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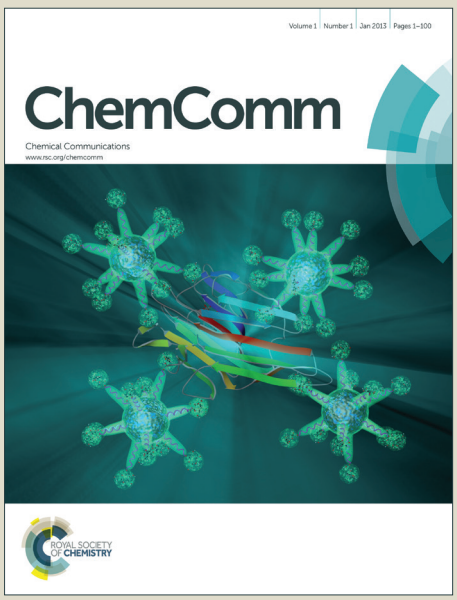

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Cite this: DOI: 10.1039/c0xx00000x

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ARTICLE TYPE

Synthesis and derivatization of highly-functionalized λ^5-phospholes

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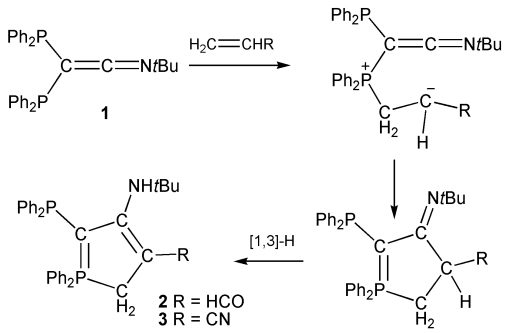
Received (in XXX, XXX) Xth XXXXXXXXX 20XX, Accepted Xth XXXXXXXXX 20XX
DOI: 10.1039/b000000x

A variety of λ^5-phosphole derivatives bearing up to three distinct peripheral functionalities have been prepared by regiospecific [3+2] cycloaddition reaction of the diphosphinoketenimine $(PPh_2)_2C{=}C{=}NtBu$ (1) with electron-poor alkenes. Selective derivatization of the exocyclic functional groups, including formation of dimetallic complexes with a phosphole core, was subsequently accomplished.

Although the chemistry of phosphole derivatives is currently well developed, relatively few systematic studies on the synthesis of functionalized phospholes have been reported.[1,2] A variety of phospholes are known to contain different functional groups attached at phosphorus or carbon atoms, such as carboxylic acid and derivatives,[3] aldehydes and ketones[4] or phospholes bearing halo substituents,[5] which are key building blocks for the synthesis of other phosphole derivatives. Notable examples are also functionalized phospholes containing π-conjugated systems, such as dithienophospholes,[6] arene-fused phospholes,[7] dithienylethene-containing phospholes,[8] dithiaphospholes[9] and phospholes bearing acetylene functions,[10] owing to their unique electronic properties. Considering all the above, the development of experimental strategies for the introduction of new functional groups at the periphery of the phosphole cycle emerges as an important goal. Herein we describe the synthesis of a variety of λ^5-phospholes featuring exocyclic functional groups such as phosphane, amine, aldehyde, nitrile or ester, as well as its selective derivatization, including formation of transition-metal complexes.

Reaction of the diphosphinoketenimine $(PPh_2)_2C{=}C{=}NtBu$ (**1**)[11] with acrolein or acrylonitrile at room temperature led to the formation of the 2H-λ^5-phospholes **2** and **3,** respectively (Scheme 1). Very likely the reaction proceeds through nucleophilic attack of a phosphorus atom of **1** to the unsubstituted carbon atom of the alkene followed by a 1,5-electrocyclization, which complete the formal [3+2] cycloaddition reaction observed. Additionally, a [1,3]-H shift from the endocyclic CH group to the iminic nitrogen atom must occur to finally generate compounds **2** and **3**. The proposed mechanism is in agreement with the regiospecificity of the reaction, as only one regioisomer was formed. Furthermore, this result is in accord with a HOMO-LUMO interaction between **1** and the alkene, as the LUMO in the latter molecule is mainly centered in the unsubstituted carbon atom.[12] Full characterization of compounds **2** and **3** was accomplished by spectroscopic methods. In the $^{31}P\{^1H\}$ NMR spectrum two doublets for the two



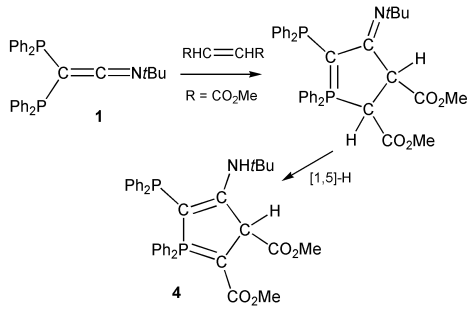
Scheme 1. Formation of 2H-λ^5-phospholes **2** and **3** by reaction of diphosphinoketenimine **1** with acrolein and acrylonitrile.

nonequivalent phosphorus atoms were observed, the high-field signal corresponding to the exocyclic diphenylphosphino group (see Supplementary Information of full characterization data).

It is worth noting the divergent reactivity of **1** with olefins in comparison with that of the alkynes, previously observed by our group, where two successive cyclization processes occurred.[13] Now the [3+2] cycloaddition reaction is limited to one alkene molecule, leaving the exocyclic diphenylphosphino group unreacted. This circumstance makes compounds **2** and **3** highly functionalized λ^5-phospholes, notably containing phosphino and amino substituents available for further transformations on these phosphaheterocycles.

Compound **1** also reacted with an internal electron-poor alkene such as dimethyl maleate. The electron affinity value of this alkene is appreciably lower than that of acrolein and acrylonitrile.[12] Consequently, stronger reaction conditions were required in this case, namely refluxing toluene for 8 h. The 3H-λ^5-phosphole **4** was formed under these conditions, a type of phosphaheterocycle very scarcely encountered in the literature,[13,14] which in addition contains functional groups at all carbon atoms of the heterocycle. As shown in Scheme 2, generation of **4** might imply a [3+2] cycloaddition reaction as for compounds **2** and **3**, but in this case a further [1,5]-H shift instead of a [1,3]-H shift occurred to yield the observed phosphaheterocycle. The structure of **4** at the solid state was confirmed by an X-ray diffraction study (Figure 1). The interatomic distances within the N1-C2-C1-P2-C4-C10 skeleton are, to a variable extent, intermediate between double and single bonds, thus showing π-electron delocalization, being largely extended to the functional groups placed on the C2 and C4

carbon atoms of the heterocycle.



Scheme 2. Formation of the 3H-λ^5-phosphole **4** by reaction of **1** with dimethyl maleate.

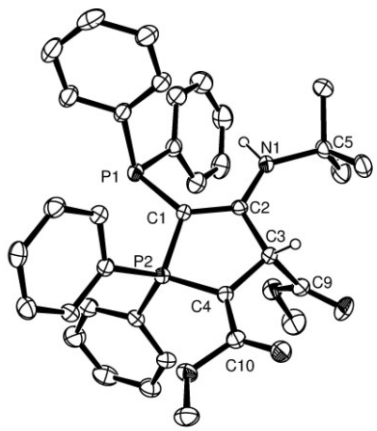
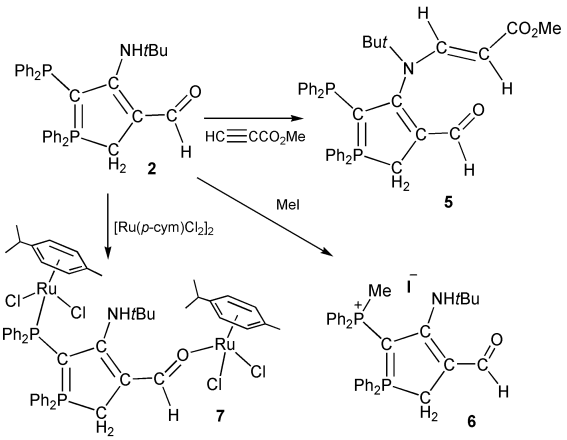


Figure 1. Molecular structure of **4**, shown with 30% thermal ellipsoids. Hydrogen atoms of phenyl and methyl groups are omitted for clarity. Selected interatomic distances (Å) and angles (deg): C1-C2 1.385(4), C2-C3 1.545(4), C3-C4 1.504(4), P2-C4 1.719(3), P2-C1 1.769(3), P1-C1 1.825(3), C3-C9 1.501(4), C4-C10 1.429(5), N1-C2 1.343(4), N1-C5 1.493(4); C1-C2-C3 115.6(3), C2-C3-C4 107.4(2), C3-C4-P2 110.0(2), C4-P2-C1 96.61(14), P2-C1-C2 109.0(2), P2-C1-P1 119.03(17), C2-C1-P1 131.6(2), N1-C2-C1 122.5(3), N1-C2-C3 122.0(3), C2-N1-C5 135.6(3).

Compounds **2-4** still retain some additional reactivity mainly based on the amino and phosphino substituents, which may promote nucleophilic attack from either the nitrogen or the phosphorus atoms to electrophilic substrates, enlarging further the functionalization of these rather sophisticated molecules. Thus, compound **2** was reacted with a terminal alkyne such as methyl propiolate to give **5** resulting from regio- and stereo-specific Michael addition of the amino substituent to the alkyne, whereas reaction of **2** with methyl iodide afforded the phosphonium salt **6** after selective quaternization of the exocyclic phosphorus atom (Scheme 3). The structure of **5** was definitively confirmed by X-ray crystallography (Figure 2), which shows the newly formed alkenyl substituent at nitrogen as the *E*-isomer, with the exocyclic diphenylphosphino substituent of the λ^5-phosphole remaining unreacted. The coordination geometry around the nitrogen atom N1 is distorted trigonal planar, and the alkenyl and carboxylate skeletons are arranged at the same plane, suggesting a strong delocalization of the nitrogen lone pair through those groups. Accordingly, the N1-C6 (1.368(9) Å) and C6-C7 (1.336(9) Å) distances are intermediate between single and double bonds. The phosphole cycle is also planar and essentially orthogonal to the alkenylamino plane.



Scheme 3. Derivatization of **2** at the exocyclic heteroatoms to afford compounds **5**-**7**.

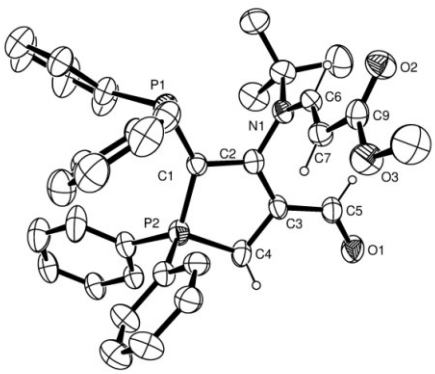


Figure 2. Molecular structure of **5**, shown with 20% thermal ellipsoids. Hydrogen atoms of phenyl and methyl groups are omitted for clarity. Selected interatomic distances (Å) and angles (deg): C1-C2 1.424(8), C2-C3 1.408(9), C3-C4 1.492(8), P2-C4 1.803(6), P2-C1 1.760(7), P1-C1 1.805(7), N1-C2 1.427(8), N1-C6 1.368(9), C6-C7 1.336(9), C7-C9 1.444(11), O2-C9 (1.203(9), C3-C5 1.394(10), O1-C5 1.249(9); C1-C2-C3 118.3(8), C2-C3-C4 112.2(7), C3-C4-P2 103.3(5), C1-P2-C4 96.3(3), C2-C1-P2 104.8(6), P2-C1-P1 133.9(4), C2-C1-P1 121.0(6), C1-C2-N1 121.2(8), C3-C2-N1 120.5(7), C6-N1-C2 115.9(7).

The UV/Vis spectra of compounds **2-6** reveal that the values of the longest-wavelength absorption maxima are strongly dependent on the nature of the peripheral substituents (from 260 to 397 nm), showing the influence of the functional groups in the electronic absorption properties of this new phosphole family (see Supplementary Information for details).

Compounds **2-4** may additionally serve as new phosphine ligands in transition-metal complexes, with donor properties

modulated by controlled functionalization at the phosphole ring. As a preliminary example compound **2** was reacted with an equivalent of $[Ru(p\text{-cym})Cl_2]_2$ readily affording the dimetallic complex **7,** which contains ruthenium atoms bonded to peripheral diphenylphosphino and aldehyde functionalities (Scheme 3), as deduced from complete spectroscopic characterization data in solution and confirmed by an X-ray diffraction analysis. Naturally, in the $^{31}P\{^1H\}$ NMR spectrum of **7** the signal corresponding to the exocyclic phosphorus atom is strongly shifted low-field (52.4 ppm) upon coordination. In the IR spectrum, the ν(CO) band of the carbonyl group appeared at 1549 cm^{-1}, which is 40 cm^{-1} lower in frequency than the un-coordinated precursor **2**. The crystal structure of **7** (Figure 3) clearly shows the two $\{Ru(p\text{-cym})Cl_2\}$ fragments bonded to the exocyclic diphenylphosphino and carbonyl groups. The bond lengths within the N1-C2-C3-C5-O1 skeleton indicate delocalization of the nitrogen lone pair towards the conjugated carbonyl group, thus enhancing the donor capability of the oxygen atom. As a consequence, the C3-C5 and C5-O1 distances are intermediate between double and single bonds, showing some enolate character for the aldehyde functionality. Compound **7** nicely illustrates the suitability of the highly functionalized λ^5-phospholes described herein to behave as multidentate ligands through the heteroatoms of the peripheral functional groups.

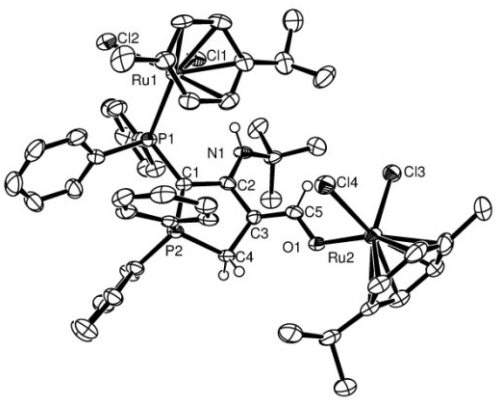


Figure 3. Molecular structure of **7**, shown with 30% thermal ellipsoids. Hydrogen atoms of phenyl, *p*-cym and methyl groups are omitted for clarity. Selected interatomic distances (Å) and angles (deg): C1-C2 1.426(9), C2-C3 1.45(1), C3-C4 1.516(9), P2-C4 1.810(7), P2-C1 1.759(7), P1-C1 1.815(7), N1-C2 1.357(8), C3-C5 1.34(1), O1-C5 1.302(9), Ru1-P1 2.398(2); C1-C2-C3 115.3(6), C2-C3-C4 111.1(6), C3-C4-P2 102.8(4), C1-P2-C4 96.0(3), C2-C1-P2 107.7(5), C3-C5-O1 123.5(7), C1-P1-Ru1 112.9(2).

In summary, we have developed a facile approach for the synthesis of new highly functionalized λ^5-phospholes, based on [3+2] cycloaddition reactions of diphosphinoketenimine $(PPh_2)_2C{=}C{=}N\textit{t}Bu$ with electron-poor alkenes such as acrolein, acrylonitrile and dimethyl maleate. 2H-λ^5-phospholes **2** and **3**, and 3H-λ^5-phosphole **4** have been prepared in this way. Compound **2** can be post-functionalized selectively at the exocyclic nitrogen or phosphorus atoms by treatment with methyl propiolate or methyl iodide, affording the λ^5-phospholes **5** and **6**, respectively. Finally, **2** can serve as polydentate ligand in transition-metal complexes, as illustrated in the synthesis of compound **7**, which contains two $\{Ru(p\text{-cym})Cl_2\}$ units bonded to peripheral diphenylphosphino and aldehyde functionalities**.**

This work was supported by the Spanish Ministerio de Economía y Competitividad (Project CTQ2012-32239).

Notes and references

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† Electronic Supplementary Information (ESI) available: Experimental details and analytical and spectroscopic data in pdf format. CCDC reference numbers 929248 (**4**), 929250 (**5**) and 929251 (**7**). See DOI: 10.1039/b000000x/

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