Synthesis and versatile reactivity of scandium phosphinophosphinidene complexes

Bin Feng¹, Li Xiang¹, Karl N. McCabe², Laurent Maron²✉, Xuebing Leng¹ & Yaofeng Chen¹✉

M=E/M≡E multiple bonds (M = transition metal, E = main group element) are of significant fundamental scientific importance and have widespread applications. Expanding the ranges of M and E represents grand challenges for synthetic chemists and will bring new horizons for the chemistry. There have been reports of M=E/M≡E multiple bonds for the majority of the transition metals, and even some actinide metals. In stark contrast, as the largest subgroup in the periodic table, rare-earth metals (Ln) were scarcely involved in Ln=E/Ln≡E multiple bonds. Until recently, there were a few examples of rare-earth monometallic alkylidene, imido and oxo complexes, featuring Ln=C/N/O bonds. What are in absence are rare-earth monometallic phosphinidene complexes with Ln=P bonds. Herein, we report synthesis and structure of rare-earth monometallic phosphinidene complexes, namely scandium phosphinophosphinidene complexes. Reactivity of scandium phosphinophosphinidene complexes is also mapped out, and appears to be easily tuned by the supporting ligand.
The synthesis and reactivity of M=E/M≡E multiple bonds (M = transition metal, E = main group element) is one of the most vibrant areas of modern chemistry. The research in this area stimulated fundamental development of chemistry i.e., chemical bonding theory, and found widespread applications in organic and polymer synthesis. The most notable example is the olefin metathesis based on the M≡C bonds, for which the Nobel Prize for Chemistry was awarded in 2005. The reactivity profile of the M=E/M≡E multiple bonds largely depends on the interaction between the σ orbitals of metal and the p orbitals of ligand E atom. Insufficient overlap creates an electronically frustrated moiety, thereby providing the electrophilic or nucleophilic metal center or ligand E atom.

There have been reports of M=E/M≡E interactions for the majority of the metallic elements of the periodic table, even some actinide metals. In stark contrast, the largest subgroup of the periodic table, rare-earth metals (Ln: Sc, Y, and lanthanides), were scarcely involved in metal–ligand multiple bonds. The scarcity is mainly attributed to energy mismatching between the frontier orbitals of the rare-earth metals and the ligand atoms. This renders the putative Ln frontier orbitals of the rare-earth metals and the ligand atoms. Insufficient overlap creates an electronically frustrated moiety, thereby providing the electrophilic or nucleophilic metal center or ligand E atom.

In this work, by introducing a phosphinophosphinidene, [PP(N(DIPP)CH2CH2N(DIPP))][26,27] with NaPH2 in THF. The 31P NMR spectrum of the potassium salt K[HP{PN(DIPP)CH2CH2N(DIPP)}] was treated with [LSc(Me)Cl] or [L′Sc(Me)Cl] in a THF/toluene mixture, and the reactions afforded scandium phosphinophosphinidene complexes 1 and 2 in 54% and 67% yields, respectively, (Fig. 1). In the 31P NMR spectrum of the potassium salt K[HP{PN(DIPP)CH2CH2N(DIPP)}] (∆119.0 ppm, δd 1Jpp = 423 Hz, 1JPP = 128 Hz). Compared with that of the phosphinophosphine, the P–P coupling constants for either the potassium salt or the scandium phosphinophosphinidene complexes are significantly larger; this indicates a shorter P–P bond and a delocalization of the negative charge of the Pn (phosphido) atom into the Pp (phosphinidene) atom. The XRD studies on the single crystals of 1 and 2 show both complexes contain a 2P–bonded phosphinophosphinidene ligand (Fig. 2). In 1, the Sc–Pp bond length (2.448(1) Å) is shorter than those found in scandium bridged phosphinidene complexes, [LSc2(µ2-CH2)(µ2-P{DIPP})] (2.495(1) and 2.508(1) Å)[22], and {[MeCNDIPP]CHC(Me)(NCH2CH2N(Me))Cl}2[µ2-P(DIPP)]2 (2.522(1) and 2.528(1) Å)[20]. This is on the other hand longer than that in a lithium capped scandium phosphinidene ate complex [(PNP)Sc(µ2-Pr(C6H5)-2,6-Mes)] (µ2-Br)Li (2.338(2) Å)[23]. The Sc–Pp bond length (2.718(1) Å) is much longer than the Sc–Pp bond length (2.448(1) Å) in the complex, and also longer than the Sc–P bond lengths in a scandium diphosphido complex [LSc2(PH2)]2 (2.570(3) and 2.609(3) Å)[22]. The P–P bond length in 1, 2,105(1) Å, is shorter than that observed in the phosphinophosphine (2.277(1) Å). This is in line with the observed larger P–P coupling constant for 1 compared with that for the phosphinophosphine. The Sc–Pp and Sc–Pp bond lengths in 2 are longer than those in 1, 2.48(1) Å and 2.81(4) Å vs 2.448(1) and 2.718(1) Å, due to an increasing in the coordination number of scandium from five.

Results

Synthesis and structural characterization. Scandium methyl chlorides [LSc(Me)Cl] (L = [MeCNDIPP]CHCNDIPP(Me)]2, DIPP = 2,6-(Pr)2C6H4, and [L′Sc(Me)Cl] (L′ = [MeCNDIPP]CHC(Me)(NCH2CH2N(Me))2) were prepared as reported. Phosphinophosphine H2PP(N(DIPP)CH2CH2N(DIPP)) was synthesized by a salt metathesis of CIP[N(DIPP)CH2CH2N (DIPP)]26,27 with NaPH2 in THF. The 31P NMR spectrum of the compound in CD2Cl2 exhibits two sets of doublet-triplets at δ = −157.6 (dt, 1Jpp = 186 Hz, 1JPP = 183 Hz, Pp) and 134.9 ppm (dt, 1Jpp = 186 Hz, 1JPP = 16 Hz, Pp). This compound was also characterized by single crystal X-ray diffraction (XRD) (Supplementary Fig. 1). The P–P bond length in the compound is 2.277 (1) Å, in line with a P–P single bond. This phosphinophosphine can be deprotonated by KCH2(C6H5) in THF to give a potassium salt K[HP{PN(DIPP)CH2CH2N(DIPP)}], which is stable in THF but decomposes when the THF is removed. Therefore the in situ generated K[HP{PN(DIPP)CH2CH2N(DIPP)}] was treated with [LSc(Me)Cl] or [L′Sc(Me)Cl] in a THF/toluene mixture, and the reactions afforded scandium phosphinophosphinidene complexes 1 and 2.

![Fig. 1 Synthesis of scandium phosphinophosphinidene complexes.](https://example.com/fig1.png)
nophosphinidenes, which are electrophilic. In contrast with one observed for the coordination-free phosphinophosphine, the coupling constant is up to 639 Hz. In accord with a large P–P bond length in the P{1H} NMR spectra in C6D6, the P–P bond length is longer than that in phosphinophosphine (2.277(1) Å). Accordingly, the P–P bond length (2.211(1) Å) is longer than in 1 (2.105(1) Å), which is in accordance with the decrease of the bond order. The P–P bond length in the complex.

Reactivity. As expected for a Sc–Pα multiple bond, complex 1 reacts with N-benzylidenepropylamine at room temperature to give a [2 + 2] cycloaddition product 3 (Fig. 3). This reactivity contrasts with one observed for the coordination-free phosphinophosphinidenes, which are electrophilic. In 3 (Fig. 4), the Pβ atom is not coordinated to the scandium center. The Sc–Pα bond length is longer than that in 1, 2.547(1) vs 2.448(1) Å, which is in accordance with the decrease of the bond order. The P–P bond length (2.211(1) Å) is longer than in 1 (2.105(1) Å) but shorter than that in the phosphinophosphine (2.277(1) Å). Accordingly, in the 31P{1H} NMR spectra in C6D6, the P–P coupling constant for 3 (384 Hz) is smaller than that for 1 (505 Hz) but larger than that for the phosphinophosphine (186 Hz). The chemical shifts of the P atoms for 3 are also dramatically changed, the Pα signal appears at δ = 40.8 ppm and the Pβ signal is at δ = 169.0 ppm.

In attempts to synthesize the scandium end-on phosphinophosphinidene, the addition of a strong donor, namely the bipyridine (bpy), to 1 was investigated. Surprisingly, the reaction gives a bpy-insertion product 4 instead of a bpy-coordination compound in a nearly quantitative yield. During the reaction, the Pβ atom of 1 nucleophilically attacks one ortho-carbon atom of bpy. This is a unique reactivity, as in all previously reported phosphinophosphinidene metal complexes, the Pβ atom hardly reacts as a nucleophile with unsaturated substrates. The newly formed sp3 carbon atom in 4 displays a featured signal at δ = 78.3 ppm (dd, Jp-C = 77.7 Hz, Jp-C = 9.3 Hz) in its 13C{1H} NMR spectrum. In the 31P{1H} NMR spectrum of the complex, the Pα and Pβ signals appear at δ = −64.4 and 110.0 ppm, respectively; the P–P coupling constant is up to 639 Hz. In constant with a large P–P bond length in 2, 2.095(1) Å, is similar to that in 1, 2.105(1) Å.

Reactions of complex 1 with N-benzylidenepropylamine, 2,2′-bipyridine, ethylene, phenylacetylene and 1-phenyl-1-propyne, and reactions of complex 2 with phenylacetylene and 1-phenyl-1-propyne.

Fig. 2 Molecular structures of complexes 1 and 2 with ellipsoids at 30% probability level. DIPP isopropyl groups and hydrogen atoms were omitted for clarity.

Fig. 3 Reactivity of scandium phosphinophosphinidene complexes.

Table 1 Important bond lengths/angles of complexes 1–9, scandium bridged phosphinidene complex [(LSc)2(μ2-CH2)(μ2-P(DIPP))] (A), lithium capped scandium phosphinidene ate complex [(PNP)Sc{μ2-P(C6H5-2,6-Mes2)}(μ2-Br)Li] (B) and scandium diphosphido complex [Sc(P(DIPP))2] (C).

| Entry | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | A     | B     | C     |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sc-Pα | 2.448(1) | 2.484(1) | 2.547(1) | 2.557(1) | 2.535(2) | 2.505(1) | 2.508(1) | 2.618(1) | 2.229(1) | 2.222(1) |       |       |
| Sc-Pβ | 2.718(1) | 2.814(1) | 2.211(1) | 2.027(1) | 2.021(1) | 2.097(2) | 2.050(1) | 2.535(2) | 2.505(1) | 2.508(1) |       |       |
| Pα-Pβ | 2.105(1) | 2.095(1) | 2.211(1) | 2.027(1) | 2.021(1) | 2.097(2) | 2.050(1) | 2.229(1) | 2.222(1) |       |       |       |
| Sc-Pα-Pβ | 72.9(1) | 75.3(1) | 121.3(1) | 96.7(1) | 89.7(1) | 91.1(1) | 92.4(1) | 111.6(1) | 110.8(1) |       |       |       |

*aBond lengths [Å] and bond angles [°].

*bThe average value of two Sc–P bond lengths in the complex.
coupling constant observed in the solution NMR study, the XRD studies on the single crystal of 4 indicate the complex has a short P–P bond length, 2.027(1) Å (Supplementary Fig. 5), which is similar to the P–P double bond lengths of the diphosphenes (~2.03 Å)\(^{30}\). As expected, the Sc–P\(_{\alpha}\) bond length in 4 (2.557(1) Å) is longer than that in 1 (2.448(1) Å), but close to that in 3 (2.547(1) Å).

Complex 1 also reacts with ethylene and phenylacetylene, yielding an insertion of the C–C double or triple bond into the Sc–P\(_{\beta}\) bond (instead of the Sc–P\(_{\alpha}\) bond), and the products 5 and 6 were isolated in high yields (Fig. 3). The reaction with phenylacetylene is highly regioselective, only the isomer 7 which minimizes the steric repulsion between the phenyl group of the alkyne and the DIPP group of the phosphinophosphinidene was obtained. The electronic effects of the phenyl substituent on the reaction also favor the formation of this isomer as it stabilizes the partial negative charge on the benzylic carbon when it is located α to the metal ion. The reaction of 1 with 1-phenyl-1-propyne gives several products, complex 7 (Fig. 3) was isolated in 34% yield while other products could not be isolated. The complex 7 comes from the insertion of the C–C triple bond of 1-phenyl-1-propyne into the Sc–P\(_{\beta}\) bond of 1, with the phenyl substituent located α to metal ion. Similar to that of 4, the \(^{31}\)P\(^{1}\)H NMR spectra of 5–7 in solutions show the large P–P coupling constants, 634, 615, and 647 Hz, respectively. In the solid states, the P–P bond lengths of 5, 6 (Supplementary Figs. 5, 6), and 7 (Fig. 4) are 2.021(2), 2.097(2), and 2.222(1) Å, respectively. The newly formed Sc–C and P–C bonds in 5, 6, and 7 are 2.126(5) and 1.840(5) Å, 2.253(4) and 1.797(4) Å, and 2.234(2) and 1.844(2) Å, respectively. It is worthy to note that the reactions occur on the Sc–P\(_{\beta}\) bond of 1 are similar to those observed for some metal-based frustrated Lewis pairs, where the unsaturated substrates inserted into the metal-phosphorus functions\(^{31–34}\).

In contrast to the reactivity of 1, complex 2 reacts with phenylacetylene to give a scandium phenylacetylide 8 (Fig. 3). The P\(_{\alpha}\) of 2 abstracts a proton from phenylacetylene in the reaction, and this resembles the reactivity of a scandium imido complex\(^{35}\). The single crystals of 8 were obtained and characterized by XRD (Fig. 4). The Sc–P\(_{\alpha}\) and P–P bond lengths in 8 are both significantly longer than those in 2, 2.618(1) and 2.229(1) Å vs 2.484(1) and 2.095(1) Å. Furthermore, complex 2 nearly quantitatively undergoes a [2 + 2] cycloaddition with 1-phenyl-1-propyne, and complex 9 is isolated in 79% yield. In the \(^{31}\)P\(^{1}\)H NMR spectra, the P\(_{\alpha}\) and P\(_{\beta}\) signals of 9 appear at \(\delta = 70.6\) and 173.5 ppm, which are significantly downshifted in comparison with those of 7 (−18.6 and 80.3 ppm); the P–P coupling constant for 9 is much smaller than that for 7, 361 Hz vs 647 Hz. Complex 9 was also characterized by XRD (Fig. 4). The Sc–P\(_{\alpha}\) and P–C49 bond lengths in 9 (2.544(1) and 1.912(2) Å) are slightly longer than the Sc–P\(_{\alpha}\) and P\(_{\beta}\)–C57 bond lengths in 7 (2.508(1) and 1.844(2) Å); however, the P\(_{\alpha}\)–P\(_{\beta}\) length in 9 (2.222 (1) Å) is much longer than that in 7 (2.050(1) Å). Complex 2 also reacts with ethylene at room temperature, but gives a complicated mixture.

**Computational studies.** In order to get some insights on the bonding properties of scandium phosphinophosphinidene complex, DFT calculations on complex 1 were carried out. Scrutinizing the molecular orbitals indicates that the HOMO-1 and

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**Fig. 4 Molecular structures of complexes 3 and 7–9.** The ellipsoids of 3 are at 30% probability level, while those of 7, 8, and 9 are at 40% probability level. DIPP isopropyl groups and hydrogen atoms (except the hydrogen atom on P\(_{\alpha}\) in 8) were omitted for clarity.
HOMO-2 are Sc–Pα π and σ bonding interactions, respectively, (Supplementary Fig. 49), whereas the HOMO displays a donor–acceptor interaction between the lone pair on Pβ and Sc (Fig. 5). This bonding situation is further confirmed by NBO analysis. The Wiberg Indexes are 1.4 and 0.3 for the Sc–Pα and Sc–Pβ bonds, respectively, in line with a double bond character for the former and a donor–acceptor nature for the latter (for set of comparison the P–P bond has a Wiberg Index of 1.0).

For the sake of comparison, the bonding situation in complex 2 was also investigated computationally. First the molecular orbitals were analyzed. Even though HOMO-1 and HOMO-2 clearly shows σ + π interaction between Sc and Pα in line with a Sc=Pα double bond character (Supplementary Fig. 50), the HOMO (Fig. 5) is quite different from that of 1 since the donation from the Pβ to Sc seems weaker. This is further highlighted by the NBO analysis and the Wiberg indexes. Indeed, the Wiberg Indexes are 1.3 and 0.2 for the Sc–Pα and Sc–Pβ bonds, and 0.7 for the P–P bond, in line with a weaker interaction between the phosphino-phosphinidene and metal center. This difference of bonding in 1 and 2 would affect the reactivity, as in 1 the stronger metal–ligand interaction seems to take place.

To rationalize the peculiar reactivity of complex 1, the Fukui condensed descriptors of 1 were computed and indicate that Pα has to be a better nucleophile than Pβ (Δf being −0.19 and −0.09, respectively) (Supplementary Table 2), which is not in line with the observed reactivity and therefore, the reaction profile was determined in the gas phase at room temperature (Fig. 6). The reaction begins with the formation of a phenylacetylene adduct whose formation is endothermic by 23.9 kcal mol$^{-1}$. Interestingly, the computed full dissociation energy of THF requires 15.7 kcal mol$^{-1}$, suggesting that reaction can occur on the most nucleophilic phosphorus in line with the experimental observation. This favorable coordination of N-benzylidenepropylamine to 1 has been computed. The THF replacement is found to be thermodynamically favored by 8.8 kcal mol$^{-1}$, so that reaction can occur on the most nucleophilic phosphorus in line with the experimental observation. This favorable coordination of N-benzylidenepropylamine is easily explained by the presence of the nitrogen lone pair that ensures the coordination to the metal center. Moreover, the latter also prevents any hydrogen transfer to the phosphinophosphinidene ligand. Interestingly, the [2 + 2] product formation is thermodynamically favorable (−34.9 kcal mol$^{-1}$), whereas the [2 + 3] is disfavored (13.0 kcal mol$^{-1}$) in line with the nucleophilicity.

The somewhat normal reactivity of complex 2 with phenylacetylene was also investigated computationally at the same level of theory (DFT, B3PW91). The THF dissociation energy from complex 2 was computed and found to be 3.4 kcal mol$^{-1}$ only (Fig. 6), which is four times lower than that in complex 1. This is due to the presence of the donation from the labile amino group on the diketiminato ligand, and in line with the longer Sc–O (THF) bond length found by XRD in complex 2 (2.275(2) vs 2.197(2) Å in complex 1). Moreover, this also explains the difference of reactivity, since with such an easy dissociation of THF the reactivity at the strongly nucleophilic Pα (NPA charge of −0.23 vs +0.69 at Pβ) can occur. Interestingly, the 1,2 insertion of phenylacetylene on the Sc–Pβ was found at a similar barrier as found for 1 (20.8 kcal mol$^{-1}$, see Supplementary Fig. 54), which is not competitive with the formation of complex 8 (Fig. 6). Indeed, the THF to phenylacetylene replacement occurs at low energy (5.6 kcal mol$^{-1}$, meaning 2.2 kcal mol$^{-1}$ with respect to the THF dissociation). From there, the proton transfer transition state was located and the associated barrier is very low (7.2 kcal mol$^{-1}$, with respect to the entrance channel that is 1.6 kcal mol$^{-1}$ only after the THF replacement) in line with a very rapid reaction, as observed experimentally. This is in line with the high nucleophilic character of the Pβ, which abstracts the proton of phenylacetylene. Replacing the hydrogen by a methyl group in the substrate would prevent this reaction and therefore yield a [2 + 2] addition product. This is exactly what is observed experimentally. Following the intrinsic reaction coordinate yields the formation of the phenylacetylide complex 8, whose formation is strongly exothermic (−15.6 kcal mol$^{-1}$).

The bonding situation in 8 was analyzed in order to compare with that in 2. In terms of molecular orbitals, the HOMO exhibits a Pβ to Sc donation (Fig. 5), whereas only the HOMO-1 indicates

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**Fig. 5** HOMO of complexes 1, 2, and 8. The HOMO presents a donor–acceptor interaction between the lone pair on Pβ and Sc. Atom color code: purple, scandium; orange, phosphorus; red, oxygen; blue, nitrogen; gray, carbon; and white, hydrogen.
Discussion

In this contribution, we report the synthesis, structures, and reactivity of two scandium phosphinio phosphinidene complexes (1 and 2). These two complexes are prepared from reactions of potassium salt K[HPpN(Dipp)CH2CH2N(Dipp)] with scandium methyl chloride [LSc(Me)Cl] or [L’S’Sc(Me)Cl] in a THF/toluene mixture via salt elimination and subsequent methane elimination. Complexes 1 and 2 are monometallic, and the bonding analysis on the complexes clearly indicates the presence of a Sc–Pσ double bond and a weak Sc–Pδ donor–acceptor interaction. Complex 1 undergoes a 1,3 addition with 2,2′-bipyridine, ethylene, phenylacetylene, or 1-phenyl-1-propyne (reaction at the least nucleophilic site Pδ), showing a peculiar reactivity. Meanwhile, complex 2 presents a normal reactivity at the most nucleophilic phosphorus site (Pα), such as a 1,2 addition with 1-phenyl-1-propyne and a proton transfer with phenylacetylene. This intriguing difference of reactivity is rationalized using DFT calculations, which demonstrate that the abnormal reactivity of complex 1 is induced by the strong coordination of the THF molecule in complex 1 preventing the reactivity at Pα. Therefore, the work demonstrates that the rare-earth monometallic phosphinidene complex is feasible, and reveals a preliminary reactivity of the Sc=P double bond (complex 2). This work creates a new horizon for rare-earth metal chemistry and metal–ligand multiple bonding chemistry.

Methods

General considerations. Experiments were carried out under an atmosphere of argon using Schlenk techniques or in a nitrogen filled glovebox. All solvents and reagents were rigorously dried and deoxygenated before use. All the new compounds were characterized by NMR and single crystal XRD, the new compounds except 2 were also characterized by elemental analyses. A satisfied elemental analysis for 2 was
Data availability

Crystalllographic data for the structures reported in this article have been deposited at the Cambridge Crystallographic Data Centre (CCDC) under deposition nos. CCDC 1945178 (H,PP[N(DIPP)CH2CH2N(DIPP)]) , 1945179 (1), 1958510 (2), 1958108 (3), 195814 (4), 1958152 (5), 1958153 (6), 1958154 (7), 1958511 (8), and 1958512 (9). These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data request/cif. All other data supporting the findings of this study are available within the Article and its Supplementary Information, at the Oxford University Research Archive (https://ora.ox.ac.uk) and from the corresponding authors upon reasonable request.

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Author contributions
Y.C. conceived this project. B.F. performed the synthesis experiments. X.L. solved all of the X-ray structures. Y.C., B.F., and L.X. analyzed the experimental data. K.N.M. and L.M. conducted the theoretical computations and analyzed the results. Y.C. and L.M. drafted the paper with support from B.F., L.X., and K. M. All the authors discussed the results and contributed to the preparation of the final manuscript.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to L.M. or Y.C.

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