Arsenic Heterocycles

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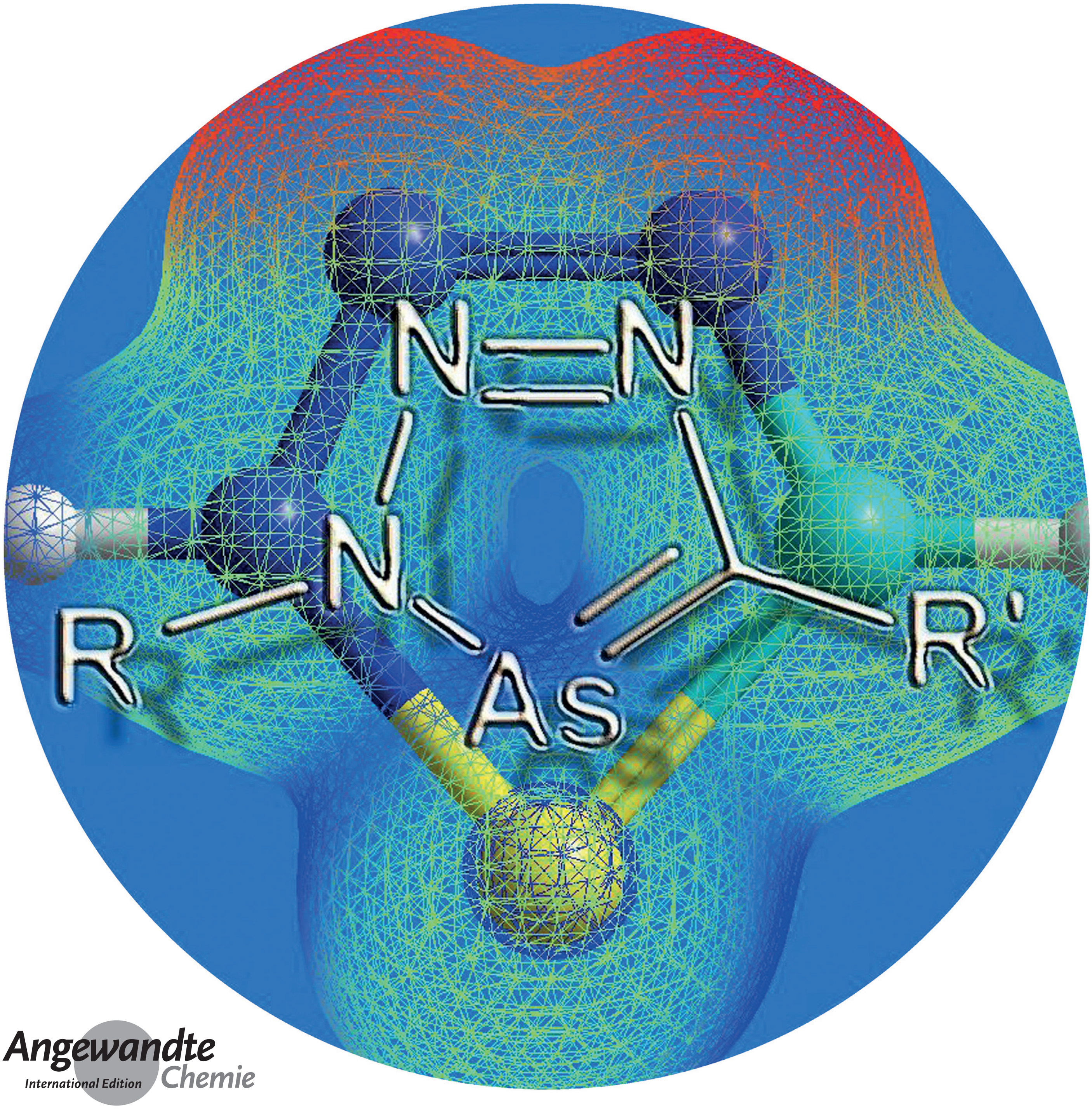
Clicking the Arsenic–Carbon Triple Bond: An Entry into a New Class of Arsenic Heterocycles

*Gregor Pfeifer, Martin Papke, Daniel Frost, Julian A. W. Sklorz, Marija Habicht, and Christian Müller**

Dedicated to Professor Konstantin Karaghiosoff on the occasion of his 60th birthday



Abstract: *Arsaalkynes can undergo regioselective and quantitative [3+2] cycloaddition reactions with organic azides to give hitherto unknown 3H-1,2,3,4-triazaarsole derivatives. The reaction product was obtained as a white, air- and moisture-stable solid, and the presence of a planar, five-membered arsenic heterocycle was unambiguously verified by means of X-ray crystallography. DFT calculations gave insight into the electronic structure of these novel compounds compared to tetrazoles and triazaphospholes. The coordination chemistry towards* Re^I *was investigated and compared with the structurally related phosphorus-containing ligand. These preliminary investigations pave the way for a new class of arsenic heterocycles and fill the gap between the azaarsoles already known.*

Since the preparation of tetramethyldiarsine by Cadet de Gassicourt in 1760, organoarsenic compounds have played an important role in various topics of chemistry, ranging from concepts of chemical bonding and valency to aromaticity.[1] In addition, various beneficial pharmacological effects as well as technological applications of organoarsenics have been reported.[1,2] Although now well-established, stable compounds containing multiple bonds between carbon and heavy main-group elements are still fascinating because they clearly violate the classical double bond rule as a result of an unfavorable overlapping of the (As_{4p}-C_{2p}) orbitals. In this respect, the chemistry of so-called low-coordinate arsenic compounds has been investigated to some extent during the last few decades, but this field is certainly dominated by their unsaturated organophosphorus congeners.

Figure 1 shows the most prominent heterocyclic species containing arsenic–carbon and arsenic–nitrogen $(p\text{-}p)\pi$ bonds. With the synthesis of arsamethine-cyanines (**A**), Märkl and Lieb reported the first evidence of the existence of this type of bonding in 1967.[3] By integrating the As=C bond into an aromatic system, Jutzi and Bickelhaupt accessed the highly reactive 9-arsaanthracene (**B**).[4] Ashe III finally prepared the more stable and aromatic parent arsinine C_5H_5As (**C**, R = H) in 1971. This was followed by the even more kinetically stabilized aryl-substituted arsinines by Märkl et al. in 1983.[5] Smaller heterocycles are also available nowadays. Jones and co-workers reported the coupling reaction of an arsaalkyne with 1,3-diarsacyclobutadiene (**D**).[6] More recently, the Goicoechea research group used the 2-arsaethynolate anion $AsCO^-$ to access four-membered anionic compounds (**E**) in a [2+2] cycloaddition reaction.[7] Arsenic heterocycles containing additional nitrogen atoms are also well known. Heinicke et al. pioneered and extensively explored the family of azaarsole derivatives of type **F**.[8] Diazaarsoles (**G**) can be prepared by the reaction of methylketone phenylhydrazone with arsenic trichloride.[9]

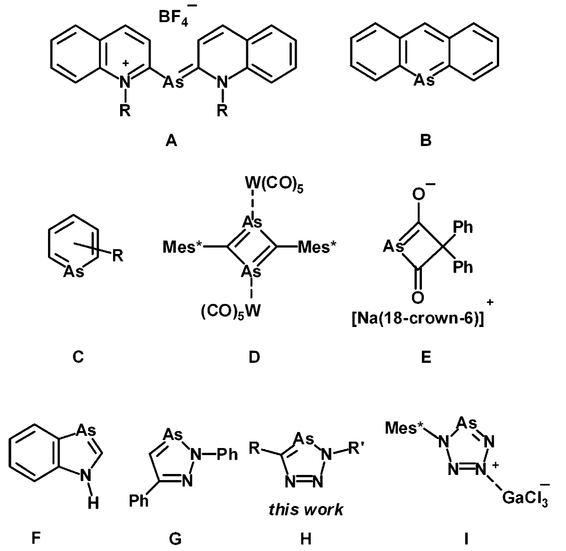


Figure 1. Arsamethine-cyanine (**A**) and arsenic heterocycles (**B**–**I**).

Recenty, the group of Schulz prepared and structurally characterized a neutral tetrazaarsole stabilized as a $GaCl_3$ adduct (**I**).[10] Intrigued by the fact that arsenic heterocycles containing three nitrogen atoms have not yet been reported, we set out to investigate an entry into the family of triazaarsoles of type **H**, as the "missing link" between **F**, **G**, and **I**.

Triazoles can generally be prepared by a Huisgen [3+2] cycloaddition reaction between an organic azide and an alkyne.[11] Regioselectivity in this transformation can, however, only be achieved in the presence of a copper catalyst (copper-catalyzed alkyne-azide "click" reaction, CuAAC).[12] On the other hand, the reaction of phosphaalkynes and azides selectively leads to 3*H*-1,2,3,4-triazaphosphole derivatives, even in the absence of a catalyst.[13] Interestingly, however, the [3+2] cycloaddition reaction of an organic azide with an arsaalkyne has not been reported before. We therefore prepared (2,4,6-tri-*tert*-butylbenzylidyne)arsane (**1**) according to a literature procedure by the reaction of 2,4,6-tri-*tert*-butylbenzoyl chloride with $LiAs(TMS)_2$ (TMS = trimethylsilyl) in THF.[14] Subsequently, **1** was treated with 2-(azidomethyl)pyridine (**3**) in dichloromethane at room temperature. Much to our surprise and as judged by means of ^1H NMR spectroscopy, the starting materials were cleanly and quantitatively converted into a single new product (**4**), which was isolated as a white solid in 32% yield. ESI-TOF analysis of **4** reveals an $[M+H]^+$ signal with $m/z = 467.2148\ g\,mol^{-1}$, which indeed indicates the presence of the triazaarsole.

Figure 2a illustrates part of the ^1H NMR spectrum of **4**, with five distinct signals in the aromatic region (1:1:2:1:1) as well as a singlet at $\delta = 6.03$ ppm, which integrates to two protons. For comparison reasons, we also reacted phosphaalkyne **2** with azide **3** to give triazaphosphole **5** (Scheme 1).[15] The ^1H NMR spectrum of **5** in CD_2Cl_2 is almost identical, except for the resonances of the CH_2 protons, which appear as a pseudodoublet at $\delta = 5.95$ ppm (Figure 2b).

Although the ^1H NMR spectra of **4** and **5** are not very informative, the the $^{13}C\{^1H\}$ NMR data show a clear differ-

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[*] Dipl.-Chem. G. Pfeifer, M. Sc. M. Papke, B. Sc. D. Frost,
M. Sc. J. A. W. Sklorz, M. Sc. M. Habicht, Prof. Dr. C. Müller
Institut für Chemie und Biochemie
Freie Universität Berlin
Fabeckstrasse 34/36, 14195 Berlin (Germany)
E-mail: c.mueller@fu-berlin.de

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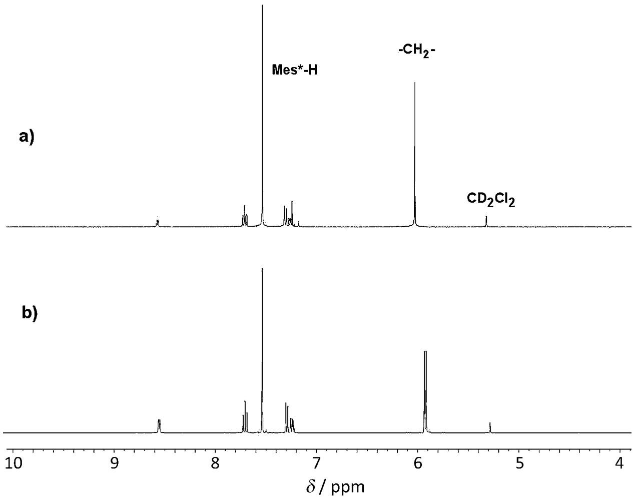
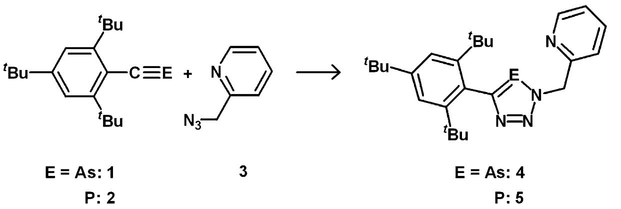


Figure 2. Part of the ^{1}H NMR spectra (CD$_2$Cl$_2$) of a) triazaarsole **4** and b) triazaphosphole **5**.



Scheme 1. Synthesis of triazaarsole **4** and triazaphosphole **5**.

ence in the resonance of the carbon atom adjacent to the heteroatom. Whereas this carbon signal can be detected at $\delta = 201.4$ ppm in the case of **4**, the corresponding resonance appears at $\delta = 183.6$ ppm (d, $J = 46.6$ Hz) in the ^{13}C{^{1}H} NMR spectrum of **5**. It should be mentioned that **4** is very insensitive towards water and oxygen, and can be stored without any decomposition in a normal vial for a prolonged period of time. This phenomenon can be attributed to the presence of the rather bulky supermesityl group, which allows significant kinetic stabilization of the arsenic heterocycle.

We were further able to obtain single crystals of triazaarsole **4** by slow crystallization from acetonitrile. The molecular structure is depicted in Figure 3 along with selected bond lengths and angles. The crystallographic characterization of **4** not only confirms that hitherto unknown triazaarsoles can be formed by a [3+2] cycloaddition reaction between an arsaalkyne and an azide, but also that this conversion proceeds regioselectively with formation of the 2,5-disubstituted heterocycle. The observed selectivity can most likely be attributed to the steric demand of both the supermesityl and benzyl groups. The five-membered arsenic heterocycle is perfectly planar with an As(1)−C(7) bond length of 1.860(5) Å and an As(1)−N(2) bond length of 1.839(4) Å, thus indicating a significant degree of π-conjugation or even aromaticity.

The single-crystal X-ray diffraction analysis of the first triazaarsole further allows a comparison of the structural parameters of **4** with the known ones of triazaphospholes.[16]

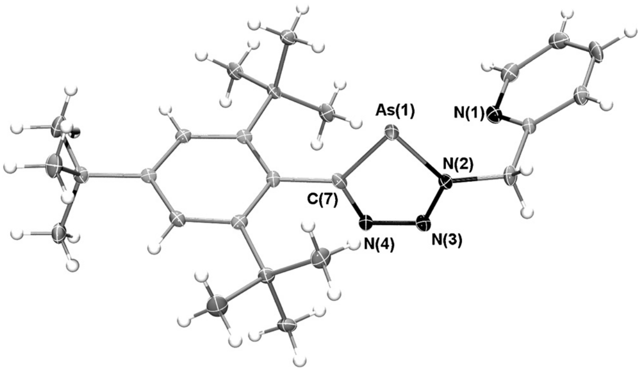


Figure 3. Molecular structure of **4** in the crystal. Displacement ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (°): As(1)-C(7): 1.860(5), As(1)-N(2): 1.839(4), N(2)-N(3): 1.341(5), N(3)-N(4): 1.320(4), N(4)-C(7): 1.353(5). C(7)-As(1)-N(2): 81.40(14).[19]

In Figure 4 it can be noted that the replacement of a phosphorus atom by an arsenic atom in an otherwise identical structure leads to a significantly smaller N-As-C angle of 81.4° compared to an N-P-C angle of approximately 86.4° in triazaphospholes. This effect is mainly due to the substantially longer As−C (and As−N) bond compared to a P−C or P−N bond. It is interesting to note that the bond distances in the remaining N-N-N-C part of the molecules are very similar in both heterocycles.

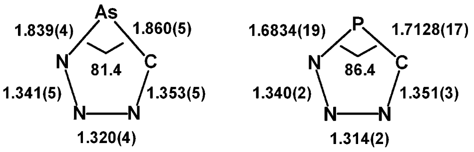


Figure 4. Structural comparison of **4** (left) with a triazaphosphole (right).

To gain insight into the electronic structure of the novel triazaarsole we performed calculations at the DFT level (B3LYP, cc-pVTZ) on the parent compound AsN(H)N$_2$C(H). The frontier orbitals are depicted in Figure 5 and are compared with those of the parent tetrazole and triazaphosphole. It can be seen that the HOMO–LUMO gap becomes smaller in going from tetrazole to triazaarsole. Similar to the situation in triazaphosphole, the LUMO of the low-coordinate arsenic heterocycle shows a large coefficient with π-symmetry at the arsenic atom, which indicates such systems have π-accepting properties through the heteroatom. This is much less pronounced in the corresponding tetrazole. The π-donor properties of triazaarsole and triazaphosphole are clear from their HOMOs, which again have a large coefficient of

π-symmetry at the As and P atoms, respectively. In contrast, the sequence of the HOMO and HOMO-1 in the parent tetrazole is reversed with respect to the situation in the other two heterocycles. This change in order has been observed for the frontier orbitals of imines and phosphaalkenes.[17] The

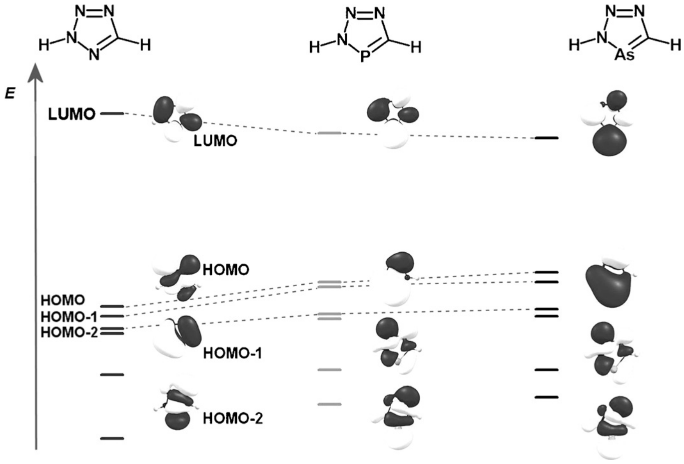


Figure 5. Selected molecular orbitals of tetrazole, triazaphosphole, and triazaarsole.

lone pair of electrons at the heteroatom is represented in all heterocycles by the energetically low-lying HOMO-2.

As pyridyl-functionalized triazaphospholes undergo facile reaction with $[Re(CO)_5Br]$ under formation of the complex $[(L)Re(CO)_3Br)]$, we decided to also explore the coordination chemistry of **4** and **5** towards Re^I.[18] Compounds **4** and **5** were thus treated with equimolar amounts of $[Re(CO)_5Br]$ in dichloromethane at $T = 80\,°C$ overnight and the final products (**6** and **7**) were isolated as light yellow solids after recrystallization from acetonitrile. To reveal the coordination mode of ligand **4** and **5**, we attempted a structural characterization of the Re^I complexes, and single crystals suitable for X-ray diffraction were obtained by slow crystallization of the coordination compounds from acetonitrile. The molecular structure of **6** in the crystal is depicted in Figures 6 along with selected bond lengths and angles (for the isostructural compound **7**, see the Supporting Information). It is clear that the chelating ligands coordinate to the Re^I center through the nitrogen atom N(3) of the triazaarsole moiety, rather than through the arsenic atom. The coordination of the least nucleophilic nitrogen atom N(3) to the metal center is apparently enforced by the chelating effect. A similar coordination mode has recently also been observed by us for analogous pyridyl-functionalized triazaphospholes.[18] Moreover, the arsenic heterocycle is again perfectly planar, as already observed for uncoordinated **4**, while the bond lengths within the five-membered ring are very similar to those of the free ligand. Interestingly, a first analysis of the IR stretching frequencies of the CO ligands reveals that **4** is a slightly stronger net donor than **5**, as $\tilde{\nu}_3$ is shifted significantly to lower wavenumbers (**6**: $\tilde{\nu} = 2023$ (s); 1925 (s); 1875 (s) cm^{-1}; **7**: $\tilde{\nu} = 2023$ (s), 1925 (s), 1894 (s) cm^{-1}).

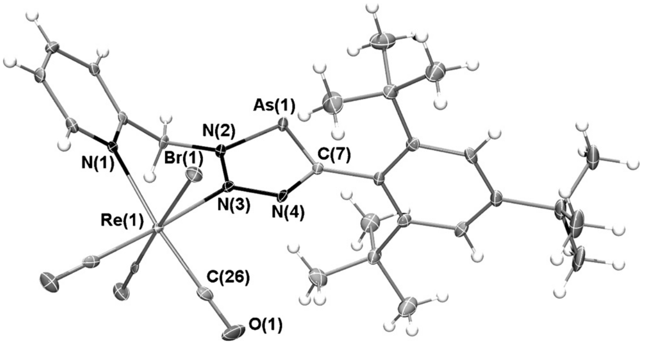
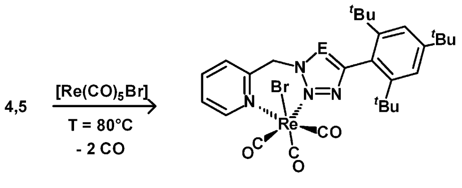


Figure 6. Molecular structure of **6** in the crystal. Displacement ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (°): As(1)-C(7): 1.859(3), As(1)-N(2): 1.832(2), N(2)-N(3): 1.342(3), N(3)-N(4): 1.319(3), N(4)-C(7): 1.343(3), N(3)-Re(1): 2.176(2), N(1)-Re(1): 2.205(2), Re(1)-Br(1): 2.6145(9). C(7)-As(1)-N(2): 81.70(11). Two CH_3CN solvent molecules are omitted for clarity.[19]

Scheme 2 summarizes the reaction of **4** and **5** with $[Re(CO)_5Br]$ to give the Re^I complexes **6** and **7**, respectively, in which coordination exclusively occurs through the nitrogen atoms to the metal center.



E = As: 6; E = P: 7

Scheme 2. Synthesis of Re^I complexes of **6** and **7**.

In summary, we have developed a facile access to a new class of arsenic heterocycles by making use of a [3+2] cycloaddition reaction between an arsaalkyne and an organic azide. The formation of the hitherto unknown air- and moisture-stable triazaarsole could be verified by means of single-crystal X-ray diffraction. A comparison with the related triazaphosphole allowed the identification of structural similarities and differences between these heterocycles, while DFT calculations provided insight into their electronic properties. The presence of an additional pyridyl group within the heterocyclic framework enabled us to probe the coordination chemistry of the potentially chelating ligand. It turned out that coordination to a Re^I fragment occurred exclusively through the pyridine moiety and the least nucleophilic nitrogen atom of the triazaarsole. Our results should offer the possibility to explore in detail the properties of this new family of nitrogen-containing arsenic heterocycles.

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Keywords: azaarsoles · cycloaddition · heterocycles · main-group chemistry · structure elucidation

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[19] CCDC 1481887 (**4**) and 1481888 (**6**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from Cambridge Crystallographic Data Centre.

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