Modifiable bidentate systems via N-C rearrangement in triazoles[†]‡

Elana A. Slutsky Smith, Gregory Molev, Mark Botoshansky and Mark Gandelman*

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A new N–C rearrangement of substituted triazoles has been discovered. This process has been applied to the synthesis of diverse classes of mixed bidentate ligands and their metal complexes with highly modifiable backbones, including the first bisphosphine zwitterionic system based on a triazole frame.

Recently, we reported on the first combinatorial approach towards the synthesis of *tridentate* ligands.¹ This methodology was based upon the Cu(1) catalyzed [2+3] cycloaddition of alkynes and azides, forming 1,4-substituted triazoles, as the general strategy for ligand assembly.^{2–4} Selective combinatorial preparation of mixed bidentate ligands by covalent assembly of two monomeric donor units would additionally be of high interest.⁵ Remarkably, while 1,4-substituted triazoles prepared by click chemistry are widely used for molecular assembly, the complementary regioisomer, the 1,5-substituted triazole, is practically unemployed for building functional compounds with completely different molecular geometry. We hypothesized that selective synthesis of 1,5-substituted triazoles via reaction of metal acetylides with organic azides could be a useful building tool for this purpose (Scheme 1).⁶ Here we report that, in the course of our studies, we have discovered a new N-C rearrangement of substituted triazoles, mediated by phosphine oxide. Although N-N rearrangements in triazoles are documented, the N-C counterparts are yet unprecedented.⁷ Based on this rearrangement, bisphosphine ligands, possessing a neutral or negatively charged highly modifiable triazole backbone, and their metal complexes were prepared for the first time.⁸ Among these complexes is an unprecedented triazole-derived bisphosphine zwitterionic metal system.

The envisioned synthetic route for ligand preparation (including a previously proposed mechanism) is presented in Scheme $1.^6$ Our approach was to combine azides 1 and acetylides 2, each decorated with a monomeric ligand unit



Scheme 1 Mechanism for selective synthesis of 1,5-substituted triazoles.

Schulich Faculty of Chemistry, Technion-Israel Institute of Technology, Technion City, Haifa 32000, Israel.



Scheme 2 Synthesis of bisphosphines 6 via rearrangement.

 $(D_1 \text{ and } D_2)$, in order to directly form desired *mixed* bidentate systems in a combinatorial manner. In order to check our hypothesis, the prepared alkyne 3 was converted to acetylide 4 and then reacted in situ with azide 5a (Scheme 2).9 To our surprise, the single isolated product of this reaction was the 4,5-substituted triazole 6a rather than the expected 1,5-substituted isomer 7a. The ³¹P NMR spectrum of 6a exhibits a singlet at 18 ppm for $(Ph)_2 P(O)$ and a multiplet (due to P-B coupling) at 31 ppm for $(i-Pr)_2 P(BH_3)$. Both signals are in the range characteristic of a $P = E (E = BH_3 \text{ or } O)$ group bound to carbon. The P-N pattern expected for the 1,5-isomer 7a would typically resonate at ~ 70 ppm in ³¹P NMR.¹⁰ The two carbons of the triazole appear as doublets in ¹³C NMR due to the coupling with P-based substituents. The molecular structure of 6a was confirmed by X-ray analysis of its single crystals (Fig. 1).¹¹ Thus, the net result of this reaction is the transfer of the phosphine group from the 1-N to the 4-C position of the triazole ring.

Remarkably, when phenyl acetylene (8a) or diphenylethynylphosphine borane complex 8b (which differs from 3 only in the phosphine protecting group) was reacted with azide 5a under conditions identical to the previous experiment, non-rearranged 1,5-substitued triazoles 9 were obtained (Scheme 3). Signals of these products in ³¹P NMR at 71 and 73 ppm, for 9a and 9b correspondingly, are typical for phosphorus substituted with a nitrogen atom ($(iPr)_2P(BH_3)$ –N fragment; for comparison of ³¹P NMR spectra of rearranged and non-rearranged products 6a and 9 see figure in ESI).‡¹⁰ The lack of N-to-C group transfer in these control experiments



Fig. 1 Perspective view of molecule 6a. Hydrogen atoms (except N–H) are omitted for clarity.

E-mail: chmark@tx.technion.ac.il; Fax: +972 4-829-5703

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Scheme 3 No rearrangement observed in reactions with acetylides lacking phosphine-oxide moiety.

indicates that the phosphine oxide group of **3** is crucially involved in the rearrangement process illustrated in Scheme 2. The observed formation of **9** points toward an intermediate of type **10** (formed in the course of the reaction of **3** with **5**; Scheme 1) as the most probable species to undergo rearrangement.¹²

The driving force of this rearrangement is apparently the formation of the stronger P–C and N–Mg bonds rather than the respectively weaker P–N and C–Mg bonds. Indeed, DFT calculations at b31yp/6-31 + g(d,p) level of theory¹³ show that such bond reorganization is favorable by 45.6 kcal mol⁻¹ for **11a** (Scheme 4). Interestingly, such rearrangement for species **11b** is equally enthalpically favored. The same thermodynamic driving force for **11a** and **11b** (the analogue of which does not, in practice, undergo N-to-C transfer) supports the involvement of the phosphine oxide unit in this rearrangement. Detailed mechanistic studies of this rearrangement as well as further applications of phosphine oxides in related activation/transfer processes are under thorough investigation in our labs and will be published elsewhere.

This new rearrangement is not limited to azide **5a**. For example, phosphinoazides **5b** and **5c** also undergo this process to furnish compounds **6b** and **6c**, respectively (Scheme 2). The fastest and most facile reaction was observed for **5b**, which bears the least sterically congested ethyl substituents on the phosphorus atom (the isolated yield was 85%).

Compounds 6 represent very attractive substrates for the synthesis of diverse families of bidentate ligands for transition metals. When refluxed in methanol, 6a undergoes selective deboranation to result in the novel triazole-based bisphosphine monooxide ligand 12 (Scheme 5). This compound on its own is of particular interest, since bidentate ligands bearing hard-soft donor pairs have found spectacular applications in









Scheme 6 Type of complex formed is dependent upon ligand charge.

catalysis.¹⁴ Compound **12** is reduced to give the nonsymmetrical bisphosphine ligand **13** in excellent yield. The triazole frame can be further functionalized by selective deprotonation of the N–H to furnish the anionic nonsymmetrical ligand **14**, or by N-substitution to form the neutral alkylated ligand **16** (Scheme 5).

Due to our interest in mixed soft ligands, we investigated the coordination behavior of bisphosphines 13, 14, and 16 with late transition metals. Ligand 13 did not demonstrate selective chelation and irresolvable mixtures of products were usually obtained upon its reaction with various metal precursors. This is likely due to the relatively acidic N-H bond of the triazole. Indeed, to our delight, both anionic 14 and methylated neutral counterpart 16 exhibited selective behavior with late transition metals and their coordination mode depends on the charge of the backbone. When ligand 16 reacts with (COD)PtCl₂ (COD = cyclooctadiene), exclusive formation of complex 17 is observed (Scheme 6). The ³¹P NMR spectrum of 17 shows two doublets at 1.8 and 35.1 ppm with a typical cis phosphorusphosphorus coupling constant of 6.9 Hz. ¹⁹⁵Pt-P satellites for both doublets with $J_{PPt} = 3741$ and 3542 Hz, respectively, clearly indicate coordination of both phosphine arms to the platinum center. An X-ray analysis of single crystals of 17 shows a distorted square planar structure with P-Pt-P bite angle of 89.81(0.12)° (Fig. 2a).

Completely different reactivity was observed for the negatively charged ligand 14. Quantitative formation of zwitterionic complex 18 was obtained upon reaction of 14 with the same platinum precursor (Scheme 6). The driving force for the formation of this bis-diphosphine compound is apparently the precipitation of NaCl. The ³¹P NMR spectrum of 18 exhibits two triplet sets with ¹⁹⁵Pt–P satellites which indicate binding of two ligands per platinum center. The structure of 18 was confirmed by X-ray analysis (Fig. 2b). The platinum atom is located at the intersection of the two five-membered chelate rings and the whole molecule has C_2 symmetry. Compound 18 represents the first example of a



Scheme 5 Synthesis of ligands 12, 13, 14, and 16.



Fig. 2 Perspective view of molecules (a) 17 and (b) 18.

zwitterionic bisphosphine complex based on a triazole frame. Although examples of mesoionic or "truly zwitterionic" metal complexes bearing chelating bidentate ligands with negatively charged backbones are limited, they have found spectacular applications in inorganic and organometallic chemistry.^{15,16} As such, complexes based on anionic ligand **14** represent an attractive extension of this family of compounds.

The prepared ligand set allows for direct access to both neutral and zwitterionic metal complexes. Since ligands 14 and 16 are isostructural and isoelectronic, they open the door to direct evaluation of the influence of ligand-charge on the properties of the metal center. Moreover, our zwitterionic system offers an interesting alternative to the known bisphosphine boronate-based zwitterionic complexes, as the charged triazolide backbone (possessing an N⁻ unit) can be further functionalized or can serve as an additional reaction center.¹⁶

In summary, we have discovered a new N–C rearrangement of substituted triazoles which represents a valuable extension of the chemistry of these increasingly useful compounds. This allowed us to prepare novel diverse classes of bisphosphine ligands and their metal complexes with highly modifiable triazole backbones. These include the first zwitterionic complex prepared based on a bisphosphine triazole frame. Investigation of the properties of these systems, especially of the potential for cooperative chemistry between the basic/ nucleophilic negatively charged triazolide ligand and the metal center, is currently underway in our labs.

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