrutinizing vanadium- and molybdenum-cyclo-P\textsubscript{4} complexes, we showed how a thorough analysis of shielding tensors of heavy nuclei can lead to a conceptual understanding of the bonding characteristics of unusual transition metal-ligand interactions.38

To understand what makes the N\textsubscript{nitr}
 nucleus more shielded in the case of K\textsuperscript{+} ligated species, we computed and analyzed the \(\text{^15N}\) magnetic shielding tensors of the above-described slightly truncated versions of the complexes \([\text{PN}]_2\text{Ti}=\text{N}\), \([\text{K}(18\text{-crown-6})]([\text{PN}]_2\text{Ti}=\text{N})\) and 1. In general, the magnetic shielding at a NMR-active nucleus and the resulting chemical shift can be calculated from first principles to a reasonable degree of accuracy19,99–101 and, accordingly, the computed values shown in Fig. 10 also agree well with measured solution-state \(\text{^15N}\) NMR spectroscopic resonances. In addition, the above-discussed large chemical shift anisotropy (CSA) is reproduced computationally (−1500 ppm vs. 1470 ppm) for \([\text{PN}]_2\text{Ti}=\text{N}\) as well as the corresponding principal components of the shielding tensor (δ\textsubscript{11} = 1562.2 ppm, δ\textsubscript{22} = 1285.0 ppm and δ\textsubscript{33} = 61.9 ppm) are in line with the experimentally determined components in solid state (δ\textsubscript{11} ≈ δ\textsubscript{22} ≈ 1392 ± 50 ppm and δ\textsubscript{33} = −78 ± 50 ppm) for \([\text{K}(2,2,2\text{-Kryptofix})]([\text{PN}]_2\text{Ti}=\text{N})\). Due to omitting the K(2,2,2-Kryptofix)\textsuperscript{+} counter ion and other...
condensed phase effects in the simulations, however, a difference of about 280 ppm between \( \delta_{11} \) and \( \delta_{22} \) appears "in silico", which manifests in an underestimated axial symmetry component (\( \kappa = 0.63 \) vs. app. 1) for the computationally considered model system, \([\text{PN}]_2\text{Ti} \equiv \text{N}^-\). As expected, the diamagnetic term displays a narrow range of shielding contributions with computed \( \sigma^d \) values of 339.7, 341.3 and 347.7 ppm for \( ^{15}\text{N}_{\text{nitr}ide} \) in \([\text{PN}]_2\text{Ti} \equiv \text{N}^-\), \([\text{K}(18\text{-crown-6})][\text{PN}]_2\text{Ti} \equiv \text{N}^-\) and 1, respectively. The paramagnetic contribution, on the other hand, differs significantly with computed shielding parameters of \(-1050.3\), \(-996.3\) and \(-967.3\) ppm, respectively. These values illustrate the general concept mentioned above that \( \sigma^p \) dominates the overall shielding of heavy nuclei and, thus, determines the chemical shift \( \delta_{\text{avg}} \) against a reference.

**Fig. 10** Most relevant occupied MOs for \([\text{PN}]_2\text{Ti} \equiv \text{N}^-\), \([\text{K}(18\text{-crown-6})][\text{PN}]_2\text{Ti} \equiv \text{N}^-\) and 1 describing the electronic structure of the Ti\( \equiv \text{N} \) functionality. One of the unoccupied orbitals, \( \pi^* \), which is critical for the paramagnetic shielding of \( \text{N}_{\text{nitr}ide} \) is also depicted.
As we demonstrated recently, the thorough analysis of the paramagnetic contribution to the shielding can be challenging, because one has to decompose the sum of a great number of individual magnetic fields originating from occupied–unoccupied orbital pairs that couple through the angular momentum operator. In addition, the magnetic fields generated by what is most spontaneously understood as electron density fluctuations are hard to visualize or imagine. Finding a few numbers of distinguishing orbital-pairs that make a decisive contribution and that are characteristic for the certain species under investigation is the key to understanding such paramagnetic shielding. Nevertheless, we could pinpoint one occupied orbital, $\sigma^a$, whose contribution to shielding changes significantly in the presence of a nearby $K^+$ (Fig. 10). For example, the total paramagnetic shielding contribution of $\sigma^a$ is $-504.6$ ppm in $\left([\text{PN}]_2\text{Ti=NN}\right)^-$ whereas it drops to $-128.0$ ppm in $\left([\text{K(18-crown-6) }]\left([\text{PN}]_2\text{Ti=NN}\right)\right)^-$ and even becomes shielding (157.6 ppm) in 1. This $\sigma^a$ MO couples most intensively with the vacant $\pi^*$ orbitals corresponding to the antibonding combinations of $\text{Ti}^*$-$\text{N_nitride}$ $\pi$-bonds, e.g. $\pi_1^a$, illustrated in Fig. 10. In this context it is worth noting that Morokuma, Schrock, Griessen and Cummins reported very similar findings for the unusual $^{31}$P NMR chemical shielding tensors of terminal phosphide (M=P) complexes of molybdenum and tungsten.94 In the latter systems the $\sigma$($\text{M=PP}$) and $\pi^*$($\text{M=PP}$) MO mixing makes the primary contribution to the $^{31}$P paramagnetic shielding due to the components of the applied magnetic field which are oriented perpendicular to the $\text{M=PP}$ bond. Fig. 10 also illustrates how the paramagnetic shielding contribution of $\sigma^a \leftrightarrow \pi_1^a$ mixing varies for each nitride species.

The coupling of these orbitals in an external magnetic field induces a density flow that has a deshielding effect in $\left([\text{PN}]_2\text{Ti=NN}\right)^-$, whereas it generates a shielding effect in $\left([\text{K(18-crown-6) }]\left([\text{PN}]_2\text{Ti=NN}\right)\right)^-$ and 1, where the $K^-$ affects the bonding characteristics. The energy gap ($\Delta E$) between interacting orbitals is also given in Fig. 10, as the coupling efficiency is inversely proportional to the energy difference between the interacting orbitals.99 For example, the $^{31}$P NMR chemical shift of triple bonded phosphorus has been found to correlate very well with the $\sigma-\pi^*$ energy gap as well as we also reported the significance of energy gap of coupling orbitals in determining the chemical shielding of phosphorous nuclei in metal-cyclo-P$_3$ complexes.99 The very small differences in energy gaps ($\Delta E$ in Fig. 10), however, cannot account for the qualitatively different paramagnetic shielding effects of $\sigma-\pi^*$ coupling in the studied systems. Rather, the qualitative difference of paramagnetic contributions, i.e. deshielding in $\left([\text{PN}]_2\text{Ti=NN}\right)^-$ and more shielding in $K^-$-ligated systems, implies that the spatial distribution of these molecular orbitals alters upon $K^-$ coordination. Accordingly, the localization of $\sigma^a$ on the nitride center as well as the localization of $\pi_1^a$ on Ti in $K^-$-ligated systems results in a constructive orbital overlap when these orbitals couple through the angular momentum operator, in contrast to the destructive overlap (deshielding effect) in naked $\left([\text{PN}]_2\text{Ti=NN}\right)^-$. Hence, the upfield shift of $^{15}$N$_\text{nitrde}$ resonance is linked to the $K^-$ induced electronic structure change of the titanium-nitride functionality as demonstrated through a quantum chemical analysis of the corresponding shielding tensors.

Finally, our calculations reveal, in line with the N--K distances larger than 2.7 Å, that the $\text{Ti=NN--K}^-$ interaction is merely electrostatic in nature without any sign of covalent contribution. This electrostatic interaction, beyond inducing the above-scrutinized change of the $\text{Ti=NN}$ functionality, represents the main source of thermodynamic stabilization and driving force for forming well-structured complexes such as $\left(K(18\text{-crown-6})\right)\left([\text{PN}]_2\text{Ti=NN}\right)$ and the dimer 1.

Conclusions

No previous study has thoroughly explored or elucidated the reactivity of molecular titanium nitrides prior to the work presented herein. Our findings imply in general that the $\text{Ti=NN}$ functionality is a very strong nucleophile, which readily reacts with electrophilic reagents to serve as a full or partial N-atom transfer reagent. A combined experimental and theoretical investigation has helped us understand the bonding and structure in these systems as well as rationalize the nature of the $^{15}$N chemical shift of the nitride ligand and the role of the $K^-$ counterion. Looking forward, we seek to further understand how this nitride moiety can be tuned and modified to generate ammonia under hydrogen, and further, generate the nitride instead from nitrogen as opposed to azide to extend the scope of this chemistry to a more sustainable and atom-efficient process.

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References


73 See ESL†.


83 Bordwell’s table of the corresponding acidity of the phosphonium was used to calculate the basicity of the ylide which can be found at http://www.chem.wisc.edu/areas/reich/pkatable/. For calculating pKₐ from pKₐ in DMSO and assuming non-protic conditions: pKₐ = log₁₀[pKₐ] and Kₐ = ([H][A⁻][HA])/[H][A⁻]⁻[HA]). Therefor in an aprotic solvent, Kₐ = 1/10ᵖKₐ.


