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Au(I)-mediated N_2-elimination from triazaphospholes: a one-pot synthesis of novel N_2P_2-heterocycles†

Erlin Yue, ‡[ab] Lea Dettling, ‡[a] Julian A. W. Sklorz,[a] Selina Kaiser,[a] Manuela Weber[a] and Christian Müller *[a]

Novel tosyl- and mesitylsulfonyl-substituted triazaphospholes were synthesized and structurally characterized. In an attempt to prepare the corresponding Au(I)-complexes with stoichiometric amounts of AuCl·S(CH_3)$_2$, *cyclo*-1,3-diphospha(III)-2,4-diazane-AuCl-complexes were obtained instead. Our here presented results offer a new strategy for preparing such coordination compounds selectively in a one-pot approach.

According to the isolobal relationship between a trivalent P-atom and a C–H fragment, the 3,5-disubstituted 3*H*-1,2,3,4-triazaphosphole derivatives of type **B** are the phosphorus congeners of the well-studied 1,2,3-triazoles **A** (Chart 1).

These $\lambda^3\sigma^2$ phosphorus heterocycles can be prepared in a modular [3+2] cycloaddition reaction, starting from organic azides and phosphaalkynes, as first reported independently by Carrié and Regitz in 1984.[1] Generally, only one regioisomer is formed thermally and selectively, without the need of a copper-catalyst. 3*H*-1,2,3,4-triazaphosphole derivatives have a conjugated π-system with a high degree of aromaticity.[2] Typically, a whole variety of alkyl- and aryl-substituted as well as donor-functionalized azides (*R*-N_3) can be used for the preparation of triazaphospholes, but also TMS-N_3 or even H–N_3.[3] On the other hand, the substituent *R*′ can only be varied to some extend due to the limited availability of the corresponding phosphaalkynes, although less sterically demanding phosphaalkynes can be generated *in situ* prior to the cycloaddition reaction.[4]

The first few reports on the coordination chemistry of triazaphospholes have only appeared in literature as recently as 2010.[5] As ambidentate ligands the coordination to a metal center can proceed either *via* the phosphorus atom or the nitrogen donors N(1) or N(2) (Chart 1, **C**).[6]

Despite the few reported examples on the coordination chemistry of 3*H*-1,2,3,4-triazaphosphole derivatives, very little is known about their reactivity.[7] *N*-Aryl/alkyl-substituted triazaphospholes are thermally robust and do not show any sign of reactivity upon irradiation with UV light ($\lambda \geq 280$ nm).[7a] We therefore anticipated that the hitherto unknown introduction of an electron-withdrawing substituent at the N(3)-atom might change the coordination properties and reactivity of the corresponding heterocycle considerably. As a matter of fact, the phosphorus-lacking *N*-sulfonyl-1,2,3-triazoles show interesting chemical transformations in the presence of [$Rh_2(OAc)_4$].[8,9] Inspired by this fascinating reactivity, we started to transfer the chemistry of *N*-sulfonyl-1,2,3-triazoles to their phosphorus congeners and report here on our first results into this direction.

4-Methylbenzenesulfonylazide (**1a**) and mesitylsulfonylazide (**1b**) were prepared according to literature procedures.[10] As anticipated, the 1,3-dipolar cycloaddition reaction of **1a/b** with ^{t}BuC≡P afforded the desired *N*-arylsulfonyl-substituted triazaphospholes **2a/b**, which were obtained as white solids in up to 85% yield after recrystallization from pentane (Scheme 1). Both compounds do not show any sign of decomposition when stored under inert conditions for several weeks.

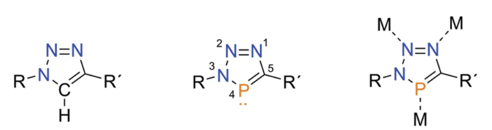

Chart 1 Triazaphosphole **A**, triazole **B** and possible coordination modes **C**.

[a] Freie Universität Berlin, Institute of Chemistry and Biochemistry, Fabeckstr. 34/36, Berlin 14195, Germany. E-mail: c.mueller@fu-berlin.de, yueerlin@yau.edu.cn
[b] Shaanxi Key Laboratory of Chemical Reaction Engineering, Key Laboratory of New Energy & New Functional Materials, College of Chemistry and Chemical Engineering, Yan'an University, Yan'an, Shaanxi 716000, People's Republic of China

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‡ These authors have contributed equally.

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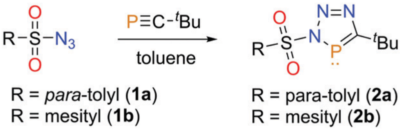

Scheme 1 Synthesis of triazaphospholes **2a/b**.

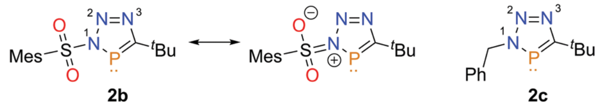

Fig. 2 Resonance structures of **2b** and comparison of **2b** with **2c**.

The hitherto unknown *N*-arylsulfonyl-triazaphospholes show single resonances in the $^{31}P\{^1H\}$ NMR at δ(ppm) = 177.2 (**2a**) and δ(ppm) = 175.2 (**2b**) in DCM-d_2. Although the *N*-arylsulfonyl group is supposed to be an electron withdrawing substituent, the resonances of **2a/b** in the $^{31}P\{^1H\}$ spectra are only slightly shifted more downfield compared to the literature known benzyl-substituted triazaphosphole **2c** (δ(ppm) = 171.4, DCM-d_2, see Fig. 2).[1b,6b]

Single crystals of **2b** suitable for X-ray diffraction were obtained by slow diffusion of diethyl ether into a dichloromethane solution of the compound at low temperature. The molecular structure is shown in Fig. 1 along with selected bond lengths and angles. Compound **2b** crystallizes in the monoclinic space group $P2_1/c$. While the NMR spectroscopic data of **2a/b** are very similar to triazaphosphole **2c**, the crystallographic characterization of **2b** reveals a clear influence of the *N*-arylsulfonyl group on the bond distances within the P-heterocycle (Fig. 2 and Table 1). As a matter of fact, the N(1)–N(2) distance in **2b** is longer than in the known compound **2c**, while the N(2)–N(3) distance is shorter. Moreover, both the C(1)–N(3) and P(1)–N(1) bond lengths in **2b** are longer, while the C(1)–P(1) bond lengths is shorter compared to the situation in **2c**.[6b]

As also observed for *N*-sulfonamides, the N(1)–S(1) bond is with 1.7108(16) significantly shorter than the predicted value for pure S–N-single bonds, indicating the presence of a resonance structure with a partial S=N double bond (Fig. 2).[11]

Accordingly, the structural parameters are in line with a significant disruption of the aromaticity in **2b** along with more localized bonds (Fig. 2).

Apparently, the electronic structures of the hitherto unknown *N*-sulfonyl-substituted phosphorus heterocycles **2a/b** differ considerably from classical aryl- and alkyl-functionalized triazaphospholes. This should consequently also lead to a pronounced different chemical reactivity of **2a/b** in comparison to **2c**. As we were primarily interested in the coordination chemistry of aromatic $\lambda^3\sigma^2$-phosphorus compounds, also with respect to applications, we first considered the reaction of **2a/b** with AuCl·$S(CH_3)_2$. It is well documented that phosphorus in low-coordination readily forms complexes with Au(I).[12]

Table 1 Comparison of selected bond lengths in **2b** and **2c**[6b]

	P(1)–C(1)	P(1)–N(1)	N(1)–N(2)	N(2)–N(3)	N(3)–C(1)
2b	1.7047(16)	1.7047(16)	1.364(2)	1.298(2)	1.369(2)
2c	1.7128(17)	1.6834(19)	1.340(2)	1.314(2)	1.351(3)

Interestingly, a spontaneous and vigorous gas-evolution is observed when dichloromethane is added to a 1 : 1 mixture of either **2a** or **2b** and AuCl·$S(CH_3)_2$ at room temperature. The gas was identified as dinitrogen by means of GC-TCD. For triazaphosphole **2b** (R = mesityl), the $^{31}P\{^1H\}$ NMR spectrum of the slightly yellow reaction mixture shows only two resonances at δ(ppm) = 133.9 and δ(ppm) = 11.6 in a ratio of approximately 4 : 1. Stirring the reaction solution for 2 h at T = 60 °C immediately after addition of the solvent leads, however, to a ratio of 20 : 1 (Fig. 3b). The isolation of the pure, air and moisture sensitive product **3b** in 36% yield was achieved by washing the reaction mixture with toluene. For **2a** (R = *p*-tolyl) the reaction seems to be less selective (see Fig. S10, ESI†).

Crystals of **3a** and **3b**, suitable for X-ray diffraction, could be obtained from both reaction mixtures. Dissolving the crystalline material of **3b** in dichloromethane gave indeed the identical resonance of the major product observed in the $^{31}P\{^1H\}$ NMR spectrum of the reaction mixture (Fig. 3c). Much to our surprise, the crystallographic characterization of **3a** and **3b** reveals the formation of a *cyclo*-1,3-diphospha(III)-2,4-diazane, rather than the presence of a simple triazaphosphole-Au(I) complex. Moreover, the *cyclo*-diphosphadiazane serves as a ligand, which binds to a total of two Au(I)Cl fragments *via* both phosphorus donors. The molecular structure of **3b** is depicted in Fig. 4, along with selected bond lengths and angles (for the

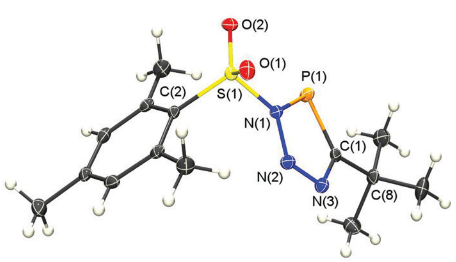

Fig. 1 Molecular structure of **2b** in the crystal. Displacement ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (°): P(1)–N(1): 1.7047(16), N(1)–N(2): 1.364(2), N(2)–N(3): 1.298(2), N(3)–C(1): 1.369(2), C(1)–P(1): 1.715(2), N(1)–S(1): 1.7108(16), S(1)–O(1): 1.4232(14), S(1)–O(2): 1.4280(14). N(1)–P(1)–C(1): 85.35(9).

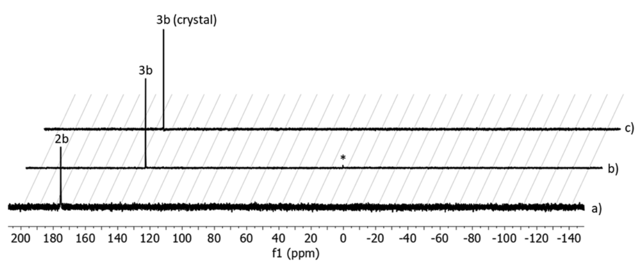

Fig. 3 $^{31}P\{^1H\}$ NMR spectra of **2b** (a), the reaction mixture (b) and of the obtained crystals (c). (*): unidentified species.

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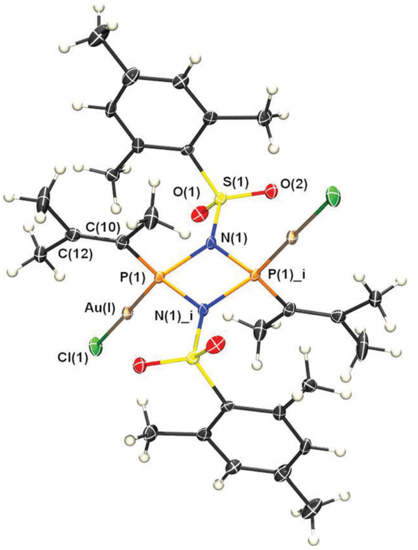


Fig. 4 Molecular structure of **3b** in the crystal. Displacement ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angels (°): P(1)–N(1): 1.730(3), N(1)–P(1)_i: 1.727(3), N(1)–S(1): 1.675(3), P(1)–Au(1): 2.2087(11), P(1)–C(10): 1.778(4), C(10)–C(12): 1.352(6). N(1)–P(1)–N(1)_i: 79.87(18), P(1)–N(1)–P(1)_i: 100.13(18).

single crystal X-ray structure of **3a** see Fig. S2, ESI†). Based on the structural characterization of **3a/b**, the novel and, in the case of **2b**, highly selective "one-pot" reaction with stoichiometric amounts of $AuCl{\cdot}S(CH_3)_2$ under formation of a dinuclear *cyclo*-diphosphadiazane–Au(I) complex is summarized in Scheme 2.

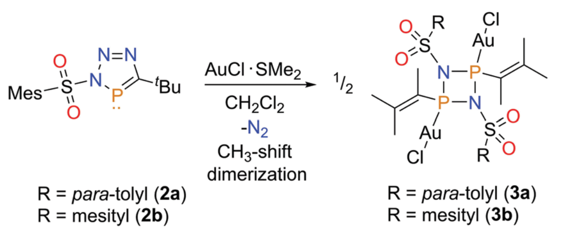
As a matter of fact, such N_2P_2 heterocylces are most commonly obtained as 1,3-dichloro-*cyclo*-1,3-diphospha(III)-2,4-diazanes of the type [ClP(μ-NR)$_2$PCl] by reacting primary amines with PCl_3.[13] Subsequent reaction with appropriate nucleophiles leads to *cyclo*-diphosphadiazanes of the type [R′P(μ-NR)$_2$PR′] (R′ = alkyl, aryl; OR, NR″$_2$, NHR″), which can then be converted to the corresponding coordination compounds by reaction with an appropriate metal precursor.[14] Importantly, there are no reports on cyclodiphospha(III)zanes featuring the exact susbstitution pattern of **3a/b**, potentially due to synthetic difficulties.[15] Therefore, our here described approach offers access to novel P_2N_2 heterocycles, which were so far not accessible.

3b crystallizes in the space group $P2_1/c$. In **3b** (as well as in **3a**, Fig. S2, ESI†) a perfectly planar P_2N_2-ring with both the R-groups and the Au(I)Cl-fragments at the phosphorus atoms pointing in opposite directions (*trans* isomer) is present. As observed for other *cyclo*-1,3-diphosphadiazanes, the nitrogen atoms are almost planar (sum of bond angles 359.3°), while the λ^3,σ^3-phosphorus atoms are pyramidally coordinated and bind each *via* the lone pair to the Au(I) center.[14a] The P–N bond lengths of 1.730(3) Å and 1.727(3) Å are slightly shorter than observed in other *cyclo*-diphosphadizanes, which might be due to a reduced electrostatic repulsion between the P- and N-lone pairs, which are involved in an interaction with the metal center and the $-SO_2R$ substituent, respectively.

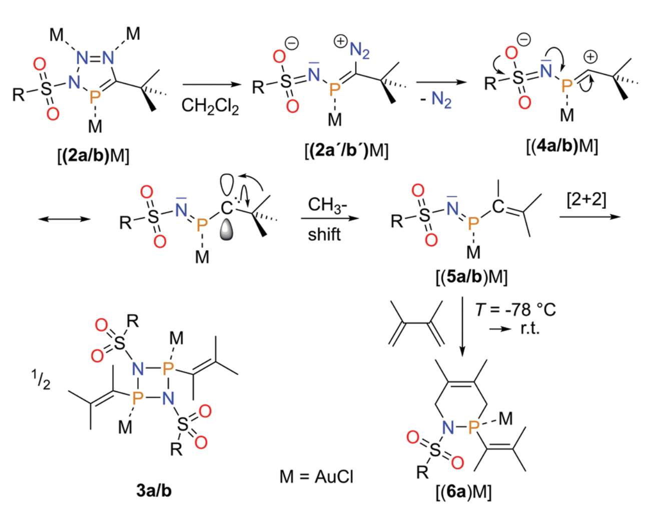
The most striking feature of **3b** (and **3a**, Fig. S2, ESI†) is, however, that the ^{t}Bu-group of the original triazaphosphole was converted into an iso-pentenyl substituent. Obviously, a CH_3-shift took place during the conversion **2a/b** → **3a/b**, which implies the formation of a carbene intermediate. This has also been observed by Fokin and co-worker during the Rh-catalyzed denitrogenative transformation of a ^{t}Bu-substituted 1-sulfonyl-1,2,3-triazole into a tetrasubstituted iminoalkene.[8]

The rather selective conversion **2a/b** → **3a/b** requires the presence of stoichiometric amounts of $AuCl{\cdot}S(CH_3)_2$. We could not observe the formation of any *cyclo*-diphosphadiazane upon heating **2a/b** in the absence of Au(I). Moreover, the presence of the electron withdrawing *N*-sulfonyl-group at N(3) is crucial for the dinitrogenative generation of **3a/b**, as the $PhCH_2$-substituted triazaphosphole **2c** does not undergo the transformation to the corresponding N_2P_2-heterocycle.

Based on NMR-spectroscopic data, we propose the following mechanism for the conversion of the *N*-sulfonyl-triazaphosphole into the corresponding Au(I)-complex: the Au(I)Cl-fragment first coordinates to the donor-atoms of the phosphorus heterocycle in a dynamic exchange process (Scheme 3).[16] Due to the electron-withdrawing nature of the *N*-sulfonyl-group, the aromaticity of the triazaphosphole is strongly disrupted and ring-opening to [(**2a′**/**b′**)AuCl] is facilitated. Loss of dinitrogen gives the zwitterionic species [(**4a/b**)AuCl], for which a neutral resonance structure exist. According to the HSAB concept, we anticipate that the Au(I)-fragment coordinates exclusively to the remaining soft phosphorus atom in [(**4a/b**)AuCl]. The neutral species is an



Scheme 2 Synthesis of *cyclo*-1,3-diphospha-2,4-diazane-Au(I)-complexes **3a/b**.



Scheme 3 Proposed mechanism for the formation of **3a/b**.

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iminophosphine-carbene, which undergoes a [1,2]-CH_3-shift to the more stable iminophosphine [(**5a/b**)AuCl]. Iminophosphinines are known to form dimers and even trimers from the parent monomer depending on the substituents on both the phosphorus and nitrogen atom. Dimerization of [(**5a/b**)AuCl], especially in presence of electron-withdrawing sulfonyl groups then leads to the observed main product **3a/b** (Scheme 3).[17]

In order to identify the reactive iminophosphine [(**5a/b**)AuCl] as an intermediate in the proposed mechanism, *N*-tosyl-triazaphosphole **2a** and AuCl·SMe_2 were cooled to $T = -196$ °C and a solution of dimethylbutadiene as a trapping reagent in dichloromethane was condensed into the reaction vessel. The solution was first stored at $T = -78$ °C and then slowly warmed to room temperature over 6–8 hours. Subsequent $^{31}P\{^1H\}$ NMR spectroscopy at room temperature showed only one major phosphorus resonance at δ(ppm) = 104.0. Analysis of the product by means of ESI-MS indeed provided evidence for the expected trapping product [(**6a**)AuCl] (Scheme 3). Further confirmation for cyclodiphosphazane formation *via* dimerization of two iminophosphines is provided by a cross-reaction of a 1 : 1 mixture of **2a** and **2b** with AuCl·SMe_2 in DCM. In this case the $^{31}P\{^1H\}$ NMR of the reaction mixture showed the formation of **3a** and **3b** as well as a third species at δ(ppm) = 130.7, which we tentatively assigned to a mixed N-SO_2-Tol/N-SO_2-Mes substituted P_2N_2 ring. A similar cross reactivity in phosphazane chemistry has recently been described by Wright *et al.* as the authors also found evidence for the transient formation of monomeric phosphazane intermediates.[18]

We could demonstrate for the first time that 3*H*-1,2,3,4-triazaphosphole derivatives, containing electron-withdrawing *N*-sulfonyl-groups at the N^3 atom, are synthetically accessible. These phosphorus heterocycles show a remarkable different reactivity compared to their classical alkyl- or aryl-substituted counterparts. Interestingly, the hitherto unknown *N*-sulfonyl-1,2,3,4-triazaphospholes undergo a highly selective and unprecedented transformation to *cyclo*-1,3-diphospha(III)-2,4-diazane-Au(I) complexes in the presence of stoichiometric amounts of AuCl·$S(CH_3)_2$ and loss of N_2. Single crystal X-ray diffraction studies show, that the *trans*-isomer of the substituted N_2P_2 heterocycle has been generated, while NMR-spectroscopic and mass-spectrometric investigations give insight into the mechanism of its formation. Our results pave the way to explore the chemistry of *N*-sulfonyl-substituted triazaphospholes in detail and provide a first step in transferring the fascinating chemistry, reported for the phosphorus-lacking *N*-sulfonyl-1,2,3-triazoles, to their isolobal phosphorus congeners.

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Conflicts of interest

There are no conflicts to declare.

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