

# Selective P<sub>4</sub> activation by an organometallic nickel(I) radical: formation of a dinuclear nickel(II) tetraphosphide and related di- and trichalcogenides†‡

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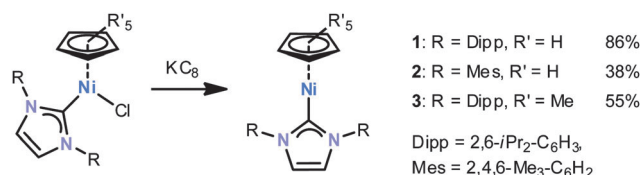
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The reaction of the 17e nickel(I) radical [CpNi(IDipp)] (**1**, IDipp = 1,3-bis(2,6-diisopropylphenyl)imidazolin-2-ylidene) with P<sub>4</sub> results in a nickel tetraphosphide [(CpNi(IDipp))<sub>2</sub>(μ-η<sup>1</sup>:η<sup>1</sup>-P<sub>4</sub>)] with a butterfly-P<sub>4</sub><sup>2-</sup> ligand; related chalcogenides [(CpNi(IDipp))<sub>2</sub>(μ-E<sub>2</sub>)] (E = S, Se, Te) and [(CpNi(IDipp))<sub>2</sub>(μ-E<sub>3</sub>)] (E = S, Se) are formed with S<sub>8</sub>, Se<sub>∞</sub> and Te<sub>∞</sub>.

The P<sub>4</sub> molecule is the most reactive allotrope of phosphorus; its activation and transformation by transition metal compounds has attracted substantial interest over the years.<sup>1</sup> While many low-valent metal complexes, *e.g.* transition metal carbonyls or anionic metalates, react with P<sub>4</sub>, it is still challenging to design highly selective transformations.<sup>2,3</sup>

White phosphorus is able to efficiently trap organic and main group element radicals.<sup>4</sup> Therefore, one potential solution to the selectivity issue is to use a radical pathway in transition metal-mediated P<sub>4</sub> transformations. While 2nd and 3rd row metalloradicals are well-established,<sup>5</sup> nickel(I) radicals have attracted significant attention recently.<sup>6,7</sup> Importantly, Driess *et al.* have shown that reactions of β-diketiminato nickel(I) complexes with P<sub>4</sub> yield dinuclear complexes [(L<sup>R</sup>Ni)<sub>2</sub>(μ-η<sup>3</sup>:η<sup>3</sup>-P<sub>4</sub>)] (L<sup>R</sup> = HC[CMeN(2,6-R<sub>2</sub>C<sub>6</sub>H<sub>3</sub>)<sub>2</sub>], with R = Et, *i*Pr).<sup>8</sup> The P–P bond activation in the doubly η<sup>3</sup>-coordinated ligand is reversible and occurs without the reduction of P<sub>4</sub> to formally P<sub>4</sub><sup>2-</sup>.

We have been interested in designing new reactive nickel(I) radicals for element–element bond activations. We now report the synthesis of complexes **1–3** featuring an NHC and a

Scheme 1 Synthesis of nickel(I) complexes **1–3**.

cyclopentadienyl ligand, and an initial reactivity study of complex **1** with P<sub>4</sub> and related small molecules.

Complexes **1–3** are accessible according to Scheme 1 by the reduction of the appropriate nickel(II) halides with KC<sub>8</sub> in THF. <sup>1</sup>H NMR monitoring shows that **1–3** are formed very selectively; they can be isolated as yellow crystalline solids in modest to high yields. Single X-ray structure analyses (ESI†) revealed that the nickel centre is surrounded by the carbene carbon and one η<sup>5</sup>-coordinated Cp or Cp\* moiety. No further significant interactions between nickel and the diisopropylphenyl groups are apparent. Nonetheless, the cyclopentadienyl ligand is tilted with respect to the nickel carbene bond with an angle C<sub>carbene</sub>–Ni–(C<sub>5</sub>R<sub>5</sub>)<sub>centroid</sub> of 154.3(1)° for **1**, 151.9(1)° for **2** and 164.6(1)° for **3**.§

Cyclic voltammograms show one electrochemically quasi-reversible wave at E<sub>1/2</sub> = –1.02 and –1.06 V vs. Fc/Fc<sup>+</sup> for Cp-substituted **1** and **2**, respectively, and a reversible wave at –1.18 V vs. Fc/Fc<sup>+</sup> for the Cp\* complex **3** (ESI†). UV/vis-spectroelectrochemistry (see Fig. 1 for **1**) confirms that these processes correspond to chemically reversible oxidations of neutral **1–3** to stable cationic nickel(II) complexes, which probably bind THF in the case of **1** and **2**. Indeed, the preparative oxidation of **1** with [Cp<sub>2</sub>Fe]PF<sub>6</sub> affords the THF adduct [(C<sub>5</sub>H<sub>5</sub>)Ni(IDipp)(THF)]PF<sub>6</sub> (**1-THF**) (ESI†).§

Complexes **1–3** show identical magnetic moments of 2.3(1), 2.3(1), and 2.2(1) μ<sub>B</sub> in [D<sub>8</sub>]THF, which indicate the presence of one unpaired electron per molecule. The EPR spectrum of **1** is characteristic for an S = 1/2 system and reveals a rhombic g-tensor with significant deviations from g<sub>e</sub> pointing to metalloradical character. DFT calculated g<sub>11</sub> and g<sub>22</sub> values are somewhat smaller than the experimental ones, but show a similar rhombicity (Fig. 1).

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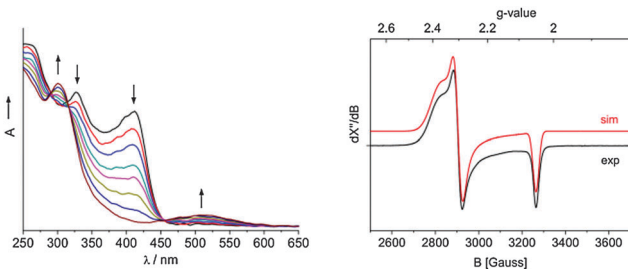
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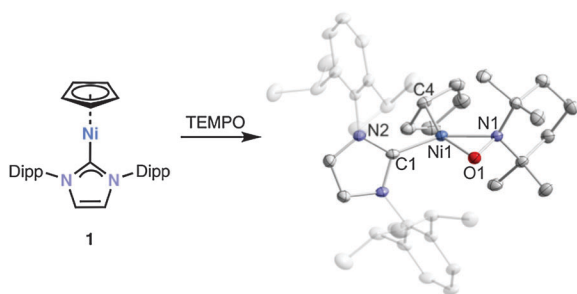
† Dedicated to the memory of Prof. Michael F. Lappert.

‡ Electronic supplementary information (ESI) available. Full experimental details, electrochemical, EPR and crystallographic data. CCDC 995931–995941 and 999501. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c4cc02601b





**Fig. 1** Left: UV/Vis monitoring of the oxidation of **1** performed at  $-0.83$  V vs.  $\text{Fc}/\text{Fc}^+$  within an OTTE cell equipped with a Pt minigrid working electrode, THF/TBAH under Ar, 293 K. Right: experimental and simulated X-band EPR spectrum of **1** in frozen THF. Freq. 9.3646 GHz, 0.063 mW, 20 K, mod. 4 Gauss;  $g$ -tensor parameters obtained from simulations and DFT calculations (b3-lyp, def2-TZVP) are:  $g_{11} = 2.377$  (2.220),  $g_{22} = 2.306$  (2.187),  $g_{33} = 2.050$  (2.078) (DFT-calculated values in parentheses).



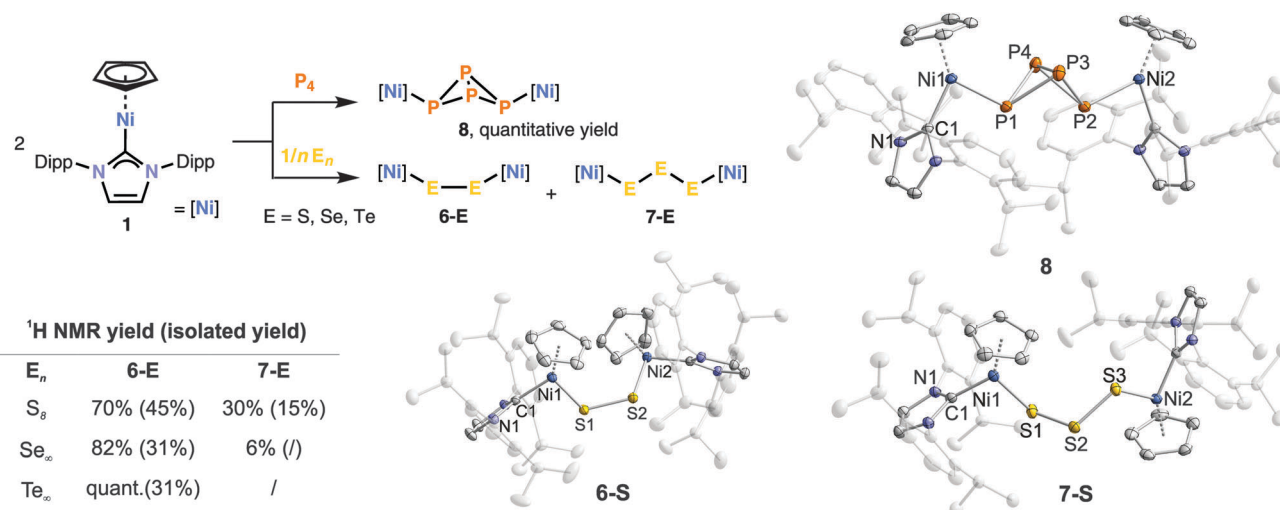
**Fig. 2** Reaction of **1** with TEMPO and solid-state molecular structure of  $[(\text{C}_5\text{H}_5)\text{Ni}(\text{TEMPO})(\text{IDipp})]$  (**5**). The hydrogen atoms are omitted for clarity. Thermal ellipsoids are drawn at 40% level. Selected bond lengths [Å] and angles [°]: Ni1–O1 1.8408(14), Ni1–N1 1.9581(16), N1–O1 1.3989(20), Ni1–C1 1.8824(19), Ni1–C4 2.034(2), C1–Ni1–O1 104.50(7), O1–Ni1–N1 43.07(6), C1–Ni1–C4 97.104(4), N1–Ni1–C4 115.325(2).

Initial reactivity studies of **1** established its behavior as a typical metal-centered radical. The reactions of phenyl disulfide

and TEMPO with **1** in THF afforded the known thiolate  $[(\text{C}_5\text{H}_5)\text{Ni}(\text{SPh})(\text{IDipp})]$  (**4**)<sup>9</sup> and the new TEMPO adduct **5** in quantitative yield (Fig. 2). The molecular structure of **5** shows a side-on  $\eta^2$ -coordinated TEMPO ligand and an  $\eta^1$ -coordinated Cp ligand at the distorted square planar nickel(II) atom. The structural parameters agree with presence of a formally anionic TEMPO<sup>−</sup> ligand.<sup>10</sup> A sharp <sup>1</sup>H NMR singlet at 5.93 ppm is observed for the Cp moiety even at  $-90$  °C presumably due to rapid haptotropic migration.

We next investigated the reactivity of **1** with the heavier chalcogens. The reaction with  $\text{S}_8$  (1/8 equivalents) gave the blue disulfide **6-S** and the purple trisulfide **7-S** (Fig. 3) in a 7 : 3 ratio according to <sup>1</sup>H NMR analysis. **6-S** is soluble in *n*-hexane and diethyl ether and can thus be separated from **7-S** by extraction and subsequent crystallisation (ESI†). Disulfide-bridged dinuclear complexes with an M–S–S–M motif are well-known,<sup>11</sup> while complexes with an unsupported  $\mu\text{-S}_3^{2-}$  bridge are still rather scarce.<sup>11a,b,12</sup> The structure of **7-S** shows a similar S1–S2–S3 angle and S–S bond lengths as the structure of  $[(\text{C}_5\text{H}_5)\text{Fe}(\text{CO})_2]_2(\mu\text{-S}_3)$ .<sup>11a</sup> Diselenide **6-Se** (31% isolated) is the major reaction product of **1** with one equivalent of elemental selenium. A <sup>1</sup>H NMR spectrum of the reaction mixture (THF, room temperature) shows that **6-Se** is formed in more than 80% yield whereas the triselenide **7-Se** is a minor by-product. Ditelluride **6-Te** was the only product to be detected after stirring **1** with one equivalent of grey tellurium for seven days. It was isolated as a dark brown crystalline solid in 31% yield. The molecular structures of **6-Se**, **6-Te** and **7-Se** are analogous to the corresponding sulfides **6-S** and **7-S** (ESI†).

Considering that a mixture of at least two products is formed with sulfur and selenium, it was gratifying to discover that complex **1** reacts with  $\text{P}_4$  in a highly selective fashion in THF at room temperature, giving tetraphosphide **8** as the sole product. The reaction is instantaneous, and compound **8** can be isolated as an analytically pure, dark purple powder in quantitative yield simply by removing the solvent. Its molecular structure (Fig. 3)



**Fig. 3** Left: reactions of **1** with  $\text{P}_4$ ,  $\text{S}_8$ ,  $\text{Se}_\infty$  and  $\text{Te}_\infty$ . Right: solid-state molecular structures of the products **6-S**, **7-S** and **8**. The hydrogen atoms are omitted for clarity. Thermal ellipsoids are drawn at 40% level. Selected bond lengths [Å] and angles [°]: **6-S**: Ni1–S1/Ni2–S2 2.1800(1)/2.1797(1), S1–S2 2.0476(1), Ni1–S1–S2–Ni2 78.601(5), **7-S**: Ni1–S1/Ni2–S3 2.1936(6)/2.1748(5), S1–S2/S2–S3 2.0561(7)/2.0522(7), S1–S2–S3 111.58(3), **8**: Ni1–P1/Ni2–P2 2.2107(6)/2.2103(6), P1–P3/P4 2.2334(7)/2.2111(7), P3–P4 2.1649(7), P1–P2 2.8897(8).



shows an *exo/exo* configuration for the two  $[(C_5H_5)Ni(IDipp)]$  units. The P–P bond lengths (2.2111(7)–2.2334(7) Å) are very similar to those in  $P_4$  (P–P 2.21 Å). The  $^{31}P\{^1H\}$  NMR spectrum shows two triplets at  $\delta = -307.4$  and  $-45.8$  ppm with  $^1J_{P-P} = -190.5$  Hz. These values are similar to those of  $[(Cp^RFe(CO)_2]_2(\mu-\eta^1:\eta^1-P_4)]$  ( $Cp^R = C_5H_3-1,3-tBu_2, C_5H_2-1,2,4-tBu_3, C_5H-iPr_4, C_5Me_5$ ) and  $[(Cp^*Cr(CO)_3]_2(\mu-\eta^1:\eta^1-P_4)]$ , which also display a tetraphospha-[1.1.0]bicyclobutane framework.<sup>13</sup>

In conclusion, we have prepared rare mononuclear cyclopentadienyl nickel(i) complexes **1–3** with significant metallo-radical character.<sup>6,7</sup> This feature was successfully utilized for the high-yield synthesis of the novel tetraphosphido complex  $[(C_5H_5)Ni(IDipp)]_2(\mu-\eta^1:\eta^1-P_4)$  (**8**), which features an uncommon  $\mu-\eta^1:\eta^1$ -bridging  $P_4^{2-}$  ligand.<sup>14</sup> Further reactivity studies of **1–3** and **8** are in progress; the results will be reported in due course.

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## Notes and references

§ During the preparation of this manuscript, Hazari *et al.* reported the synthesis and characterization of **1**, **1-THF** and closely related mono- and dinuclear species by a different synthetic route.<sup>7</sup> Based on DFT calculations, the bending of the  $C_{\text{carbene}}-Ni-(C_5H_5)_{\text{centroid}}$  angle in the structure of **1** was attributed to the asymmetric spin density distribution.

¶ The hydride complex  $[(C_5H_5)NiH(IDipp)]$  (**1-H**) was identified as a minor by-product (<5%) of the synthesis of **1**. Compound **1-H** was prepared independently and features a distinct molecular structure from **1**; see the ESI† for details.

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