# FINAL REPORT

Structural study of short lived organophosphorus and organosilicon compounds

In the recent project our primary interests were the multiple bounded and hypovalent phosphorus and silicon derivatives. The main questions of the project aim the synthesis, stabilization and reactivity of these compounds. Here below we collected our results according to the following topics:

1. Insertion reaction of silylenes
2. Ionic liquids using N-heterocyclic carbenes
3. Mechanisms of tri-and polymerization of phosphaalkynes
4. Synthesis and structural study of unsaturated phosphinoboranes and allanes
5. Synthesis and characterization of novel tree- and four-membered ring systems.
6. Combining the chemistries of silylene and sulfur-nitrogen compounds
7. Moleculat tayloring
8. Mercury dications: linear form is more stable than aromatic ring
9. 1,3,5-trimethylenebenzene triradicals

1. One of the most special reactions of silylenes is the insertion into different molecules. The reaction proceeds via a concerted transition state in which the vacant p-orbital and the lone pair of silicon atom interact with the σ-bonding and σ*-antibonding orbitals of the reactant, forming a three-membered ring structure and finally the product (Scheme 1):
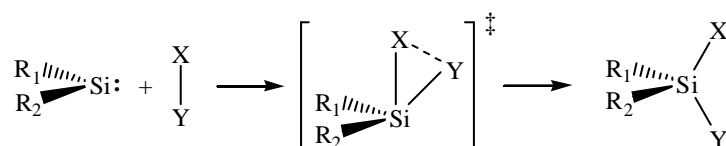
Scheme 1

In order to analyze the mechanisms, the following 56 insertion reactions between seven silylenes and eight reactants were investigated. The selected reactions were studied because experimental data for those were available. We applied the B3LYP/cc-pVTZ method for the calculations.
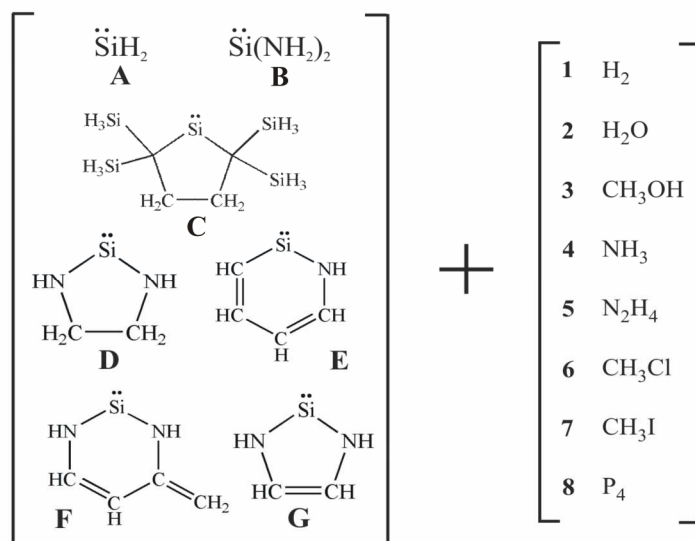
The reaction energies and the stability of the silylenes are in good correlation. Silaimidazole-2-ylidene gives the highest reaction energies while Kira's stable five membered ring dialkylsilylene shows the smallest reaction energies. All the reaction energies and activation energies of the six-membered ring diazasilylene ({HC[CMeN(R)]$_2$}Si, R= 2,6-diisopropylphenyl) were found equal to that of the saturated five-membered diazasilole. The sum of the reaction free energies (ΔG) and activation free energies (ΔG‡) of a reactant depend of the reactant but independent of the silylene (Fig. 1). [1]
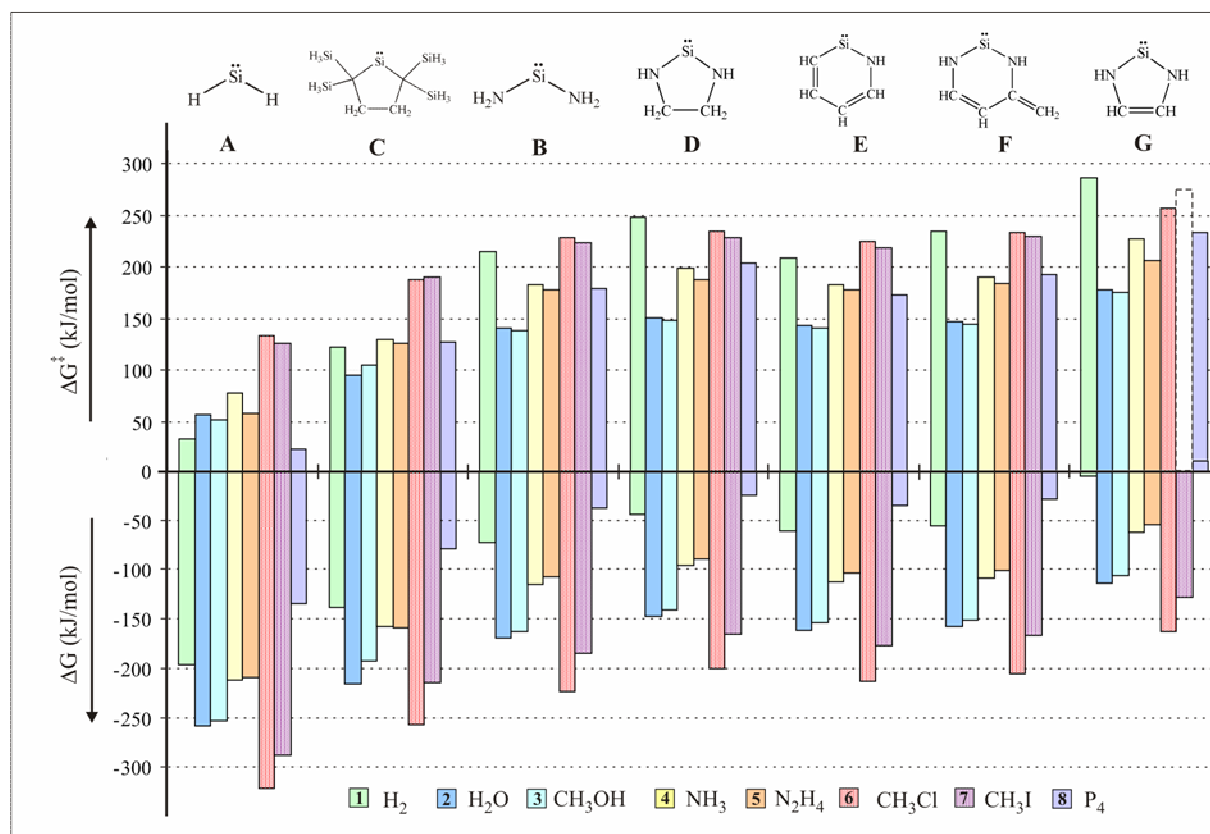

Figure 1. Gibbs free energies (negative) and activation Gibbs free energies (positive) of the investigated insertion reactions at the B3LYP/cc-pVTZ level

Since the first stable six-membered ring silylene ({HC[CMeN(R)]2}Si, *R* =2,6-diisopropylphenyl) is somewhat unique, their structure, stability and insertion reactions were separately investigated. [2,3]

The structure and stability of the unique six-membered ring silylene and its three most stable structural isomers were compared to the well-known stable Denk-silylene. The related analogous carbenes and germylenes were also studied. According to the calculated isodesmic reaction energies and NICS(0) values the six-membered ring silylene is non-armatic, but since the missing aromaticity is compensated by the reduced ring strain it is nearly as stable as the Denk-silylene. The more stable five membered ring isomer shows considerable aromatic character. The analysis of the molecular orbitals indicate that the six-membered ring is less reactive in either nucleophilic or in electrophilic reactions than the five-membered Denk-silylene. On the other hand, the analogous carbene derivatives seem to be less stable both in thermodynamic and kinetic aspects.

The insertion reactions of six-membered ring silylene with eight reactants were also studied using B3LYP/cc-pVTZ method. The initial step of all the reactions is the formation of an intermediate 1,4-adduct, which will be then the starting point towards the different final states. Three different mechanisms were found and studied to the 1,4-adduct and six reaction paths from the 1,4-adduct to the final products. Based on the results, the different reaction paths, the experimental insertion products and the special reactivity of the six-membered ring silylene have be explained.

A special insertion reaction, the activation and functionalisation of white phosphorus by transition metal complexes has recently been the focus of research because of their potential industrial applications in the synthesis of organophosphorus compounds. Though a few dozen stable silylenes have been prepared, to the best of our knowledge, so far only one could react with white phosphorus. The zwitterionic silylene **1**, reacts gently with P_4 at ambient temperature to lead to compound **2**. After one week, another insertion step takes place to give product **3** (Scheme 2).

$R=2,6\text{-}iPr_2C_6H_3$
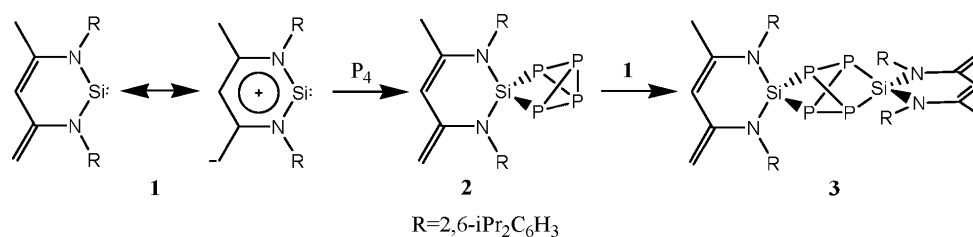
Scheme 2.

Four different mechanisms and the effect of bulky groups were studied in the reaction above. The carefully tested B3LYP-D, wB97X-D, and SOS-MP2 methods, by the CCSD(T) method, with cc-pVTZ basis set provided consonant results which support the reliability of our results and the applicability of these methods. The dispersion energy contribution to the total energy is estimated to about ~70 kJ mol-1 which proves the essential role of dispersion corrected methods. Based on the computed results we suggest a new mechanism which is fully supported by the experimental conditions. The investigation of the bulky groups clearly demonstrates an internal catalytic feature which has an essential role in the reaction mechanism. Usually bulky substituents prevent or reduce the reactivity, in this case however, substituents promote the reaction. In Fig. 2 the scheme of the mechanism can be seen.[4]
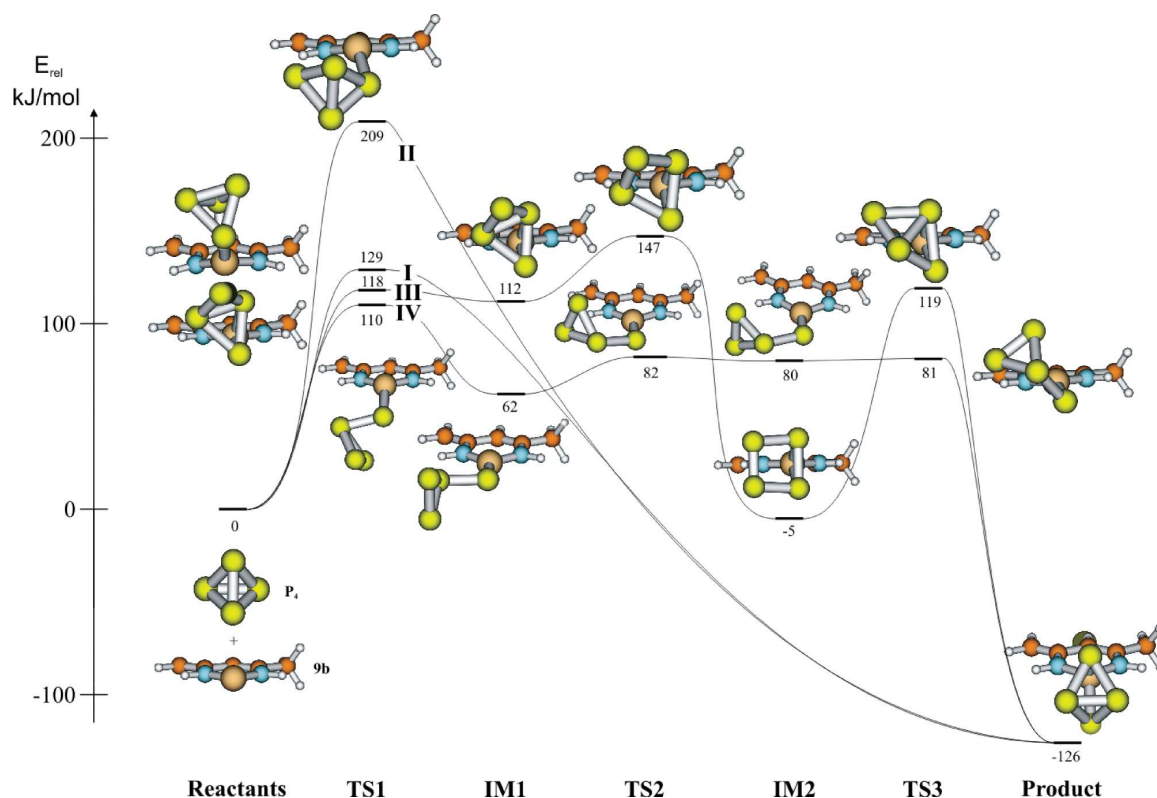
Fig. 2 Energy profile for the reaction of 1 + P4 at the SOS-MP2/cc-pVTZ//B3LYP/cc-pVTZ level. Yellow, tan, cyan, orange and white colors refer to P, Si, N, C and H atoms, respectively.

[1] Kinga Nyiri and Tamás Veszprémi: *On the Stability of Six-Membered-Ring Carbenes and Silylenes.* Organometallics 2009, 28, 5909–5914.

[2] Kinga Nyíri, Tibor Szilvási and Tamás Veszprémi: *The mechanism and energetics of insertion reactions of* Silylenes *Dalton Trans.*, 2010, 39, 1–6.

[3] Tibor Szilvási, Kinga Nyíri, and Tamás Veszprémi: *Unique Insertion Mechanisms of Bis-dehydro-β-diketiminato Silylene,* Organometallics, 2011. 30, 5344-5351.

[4] Tibor Szilvási and Tamás Veszprémi: *On the mechanism of the reaction of white phosphorus with silylenes*, Dalton Trans., 2011, 40, 7193.

2.   The chemistry of 1,3-dialkylimidazolium-based ionic liquids can easily be linked to that of N-heterocyclic carbenes (NHCs) in the presence of sufficiently basic counteranions. B3LYP/6-31+G*, B3LYP/aug-cc-pVTZ and MP2/6-311+G** studies show that increasing the basicity of the anionic component the relative stability of the ion pair and that of the hydrogen bonded complex of the corresponding free acid and NHC itself can be shifted toward the formation of NHC. In the case of acetate anion the ion pair and the NHC-acetic acid complex have similar stability. Photoelectron spectroscopic studies show that the vapor of EMIM-acetate is dominated by the NHC – acetic acid complex. The mass spectrum of the same comopund shows the presence of both acetic acid and 1-ethyl-3-methylimidazolium-2-ylidene, in agreement with the low pressure during the MS experiment, which facilitates dissociation. The possibility of systematic and simple variation of the NHC content of the IL's facilitates the extension of carbene chemistry in ionic liquids.[5]

In a separate work electronic structure of N-heterocyclic carbenes with five member rings and two nitrogen atoms was studied using the natural resonance theory in the framework of density functional theory. Also the role of the hydroxyl substituents on the carbon atoms was investigated. The analysis provides a consistent picture of chemical bonding, even in cases where no single Lewis structure can be drawn. It interprets the observed stabilities and aromaticities of the different isomers. A carbene lone pair on C_1 atom was identified in all cases, while the electron donation to the formally empty p_z orbital of this atom was found to be a crucial effect in all cases.[6]

[5] Oldamur Hollóczki[a] Dirk Gerhard,[b] Klemens Massone,[*b] László Szarvas,[b] Balázs Németh,[a] Tamás Veszprémi[*a] and László Nyulászi: *Carbenes in Ionic Liquids*, New Journal of Chemistry, 2010, 34, 3004–3009.
[6] Tibor. Höltzl, Tamas Veszprémi, Vu Thi Ngan b, Minh Tho Nguyen: *Resonance structures of N-heterocyclic carbenes,* Chemical Physics Letters 481 (2009) 54–57

3.   Due to their unsaturation, high and novel reactivity, phosphaalkynes (or with other name, phosphaacetylenes) play a very important role in the low coordinated phosphaorganic chemistry. One of the most interesting reactions of phosphaalkynes is their oligomerization and polymerization. Earlier we studied theoretically the low energy HCP dimers, including altogether 17 isomers, as well as the possible reaction pathways leading to these compounds, and their interconversion.[7] In the frame of this project we investigated the phosphaethyne trimers with $(HC)_3P_3$ formula. The aim of our theoretical work was to determine the hitherto missing reaction pathways leading to the synthesized phosphaalkyne trimers and to interpret the formation of the experimentally found side products. Since the electronic structure and chemical bonding of many compounds cannot be described with the $(HC)_3P_3$ formula, we have studied the electronic structure of the intermediates and the products and also highlight some new and potentially synthesizable compounds with peculiar electronic structure. Scheme 3 indicates the hitherto synthesized phosphaalkynes.
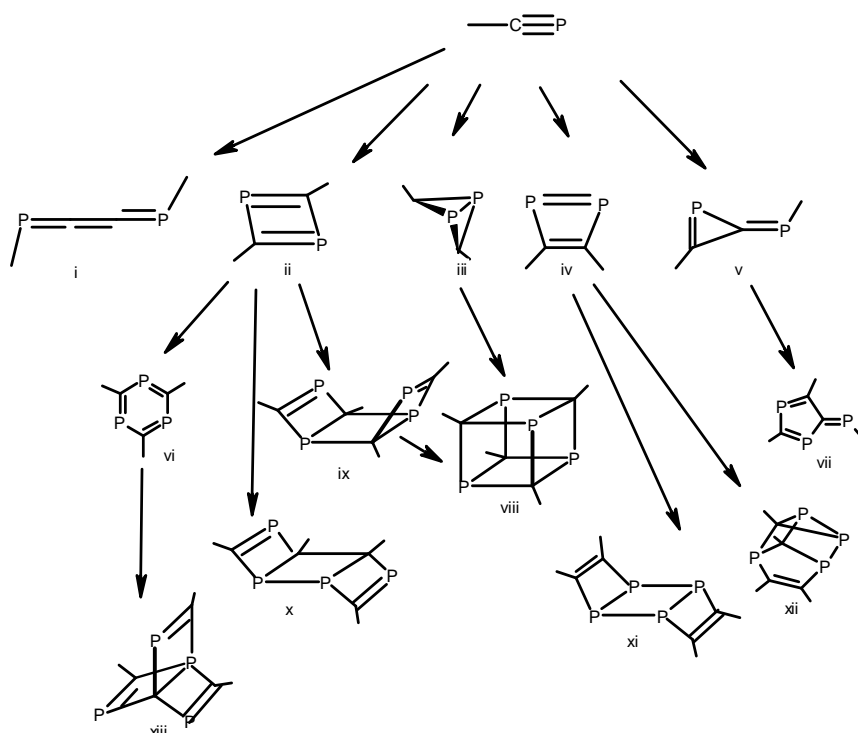
Scheme 3.

Geometric and electronic structure of phosphaethyne trimers was studied using density functional theory (B3LYP/cc-pVTZ) as well as CBS-QB3, CCSD(T) and complete active space self consistent field (CASSCF) computations. The effect of the substituents was also investigated. Our aim was to identify the low energy equilibrium structures with synthetic interest, therefore we were determining minima without any restriction on the chemical structure. The global minimum of the $C_3P_3H_3$ potential energy surface is confirmed to be the 1,2,3-triphosphinine. The next energetically stable isomer is a potentially synthesizable target with a P_3 ring, which is only 34 kJ/mol above the global minimum. Formation of phosphaethyne trimers by reaction of phosphaethyne and 1,4-diphosphatriafulvene has been determined. This suggests that the thermodynamically controlled product is the 1,3,5-triphosphinine, while 1,3,6-triphosphafulvene is the kinetically favored product. For the latter a biradical reaction pathway also exists. Analysis of the effect of the substituents shows that the reaction barriers increase with the size of the substituent. Using the bulky 2,4,6-tri-t-butylphenyl (supermesityl) substituent the relative stability of 1,3,5-triphosphinine and 1,3,6-triphosphafulvene is reversed, and the latter is expected to be the most stable phosphaalkyne trimer with bulky substituents. Head-to-tail reaction of phosphaethyne and phosphanylidene carbenoid yields 1,3,6-triphosphafulvene with very small barriers, while 1,4-diphosphafulvene is expected to be a byproduct. The results are in good agreement with the experimental findings.[8] Fig. 3 indicates the relative Gibbs-free energies of phosphaalkyne trimers (in kJ/mol) with respect to 1,2,3-triphosphinine.
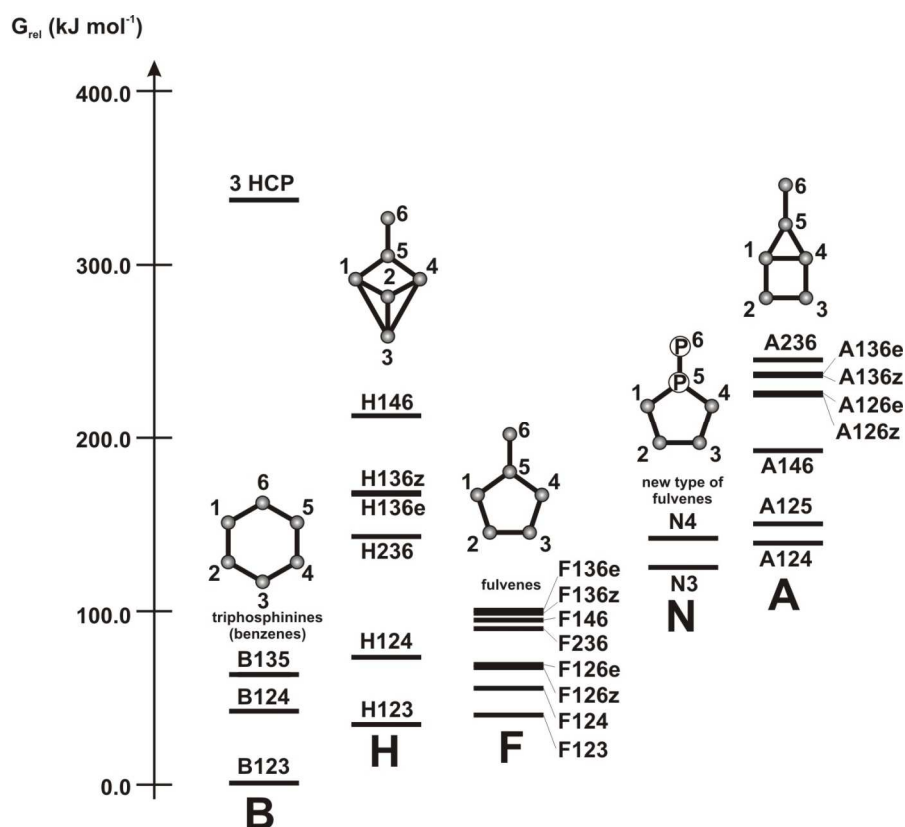

Figure 3. Phosphaalkyne trimers. Relative Gibbs-free energies are indicated in kJ/mol with respect to 1,2,3-triphosphinine.

One of the most interesting achievements in the recent carbon chemistry is the successful isolation and characterization of graphene, a single graphite layer. This compound has many interesting properties, like planarity, exclusive band structure and magnetic properties, which make it a promising candidate for future developments in many fields including the semiconductor industry and other diverse applications, like ionic sieves. Also the chemistry of graphene and graphene nano-ribbons is subjected now to an extensive research. Black phosphorus is also a layered material, where chair conformation P_6 rings form the two dimensional lattices. Thus, this compound is structurally similar to the graphane (the hydrogenated derivative of grapheme), although their symmetries are different. Black phosphorus can formally be regarded as the polymer of P_2, the all-phosphorus analogue of acetylene. Phosphaethyne (HCP) stands between acetylene and P_2. Their polymer is a black compound, which, according to element analysis, has 1:1:1 C:P:H ratio, indicating that this is really the polymer of phosphaethyne and no side-products of the preparation reaction were incorporated. In our work we analyzed the geometric and electronic structures of one (cis-polyacetylen-type) or two dimensional (graphane-type) polymers of phosphaethyne and compared these with that of the acetylene (graphane) and diphosphorus (black phosphorus).

Stability and electronic structure of phosphaethyne polymers were studied using density functional methods and were compared with that of the polymers of acetylene (cis-polyacetylene and graphane) and phosphorus (black phosphorus allotrope). Similarly to the reference compounds, the graphane-like layer structure poly-phosphaethyne is considerably more stable thermodynamically than the oligomers and has no unsaturated chemical bonds, hence it may be synthesized. This may also open the way to chemically modify and fine-tune the properties of graphane by synthetically incorporating poly-phosphaethyne units in the layer structure. Spontaneous, rapid polymerization of phosphaethyne was observed previously, however the crystal structure and electronic properties of the polymer has not been studied in detail. From the calculations it can be concluded that using appropriate reaction conditions, graphane-like structures are synthesizable by polymerization of *phosphaethyne*. In Fig. 3 the geometries of the graphane-like two dimensional polymers of acetylene, phosphaethyne and diphosphorus can be found.[9]

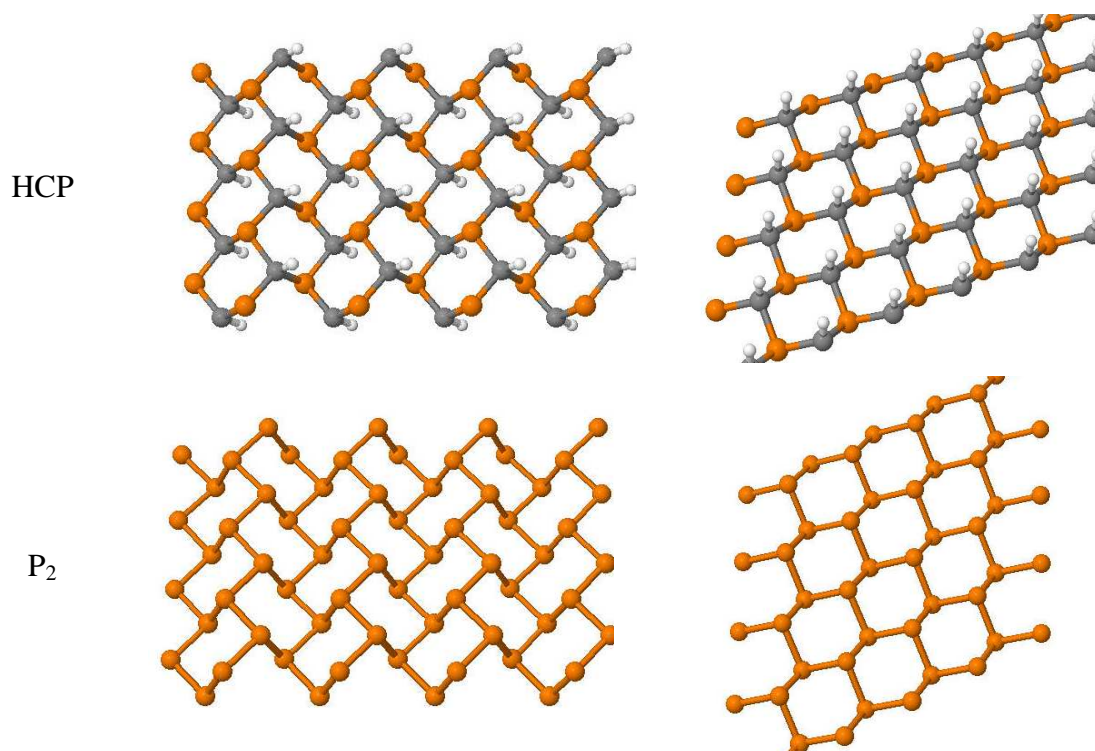| Symmetry	PMM	P3M1
C_2H_2		
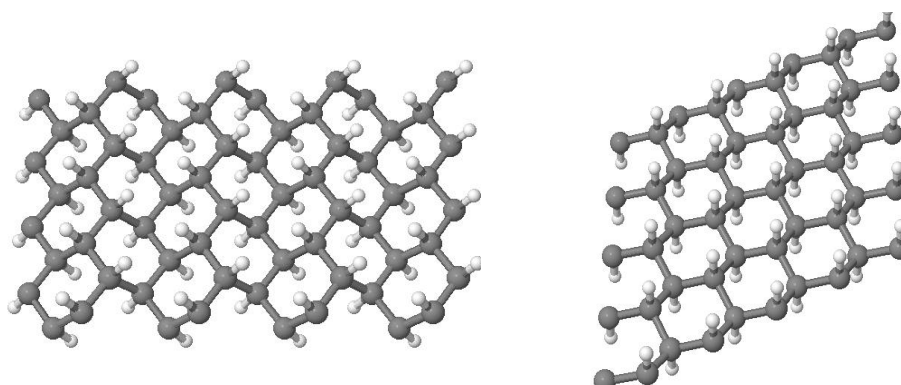
Figure 4. Geometries of the graphane-like two dimensional polymers of acethylene, phosphaethyne and diphosphorus

[7] T. Höltzl, D: Szieberth, M.T. Nguyen, T. Veszprémi: Chem. Eur. J. **12**, 8044, (2006).

[8] Tibor Höltzl,†,‡ Minh Tho Nguyen,‡ and Tamás Veszprémi, *Formation of Phosphaalkyne Trimers: A Mechanistic Study*, Organometallics 2010, 29, 1107–1116.

[9] Tibor Höltzl, Tamás Veszprémi, Minh Tho Nguyen: *Phosphaethyne polymers are analogues of cis-polyacetylene and Graphane,* C. R. Chimie 13 (2010) 1173–1179

4. Borane complexes of aziridine, phosphirane, cyclopropylamine, cyclopropylphosphine, cyclopropylmethylamine, and cyclopropylmethylphosphine have been prepared by the reaction of a borane complex or diborane on the free phosphine or amine at low temperatures. The following compounds were investigated[10]:
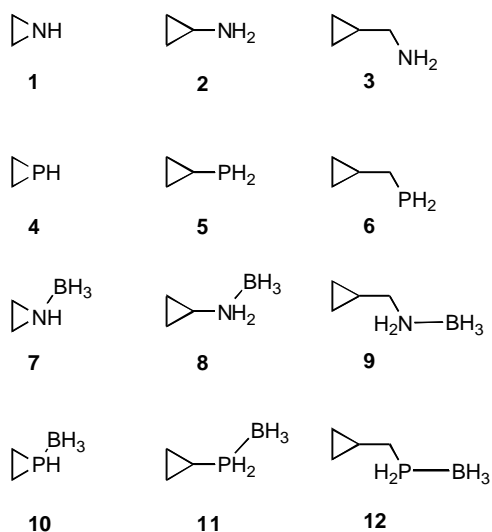
The products characterized by NMR spectroscopy and mass spectrometry have then been investigated by photoelectron spectroscopy and B3LYP/aug-cc-pVTZ quantum chemical study. The complexation led to rotamers with structures similar to the ones of the corresponding free systems. The main geometry change with the complexation is the P-C bond elongation and the N-C bond shortening, which can be rationalized by the charge transfer attached to the electron donation. The calculated relative stability order of the conformers changes with the complexation only in the case of cyclopropylamine. The calculated complexation energies are higher for the amines, in accord with the differences observed in the flash vacuum thermolysis of methylamine-, methylphosphine-, and aziridine-borane. The photoelectron spectra indicate essential differences between the amines and phosphines toward borane complexation. The dative bond is more stable in the studied amine-boranes than in phosphine-boranes, while the σB-H orbitals are more stable in the latter compounds. The enthalpy of the hydrogen release reaction of aziridine-borane is almost thermoneutral, indicating the potential of this complex as recyclable hydrogen storage material.

Trimethylaluminum (TMA) complexes of methyl-, n-propyl-, cyclopropyl-, allyl- and propargylamine were also synthesized and their experimental properties and theoretical characteristics were compared with the respective amine-borane analogues.[11] The amine ligand of an amine-TMA Lewis acid-base complex can be easily changed by another amine through a 2:1 amine-TMA intermediate in pentane at room temperature. The exchange of the same ligands in the case of amine-boranes requires remarkably more time in line with the calculated relative energy of the respective transition state. The ^{1}H and ^{13}C NMR experiments examining the addition of one or more equivalent of amine to the respective Lewis acidbase complex conclude to the fast exchange of the amine ligand in the NMR timescale only in the cases of amine-TMA complexes, which could also be caused by similar 2:1 complexes. However, in gas phase, only 1:1 amine-TMA complexes are present as evidenced by ultraviolet photoelectron spectroscopy (UPS). The observed UP spectra, which are the first recorded photoelectron spectra of primary amine-TMA compounds, indicate that the stabilization effect of the lone electron pair of nitrogen atom in amines during the borane complexation is stronger than that of the TMA complexation. In line with this observation, the destabilization of the σAl-C orbitals is lower than that of σB-H orbitals during the formation of amine-TMA and amine-borane complexes, respectively. As showed by theoretical calculation, the CH$_4$ elimination of the studied amine-TMA complexes is exothermic, indicating the possibility of using these compounds in metal organic chemical vapour deposition techniques (MOCVD). On the other hand, our experimental conditions avoid this methane elimination, and constitutes the first procedure employing distillation to isolate primary amine-TMA complexes.

[10] Balázs Németh, Brahim Khater, Jean-Claude Guillemin, and Tamás Veszprémi: *Differences Between Amine- and Phosphine-Boranes: Synthesis, Photoelectron Spectroscopy, and Quantum Chemical Study of the Cyclopropylic Derivatives,* Inorg. Chem. 2010, 49, 4854–4864.

[11] Balázs Németh†‡, Jean-Paul Guégan†, Tamás Veszprémi*‡ and Jean-Claude Guillemin: *Trimethylaluminum and borane complexes of primary Amines,* Inorg. Chem. 2013, 52, 346–354.

5. Electronic and steric factors that control the bond-stretch isomerism phenomenon in 2-chalcogen-trimetallabicyclo[1.1.0]butane systems have been investigated using B3LYP functional with aug-cc-pVTZ basis set. Beside the short-bond and long-bond extremes we found and characterized a third, stable conformer with significantly elongated central bond

and anti arrangement of the bridgehead substituents. Electronic structures of the isomers have been described and interpreted in details within the framework of MO theory. Germanium analogues of trisilirene have been predicted to also react with sulphur to form the corresponding 2-thia-trimetallabicyclo[1.1.0]butane analogues. The systematic analysis of the relative stability dependence on the ring composition as well as the bridgehead substituents revealed that the hitherto unknown anti isomer is a promising synthetic target in germanium bridged bicyclo compounds with bridgehead substituents containing carbon contact atom.

[12] Klara Tarcsay Petrov, Balazs Pinter, Tamas Veszpremi: *Bond-Stretch Isomerism in 2-Chalcogen-trimetallabicyclo[1.1.0]butane Derivatives* Journal of Organometallic Chemistry 706-707 (2012) 84-88.

6.   A new class of inorganic systems is introduced in which a silylene fragment is combined with a sulfur-nitrogen fragment. The properties of the resulting "sulfur-nitrogen silylenes" have been studied using quantum chemical calculations, focussing on isodesmic reaction energies, dimerization, electro- and nucleophilicity, and the singlet–triplet energy gap–a number of as yet unsuccessful attempts to prepare the compounds is also reported. These new systems are found to be stable silylenes in which the sulfur-nitrogen fragment stabilizes both the singlet and the triplet states through extensive electron delocalization. The following compounds were investigated:

    9a   9b   9c   9d   10

    11   12   13   14   15
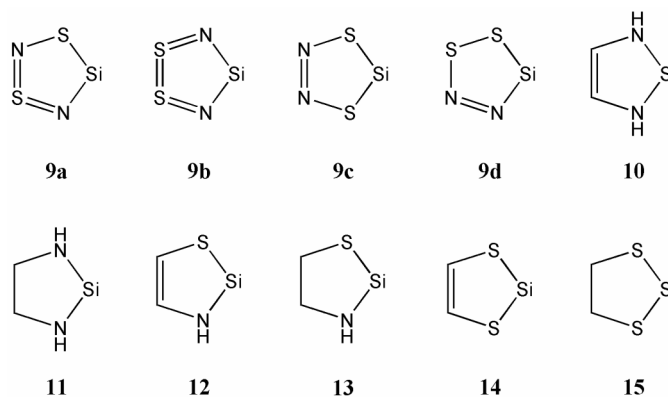
[13] Julianna Oláh, Tamás Veszprémi, J. Derek Woollins and Frank Blockhuys: *Combining the chemistries of silylene and sulfur-nitrogen compounds—SiS2N2 and related systems*, Dalton Trans., 2010, 39, 3256–3263.

7.   Steric groups are often regarded in reactions as chemically irrelevant, inert parts of the molecules, which have no influence on the structure of the forming reactive center of the product but rather on the reaction rate; therefore, they are usually not taken into account in theoretical work. However, in some cases, e.g. in the general reaction scheme of reductive dehalogenation of halosilanes, bulky substituents can cause major structural changes in the product simply by their presence.

    In this work[14] it was shown how steric groups have reaction path controlling ability that can govern the reaction to different products. We analyzed the experimental data of the synthesized persila compounds (Scheme 4) which all follow the same reaction scheme by the reductive dehalogenation of trihalosilanes.
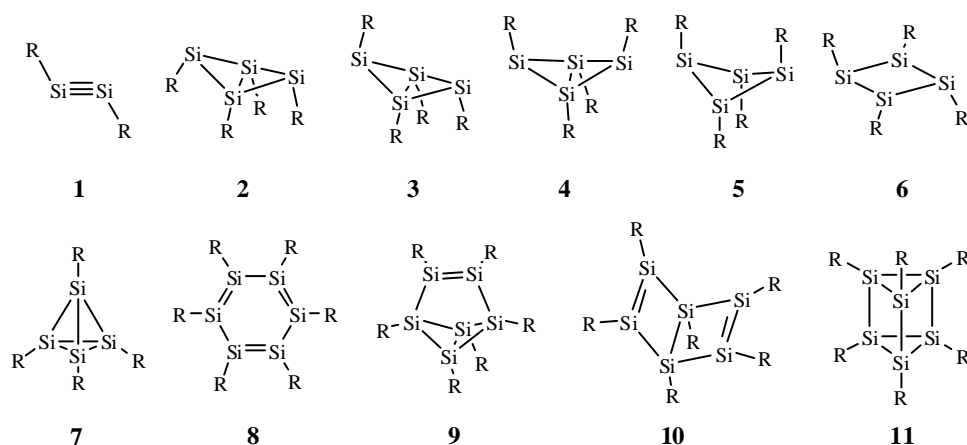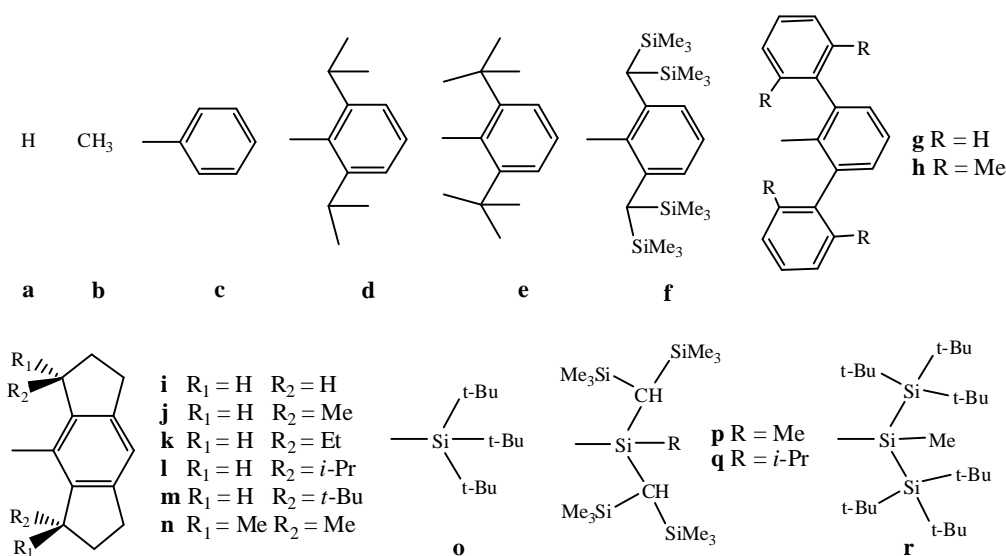
Scheme 4

We investigated all the possible structures (**1-11**) applying different bulky groups (Scheme 5) to estimate the possible synthesizability of these compounds.

It was found that with the modification of the bulky groups it could be achieved that only one energetically relevant minimum remained on the PES, moreover, in some cases only one true minimum existed. By this, the selective formation of the different silicon structures can be fully explained together with the principle of minimum energy. In the consequence of this observation, the modeling of real bulky substituents turns out to be much easier than it has thought since the extremely expensive reaction route mapping can be saved. Moreover, it suggests a general method for the prediction of the synthesis of still unknown reactive compounds by designing proper bulky substituent for it which allows only one, the chosen one, minimum on the PES.

We have shown that theoretical substituent design, or as we call it: *molecular-tailoring*, for a certain chemical structure is possible with this methodology. As an example, hexasilabenzene, one of the best wanted unknown silicon compound was studied as an ideal target to our new approach.

Scheme 5

We have tried substituents in consonance with previously applied substituent classes, which seems to be adequate for stabilization of hexasilabenzene and found several possible choices (**g**, **j**, **k**, **l**). Substituent **g** excels from the other substituents because only one true minimum exists on the $(SiR)_6$ PES which makes it a promising candidate. Interestingly, this statement also true for its $(SiR)_4$ PES, it contains a butterfly-shaped silicon center ring which is also unknown, therefore **g** seems to be important in two aspects.
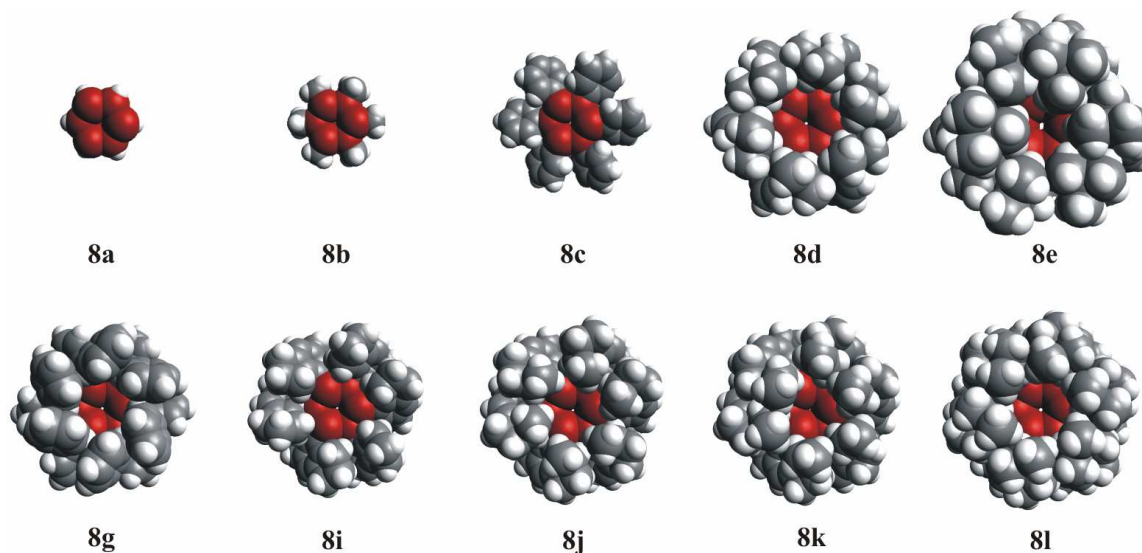

Figure 5. Van der Waals representation of hexasilabenzene analogs with several substituents. Red, grey and white spheres refer to silicon, carbon and hydrogen atoms, respectively.

Molecular-tailoring concept can also be applied in several other fields. It can be used to optimize a catalyst which allows less or no side reactions, simply with the destabilization of the product or the intermediate of the side reaction. To demonstrate the concept further, we analyzed the general reaction scheme of reductive dehalogenation of halogenmanes.[15] First, we explored the possible stable $(GeR)_{2n}$ structures up to octagermanes (n = 4) with small substituents. Then, we investigated previously reported experimental results applying real bulky substituents and found all preparations can be easily explained by the principle of energy minimum and the special steric effect of the bulky substituents. We found with the proper choice of the bulky groups all structures could be destabilized owing to steric hindrance but one of which stability remained almost the same. These findings can be applied to design substituent for still unknown compounds such as tetragermacyclobutadiene and hexagermabenzene. We found perfect substituents for the synthesis of tetragerma-cyclobutadiene and for hexagermabenzene; they fulfill all criteria that have been raised based on the discussion of previous successful experimental results.

The study of the substituent-dependence of the thermodynamic stability solves only the necessary condition of the achievement of a chemical reaction. The possible reaction pathways can be controlled with suitably chosen bulky groups by eliminating competitive structures and side reactions from the Potential Energy Surface (PES) and directing the process toward the desired compound. However, in spite of the demonstrative thermodynamic effect of the proper bulky group, the kinetics of the synthesis route can modify the picture which has not been taken into account so far.

A proper bulky group has to support the synthesis from kinetic point of view as well. Bulky substituents have to allow the formation of the desired product by providing small

activation barriers toward the product; in other cases the reaction will stop at an intermediate regardless of the favorable thermodynamics. On the other hand, appropriate substituents have to hinder the reaction beyond the desired product possessing large activation barriers beyond it. As a further example, the reaction mechanism of a possible hexasilabenzene synthesis as the consecutive reaction of three disilyne units were studied and discussed.[16] The theoretical calculations were carried out at B97-D/cc-pVTZ//B97-D/6-31G* level of theory. Studying the effects of four substituents (hydrogen (**A**), phenyl (**B**), terphenyl (**C**) and methylated terphenyl (**D**) – see Scheme 6) we pointed out that in order to obtain hexasilabenzene, the appropriate substituent has to be selected, and terphenyl group is suitable from both thermodynamic and kinetic point of view.
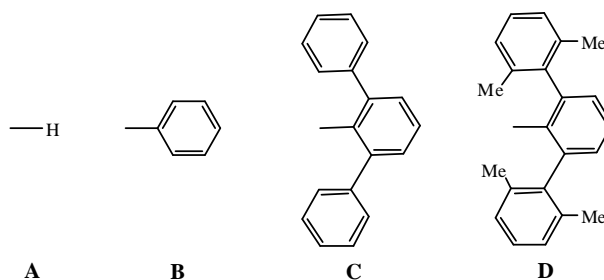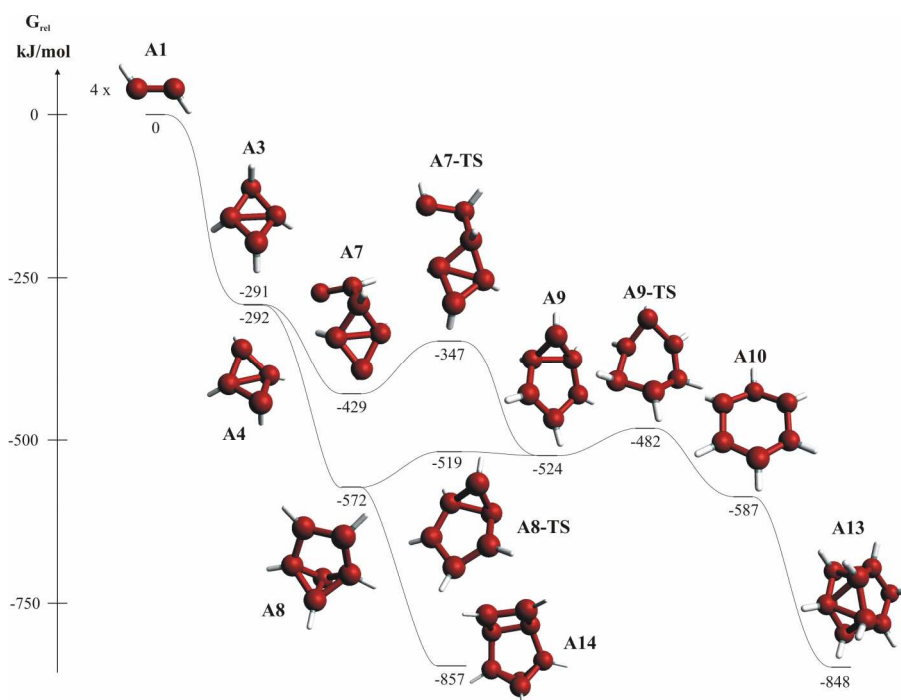

Scheme 6

Figure 6. Mechanism of hexasilabenzene formation with hydrogen substituents. (Relative Gibbs free energies are compared to four separate disilyne molecules.)
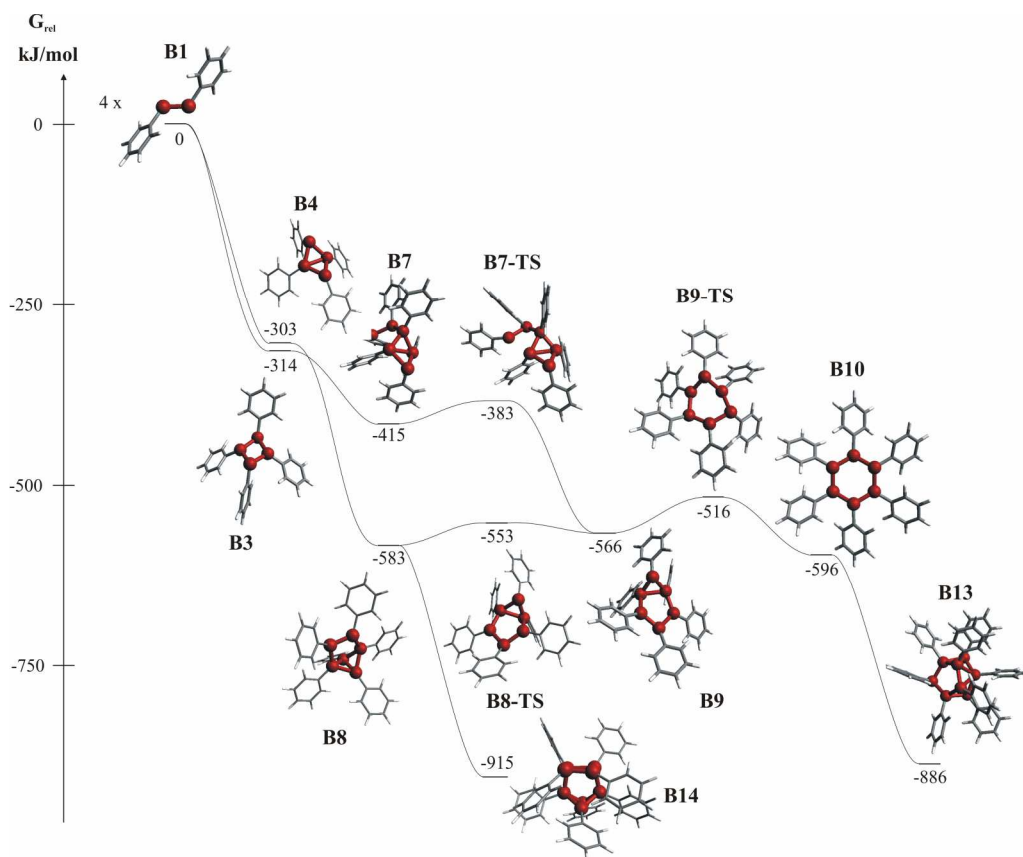
Figure 7. Mechanism of formation of hexasilabenzene with phenyl substituents. (Relative Gibbs free energies are compared to four separate diphenyl-disilyne molecules.)
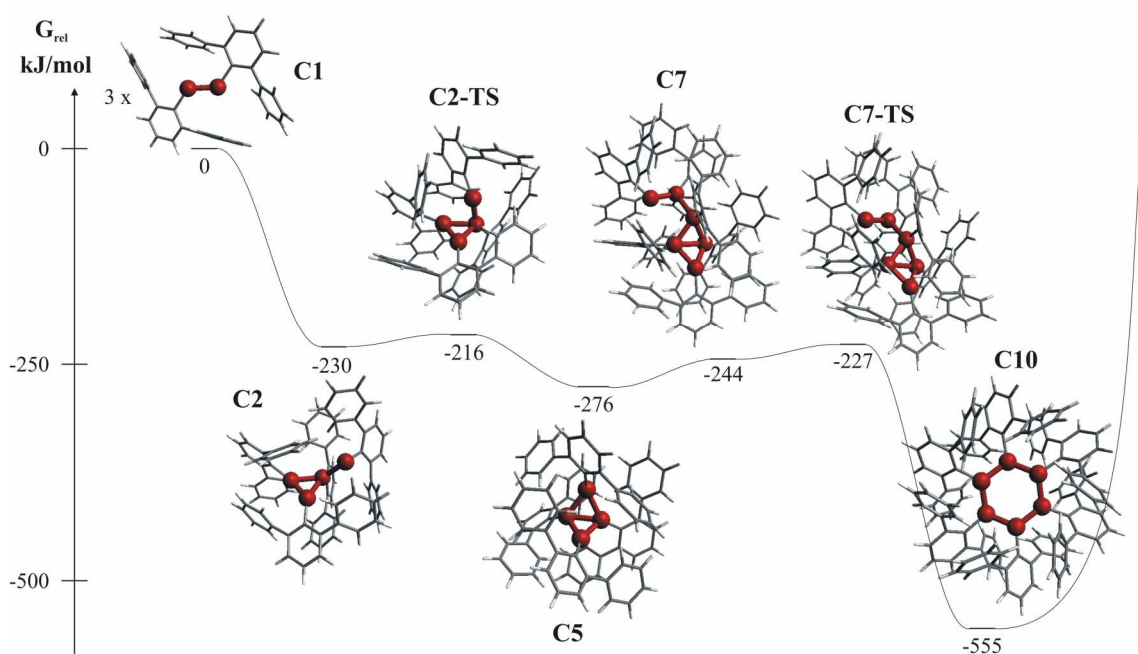

Figure 8. Mechanism of formation of hexasilabenzene with terphenyl substituents. (Relative Gibbs free energies are projected to three separate di(terphenyl)disilyne molecules.)
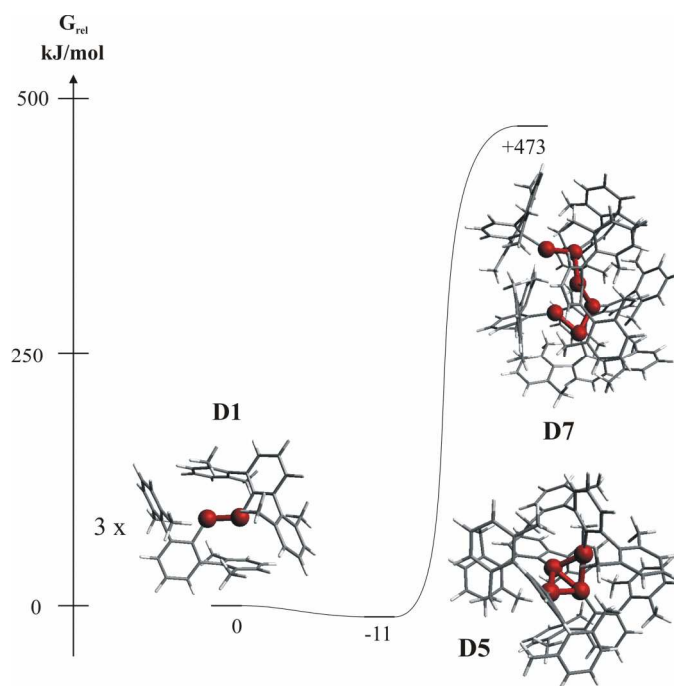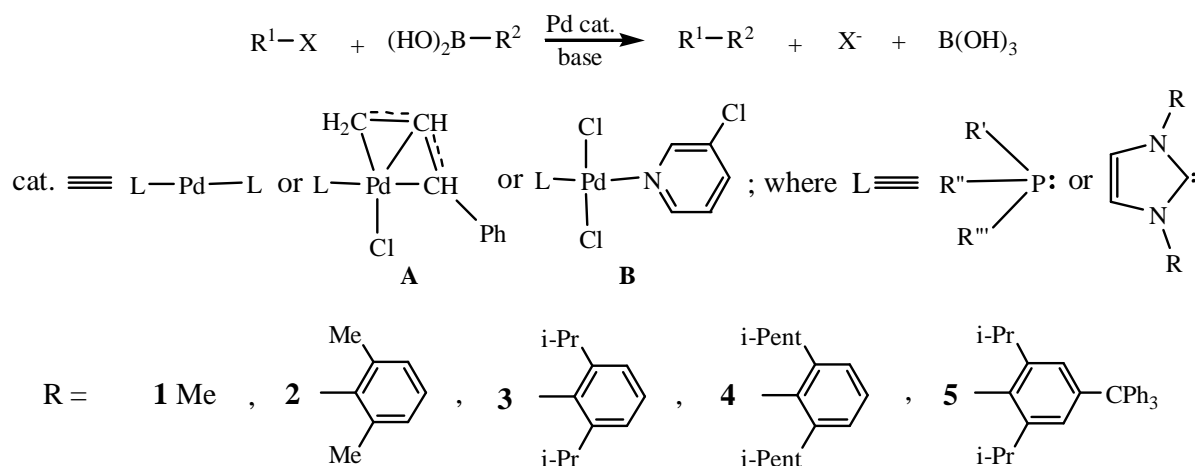
Figure 9. Intermediers with methylated terphenyl substituents (Relative Gibbs free energies are projected to three separate substituted disilyne units.)

The calculated results unambiguously demonstrate the usefulness of this method (Figs. 6-9). In the case of the first three substituents, a thermodynamically favorable reaction pathway with small activation barriers was found which led to substituted hexasilabenzene. With hydrogen and phenyl groups, two in situ formed disilyne units form a four-membered ring which is followed by the addition of the third disilyne. However, hexasilabenzene derivatives easily react further with a fourth disilyne unit. Consequently, these substituents cannot be applied in the synthesis of hexasilabenzene in practice. In case of terphenyl substituent, the addition of the third substituted disilyne is immediately followed by the formation of hexasilabenzene which is surrounded tightly by the phenyl rings, excluding further additions. Since, according to previous theoretical examinations, formation of other structures is not expected, it can be stated with high certainty that reductive dehalogenation of terphenyl-halosilanes gives hexasilabenzene. Methylated terphenyl groups (**D**) prevent the formation of stable four or six membered silicon rings because of the increased steric hindrance which clarifies the previous experimental results that in this case only insertion reactions are observed. Overall, we suggest synthesizing hexasilabenzene from terphenyl-halosilanes, performing reductive dehalogenation.

We have to note that although the molecular-tailoring concept till was demonstrated in case of a few silicon and germanium compounds for a certain reaction scheme, it is more universal. It must be true that every reactive structure for every type of reaction has one or few optimal substituents that can be found by theoretical prediction. Since the synthesis of hitherto unknown reactive compounds is slow, expensive and unpredictable procedure this approach may bring fundamental breakthrough in this area.

To demonstrate the power of this method further, the catalytic cycle of Suzuki-Miyaura coupling was investigated using N-heterocyclic carbene (NHC) ligands.[17] The Suzuki-Miyaura reaction is widely used to form carbon-carbon cross coupling (Scheme 7).

$$R^1-X \; + \; (HO)_2B-R^2 \; \xrightarrow[\text{base}]{\text{Pd cat.}} \; R^1-R^2 \; + \; X^- \; + \; B(OH)_3$$

cat. $\equiv$ L—Pd—L or L—Pd—CH (with H₂C⋯CH, Ph, Cl) **A** or L—Pd—N(Cl)(Cl)(pyridine-Cl) **B** ; where L $\equiv$ R″—P: (R′, R‴) or NHC (N-R, N-R)

R = **1** Me , **2** (2,6-Me₂C₆H₃) , **3** (2,6-i-Pr₂C₆H₃) , **4** (2,6-i-Pent₂C₆H₃) , **5** (2,6-i-Pr₂-4-CPh₃C₆H₂)

Scheme 7.

The reaction, originally with phosphine ligands on the Pd center, has been widely studied both experimentally and theoretically in several aspects. These studies have determined that the most important step is the formation of the active Pd(0) compound and its stability is the key for more efficient catalysts. The effect of the bulky phosphine ligand has been deeply investigated and found that both steric and electronic effects have considerable impact on the catalytic features.

N-heterocyclic carbenes (NHC) have been recently reported as successful ligands for Suzuki-Miyaura coupling. Steric groups are necessary for the catalyst; it gives kinetic stability of the compound, supporting reductive elimination, on the other hand, it may cause the failure of the catalytic reaction by the increasing steric hindrance in oxidative addition especially for sterically demanding ortho-substituted aryl reagents. The main goal of our work was to understand the specific ligand effects by theoretical tools which might help to design more suitable catalysts in the future. We found two distinct effects of bulky groups: they cause steric repulsion with the protecting group in the precursor catalyst promoting the formation of the active Pd(0) compound and then, in the rate determining oxidative addition step, favorable nonbonding intramolecular π-π and C-H/π interactions between the reactants and the bulky groups decrease the activation barrier which explains the positive effect of bulky groups on the reaction rate.

Geometries were computed at the RI-B97-D/6-31G* level of theory then single point energy calculations were performed at the optima using RI-B97-D/cc-pVTZ level and Polarizable Continuum Model (PCM) to model isopropanol solvent. For Pd atoms, cc-pVTZ-PP pseudo potential was used both for geometry optimization and for single point energy calculations.
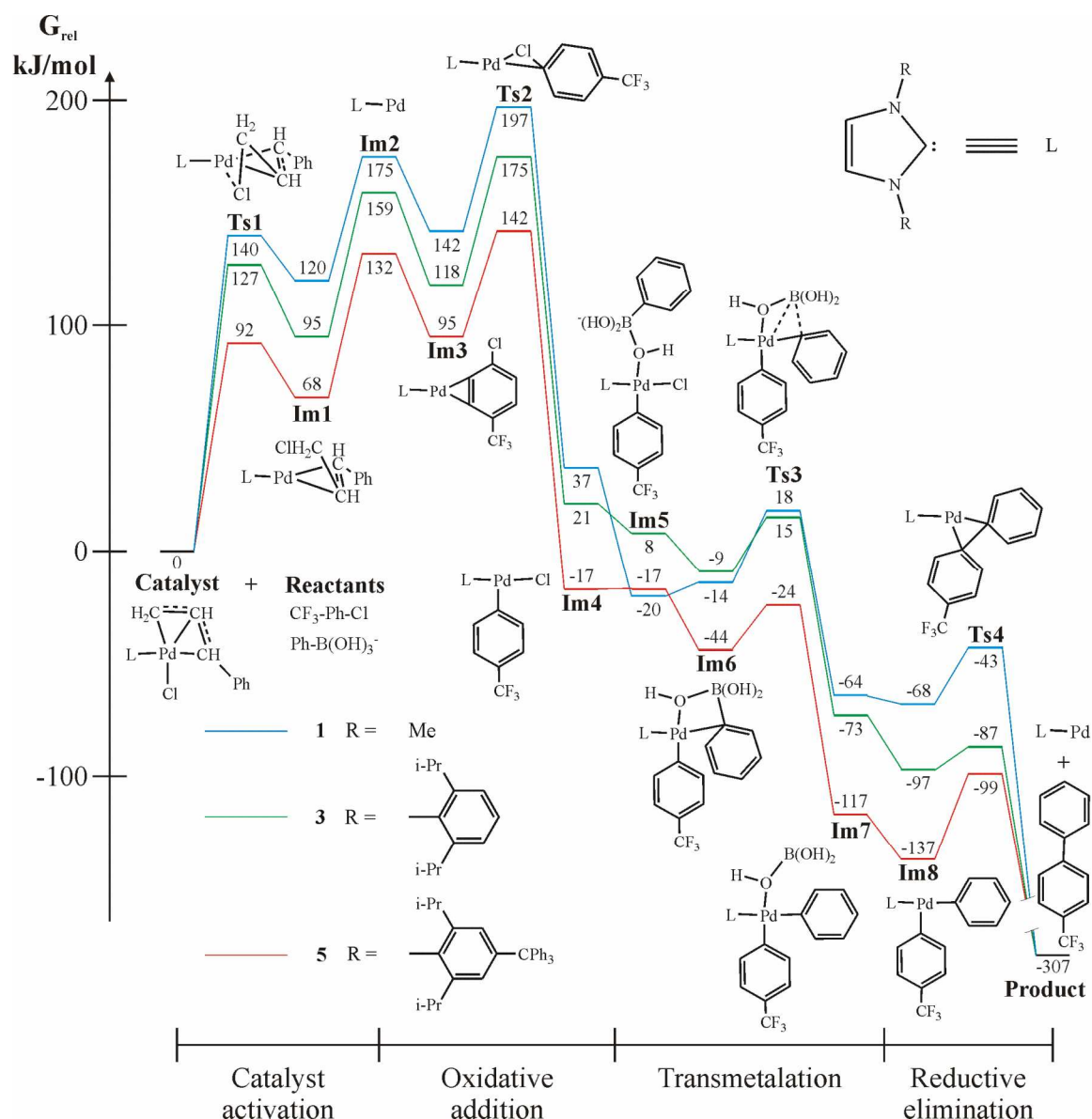
Figure. 10. Mechanism and reaction profile for Suzuki-Miyaura coupling with NHC substituents A1, A3 and A5. The schematic arrangement around the Pd center is plotted in every single step and also the main parts of the reaction profile are signed in accordance with Scheme 3.

The general results of the calculations are demonstrated in Fig. 10. Two distinct effects were found which could significantly promote the reaction in consistent with experimental results can be summarized (Fig. 11). First, large bulky groups provide steric repulsion with the protecting group of the initial Pd complexes. Therefore the systematic increasing of the alkyl chain causes increased steric repulsion within the Pd complexes which triggers the elimination of the protecting group enhancing the formation of the active Pd species (**Im2**).
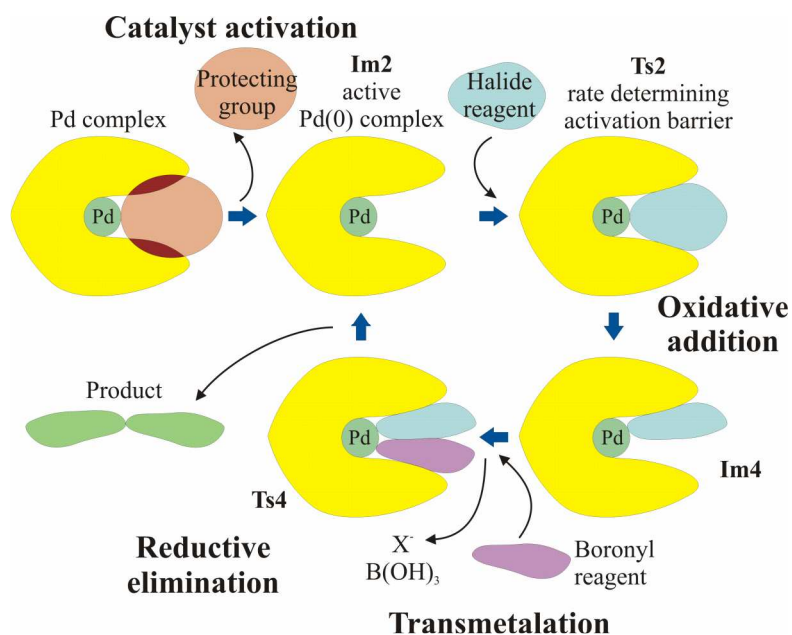
Figure. 11. Lock-key model for internal catalytic effect of bulky groups. Bulky groups (yellow) cause steric repulsion (ruby red) with the protecting group (orange) of the initial Pd complex which enhances the elimination of the protecting group promoting the formation of the active Pd(0) species (Im2). In the oxidative addition step (Ts2), favorable π-stacking and C-H/π interactions between the bulky groups and the joining aryl-halide reagent promotes the reaction towards Im4. After the conformation change in Im4, aryl reagent and the bulky groups provide enough space for transmetalation and reductive elimination to close the catalytic cycle resulting in the product and Im2.

Second, we demonstrated that using large but flexible alkyl groups there is no evidence for increased steric hindrance in oxidative addition step. Our results reveal that the bulky groups and the aryl-chlorine reactant form favorable π-stacking and C-H/π interactions (steric attraction) decreasing the rate determining activation barrier promoting the reaction. These results suggest that bulky groups can accelerate oxidative addition step not just reductive elimination step as previously thought. Our model suggests that the whole catalytic cycle can be interpret as an enzyme-like lock-key connection where bulky groups are designed for steric repulsion in the catalyst activation steps and steric attraction in the rate determining step significantly enhancing catalytic processes. This work is an example how to design optimal substituents in silico which can be easily done in the future owing to the fast development of computational chemistry.

The results above clearly demonstrate the power of the Molecular Tailoring concept: Chemical reactions have one or a few optimal substituents that can be found based on in silico. It can be used for optimizing a catalyst to accelerate the desired reactions and eliminate side reactions, simply with the stabilization or destabilization of the product or the intermediate during the reaction paths. Since the synthesis of hitherto unknown reactive compounds is slow, expensive and unpredictable procedure our approach may bring fundamental breakthrough in this area.

[14] Tibor Szilvási and Tamás Veszprémi: *Molecular Tailoring: Reaction Path Control with Bulky Substituents*. Organometallics 2012, 31, 3207−3212.
[15] Tibor Szilvási and Tamás Veszprémi: *Molecular Tailoring: Substituent Design for Hexagermabenzene*, Organometallics.

[16] Zsolt Benedek, Tibor Szilvási and Tamás Veszprémi: *Molecular tailoring: a possible synthetic route to Hexasilabenzene.* Dalton Trans., 2014, 43, 1184-1190.
[17] Tibor Szilvási and Tamás Veszprémi: *Internal Catalytic Effect of Bulky NHC Ligands in Suzuki−Miyaura Cross-Coupling Reaction.* ACS Catal. 2013, 3, 1984–1991

8. Analysis of the molecular orbitals and the nucleus independent chemical shift showed that the D4h and D6h symmetry Hg_4^{2+} and Hg_6^{2+} rings are aromatic. However, accurate quantum chemical methods indicated that the linear forms are more than 100 kJ mol^{-1} lower in energy. This surprising case, where the non-aromatic species are considerably more stable than the aromatic rings, was explained by the charge distribution and the ring strain. Electronic structures of these species were consistently described using the phenomenological shell model of metal clusters (Fig. 12).[18]
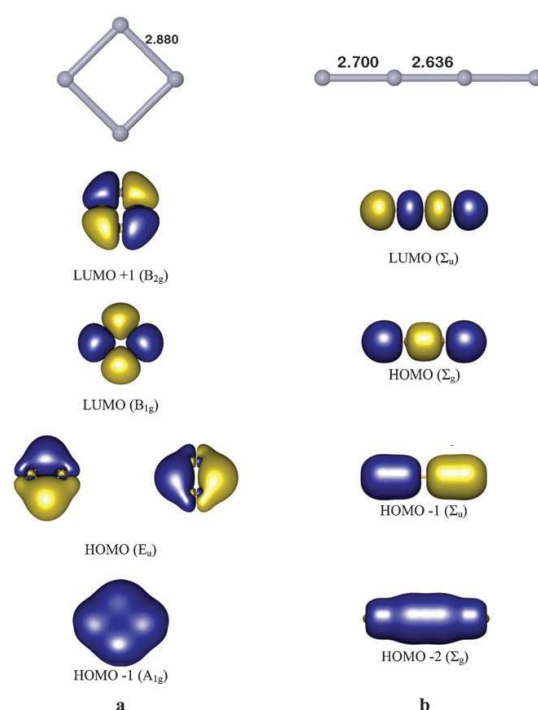

Figure 12. Geometric parameters (QCISD(T)/cc-pVTZ-PP) and molecular Orbitals (BP86/cc-pVTZ-PP) of a) cyclic and b) linear isomer of Hg_4^{2+}.

[18] Tibor Höltzl, Minh Tho Nguyen and Tamás Veszprémi: *Mercury dications: linear form is more stable than aromatic ring*, Phys. Chem. Chem. Phys., 2010, 12, 556–558.

9. Substitution of CH groups in 1,3,5-trimethylenebenzene (1,3,5-TMB) triradical by one, two or three N, P and As atoms was studied using CASSCF/CASPT2 computations with a ANO-RCC triple-ζ basis set. The computations showed that consistently with the previous results, the unpaired electrons in 1,3,5-TMB are highly delocalized, but our computations show that they become localized on the P and As atoms, with a more pronounced localization effect of As. All studied compounds have a quartet ground state, but the results showed in this paper indicate that the quartet-doublet energy gap is reduced upon substitution. Localization

of the unpaired electrons on the ring reduces the average distances between them, which induces a destabilization of the quartet states compared to the doublet. Therefore the position of the unpaired electrons and the doublet-quartet gap can be tuned by chemical methods, which opens the way to fine-tune the properties of the building blocks of organic magnets.

[19] Tibor Höltzl, Tamás Veszprémi, Minh Tho Nguyen: *Tuning the position of unpaired electrons and doublet–quartet gap of the 1,3,5-trimethylenebenzene triradical by nitrogen, phosphorus and arsenic substitution,* Chemical Physics Letters 499 (2010) 26–30.