UNIVERSITY OF CALIFORNIA, SAN DIEGO

OCTET-DEFYING MOLECULES:

UNDERSTANDING THE ELECTRONIC PROPERTIES OF CARBENES

AND

ISOLATION OF A STABLE NITRENE

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy

in

Chemistry

by

Martin Remi Ellinger

Committee in charge:

Professor Guy Bertrand, Chair
Professor Michael Gilson
Professor Carlos Guerrero
Professor Arnold Rheingold
Professor Emmanuel Theodorakis

2014

The Dissertation of Martin Remi Ellinger is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chair

University of California, San Diego

2014

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LIST OF ABBREVIATIONS

Ad: 1-adamantyl

Ar: aryl

Cy: cyclohexyl

DFT: Density Functional Theory

Dipp: 2,6-diisopropylphenyl

Et: ethyl

HOMO: highest occupied molecular orbital

i-Pr: isopropyl

KHMDS: potassium bis(trimethylsilyl)amide.

LDA: lithium diisopropylamide.

LEP: Lever Electronic Parameter

LiHMDS: lithium bis(trimethylsilyl)amide

LUMO: lowest unoccupied molecular orbital

Me: methyl

Mes: mesityl, 2,4,6-trimethylphenyl

Mes*: 2,4,6-tri(tertbutyl)phenyl

NaHMDS: sodium bis(trimethylsilyl)amide

n-Bu: 1-butyl

NHC: N-heterocyclic carbene

NMR: Nuclear Magnetic Resonance

Ph: phenyl

t-Bu: tertbutyl

TEP: Tolman Electronic Parameter

Tf: trifluoromethanesulfonyl

THF: tetrahydrofuran

TMS trimethylsilyl

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you know, it's an hour and a half later and it's over", sports and our shared values. You are not a colleague; you are a true friend.

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VITA

Education

2014: **Ph.D.** in **Chemistry**, PI: **Prof. Guy Bertrand**
2012-present: **University of California, San Diego**
2009-2012: University of California, Riverside (**GPA: 4.0**)

2009: **M. Sc.** in **Organic Chemistry** at the **Université Pierre et Marie Curie** (Paris, France)
- Academic oriented training in organic and bioorganic chemistry

2006-2009: **"Diplôme d'Ingénieur ENSCP"** at **École Nationale Supérieure de Chimie de Paris** (**Chimie** ParisTech, Paris, France)
- Problem-solving oriented training in chemistry (organic, inorganic, analytical, chemical engineering), conferring the same rights as an international **MSc** in **Chemical Sciences and Engineering**

Work Experience

Industrial Experience

Mar.-July 2008: **Sanofi-Aventis** (Vitry-Sur-Seine, France): **Industrial Internship**
- Worked on solvent replacement for the production of Zopiclone to comply with regulatory accreditation of the new production site
- Modified the conditions for the production of Ketoprofen resulting in the reduction by 90% of the benzene load in the process

Academic Research Experience

2009-2014: **UCSD-CNRS** *(San Diego, CA) and* **UCR-CNRS** *(Riverside, CA):* **Research Assistant**

Apr.-May 2011: **Fachbereich Chemie, AG Frenking** *(Phillips-Universität, Marburg, Germany)*: **Visiting Scholar**

Feb.-July 2009: **Laboratoire Charles Friedel** *(UMR CNRS 7223, ENSCP, Paris, France)*: **MSc practical internship**

Oct.-Nov. 2007: **Laboratoire de Chimie et Biochimie des Complexes Moléculaires** *(UMR CNRS 7576, ENSCP, Paris, France):* **Undergraduate research**

Teaching Experience

2009-2014: **Teaching Assistant**, undergraduate **Organic Chemistry**

UCSD: CHEM140A Winter 2013, Winter 2014, Spring 2014

- Developed problem sets and taught weekly discussion sessions for undergraduate students
- Participated in the design of examinations and graded midterm and final examinations

UCR: CHEM112A: Fall 2009, Winter 2010, Winter 2011, Winter 2012

CHEM112B: Spring 2010

- Taught weekly laboratory classes supervising 20 students per section

Skills and Qualifications

- **Area of expertise:** Organic chemistry, organometallic chemistry, inorganic chemistry
- **Specialized expertise:** Carbene chemistry, heterocyclic chemistry, synthesis and handling of highly reactive species, wet chemistry, kg-scale synthesis, inert-atmosphere techniques (, analysis and characterization of molecules (NMR (^{1}H, ^{13}C, ^{11}B, ^{19}F, ^{31}P), MS, LC/MS, GC/MS, GC, UV-vis, cyclovoltametry, X-Ray diffraction analysis), purification of molecules (flash chromatography, crystallisation, distillation, sublimation, HPLC)
- **Proficient in Computing:** ChemOffice, Gaussian and ADF software packages, NMR software (Jeol Delta, Brucker Topspin, Varian Vnmr), X-Ray diffraction solving software (Olex)
- **Languages:** Native French

Publications

1. "Rearrangement of 2,5-bis(silylated)-N-Boc Pyrroles into the Corresponding 2,4-Species"
   J.-H. Mirebeau, M. Haddad, **M. Henry-Ellinger**, G. Jaouen, J. Louvel, F. Le Bideau, **J. Org. Chem.**, *2009*, 74, 8890
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   Highlighted in: "Stabilized Transient R2PN Species"
   A. Schulz, A. Villinger, **Angew. Chem. Int. Ed.**, *2013*, 52, 3068
3. " ^{31}P-NMR Chemical Shifts of Carbene–Phosphinidene Adducts as an Indicator of the π-Accepting Properties of Carbenes"
   O. Back, **M. Henry-Ellinger,** C.D. Martin, D. Martin, G. Bertrand, **Angew. Chem. Int. Ed.**, *2013*, 52, 2939

ABSTRACT OF THE DISSERTATION

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Professor Guy Bertrand, Chair

For a long time, carbenes were considered as intermediates so reactive that their isolation was deemed impossible. From the seminal works of Curtius and Staudinger to their isolation as stable molecules, carbenes led to tremendous advances in numerous fields of chemistry, from synthetic applications such as organocatalysis and transition

metal chemistry, to advances in the fields of medicine and materials. In addition, a paradigm shift recently emerged with the use of stable carbenes for the activation of small molecules and the stabilization of highly reactive species, an infringement on a domain that remained exclusive to transition metal complexes. The wide scope of application of carbenes is intrinsically related to the extremely varied yet uncommon electron configuration and the understanding of the latter is of critical importance. The first part of this manuscript describes the development of a simple and inexpensive experimental method to probe the electronic properties of carbenes. The ^{31}P NMR spectrometry of carbene-phosphinidene adducts allows the assessment of the π-accepting abilities of carbenes, and by correlation with other experimental probes, the deconvolution of σ-donating and π-accepting properties. With this knowledge in mind, we will attempt to extend the scope of known stable carbenes through the development of new carbene families. Finally, we will apply our understanding of carbene stabilization mechanisms to the arduous quest for their nitrogen analogs, the so-far elusive nitrenes. Almost three decades after the isolation of the first stable carbene, a phosphinocarbene, we will report the synthesis of the first stable phosphinonitrene. This last part is a perfect example of the use of carbenes and their derivatives to stabilize highly reactive species, illustrating the previously mentioned paradigm shift.

GENERAL INTRODUCTION

In 1835, Dumas and Péligot[1] reported their attempts to synthesize the molecule of methylene CH_2 (Scheme I.1). Their approach was based on dehydrating methanol in the presence of compounds likely to trap the eliminated water molecule. Methylene is the parent compound of a family of molecules called carbenes. These are neutral compounds featuring a divalent carbon atom. This atom features a sextet of electrons, four from the two single bonds with its substituents and two unpaired electrons (Figure I.1).

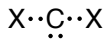
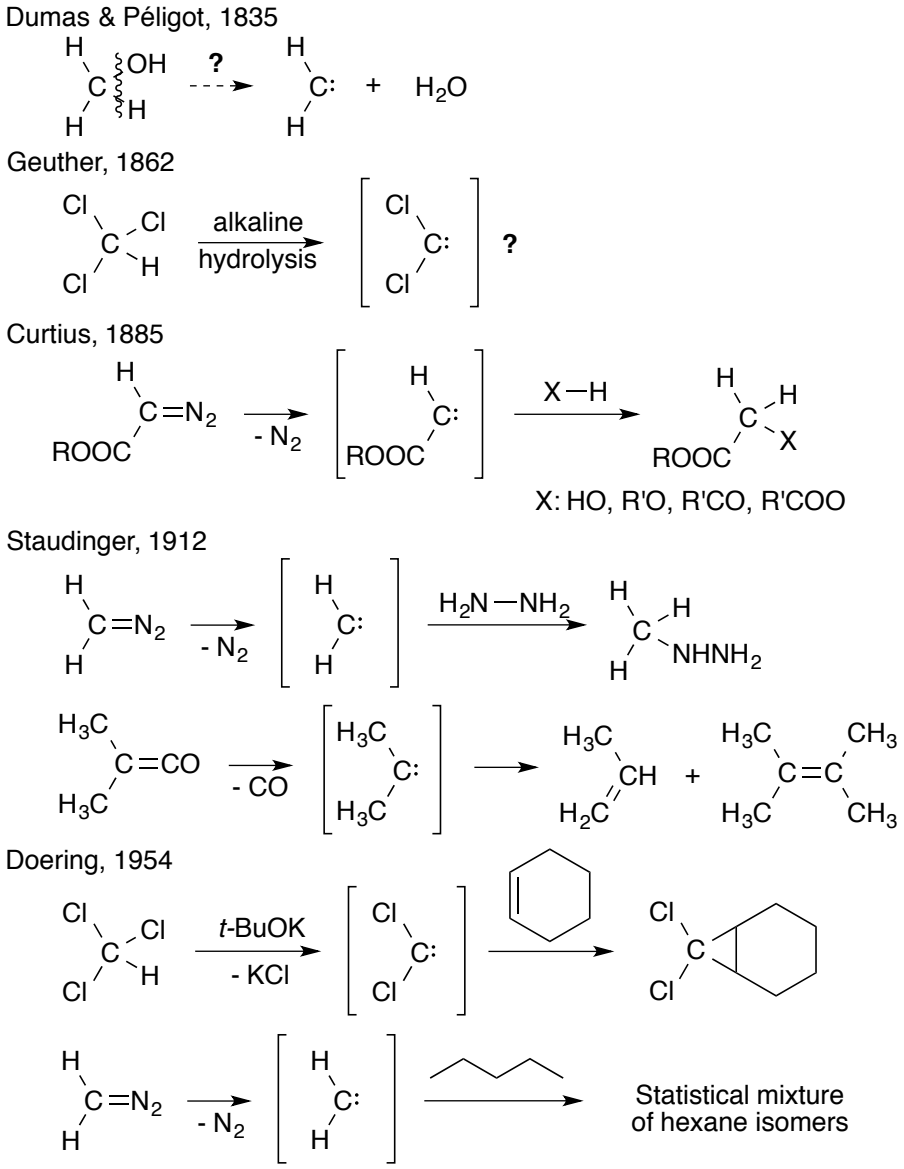


Figure I.1: Lewis structure of a carbene featuring its electron sextet

To the extent of chemical understanding at this time, methylene was a likely target as it respected the principle of electroneutrality. However, carbenes would soon be considered non-viable species. Extending on the work of Lewis,[2] Langmuir would actually dismiss the idea of the very existence of CH_2.[3] According to Langmuir's *reductio ad absurdum*, in order for the carbon atom of CH_2 to achieve an octet of electrons, it would need to form a bond with another atom. However, no other partner is available, and therefore the carbon atom would need to form a bond with itself, which is obviously impossible. Langmuir's findings temporarily sealed the fate of carbenes as impossible structures, which defied the bonding of atoms as explained by the theories of this period.

Despite being considered impossible to synthesize, carbenes were postulated as intermediates in several reactions (Scheme I.1). Geuther[4] first proposed dichloromethylene CCl_2 as the key intermediate in the alkaline hydrolysis of chloroform. Curtius[5-8] and Staudinger[9-12] then reinforced this idea working with diazo compounds and ketenes. Later on, Doering extended the study of carbenes highlighting their usefulness as synthons,[13-17] but also their incredibly high reactivity. By reacting methylene with *n*-

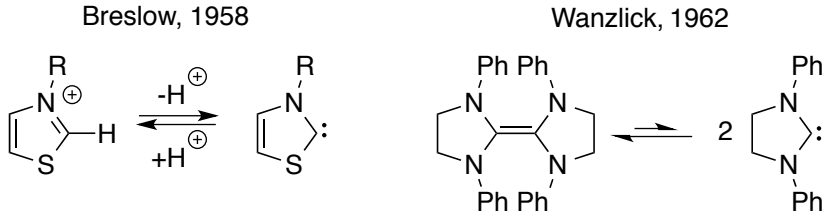
pentane and observing a statistical mixture of hexane isomers, Doering came to conclude that "*Methylene must be classed as the most indiscriminate reagent known in organic chemistry*".[16]



Scheme I.1: Early synthesis attempts and pioneering exploration of carbene reactivity

Thanks to these discoveries, carbenes would evolve from being considered as non-viable entities to highly reactive intermediates, which are powerful tools for the

synthetic chemist. Soon, Breslow[18] and Wanzlick[19] would add a new milestone on the way to understanding carbenes (Scheme I.2). Breslow, modeling the action of thiamin, proposed that thiazolium-salt-catalyzed bezoin and acetoin condensation reactions could be explained through the involvement of a persistent thiazolylidene carbene. Wanzlick later proposed that a diaminocarbene was in equilibrium with its dimer, which explained the reactivity of the dimer as a carbene source. These efforts shifted the opinion on carbenes as they were shown to be useful organocatalysts and controllable reagents.



Scheme I.2: Postulated persistent carbenes

Although carbenes were still non-isolable compounds, Fischer showed that they could be tamed when coordinated to a metal center.[20] Subsequent efforts by Öfele[21] and Lappert[22] reinforced the idea that carbenes could be used as ligands for transition metal complexes. In the meantime, Chauvin[23] was proposing carbene complexes as key intermediates in the mechanism of olefin metathesis, a reaction of industrial importance (Figure I.2).

Encouraged by these discoveries and driven by a need for better understanding of carbenes and for a more versatile ligand platform, chemists tackled the challenge of isolating a stable carbene free of metal coordination.

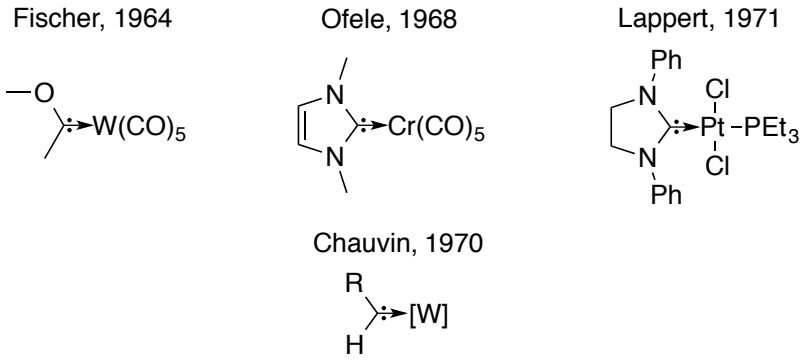


Figure I.2: Carbene-metal complexes and intermediate in olefin metathesis reaction

This quest would come to an end almost two decades later when Bertrand reported a stable (phosphino)(silyl)carbene.[24-27] Later efforts from Arduengo[28] and Enders[29] confirmed that through careful tuning of the substituents at the carbene carbon atom, such molecules could not only be isolated but even made crystalline (Figure I.3).

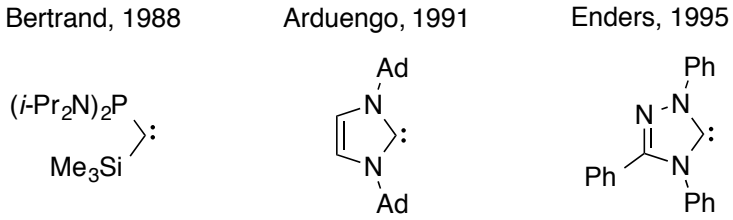


Figure I.3: First isolated carbenes

In the meantime, carbenes were also the object of the curiosity of theoretical and physical chemists as they defied the "octet rule". A tremendous amount of computational and physical studies deeply improved our understanding of carbenes.[30-45]

Carbenes can exist in two geometries: linear or bent. The geometry of the carbene influences its orbitals as each form can be described as having a differently hybridized carbon center. In the linear form, the carbene center is sp-hybridized. Two degenerate hybrid sp-orbitals are involved in the formation of covalent bonds with the substituents and therefore two degenerate p-orbitals are left non-bonding. In the bent form, the

carbene center is sp^2-hybridized. Two hybrid sp^2-orbitals are involved in the formation of covalent bonds with the substituents. The two non-bonding orbitals consist of a sp^2 orbital, which will be referred as the σ-orbital, and a p-orbital (Figure I.4).

Due to their electron sextet, carbenes can exist in two electronic states. In the singlet state, the two unshared electrons are of opposite spin and are paired in a same orbital, leaving one vacant. In the triplet state, the two electrons possess the same spin and therefore lie in two different orbitals. The spin-multiplicity has a tremendous influence on a carbene stability and reactivity.[40,46-48] Indeed, a wide variety of stable singlet carbenes are now known whereas triplet carbenes can only be observed as short-lived intermediates with half-lives of a few days at most.[46-50]

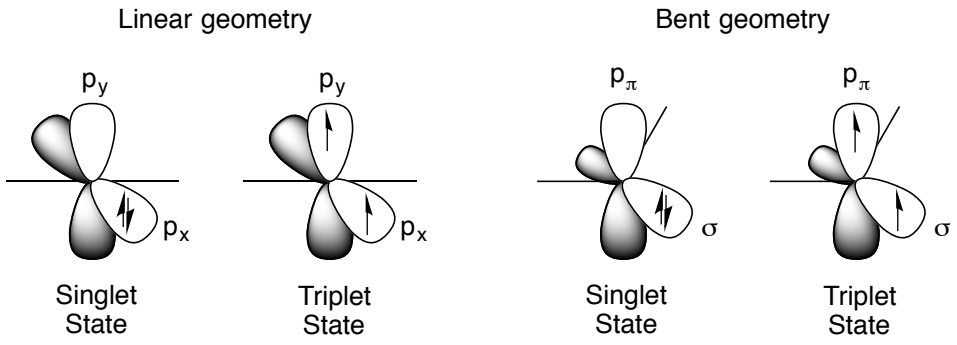


Figure I.4: Geometry and spin-multiplicity of carbenes

Spin multiplicity is dependent on a variety of factors. As mentioned previously, geometry has a significant effect on the orbitals of the carbene center. Indeed steric crowding of the substituents can force a linear geometry. Linear carbenes, in the absence of electronic factors, will tend to be triplet molecules, whereas bent carbenes favor the singlet state. However, substituents also influence the carbene multiplicity through inductive and mesomeric effects (Figure I.5).

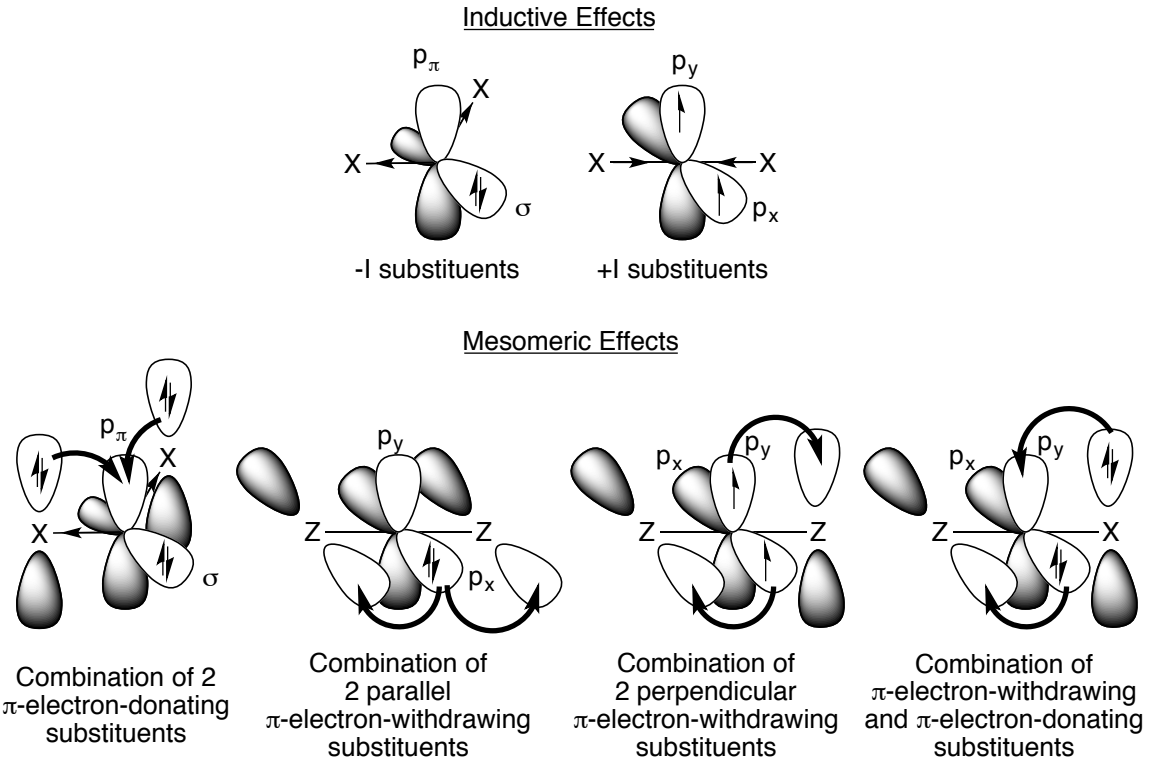


Figure I.5: Electronic factors influencing the spin-multiplicity of carbenes

Inductive substituents mainly affect the σ-system, whereas mesomeric effects will influence the π-system. In fact, inductive attracting substituents will favor a bent singlet state due to the stabilization of the σ-orbital, whereas inductive donating substituents will favor a linear triplet state. The combination of two π-donating substituents will stabilize the empty orbital of the bent singlet carbene, while two π-attracting substituents will favor linear geometries. Both triplet and singlet states can be stabilized depending on orbital alignment: if the two π-attracting orbitals are parallel, a singlet state will be favored whereas if they are perpendicular, a triplet state is postulated. However, no carbene with two π-attracting substituents has ever been isolated. The combination of one π-attracting substituent and one π-donating substituent will favor a linear singlet carbene.

Thanks to this new understanding of the mechanism of carbene stabilization, a plethora of stable singlet carbenes have been developed.[40,51-61] Stable carbenes were isolated in both acyclic and cyclic forms (Figure I.6). Cyclic carbenes were found to be better ligands for metal complexes[57,62,63] and therefore were much more widely studied than their acyclic counterparts. Acyclic carbenes can only be tuned through the nature of the carbene substituents, whereas cyclic carbenes vary not only in the number and nature of their heteroatomic substituents, but also through the ring size and the backbone functionalities. Finally, a new class of ligands called abnormal and mesoionic carbenes were developed.[64,65] The latter name comes from the impossibility of a resonance structure featuring a carbene without unreasonable charge separation. Nevertheless, these compounds share many similarities with classical carbenes as they can be used as ligands and organocatalysts.[65-74]

The development of stable carbenes led to tremendous advances in the field of catalysis, be it organometallic catalysis or organocatalysis.[57,75-79] However, this area of carbene chemistry is not the topic of this manuscript and shall not be further developed.

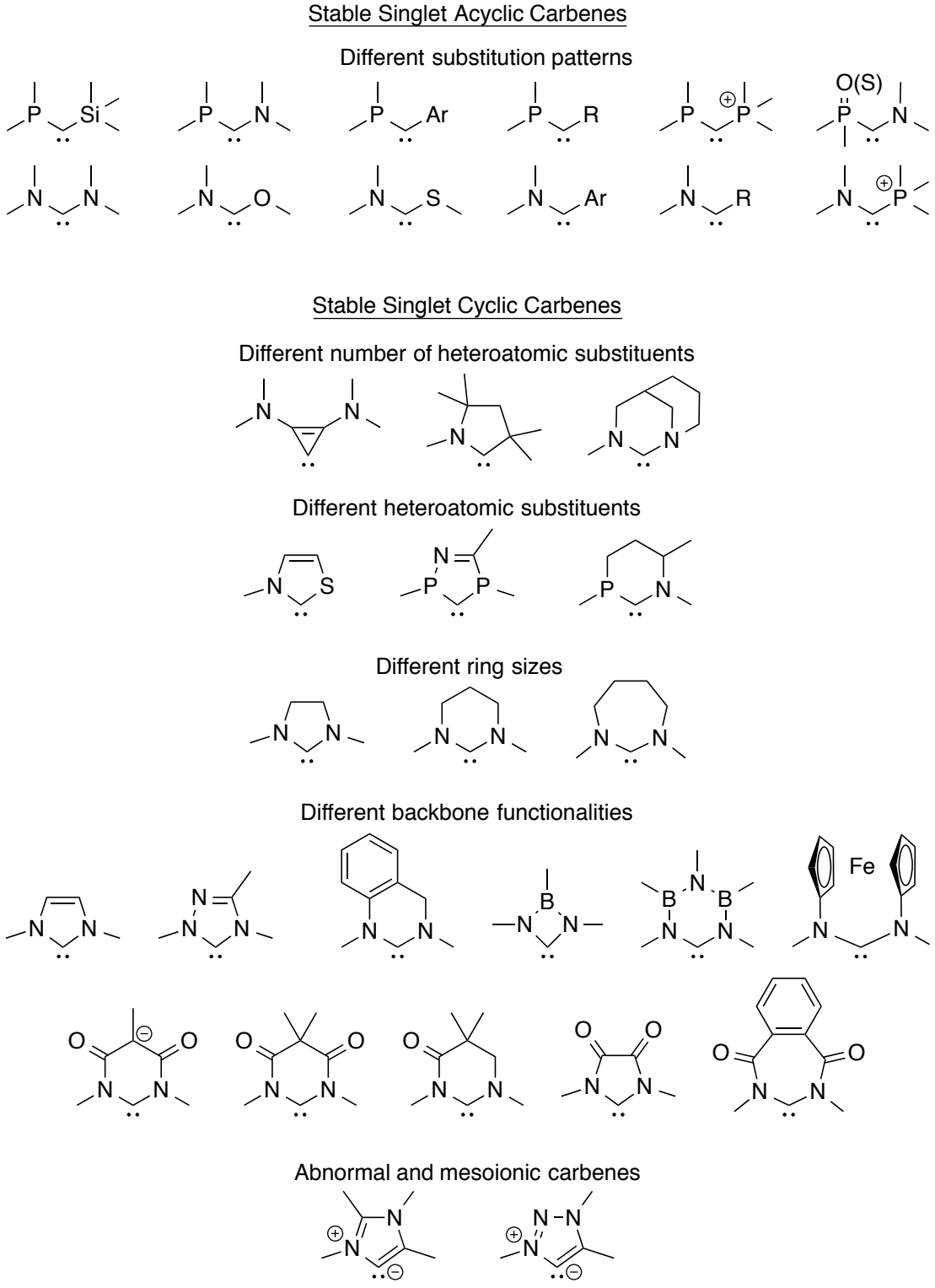


Figure I.6: Examples of stable carbenes highlighting their wide variety

One of the main advantages of carbenes is the tunability of their electronic properties and assessing the latter has been the object of numerous efforts.[54,59-61,80-83] Most stable singlet carbenes are good σ-donors but the σ-system is not easily modulated. However, through modification of the nature and number of substituents and the backbone functionalities of the carbene, their π-accepting ability is extremely tunable.

A new paradigm shift was introduced by Bertrand[84] when observing the splitting of dihydrogen and ammonia by (alkyl)(amino)carbenes. It was reasoned that they could mimic metal centers, as they both possess filled and empty orbitals conferring them amphiphilic reactivities.

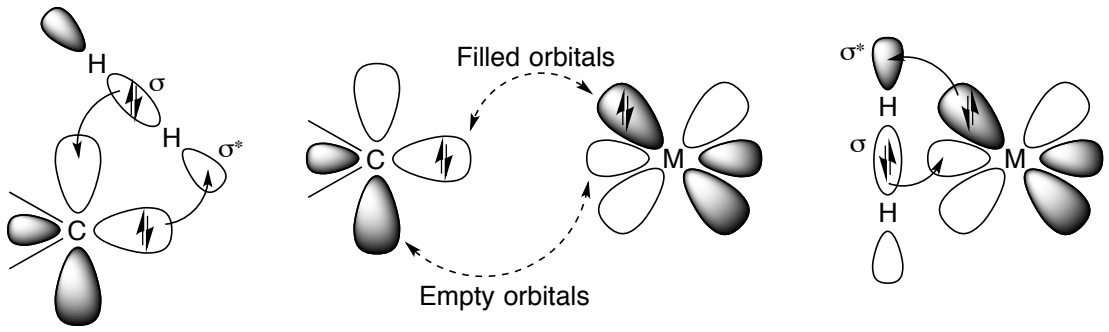


Figure I.7: Analogy between carbenes and metal centers based on their splitting of H_2

This discovery led to considerable developments as carbenes were used to activate small molecules such as H_2, NH_3 and P_4 to name only a few (Figure I.8).[40,84-89]

Carbenes, through their peculiar electronic and steric properties, were also used as ligands for unusual metal complexes (Figure I.9). Noteworthy are a few coordinatively unsaturated complexes as well as some formal zero-degree oxidation state complexes.[90-93]

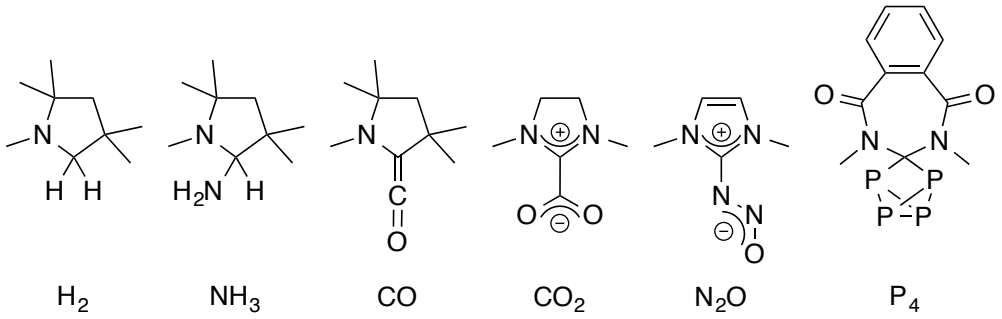


Figure I.8: Products of the activation of small molecules by carbenes

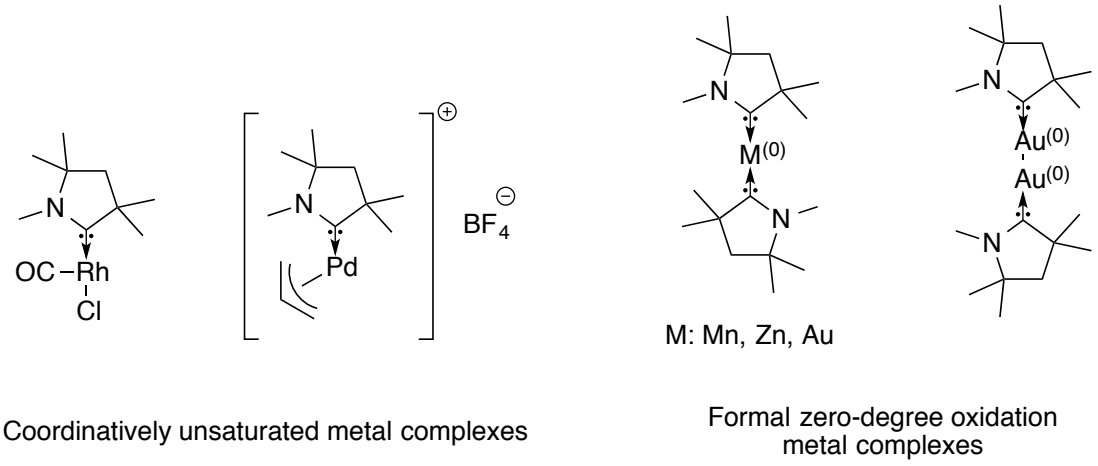


Figure I.9: Unusual metal complexes stabilized by carbenes

Carbenes also have had a tremendous impact in the field of main group chemistry. They allowed the isolation of numerous compounds that can be viewed as formal complexes of soluble allotropes of main group elements as well as their derivatives of different oxidation states (Figure I.10).[85,86,88,94-107] Most of those allotropes eluded isolation as their corresponding non-carbene-stabilized form so far. For most of them, it is due to the fact that they are predicted as unstable compounds.[100,104,108,109]

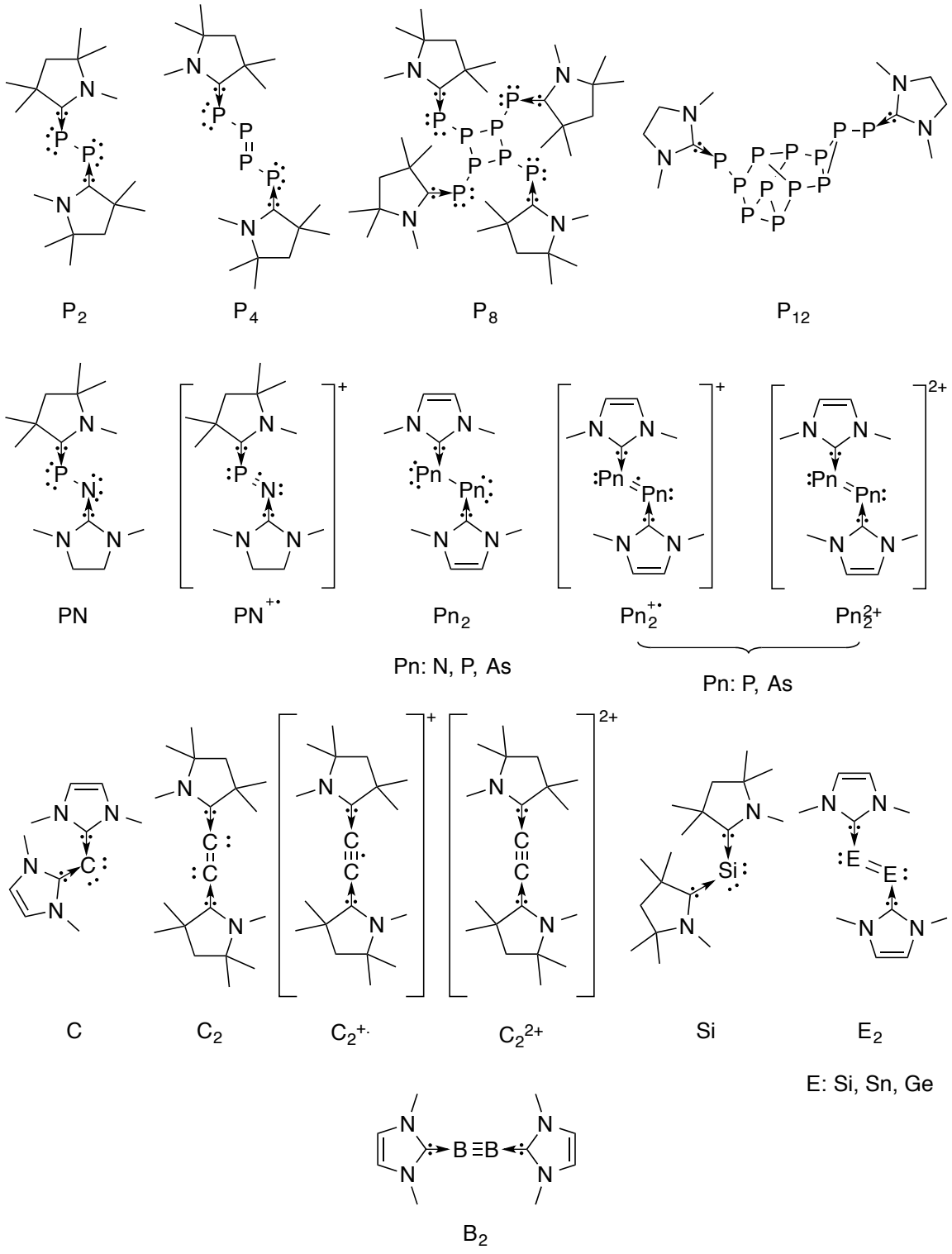


Figure I.10: Main group elements allotropes and related species stabilized by carbenes

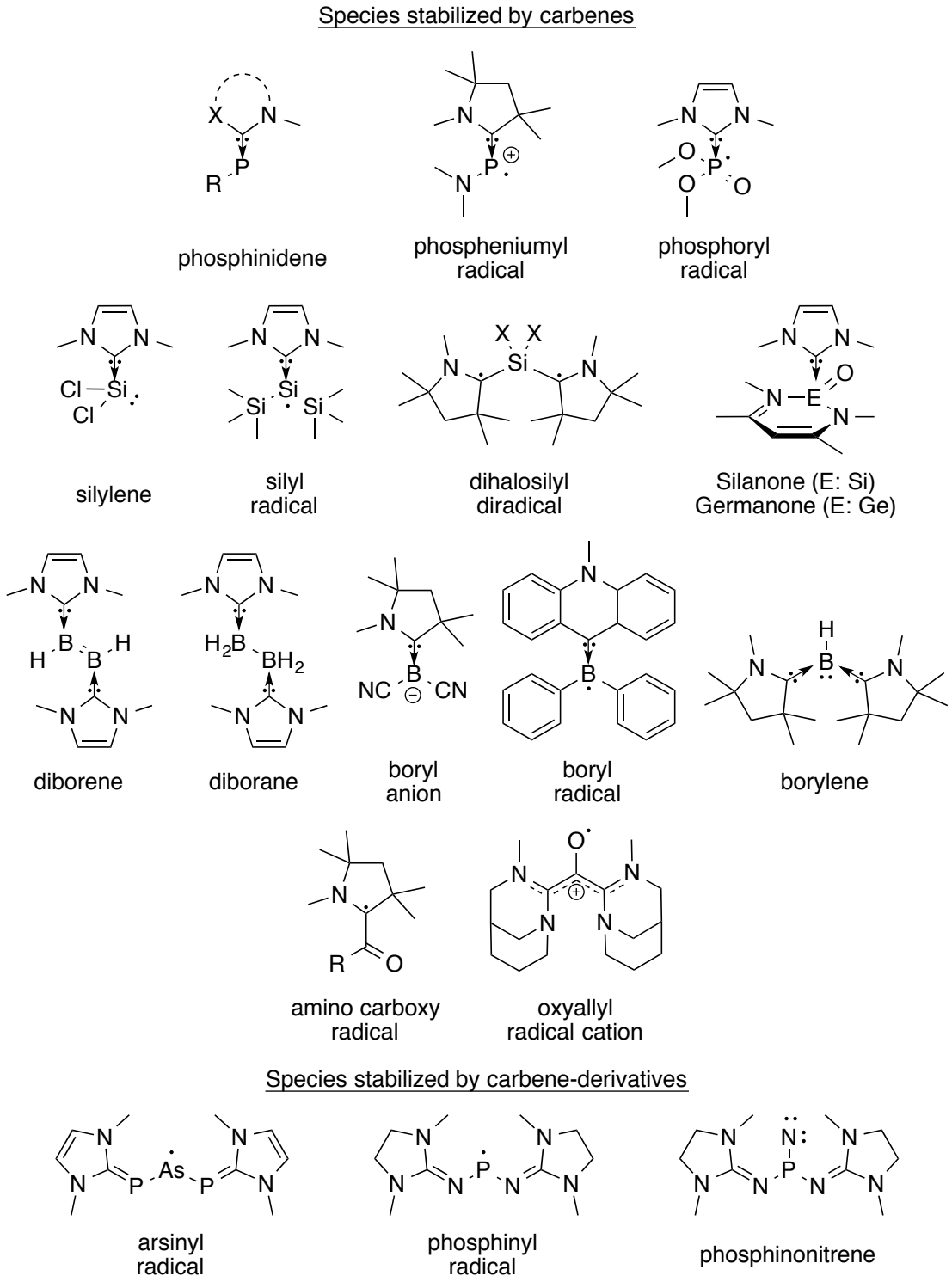


Figure I.11: Examples of highly reactive species stabilized by carbenes and their derivatives

Although it seems counter intuitive that such unstable compounds could be stabilized by carbenes, molecules once similarly considered unstable, the latter and their derivatives proved to be powerful tools for the isolation and characterization of numerous radicals, radical ions and other octet-defying compounds such as borylenes, phosphinidenes and nitrenes (Figure I.11).[100,103,110-119]

In this manuscript, we will try to improve our understanding of the electronic properties of carbenes through the design of a π-accepting ability scale based on the ^{31}P NMR spectrum of carbene-phosphinidene adducts. This will be explored in Chapter 1. In Chapter 2, we will discuss our attempts at synthesizing carbenes with new electronic properties. Finally, in Chapter 3, we will use carbene derivatives to stabilize a long sought target in our group, namely a stable phosphinonitrene.

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CHAPTER 1:

Understanding the Electronic Properties of Carbenes

Adapted from:

O. Back, M. Henry-Ellinger, C. D. Martin, D. Martin and G. Bertrand,

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A) Introduction

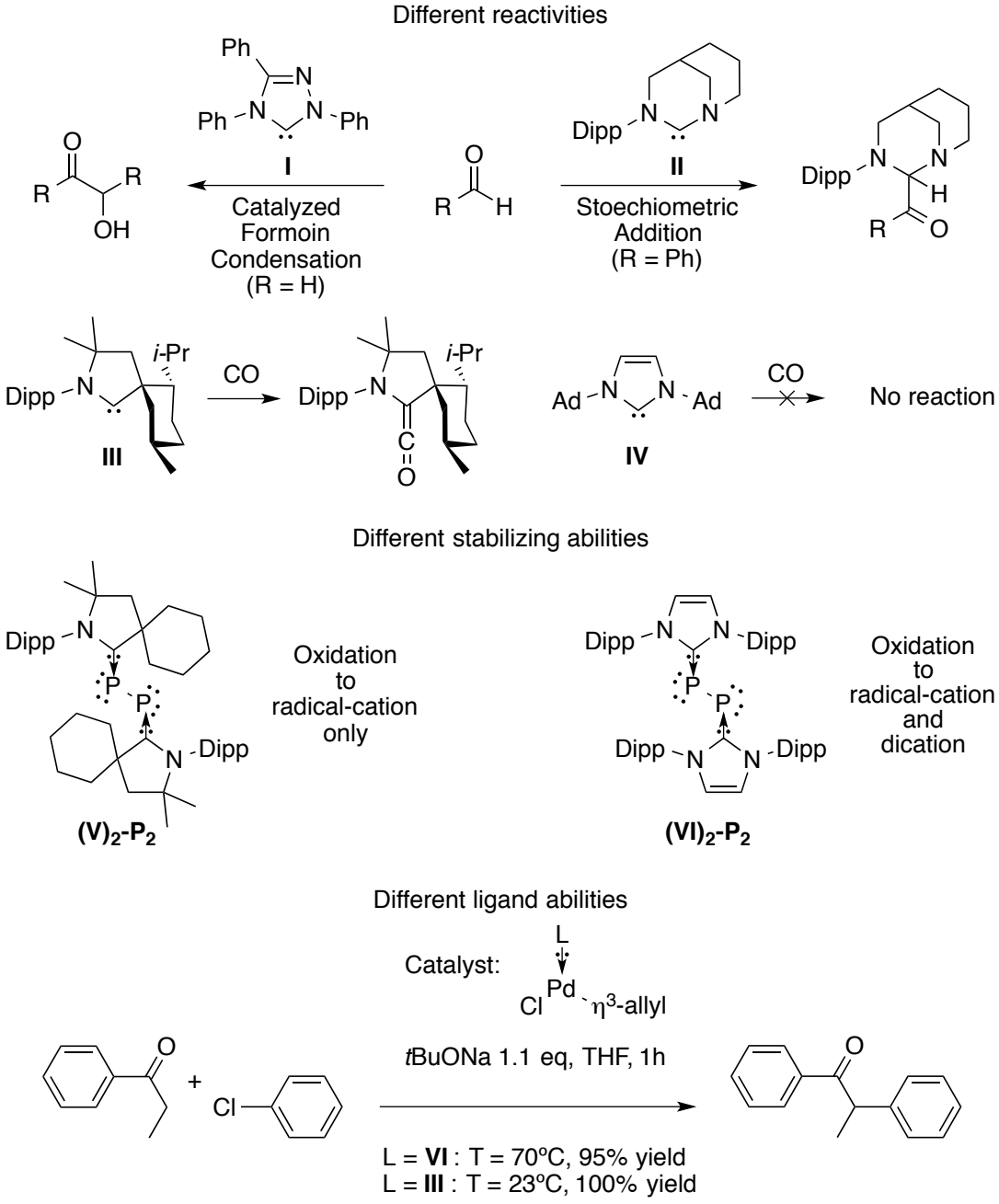
Since the seminal work of Breslow,[1] carbenes were established as excellent organocatalysts for several reactions. Indeed, one of the first application of carbene **I** was as a catalyst for the benzoin-type condensation of formaldehyde into glycolaldehyde (Scheme 1.1).[2] Since then stable carbenes have found numerous applications in the field of organocatalysis.[3-10] However, not all stable carbenes are effective in such catalysis. For example, when carbene **II** is subjected to an excess of benzaldehyde, no benzoin is formed. Instead, a stoechiometric reaction takes place resulting in the isolation of the the insertion product of **II** into the C-H bond of the aldehyde group (Scheme 1.1).[11]

Such different reactivities are not limited to the field of organocatalysis. Cyclic (alkyl)(amino) carbenes (CAACs) such as **III** react with carbon monoxyde (CO) to give a ketene[12] whereas the so-called N-heterocyclic carbenes (NHCs) such as **IV** do not (Scheme 1.1).[13]

In main-group chemistry, carbene-stabilized P_2 adducts exhibit different properties depending on the stabilizing carbene. The cyclic voltamogram of the adduct stabilized by carbene **V** displays only one one-electron oxidation wave at $E_{1/2}$ = -0.536 V, whereas, if carbene **VI** is the stabilizing partner, two one-electron oxidation waves are observed at $E_{1/2}$ = -0.178V and $E_{1/2}$ = -1.408 V, respectively.[14]

As ligands in transition metal-complexes, carbenes also exhibit different abilities. A good example of these differences is the palladium-catalyzed α-arylation of ketones. In fact, coupling of chlorobenzene with propiophenone is accomplished quantitatively in an hour at room temperature by catalyst **(III)-Pd(allyl)Cl** featuring carbene **III**,[15] whereas,

when **III** is replaced by **VI**, a temperature of 70ºC is required to achieve similar yields in the same time frame (Scheme 1.1).[16]



Scheme 1.1: Different reactivities and properties of carbenes

Regardless of the field of interest, understanding the causes for such different properties is of tremendous importance. Indeed, such differences cannot be attributed

only to different steric environments. For example, in the reaction or absence thereof between carbon monoxide and carbenes **III** and **IV**, respectively, CO is a small enough molecule to access both carbene centers, thus other factors must be in play. In fact, calculations by Bertrand[11] on the model reaction between carbenes and isocyanides, as molecules isoelectronic to CO, showed that more electrophilic carbenes such as **III** can stabilize the adduct thanks to their pronounced π-accepting ability, whereas imidazol-2-ylidenes such as **IV** could not stabilize the adduct. The reaction between the model imidazol-2-ylidene and isocyanide was even predicted to be thermodynamically disfavored with a ΔG value of +5.6 kcal/mol.

In order to understand carbenes properties, be it as reagents, as organocatalysts, or as ligands for main-group elements or transition metals, one must understand their peculiar electronic situation. Several methods have been developed to assess this issue, relying both on experimental and computational observations.

1) Experimental Approach:

The understanding of ligand properties has been a longstanding issue in organometallic catalysis. A variety of methods were developed to solve this problem, relying on various experimental techniques.

a) Infrared Spectroscopy

The first widely used method of characterizing ligands electronic properties was introduced by Tolman in 1977.[17] The Tolman Electronic Parameter (TEP) was first introduced for phosphine ligands. The TEP value for a given L ligand is defined as the infrared (IR) frequency of the symmetrical A_1 stretching vibration of the carbonyl (CO) ligands of the nickel complex $Ni(L)(CO)_3$ in dichloromethane (Figure 1.1). The TEP value correlates with the strength of the CO bonds in the complex, which is directly influenced by the electron density at the Ni center. A simple approach to understanding TEP values relies on the fact that the Ni-CO bonds can be described as consisting of two terms: the σ-donation of the carbon lone pair of the CO ligands into the metal center and the π-back-donation of the metal center into the π*-antibonding orbital of the CO ligands. Indeed, the more electron-donating the L ligand is, the more electron rich the nickel center and therefore the more pronounced the back-donation into the π*-antibonding orbital becomes. As a result, the CO bonds are weakened and the A_1 stretching frequency is shifted towards the red (*i.e.* smaller wavenumbers). Indeed the smaller the TEP value, the better donor the ligand will be (Figure 1.1). TEP values were recorded for a wide variety of ligands, including carbenes.[18]

However this analysis assumes that the L ligand influences the metal center mostly by σ-donation. While this assumption was historically logical, as phosphines were considered purely σ-donor ligands, it was later proved that phosphines were capable of accepting electron density from the metal center through π-back-donation into the σ^*_{PR} antibonding orbital between the phosphorus atom and its substituents.[19] This

phenomenon actually impacts the TEP value as it is influenced the electron density on the Ni center. This is even more important in ligands such as carbenes where the π-accepting ability can be much more pronounced than in phosphines (Figure 1.1).

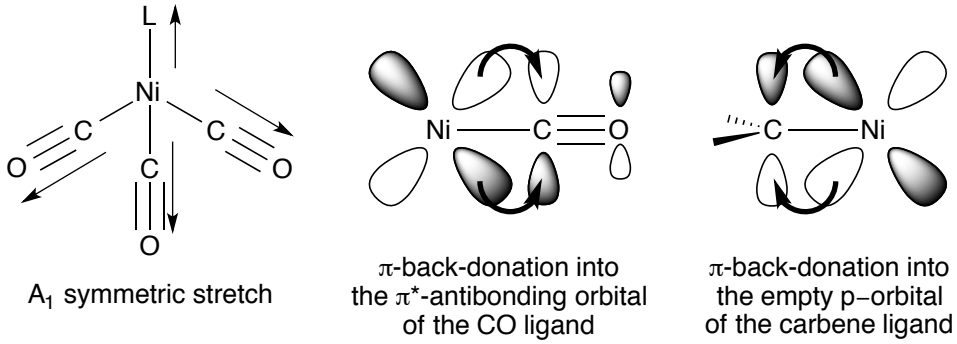


Figure 1.1: A_1 symmetric stretching vibration and selected factors influencing the electron density on the metal center

Although widely used, the TEP relies on nickel carbonyl complexes, which are highly toxic and in some case unstable. To circumvent this problem, two similar scales were developed, using *cis*-carbonyl complexes of rhodium[20-24] and iridium, [20,24,25] of type $M(L)(CO)_2(Cl)$. For both scales, the reported value ($\nu_{CO}^{av/Rh}$ for Rh and $\nu_{CO}^{av/Ir}$ for Ir) is the average of the symmetric and asymmetric modes of the carbonyl ligands. This is problematic as the two modes might be differently influenced by both steric and electronic effects. [22,26] Moreover, the correlation between these scales and the TEP is not perfect as exemplified by the reversal in the relative order of donor strength between P*t*Bu$_3$ and PCy$_3$ (TEP (in CH_2Cl_2): P*t*Bu$_3$ = 2056.1 cm^{-1}, PCy$_3$ = 2056.4 cm^{-1}, *vs.* $\nu_{CO}^{av/Ir}$ (Nujol): P*t*Bu$_3$ = 2031 cm^{-1}, PCy$_3$ = 2024 cm^{-1}).[17,26]

Although eliminating the issue of the toxicity of nickel complexes, both new scales are also limited by the possibility of synthesizing the desired complexes and by cost considerations, as both rhodium and iridium are expensive metals.

In summary, the Tolman Electronic Parameter and related rhodium and iridium scales should be viewed as a measure of the overall donating ability of a ligand, taking into account both σ-donating and π-accepting contributions of the considered ligand to the electron density of the chosen metal center.

b) Cyclic Voltammetry

Another method of assessing ligands electronic properties is the measure of the redox potential of a given metal center. For example, the Lever Electronic Parameter (LEP) has been developed with ruthenium complexes (Ru^{II}/Ru^{III} couples) and is often used in inorganic chemistry.[27,28] The systematic variation of only one ligand on a given complex provides a series of results from which one can observe the influence of the varied ligands on the potential of the considered redox couple. As the redox potential is directly related to the electron density on the metal center, the relative electron donating abilities of a series of ligands can be inferred. Different redox couples[29-33] were considered to assess the properties of carbenes, however, sufficiently wide studies are still lacking. Moreover, as a measure of the electron density of the metal center, such studies are effectively an indication of the overall donating abilities of ligands and do not deconvolute σ- and π-contributions. Additionally, recent results suggest that ligands, and especially carbenes, can possess a non-innocent character in redox processes and in the stabilization of metal centers.[34-38] Lastly, despite their superior precision, electrochemical techniques are far less widespread compared to infrared spectroscopy.

c) Nuclear Magnetic Resonance Spectroscopy

The most widespread analytical technique among organic and organometallic chemists is arguably Nuclear Magnetic Resonance spectroscopy (NMR). NMR is yet another method influenced by the electron density at the observed nuclide. As such, carbon 13 (^{13}C) NMR was used to study the ligand influence in different series of organometallic complexes of carbenes. Noteworthy are the palladium complexes of type $Pd(Br)_2$(**VII**)(L), where **VII** is the N,N'-diisopropylbenzymidazol-2-ylidene carbene, used by Huynh.[39,40] In these complexes, the chemical shift of the carbenic carbon of **VII** serves as a probe throughout the series of ligands (Figure 1.2). Observing poor correlation between chemical shifts and TEP values, it was concluded that different factors might be at work between the two scales. Although NMR is a routine technique in the organic and organometallic chemistry toolbox, this scale is limited by the narrow range of observed chemical shifts (*ca.* 10 ppm wide). Moreover, only a few examples can be found in the literature. In addition, the mechanism of influence of the observed ligand remains unclear.

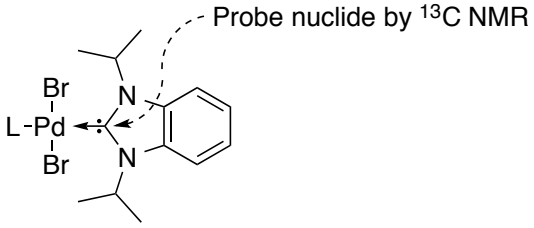


Figure 1.2: ^{13}C NMR probe developed by Huynh

In conclusion, despite several experimental techniques to evaluate the overall donating ligands properties, the detailed understanding of the σ-donating and π-accepting abilities of carbenes remains limited mainly to computational analyses.

2) Computational Approach:

The development of density functional theory (DFT) led to a tremendous improvement of our understanding of the bonding of atoms in molecules.[41] Molecular orbitals (MO) can be computed and information regarding the reactivity of a molecule can be inferred from the frontier orbitals, namely the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO).[42] In the case of carbenes, the key frontier orbitals are the filled σ-orbital, which is the HOMO, and the empty p-orbital, which is the LUMO. Shapes and energies of these orbitals can provide information on potential reactivity[11,43] and prospective stability.[44]

The energies of the HOMO (E_{HOMO}) and LUMO (E_{LUMO}) are correlated to the nucleophilicity as well as to the σ-donating abilities for the former, and electrophilicity as well as to the π-accepting abilities for the latter. The higher the E_{HOMO} value, the more nucleophilic and better σ-donor the carbene, and conversely, the lower the E_{LUMO} value, the more electrophilic and more π-accepting the carbene will be. However, direct evaluation of the energy of empty orbitals such as the LUMO proved to be a difficult task as DFT inaccurately describes virtual orbitals.[45] Interestingly, DFT methods are not limited to the study of the free carbenes. TEP and LEP values can be derived with reasonable accuracy from calculations on the relevant metal complexes.[26,46,47]

Although DFT calculations provide good insights into the electronic situation of carbenes and their properties, such results remain based on approximations and are highly dependent on the methods used to perform the analysis. Indeed, careful choice of functionals and basis sets must be effected, and some expertise is needed in order to obtain trustworthy results. Therefore, DFT results should be used very cautiously when

trying to predict properties[48] and should rather be used as supporting arguments when discussing experimental observations

3) Concluding Remarks

Despite numerous techniques to assess the properties of carbenes, methods to separately evaluate σ-donating and π-accepting abilities are still lacking. The understanding of these properties is however of paramount importance.

Indeed, when looking back at the different redox behaviors of **$(V)_2$-P_2** and **$(VI)_2$-P_2**, DFT analysis of the bonding situation between the carbenes and the P_2 core shows that the main differentiating factor is the polarization of the bond between the carbenic carbon atoms and the phosphorus atoms.[14] Compounds **$(V)_2$-P_2** and **$(VI)_2$-P_2** are actually best described as adducts of two carbene fragments and a central bisphosphinidene core. The difference in bonding can then be rationalized as different back-donation of the phosphinidene lone pair into the carbene empty orbital. Carbene **V** is effectively able to accept more electron density than carbene **VI**. The result is a more electron-rich P_2 core in **$(VI)_2$-P_2** that is indeed easier to oxidize.

Another striking difference is observed by NMR spectroscopy. In fact, the ^{31}P chemical shift in **$(V)_2$-P_2** is δ = 59.4 ppm,[49] whereas in **$(VI)_2$-P_2** it is δ = -52.4 ppm.[50] NMR, as a measure of electron density at the phosphorus atom proves to be a good probe for the different electronic situations in **$(V)_2$-P_2** and **$(VI)_2$-P_2**.

B) Evaluation of π-accepting properties of carbenes

1) Design of the scale:

The aforementioned bis-carbene-P_2 compounds are a perfect example of the fact that ^{31}P chemical shifts of carbene-phosphinidene adducts can inform on the π-accepting properties of carbenes. However, such compounds are scarce in the literature and difficult to synthesize. Closer examination of such compounds reveals that, despite the fact they are best described as a bisphosphinidene P_2 core ligated by two carbenes, another depiction of the bonding situation is to regard them as bisphosphaalkenes. Phosphaalkenes are classical compounds in phosphorus chemistry and numerous examples have been synthesized and studied. [51-79] Therefore, we rationalized that such compounds would provide a much simpler probe than the bis-carbene-P_2 adducts.

The influence of the carbene on the electron density at the phosphorus atom can be explained exactly as previously stated. Strongly π-accepting carbenes will favor a phosphaalkene structure, whereas their weakly π-accepting congeners will be better described as carbene-phosphinidene adducts (Figure 1.3).

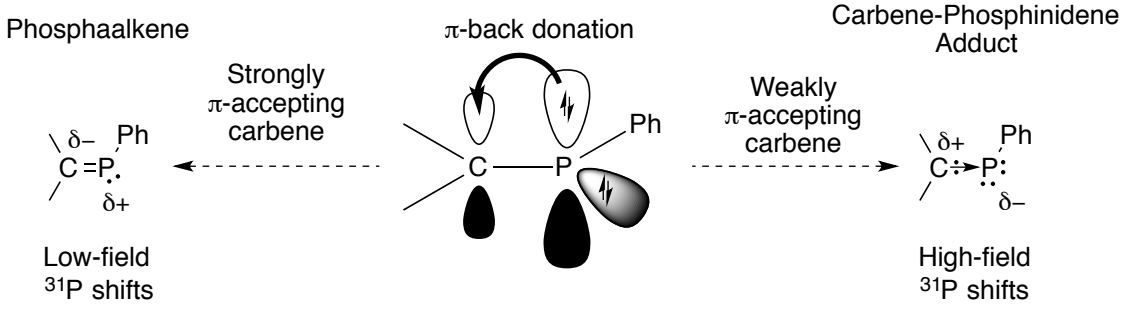


Figure 1.3: Influence of the carbene on the ^{31}P chemical shifts of phosphaalkenes

Indeed, traditional phosphaalkenes feature a polarized P=C double bond in which the P atom is the positive pole, leading to low-field ^{31}P chemical shifts. In contrast,

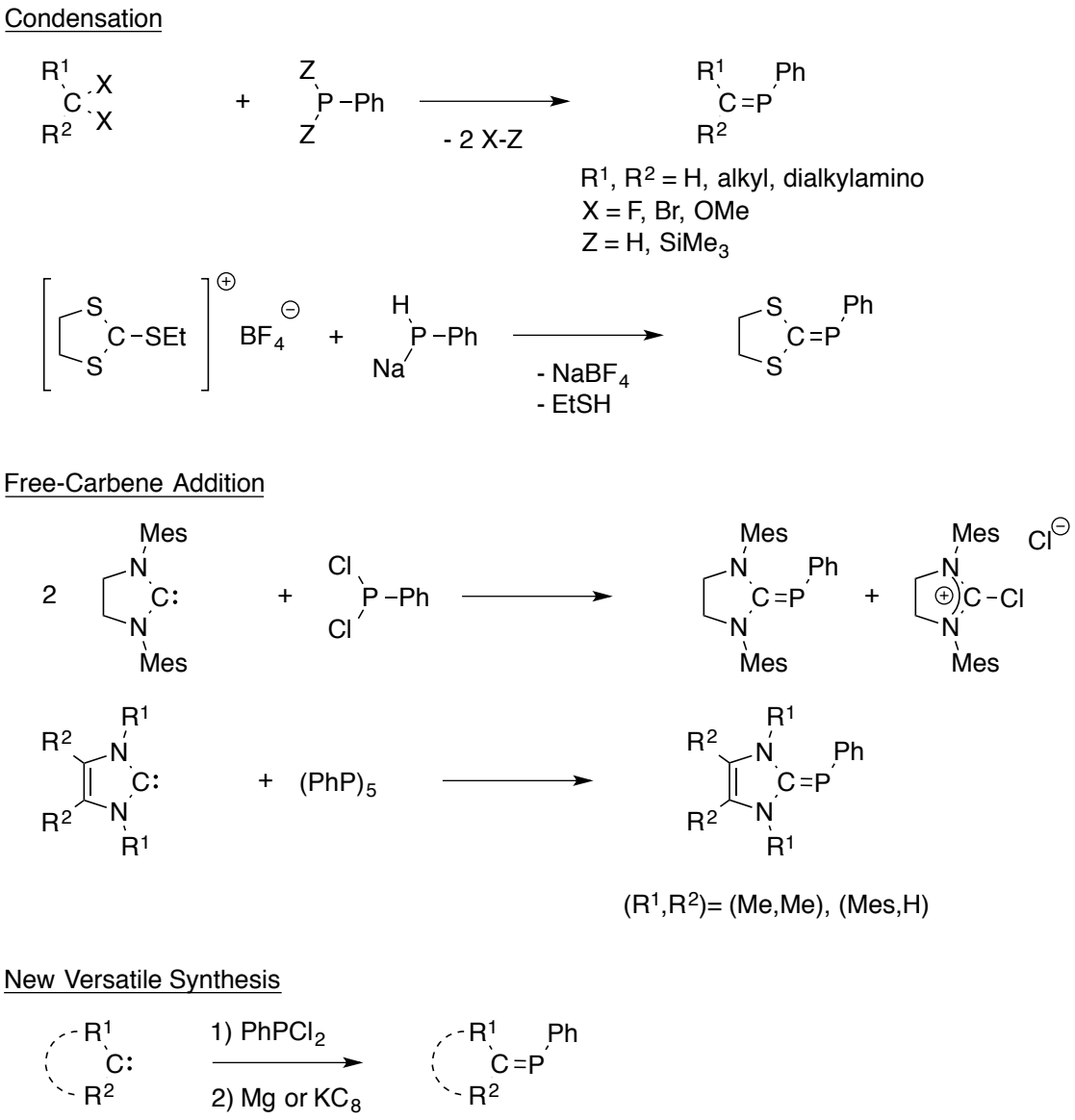
carbene-phosphinidene adducts feature a reversed polarization, with a phosphorus atom exhibiting a pronounced negative charge, resulting in high-field ^{31}P chemical shifts (Figure 1.3). Historically, such carbene-phosphinidene adducts have been referred to as inversely polarized phosphaalkenes.

2) Synthesis of target compounds

Numerous synthetic routes have been developed to access phosphaalkenes (Scheme 1.2). [54-79] These routes are fairly diverse and mostly rely on the condensation of a phosphine derivative on various electrophiles. Interestingly, Arduengo reported that the addition of free carbenes to pentaphenylcyclopentaphosphane or to half an equivalent of dichlorophenylphosphine afforded the desired phosphaalkenes (Scheme 1.2).

In order to have a unified set of carbene-phosphinidene adducts, we chose to restrict our study to P-phenyl phosphaalkenes as a wide variety of those compounds can be found in the literature.

Additionally, we consider the design of a unified versatile synthesis using free carbenes as starting materials. The first step of this new synthetic route involves the addition of a free carbene to dichlorophenylphosphine in benzene or hexane resulting in a salt. The solution is then simply filtered out and with no further purification, the salt is reduced using two equivalents of either magnesium or potassium graphite (KC_8). The desired carbene-phosphinidene adduct can be obtained after subsequent workup, but a ^{31}P NMR analysis of the crude mixture after reduction affords all the necessary information.



Scheme 1.2: Examples of synthesis of P-phenyl phosphaalkenes

This strategy also proved to be adapted to a wide variety of carbenes as adducts of carbenes **6**, **9**, **10**, **11**, **13**, **14**, **16**, **18**, **19**, **22**, **25**, **26** and **27** were obtained. The main advantage of this approach lies in the fact that isolation of the intermediate salt and purification of the final phosphaalkene are not mandatory, providing a versatile and easy to implement access to the desired compound (Scheme 1.2).

3) Discussion

Note: Relevant ^{31}P chemical shifts data from this study and the literature have been compiled in Tables 1.1-1.4

a) Influence of the nature of the carbene substituents

It is well understood that the nature of a carbene substituents has a tremendous influence on its stability as they influence the singlet-triplet gap.[44] Whereas inductive effects impact mostly the energy of σ-orbital (HOMO), mesomeric effects mainly influence the LUMO. This is perfectly illustrated when considering the acyclic carbene series. Indeed, when comparing the different chemical shifts of **4**·**PPh** and **6**·**PPh** (221.0 and 126.3 ppm, respectively), the replacement of a hydrogen atom by a π-donating dialkylamino group reduces the ability of the carbene to accept electron density from the phosphinidene fragment. The same effect accounts for the difference between **6**·**PPh** and **9**·**PPh** (126.3 and 69.5 ppm, respectively) when, in **9**, a second π-donating dialkylamino group replaces the alkyl substituent of **6**. Another similar effect is highlighted by the chemical shifts of **7**·**PPh** and **9**·**PPh** (124.3 and 69.5 ppm, respectively). Indeed, in **7** the dialkylphosphino substituent is a poorer π-donor than its nitrogen analog in **9**, accounting for the increased π-accepting ability of **7**.

These effects can also be found in the cyclic series. Indeed, cyclic (alkyl)(amino)carbenes **18**, **19** and **20** (68.9, 56.2, 49.0 ppm for the ^{31}P chemical shifts of their respective adducts) have only one π-donating substituent whereas diaminocarbenes **22** and **23** (-10.2 and -10.4 ppm for the ^{31}P chemical shifts of their respective adducts) possess two. In parallel, **21** (44.9 ppm for **21**·**PPh**) is more accepting than **22** and **23** due

to the poorer donating ability of sulfur compared to nitrogen. The exact same argument can be made to explain the difference between **10** and **11** (57.0 and -18.9 ppm for the ^{31}P chemical shifts of their respective adducts). Along this line, when comparing **15** and **16** to **11** and **12** (-53.5 and -61.2 *vs.* -18.9 and -23.0 ppm for the ^{31}P chemical shifts of their respective adducts), the alkylsubstituted nitrogen substituents of **15** and **16** are better donors than the arylsubstituted ones of **11** and **12**.

In summary, the more π-donating substituents a carbene has, the less π-accepting it will be. Additionally, the better π-donors the substituents are, the less π-accepting the carbene is.

b) Acyclic *vs.* cyclic carbenes

Adducts **8·PPh** and **20·PPh** have significantly different ^{31}P chemical shifts (85.6 and 49.0 ppm, respectively). This can be explained by considering the flexibility of the structure of the corresponding carbenes. Indeed, the inclusion of the carbene center into a cycle restrains the rotation around the C-N bond between the carbene center and its nitrogen substituent. Therefore, the lone pair of the nitrogen substituent is constrained in a conformation that is favorable to π-donation into the empty orbital of the carbene, competing with the back-donation of the phosphorus lone pair in the case of the carbene-phosphinidene adduct. In the acyclic case, rotation around the C-N bond is less hindered and back-donation becomes much more possible. The same argument accounts for the observation in the case of diamino carbenes **9** and **22**.

To summarize, increased flexibility results in enhanced π-accepting abilities.

c) Additional factors in the cyclic series

i) Influence of the ring aromaticity

When comparing **11** to **22** (-18.9 and -10.2 ppm for **11·PPh** and **22·PPh**, respectively) and **12** to **23** (-23.0 and -10.4 ppm for **12·PPh** and **23·PPh**, respectively), the two couples have identical substituents at the nitrogen but differ in the presence of a double bond in the backbone of **11** and **12** making these 5-membered rings aromatic. The saturated counterparts **17** and **18** are more π-accepting as previously observed by Nolan using as series of platinum complexes.[80] Indeed, the aromaticity of the ring accounts for the high-field chemical shifts of adducts **11·PPh** to **16·PPh**. Of particular interest is carbene **14** as, despite having no heteroatomic substituent attached to the carbene center, the aromatic nature of the cyclopropene ring is responsible for the observed chemical shift as **14·PPh** can be seen as a zwitterionic compound with an aromatic cyclopropenium unit connected to a negatively charged phenylsubstituted phosphorus atom. Another revealing example is the case of carbenes **13** and **16** (-34.6 and -61.2 ppm, for the ^{31}P chemical shifts of their respective adducts). As expected, benzannulation increases the π-accepting ability of the carbene as the extended aromatic system can accommodate more electron density. This result is reminiscent to the observation of Heinicke using rhodium complexes.[81]

In summary, aromaticity in cyclic carbenes results in enhanced electron donation in the empty orbital of the carbene. The consequence is that carbenes incorporated in aromatic rings are less π-accepting than their saturated analogues.

ii) Influence of the ring size

Expanding the size of the cycle results in a more flexible structure. Indeed, as discussed in the case of acyclic *vs.* cyclic carbenes, this results in enhanced π-accepting abilities. This is clear when comparing carbenes **22** and **27** that only differ in the size of their respective rings, as the substituents at the nitrogen atoms are identical. **22·PPh** presents a ^{31}P chemical shift at higher field than **27·PPh** (-10.2 and 14.8 ppm, respectively).

iii) Influence of the donating abilities of the carbene substituents

As discussed earlier, the π-donating ability of the carbene substituents plays a dramatic role on the π-accepting ability of the carbene. It can be tuned by changing the nature of the substituent, for example changing a nitrogen atom for sulfur, but it can also be affected by preventing the donation of the nitrogen lone pair into the empty orbital of the carbene by other mechanisms. The introduction of electron withdrawing functional groups competing with the carbene empty orbital for the π-donation of the substituent results in more π-accepting carbenes. This is apparent in the carbonyl-decorated carbenes **17**, **24** and **25**. Indeed, **17·PPh** displays a much lower ^{31}P chemical shift that **23·PPh** (78.6 and -10.4 ppm, respectively). The same phenomenon is observed when comparing **27·PPh** to **24·PPh** and **25·PPh** (14.8, 39.7 and 83.0 ppm, respectively). Another mechanism for influencing the π-donating ability of the carbene substituents is exemplified by the anti-Bredt carbene **26**. In this case, the lone pair one of the nitrogen substituent is prevented from donating into the carbene empty orbital by forcing the nitrogen atom in a bridgehead position. The nitrogen lone pair becomes perpendicular to

the carbene empty orbital, preventing donation. Additionally, donation of this lone pair into the empty orbital could be described by a resonance structure featuring a double bond to an atom in a bridgehead position in a strained [4.4.0]-bicyclic compound, resulting in a violation of the so-called Bredt's rule.[82]

To summarize, π-accepting abilities of a carbene can be tuned through modulation of the π-donor strength of its substituents.

d) Sensitivity to steric effects

Similarly to the TEP being affected by the steric properties of ligands, the developed carbene-phosphinidene probe is not exempt from such considerations. Indeed, in the case of the unsymmetrically substituted carbenes, phosphaalkenes can exist in two stereoisomeric forms. Indeed, both isomers exhibit different ^{31}P chemical shifts as exemplified by the case of carbene **5** (**Z-5·PPh**: 134.0 ppm and **E-5·PPh**: 149.2 ppm). This can be rationalized as the substituent *trans* to the phenyl group is allowed better conjugation because of less steric strain. This results in less back-donation from the phosphorus moiety and therefore a lower field chemical shift.[83] Although our methodology seems selective towards the most stable isomer, as we never observed any mixture of isomers, carbenes with different steric demands can give rise to different geometries. This can be observed in the case of cyclic (alkyl)(amino) carbenes **18** and **19**. Indeed, the cyclohexyl flanker of **18** is much more flexible that the conformationally locked menthyl flanker of **19**. Single crystal X-Ray diffraction studies of their respective adduct shows that **18·PPh** exhibits an E-geometry at the C=P double bond, whereas **19·PPh** shows a Z-configuration (Figure 1.4). Consequently, despite most likely sharing

similar π-accepting abilities, the ^{31}P chemical shifts of the two adducts differ by *ca.* 13 ppm (**18·PPh**: 68.9 ppm, **19·PPh**: 56.2 ppm).

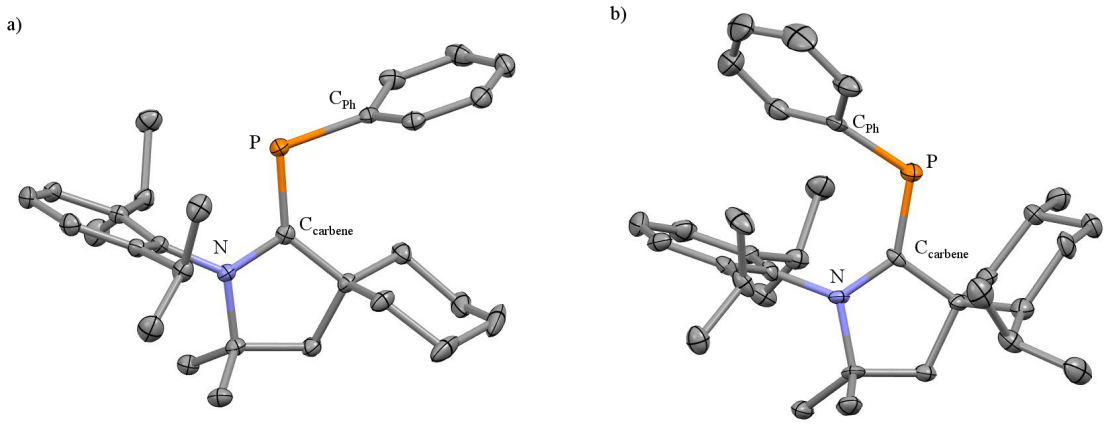


Figure 1.4: Solid-state structures of (a) **18·PPh** and (b) **19·PPh**. Ellipsoids are drawn to 50% probability; hydrogen atoms are omitted for clarity. In the case of **21·PPh**, only one molecule from the asymmetric unit is shown. Selected angles: a) N-$C_{carbene}$-P-C_{Ph} = 179.0º b) N-$C_{carbene}$-P-C_{Ph} = 4.2º

e) Evaluating non isolable carbenes

One advantage of this probe resides in the possibility to access information pertaining to carbenes that cannot be isolated. Indeed, carbenes **1-4** possess triplet ground states and are too reactive for isolation.[44] Carbene **21**, on the other hand, is suspected to decompose into ethylene and carbon disulfide.[84] Thanks to the well-established phosphaalkene chemistry, a wide variety of carbenes can be studied, as their phosphinidene adducts are accessible through a diverse array of synthetic approaches.

f) Deconvolution of σ-donating and π-accepting properties

The carbene-phosphinidene probe provides a good measure of π-accepting properties. When these results are combined with another metric such as the TEP, σ-donating and π-accepting contributions can be deconvoluted. Indeed, carbenes **10** and **13**

possess identical TEP values (2054 cm^{-1}), however **10** is much more electrophilic as expected from the presence of the poorer π-donating sulfur substituent. This suggests that **10** is a much better σ-donor than **13**. This is coherent with the more electropositive sulfur atom not being able to stabilize the σ-orbital as well as nitrogen through attracting inductive effects. Along this line, carbenes **6** and **27** possess identical TEP (2044 cm^{-1}), suggesting similar overall donating properties. However, as expected from the reduced stabilization of the empty orbital by the unique dialkylamino substituent and the more electropositive carbon substituent being poorly able to stabilize the σ-orbital, carbene **6** is both more σ-donating and π-accepting than **27**.

Following the same reasoning, the observation of the TEPs of CAACs **18** and **19** (2042 and 2049, respectively) and of NHCs **11**-**13**, **15**, **16**, **22** and **23** (2051-2054 cm^{-1}) allows for the conclusion that not only are CAACs overall stronger ligands than NHCs, they are actually both better π-acceptors and much better σ-donors as predicted by calculations.[85]

g) On the possibility of extending the scale to non-carbene ligands

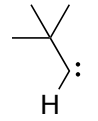
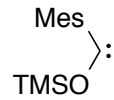
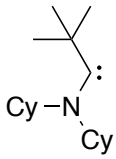
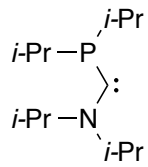
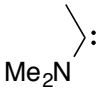
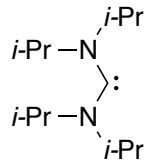
Careful analysis of the literature reveals that other compounds can be considered as ligand-phosphinidene adducts (Table 1.5). Compounds **28**·**PPh** and **29**·**PPh** can be viewed as adduct of phosphinidene ligand **28** and nitrene ligand **29**, respectively. As intuited for such electron deficient species, their adducts display extremely low field ^{31}P chemical shifts (**28**·**PPh**: 525 ppm, **29**·**PPh**: 415 ppm). Derivative **30**·**PPh** can be viewed as the adduct of isocyanide **30** and displays a significantly high field shift signal (**30**·**PPh**: -99 ppm). The interpretation in terms of π-back donation should be considered very

carefully here as the formation of the adduct involves dramatic structural changes. Effectively, free isocyanides present an almost linear dicoordinated nitrogen atom,[86] whereas in the adduct the bond angle at the nitrogen center is of *ca.* 128º.[87] For compounds **29** and **31-33** similar adducts have been isolated, however, the substituent on the phosphorus moiety is the more sterically protecting 2,4,6-tri(tertbutyl)phenyl group (Mes*), preventing direct quantitative comparison with the previously considered adducts. Nevertheless, in the case of phosphines **31** and **32**, the observed ^{31}P chemical shifts of their respective adducts (-134 and -153.7 ppm, respectively) seem to confirm the idea that phosphines are indeed poor π-acceptors. These data suggest that the scale developed in this work could be extended to other ligands. Indeed, such an expansion would require detailed computational support to confirm that the bonding situations across the various ligand families can be readily compared.

C) Conclusion

In this chapter, we have demonstrated that the ^{31}P chemical shift of carbene-phosphinidene adducts provides a probe of the relative π-accepting abilities of carbenes. We developed a versatile and easy synthesis of such compounds involving free carbenes and dichlorophenylphosphine. This scale is more spread out than the TEP scale and much more sensitive as subtle variations in the electronic structure of the carbenes result in significantly different ^{31}P chemical shifts. Additionally, the combination of both metrics allows for the deconvolution of σ-donating and π-accepting properties. Finally, we propose that this concept could be extended to different ligands on the condition that additional computational information confirms the validity of the analogy.

Table 1.1: Acyclic carbenes

	Carbene	Carbene-PPh Adduct δ ^{31}P (ppm)	Solvent	T (ºC)	TEP (cm^{-1})
	Acyclic Carbenes				
1		332 [64] 372 [70]	N/A N/A	N/A 50	N/A
2		266.0 [72]	THF/C_7D_8 3/1	-80	2089 (a)[46]
3		232 [63]	N/A	N/A	N/A
4		221.0 [69]	C_6D_6	25	N/A
5		Z: 134.0 [75] E: 149.2 [75]	C_6D_6	N/A	N/A
6		126.3 [77]	$CDCl_3$	25	2044 (d)[77]
7		124.3 [74]	C_6D_6	25	N/A
8		85.6 [61]	C_6D_6	34	N/A
9		69.5 [77]	C_6D_6	25	2037 (d)[77]

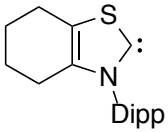
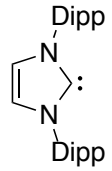
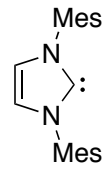
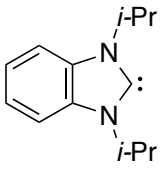
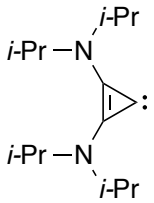
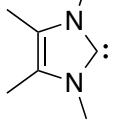
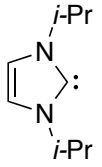
(a) Computational value

(b) Experimental value from $Ni(CO)_3$ complex

(c) Linear regression from experimental ν_{CO}^{av} of $Ir(L)(CO)_2(Cl)$ complex

(d) Linear regression from experimental ν_{CO}^{av} of $Rh(L)(CO)_2(Cl)$ complex

Table 1.2: Cyclic carbenes with aromatic cycles

	Carbene	Carbene-PPh Adduct δ ^{31}P (ppm)	Solvent	T (ºC)	TEP (cm^{-1})
		Cyclic Carbenes			
		Aromatic Cycles			
10		57.0 [77]	C_6D_6	25	2054 (c)[77]
11		-18.9 [77]	C_6D_6	25	2052 (b)[77]
12		-23.0 [77]	D_8-THF	25	2051 (b)[77]
13		-34.6 [77]	C_6D_6	25	2054 (a)[77]
14		-34.9 [77]	C_6D_6	25	2045 (d)[77]
15		-53.5 [77]	D_8-THF	25	2052 (a)[77]
16		-61.2 [77]	C_6D_6	25	2052 (a)[77]

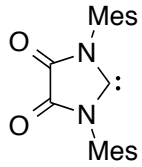
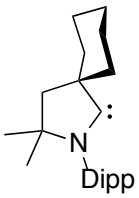
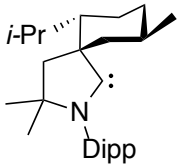
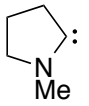
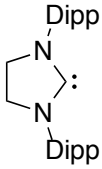
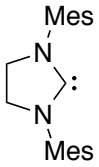
(a) Computational value

(b) Experimental value from $Ni(CO)_3$ complex

(c) Linear regression from experimental ν_{CO}^{av} of $Ir(L)(CO)_2(Cl)$ complex

(d) Linear regression from experimental ν_{CO}^{av} of $Rh(L)(CO)_2(Cl)$ complex

Table 1.3: Cyclic carbenes with non-aromatic 5-membered cycles

	Carbene	Carbene-PPh Adduct δ ^{31}P (ppm)	Solvent	T (ºC)	TEP (cm^{-1})
		Cyclic Carbenes			
		Non-Aromatic Cycles			
		5-Membered Cycles			
17		78.6 [78]	C_6D_6	25	2068 (d)[77]
18		68.9 [77]	C_6D_6	25	2049 (d)[77]
19		56.2[77]	C_6D_6	25	2042 (c)[77]
20		49.0 [61]	C_6D_6	34	2055 (a)[47]
21		44.9 [79]	N/A	N/A	N/A
22		-10.2 [77]	$CDCl_3$	25	2052 (b)[77]
23		-10.4 [77]	D_8-THF	25	2052 (b)[77]

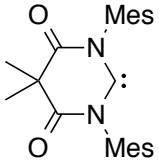
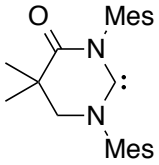
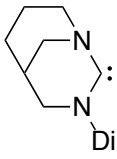
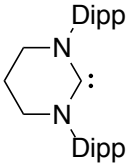
(a) Computational value

(b) Experimental value from $Ni(CO)_3$ complex

(c) Linear regression from experimental ν_{CO}^{av} of $Ir(L)(CO)_2(Cl)$ complex

(d) Linear regression from experimental ν_{CO}^{av} of $Rh(L)(CO)_2(Cl)$ complex

Table 1.4: Cyclic carbenes with non-aromatic 6-membered cycles

	Carbene	Carbene-PPh Adduct δ ^{31}P (ppm)	Solvent	T (ºC)	TEP (cm^{-1})
	Cyclic Carbenes				
	Non-Aromatic Cycles				
	6-Membered Cycles				
24		83.0 [78]	C_6D_6	25	2057 (d)[23]
25		39.7 [77]	C_6D_6	25	2050 (c)[77]
26		34.9 [77]	C_6D_6	25	2047 (c)[77]
27		14.8 [77]	C_6D_6	25	2044 (c)[77]

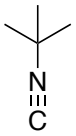
(a) Computational value

(b) Experimental value from $Ni(CO)_3$ complex

(c) Linear regression from experimental ν_{CO}^{av} of $Ir(L)(CO)_2(Cl)$ complex

(d) Linear regression from experimental ν_{CO}^{av} of $Rh(L)(CO)_2(Cl)$ complex

Table 1.5: Non-carbene ligands

	Ligand	Ligand-PPh Adduct δ ^{31}P (ppm)	Solvent	T (ºC)	TEP (cm^{-1})
		Other Ligands			
28		525 [88]	THF	N/A	N/A
29		415 [89] 396 (e)[89]	N/A	N/A	N/A
30		-99 [90]	N/A	N/A	N/A
31	PMe_3	-134.0 (e)[91]	C_6D_6	25	2064 (b)[17]
32	$Pn\text{-}Bu_3$	-153.7 (e)[91]	C_6D_6	25	2060 (b)[17]
33		-207.4 (e)[92]	C_6D_6	25	2120 (a)[46]

(a) Computational value

(b) Experimental value from $Ni(CO)_3$ complex

(c) Linear regression from experimental ν_{CO}^{av} of $Ir(L)(CO)_2(Cl)$ complex

(d) Linear regression from experimental ν_{CO}^{av} of $Rh(L)(CO)_2(Cl)$ complex

(e) The aromatic substituent at the phosphorus atom is Mes^*

Chapter 1 has been adapted from materials published in O. Back, M. Henry-Ellinger, C. D. Martin, D. Martin and G. Bertrand, *Angew. Chem. Int. Ed.* **2013**, *52*, 2939-2943. The dissertation author actively participated in this project.

D) Appendix: Experimental section

1) General considerations

All manipulations were performed under an atmosphere of dry argon using standard Schlenk techniques or in an argon filled glove box. Solvents were dried by standard methods and distilled under argon. Deuterated solvents were purchased from Cambridge Isotope Laboratories and distilled over CaH_2. Magnesium (325 mesh, 99.5%) was used as received from Sigma Aldrich. Dichlorophenylphosphine (97%) was purchased from Acros Organics, was refluxed to removed HCl, and subsequently distilled. The carbenes **6**,[93] **9**,[94] **10**,[95] **11**,[96] **13**,[97] **14**,[98] **16**,[99] **18**,[15] **19**,[15] **22**,[96] **25**,[100] **26**[101] and **27**[100] were prepared according to the literature procedures. ^{1}H, ^{31}P, and ^{13}C NMR spectra were recorded on Varian Inova 300, 400, 500 or Bruker 300, 400, 500 or JEOL 500 MHz spectrometers at 25 °C. Chemical shifts are given in ppm and are referenced to $SiMe_4$ (^{1}H, ^{13}C) and 85 % H_3PO_4 (^{31}P). NMR multiplicities are abbreviated as follows: s = singlet, d = doublet, t = triplet, q = quadruplet, quint = quintet, sept = septet, oct = octuplet, m = multiplet, br = broad signal.

2) Synthesis of carbene-phosphinidene adducts

Preparation of adduct 16·PPh: In the glovebox, pentaphenylcyclopentaphosphane (0.318 g, 0.59 mmol) was added at room temperature to a solution of **16** (0.448 g, 2.95 mmol) of THF (8 mL). Immediately upon addition the solution became red. The solution was stirred overnight. The volatiles were removed *in vacuo* and the resulting yellow solid was washed with hexane (2 X 10 mL) and dried *in vacuo* to afford **16·PPh** as a fine yellow powder. Yield 79% (0.610 g, 2.34 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 162 MHz): δ -61.2. ^{1}H NMR (C_6D_6, 400 MHz): δ 0.94 (d, J = 7.2 Hz, 12 H), 5.07 (sept, J = 7.2 Hz, J =

4 Hz, 2 H), 6.41 (s, 2 H), 6.86 (t, J = 7.2 Hz, 1 H), 7.03 (t, J = 7.2 Hz 2 H), 7.54 (t, J = 7.2 Hz, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 100 MHz): δ 22.3, 50.4 (d, J_{PC} = 9 Hz), 116.3, 122.2, 128.3, 132.0 (d, J_{PC} = 20 Hz), 151.1 (d, J_{PC} = 50 Hz), 167.8 (d, J_{PC} = 102 Hz, $C_{carbene}$).

Preparation of adduct 6·PPh: Dichlorophosphine (0.440 g, 2.46 mmol) was added at room temperature to a solution of **6** (0.613 g, 2.46 mmol) in hexane (20 mL). The mixture was stirred overnight and then cannula filtered. The solid was successively washed with hexane (20 mL) and benzene (20 mL) and then dried *in vacuo*. Magnesium (0.120 g, 4.96 mmol) was then added to the solid followed by the addition of THF (5 mL). The mixture was stirred overnight and the volatiles removed *in vacuo*. The product was extracted with benzene (15 mL). After evaporation of the solvent the residue was washed with 10 mL of hexane and the resulting solid was dried under vacuum. Compound **6·PPh** was obtained as a fine yellow powder. Yield 7% (0.060 g, 0.17 mmol). $^{31}P\{^{1}H\}$ NMR ($CDCl_3$, 121 MHz): δ +126.3. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 0.73-2.10 (m, 20 H), 1.36 (s, 9 H), 3.59 (t, J = 11.8 Hz, 2 H), 7.05-7.13 (m, 1 H), 7.15-7.20 (m, 2 H), 7.40-7.45 (m, 2 H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 125.7 MHz): δ 27.6, 28.9, 32.9 (d, J_{PC} = 18 Hz), 33.7, 42.9 (d, J_{PC} = 31 Hz), 68.7, 127.3, 128.5, 134.7 (d, J_{PC} = 10 Hz), 144.9 (d, J_{PC} = 45 Hz), 217.2 (d, J_{PC} = 83 Hz, $C_{carbene}$).

Preparation of adduct 9·PPh: Dichlorophenylphosphine (0.186g, 1.04 mmol) was added at room temperature to a solution of the **9** (0.220g, 1.04 mmol) in hexane (10 mL). Immediately a bright yellow precipitate was generated. The mixture was then stirred overnight and the precipitate cannula filtered. The solids were washed with diethyl ether (2 X 10 mL) and dried *in vacuo*. Magnesium (0.050 g, 2.08 mmol) was added followed by the addition of THF (8 mL). The mixture was then stirred at room temperature

overnight and the volatiles removed *in vacuo*. The product was extracted with benzene (15 mL). After removing the volatiles *in vacuo* compound **9·PPh** was obtained as a bright yellow oil. Yield 74% (0.246 g, 0.77 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 202.5 MHz): δ +69.5. ^{1}H NMR (C_6D_6, 500 MHz): δ 0.90 (d, J = 6.4 Hz, 12 H), 1.31 (d, J = 6.1 Hz, 12 H), 3.80 (sept, J = 6.1 Hz, 2 H), 4.14 (sept, J = 6.4 Hz, 2 H), 7.06 (t, J = 6.0 Hz, 1 H), 7.14 (t, J = 6.0 Hz 2 H), 7.61-7.69 (m, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125.7 MHz): δ 22.9, 23.6 (d, J_{PC} = 6 Hz), 50.9 (d, J_{PC} = 4 Hz), 54.3, 126.7, 128.6, 135.2 (d, J_{PC} = 12 Hz), 146.2 (d, J_{PC} = 48 Hz), 199.7 (d, J_{PC} = 68 Hz, $C_{carbene}$).

Preparation of adduct 10·PPh: Dichlorophosphine (0.805 g, 4.48 mmol) was added at room temperature to a solution of **10** (1.34 g, 4.48 mmol) in benzene (50 mL) resulting in a dark slurry. The mixture was then stirred overnight and cannula filtered. The volatiles from the supernatant were removed *in vacuo*. The residue was washed with benzene (15 mL) and subsequently with hexane (2 X 15 mL). The resulting powder was dried *in vacuo*. Magnesium (0.218 g, 8.96 mmol) was then added to the solids followed by the addition of THF (25 mL) at room temperature. The mixture was stirred overnight and the volatiles removed *in vacuo*. The product was extracted with hexane (20 mL) and the solvent was subsequently removed *in vacuo* giving an orange oil which solidified overnight. Yield 16% (0.286 g, 0.702 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 202.5 MHz): δ +57.0. ^{1}H NMR (C_6D_6, 500 MHz): δ 1.02 (d, J = 7.0 Hz, 6 H), 1.12-1.26 (m, 4H), 1.47 (d, J = 7.0 Hz, 6 H), 1.61-1.66 (m, 2H), 1.81-1.86 (m, 2H), 2.91 (sept, J = 7.0 Hz, 2H), 7.04-7.10 (m, 4H), 7.17-7.21 (m, 2H), 7.82-7.87 (m, 2H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125.7 MHz): δ 22.1, 23.1, 23.3, 24.2, 24.5, 25.4, 28.9, 115.9 (d, J_{PC} = 1 Hz), 125.4, 127.6,

128.6, 129.2 (d, J_{PC} = 4 Hz), 129.3, 130.5, 136.2 (d, J_{PC} = 12 Hz), 143.7 (d, J_{PC} = 38 Hz), 147.4 (d, J_{PC} = 3 Hz), 192.0 (d, J_{PC} = 79 Hz, $C_{carbene}$).

Preparation of adduct 11·PPh: Dichlorophenylphosphine (0.345 g, 1.93 mmol) was added at room temperature to a slurry of **11** (0.750 g, 1.93 mmol) in hexane (20 mL). The mixture was stirred overnight and the precipitate was then cannula filtered and washed with hexane (2 X 15 mL). The solid was dried *in vacuo*. Potassium graphite (0.522 g, 3.86 mmol) was added to the solid followed by the addition of THF (20 mL). The mixture was stirred overnight and the graphite was removed by cannula filtration. The volatiles were then removed *in vacuo* and the residue washed with hexane (2 X 6 mL). The resulting solid was dried *in vacuo* affording **11·PPh** as a bright yellow powder. Yield 46% (0.440 g, 0.89 mmol). $^{31}P\{^1H\}$ NMR (C_6D_6, 162 MHz): δ -18.9. ^1H NMR (C_6D_6, 400 MHz): δ 1.12 (d, J = 6.7 Hz, 12 H), 1.43 (d, J = 6.7 Hz, 12 H), 3.22 (sept, J = 6.7 Hz, 4 H), 6.19 (s, 2 H), 6.66-6.68 (m, 3 H), 6.98 (d, J = 7.6 Hz, 4 H), 7.10 (t, J = 7.6 Hz, 2 H), 7.26-7.40 (m, 2 H). $^{13}C\{^1H\}$ NMR (C_6D_6, 100 MHz): δ 23.4, 25.5, 29.3, 120.8, 124.7, 125.4, 126.9, 130.3, 135.3, 137.7 (d, J_{PC} = 13 Hz), 139.1 (d, J_{PC} = 35 Hz), 147.0, 172.9 (d, J_{PC} = 83 Hz, $C_{carbene}$).

Preparation of adduct 13·PPh: Dichlorophenylphosphine (1.350g, 7.54 mmol) was added at room temperature to a solution of **13** (1.525g, 7.54 mmol) in hexane (30 mL). Immediately upon addition a white precipitate appeared. The mixture was then stirred at room temperature overnight and the mixture cannula filtered. The white solid was then washed with diethylether (2 X 30 mL) and dried *in vacuo*. Potassium graphite (2.032g, 15.08 mmol) was then added to the solid followed by the addition of THF (35 mL). The mixture was then stirred at room temperature for 4 hours and the graphite was removed

by cannula filtration. The volatiles were removed *in vacuo* and the product extracted with hexane (75 mL). After evaporation of the solvent *in vacuo* the residue was washed with pentane (2 X 5 mL). The resulting solid was dried *in vacuo* to afford **13·PPh** as a red microcrystalline powder. Yield 24% (0.560 g, 1.81 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 162 MHz): δ -34.6. ^{1}H NMR (C_6D_6, 400 MHz): δ 1.11 (d, J = 7.2 Hz, 12 H), 5.22 (oct, J = 7.2 Hz, 2 H), 6.81-6.86 (m, 2 H), 6.90-6.96 (m, 2 H), 7.00 (t, J = 7.2 Hz, 1 H), 7.09 (t, J = 7.2 Hz, 2 H), 7.79 (t, J = 7.2 Hz, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 100 MHz): δ 19.7, 51.4 (d, J_{PC} = 15 Hz), 111.2, 121.6, 125.5, 128.7, 134.5 (d, J_{PC} = 3 Hz), 135.3 (d, J_{PC} = 16 Hz), 145.2 (d, J_{PC} = 46 Hz), 177.4 (d, J_{PC} = 97 Hz, $C_{carbene}$).

Preparation of adduct 14·PPh: .A solution of **14** (0.026 g, 0.11 mmol) in hexane (6 mL) was added at room temperature to a solution of dichlorophenylphosphine (0.020g, 0.11 mmol) in hexane (6 mL). Immediately upon the addition a light brown precipitate appeared. The mixture was then stirred for 4 hours. The precipitate was cannula filtered and washed with diethyl ether (2 X 10 mL). The resulting solid was dried *in vacuo* and magnesium (0.006 g, 0.22 mmol) was added followed by the addition of THF (4 mL). The mixture was stirred overnight and the solvent removed *in vacuo*. The product was extracted with a 1:1 benzene/hexane mixture (16 mL). After evaporating the solvent *in vacuo*, **14·PPh** was obtained as an orange solid. Yield 26% (0.010 g, 0.03 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 202.5 MHz): δ -34.9. ^{1}H NMR (C_6D_6, 500 MHz): δ 0.99 (d, J = 7 Hz, 24 H), 3.41 (sept, J = 7 Hz, 4 H), 7.04 (t, J = 7.0 Hz, 1 H), 7.13 (t, J = 7.0 Hz, 2 H), 8.02-8.09 (m, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125.7 MHz): δ 23.1, 50.1, 125.5, 126.9, 127.9, 137.7 (d, J_{PC} = 15 Hz), 138.5 (d, J_{PC} = 109 Hz, $C_{carbene}$), 148.0 (d, J_{PC} = 47 Hz).

Preparation of adduct 18·PPh: Dichlorophenylphosphine (0.462 g, 2.58 mmol) was added at room temperature to a solution of **18** (0.840 g, 2.58 mmol) in hexane (15 mL). Immediately upon addition a yellow precipitate was generated. The mixture was stirred overnight and the mixture cannula filtered. The solids were washed diethyl ether (2 X 15 mL) and dried *in vacuo*. Magnesium (0.125 g, 5.16 mmol) was added to the solids followed by the addition of THF (8 mL). The mixture was then stirred for 4 hours and the volatiles removed *in vacuo*. The product was extracted with hexane (30 mL). Evaporation of the solvent afforded **18·PPh** as a pale yellow powder. Yield 40% (0.440 g, 1.02 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 162 MHz): δ 68.9. ^{1}H NMR (C_6D_6, 400 MHz): δ 1.00-1.73 (m, 8 H), 1.04 (s, 6 H), 1.27 (d, J = 6.4 Hz, 6 H), 1.65 (d, J = 6.4 Hz, 6 H), 1.79 (s, 2 H), 2.04 (dt, J = 13.2 Hz, J = 3.2 Hz, 2 H), 3.12 (sept, J = 6.4 Hz, 2 H), 7.01-7.09 (m, 3 H), 7.11-7.16 (m, 2 H), 7.18-7.23 (m, 1 H), 7.68-7.73 (m, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 100 MHz): δ 23.7, 24.9, 26.1, 27.8 (d, J_{PC} = 9 Hz), 29.5, 29.9, 38.7 (d, J_{PC} = 4 Hz), 50.4, 56.1 (d, J_{PC} = 12 Hz), 67.5, 125.8, 127.5, 127.9, 129.4, 134.9, 138.3 (d, J_{PC} = 11 Hz), 141.5 (d, J_{PC} = 47 Hz), 148.9, 208.1 (d, J_{PC} = 66 Hz).

Preparation of adduct 19·PPh: Dichlorophenylphosphine (0.492 g, 2.75 mmol) was added at room temperature to a solution of **19** (1.050 g, 2.75 mmol) in hexane (15 mL). Immediately upon addition the solution turned blue and a precipitate appeared. The mixture was stirred overnight, during this time the solution became colorless. The precipitate was cannula filtered and washed with hexane (2 X 20 mL). The resulting solids were dried *in vacuo*. Potassium graphite (0.744 g, 5.50 mmol) was added to the solid followed by the addition of THF (20 mL) at -80 °C. The mixture was then stirred at room temperature for 3 hours and the graphite removed by cannula filtration. After

evaporation of the solvent *in vacuo*, **19·PPh** was obtained as a pale yellow powder. Yield 42% (0.565 g, 1.15 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 121 MHz): δ +56.2. ^{1}H NMR (C_6D_6, 500 MHz): δ 0.99 (d, *J* = 6.8 Hz, 3 H), 1.00 (d, *J* = 6.8 Hz, 3 H), 1.00 (s, 3 H), 1.06 (d, *J* = 6.8 Hz, 3 H), 1.13 (d, *J* = 6.8 Hz, 3 H), 1.14 (d, *J* = 6.8 Hz, 3 H), 1.16 (d, *J* = 6.8 Hz, 3 H), 1.24 (s, 3 H), 1.2-1.4 (m, 2 H), 1.51 (d, *J* = 6.8 Hz, 3 H), 1.56-1.70 (m, 2 H), 1.59 (d, *J* = 12.9 Hz, 1 H), 1.99 (d, *J* = 13.1 Hz, 1 H), 2.31 (sept, *J* = 6.8 Hz, 1 H), 2.47 (d, *J* = 12.9 Hz, 1 H), 2.50 (d, *J* = 13.1 Hz, 1 H), 2.86 (qt, *J* = 13.4 Hz, *J* = 4.2 Hz, 1 H), 3.10-3.35 (m, 1 H), 3.26 (sept, *J* = 6.8 Hz, 1 H), 6.7-7.0 (m, 8 H), 1 H belonging to the cyclohexyl ring couldn't be observed because of overlapping. $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125.7 MHz): δ 21.5 (d, J_{PC} = 10 Hz), 22.9, 23.7, 24.9, 25.0 (d, J_{PC} = 21 Hz), 25.4, 25.8, 26.2, 27.4, 27.6, 29.2, 30.1, 30.3, 30.8, 36.3, 51.6, 54.7, 56.1 (d, J_{PC} = 10 Hz), 58.6 (d, J_{PC} = 27 Hz), 68.9, 125.8, 126.1 (d, J_{PC} = 6 Hz), 127.7 (d, J_{PC} = 6 Hz), 129.36, 134.6, 134.8, 138.2, 138.6, 141.9 (d, J_{PC} = 64 Hz), 149.9 (d, J_{PC} = 12 Hz), 191.3 (d, J_{PC} = 109 Hz, $C_{carbene}$).

Preparation of adduct 22·PPh: Dichlorophosphine (0.230 g, 1.28 mmol) was added at room temperature to a slurry of **22** (0.500 g, 1.28 mmol) in hexane (12 mL). The mixture was stirred overnight and the mixture cannula filtered. The solids were washed with hexane (2 X 10 mL) and then dried *in vacuo*. Magnesium (0.062 g, 2.56 mmol) was then added to the solid followed by the addition of THF (10 mL). The mixture was stirred for 3 hours and the volatiles were removed *in vacuo*. The product was extracted with hexane (25 mL) and after evaporation of the solvent compound **22·PPh** was obtained as a fine pale yellow powder. Yield 22% (0.140 g, 0.28 mmol). $^{31}P\{^{1}H\}$ NMR ($CDCl_3$, 202.5 MHz): δ -10.2. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.38 (d, *J* = 6.5 Hz, 12 H), 1.51 (br s, 12

H), 3.44 (sept, J = 6.5 Hz, 4 H), 4.03 (s, 4 H), 6.74-6.88 (m, 3 H), 6.96-7.06 (m, 2 H), 7.17 (br s, 4 H), 7.34 (br s, 2 H). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 125.7 MHz): δ 23.6 (br s), 25.9, 28.8, 52.8 (br s), 124.3, 125.0, 126.5, 128.8, 136.5 (d, J_{PC} = 14 Hz), 138.1 (d, J_{PC} = 41 Hz), 147.6, 186.9 (d, J_{PC} = 84 Hz, $C_{carbene}$).

Preparation of adduct 25·PPh: Dichlorophosphine (0.303 g, 1.68 mmol) was added at room temperature to a solution of **25** (0.610 g, 1.68 mmol) in benzene (40 mL) to produce a yellow slurry. The mixture was then stirred overnight and cannula filtered. The solids were washed with hexane (3 X 15 mL) and the resulting powder was dried *in vacuo*. Magnesium (0.082 g, 3.36 mmol) was then added to the solid followed by the addition of THF (25 mL). The mixture was stirred overnight and the volatiles removed *in vacuo*. The product was extracted with hexane (50 mL) and the solvent subsequently removed *in vacuo* giving **25·PPh** as a yellow powder. Yield 10% (0.077 g, 0.16 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 121 MHz): δ +39.7. ^{1}H NMR (C_6D_6, 500 MHz): δ 1.21 (s, 6H), 1.93 (s, 3H), 2.12 (s, 3H), 2.14 (s, 6H), 2.43 (s, 6H), 3.04 (br s, 2 H), 6.22 (s, 2 H), 6.60-6.65 (m, 2 H), 6.75-6.71 (m, 1 H), 6.86 (s, 2H), 6.92-6.96 (m, 2 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125.7 MHz): δ 18.4, 18.5, 19.7, 20.3, 20.9, 23.3, 38.8, 60.9, 125.6, 126.5, 128.1, 129.6, 129.7, 134.2, 134.7, 136.0 (d, J_{PC} = 5 Hz), 136.2, 138.0, 138.3 (d, J_{PC} = 46 Hz), 139.8, 169.6, 180.3 (d, J_{PC} = 82 Hz, $C_{carbene}$).

Preparation of adduct 26·PPh: Dichlorophenylphosphine (0.411 g, 2.29 mmol) was added to a solution of **26** (2.14 mmol) prepared *in situ* at -78°C in THF (20 mL). After slowly warming to room temperature, the mixture was stirred overnight. The volatiles were removed *in vacuo* and the resulting solid was washed with hexane (2 X 15 mL). Magnesium (0.110 g, 4.5 mmol) was added to the solid followed by the addition of THF

(20 mL). The mixture was stirred for 5 hours and the volatiles subsequently removed *in vacuo*. The product was extracted with benzene (2 x 10mL) and the solvent was removed *in vacuo*. The resulting solid was washed with pentane (10 mL) and dried *in vacuo* affording **26·PPh** as a yellow powder. Yield 85% (0.700 g, 1.78 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 121 MHz): δ +34.9; ^{1}H NMR (C_6D_6, 400 MHz): δ 0.9-1.8 (m, 5H), 1.18 (d, J = 7 Hz, 3 H), 1.21 (d, J = 7 Hz, 3 H), 1.41 (d, J = 7 Hz, 3 H), 1.62 (d, J = 7 Hz, 3 H), 2.5-2.2 (m, 2H), 3.0-3.4 (m, 6H), 7.2-6.8 (m, 7H), 7.85 (t, J = 7 Hz, 1 H); $^{13}C\{^{1}H\}$ NMR (C_6D_6, 125 MHz): δ 21.1, 22.3, 23.6, 24.4, 24.5, 24.6, 25.4, 28.2, 28.9, 29.7, 30.1, 50.1 (d, J_{PC} = 2 Hz), 56.1 (d, J_{PC} = 7 Hz), 56.7, 125.1, 125.2, 127.5, 128.9, 134.4 (d, J_{PC} = 16 Hz), 140.3 (d, J_{PC} = 3 Hz), 144.3 (d, J_{PC} = 44 Hz), 144.7 (d, J_{PC} = 16 Hz), 148.0 (d, J_{PC} = 3 Hz), 199.9 (d, J_{PC} = 61 Hz, $C_{carbene}$).

Preparation of adduct 27·PPh: Dichlorophenylphosphine (0.411 g, 2.29 mmol) was added at room temperature to a solution of **27** (2.0 mmol) in a 1:2 hexane/benzene mixture (30 mL). The mixture was stirred overnight and the precipitate was cannula filtered and washed with diethylether (2 X 15 mL). The solid was dried *in vacuo*. Magnesium (0.100 g, 4 mmol) was added to the solid followed by the addition of THF (20 mL). The mixture was stirred 3 hours after which the volatiles were removed *in vacuo* and the product extracted with benzene (2 X 10mL). Removing the solvent *in vacuo* afforded **27·PPh** as a yellow powder. Yield 40% (0.470 g, 0.92 mmol). $^{31}P\{^{1}H\}$ NMR (C_6D_6, 121 MHz): δ +14.8; ^{1}H NMR (C_6D_6, 400 MHz): δ 1.15 (d. J = 10 Hz, 12 H), 1.42 (d. J = 10 Hz, 12 H), 1.65 (quint, J = 8 Hz, 2 H), 3.22 (dt. J = 3 and 8 Hz, 4 H), 3.35 (sept, J = 10 Hz, 4 H), 6.7-7.2 (m, 12 H); $^{13}C\{^{1}H\}$ NMR (C_6D_6, 100 MHz): δ 22.8, 24.0, 24.1, 25.9, 28.9, 51.9, 124.3, 124.8, 125.2, 127.0 (d, J_{PC} = 3 Hz), 130.0, 137.3 (d,

J_{PC} = 15 Hz), 142.3 (d, J_{PC} = 66 Hz), 146.1 (d, J_{PC} = 2 Hz), 186.5 (d, J_{PC} = 94 Hz, $C_{carbene}$).

3) Crystallographic data

Crystallographic Data and Structure Refinement

Compound	**18·PPh**	**19·PPh**
CCDC #	916091	916092
Empiric Formula	$C_{29}H_{40}NP$	$C_{33}H_{48}NP$
Fw (g/mol)	433.59	489.69
Crystal system	Triclinic	Monoclinic
Space group	P-1	$P2_1$
Radiation, λ (Å)	0.71073	0.71073
T (K)	100(2)	100(2)
a (Å)	8.6558(7)	19.4956(17)
b (Å)	10.8178(8)	15.7636(15)
c (Å)	14.3821(9)	21.397(3)
α (deg)	104.962(2)	90
β (deg)	93.145(3)	117.028(3)
γ (deg)	99.053(3)	90
V (Å^3)	1278.38(16)	5857.5(10)
Z	2	8
d_{calcd} (g·cm^{-3})	1.126	1.111
*R*1[*I*>2σ(*I*)]	0.0370	0.0612
wR2(F^2)	0.0965	0.1174
GOF (*S*)	1.060	1.006

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CHAPTER 2:

Toward the Synthesis of New Free Carbenes

A) Toward carbenes with increased electrophilicity

1) Introduction

In 2009, Bielawski described the synthesis of the first diamido carbene **Ia**.[1] This carbene differs from classical diamino carbenes **II,** as its nitrogen substituents are included in amide functional groups. Consequently, diamido carbenes **I** are less nucleophilic than their diamino counterparts **II**.[2] In addition, the carbonyl moiety of the amide function competes with the carbene center for the π-donation of the nitrogen atom. As a result, the stabilization of the carbene empty orbital is weaker than in diamino carbenes **II** and therefore, diamido carbenes of type **I** are more electrophilic (Figure 2.1). This is confirmed experimentally by the observation of the ^{31}P NMR chemical shift of their respective carbene-phenylphosphinidene adducts (see Chapter 1).[3,4]

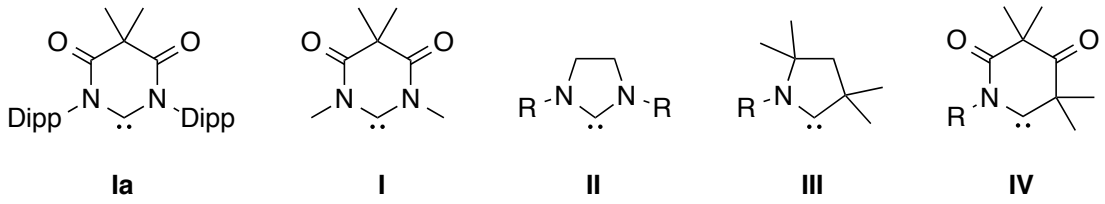
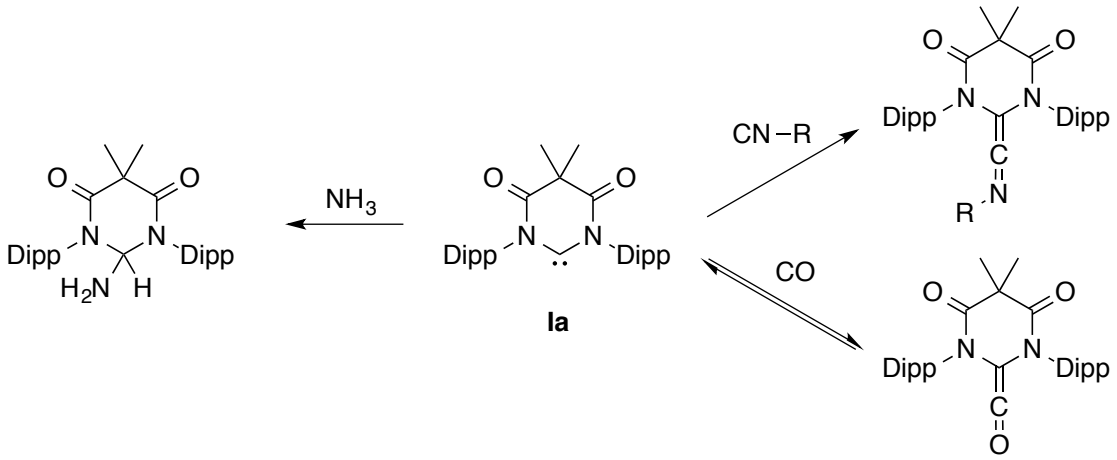


Figure 2.1: Diamido **I**, diamino **II**, cyclic (alkyl)(amino) **III** and cyclic (alkyl)(amido) carbenes **IV**

This pronounced electrophilicity confers diamido carbenes **I** a reactivity that is significantly different from diamino carbenes **II**. The former can react with isocyanides to form stable ketenimines,[5] reversibly bind carbon monoxide[1] and even react with ammonia[6] (Scheme 2.1). All these reactions are unparalleled in the case of diamino carbenes **I** but are highly reminiscent of the reactivity of another class of carbenes with enhanced electrophilicity, namely the cyclic (alkyl)(amino)carbenes **III** (Figure2.1).[7-9]



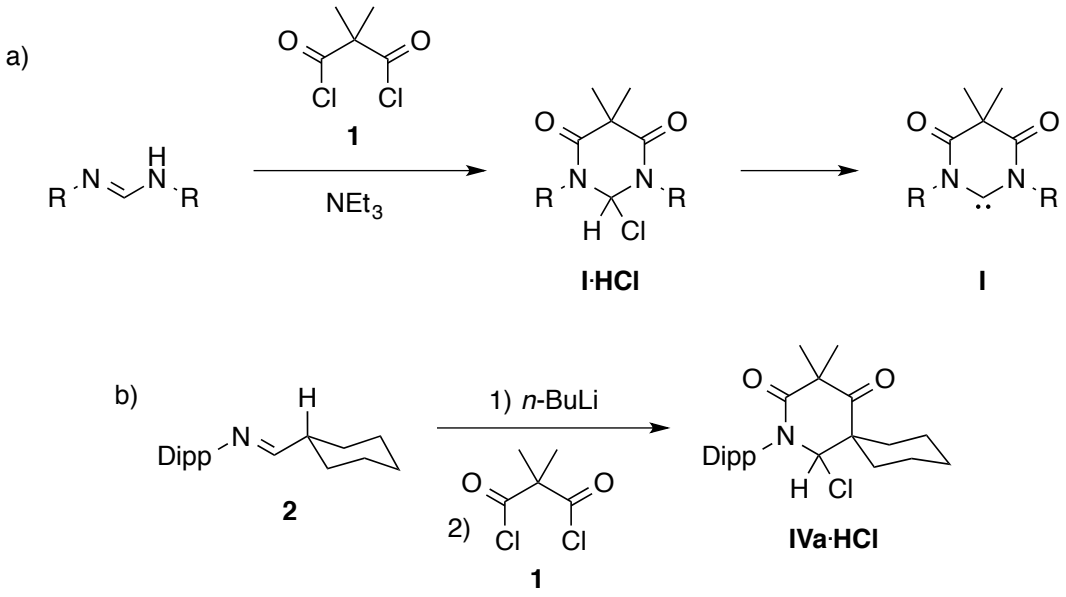
Scheme 2.1: Reactivity of diamido carbene **Ia**

Based on the observation that the transformation of an amino substituent into an amido substituent results in enhanced carbene electrophilicity, we decided to explore the possibility of translating this phenomenon to cyclic (alkyl)(amino)carbenes **III** and consequently aimed our efforts at cyclic (alkyl)(amido)carbenes **IV** (Figure 2.1). Indeed, carbenes of type **IV** would possess a very strong electrophilic character and extend the scope of available electrophilic carbenes.[1,2,10-12] Indeed, the variation of the electronic properties of carbenes leads to different reactivities. For example, the reaction of P_4 with carbenes can lead to fragmentation of the P_4 cage[13] or aggregation of two or more P_4 units.[14-16]

2) Synthesis of the precursor and attempts to generate the carbene

Diamido carbenes **I** are obtained by the deprotonation of the appropriate precursors **I·HCl** (Scheme 2.2a). Such precursors are easily obtained by reacting a formamidine with dimethylmalonyl dichloride **1** in the presence of triethylamine. Typically, precursors of diamino carbenes **II** and cyclic (alkyl)(amino) carbenes **III** are ionic salts (imidazolinium and iminium salts, for the respective precursors of carbenes of type **II** and **III**). In contrast, the precursors **I·HCl** are neutral compounds.

We reasoned that the replacement of the formamidine by the lithium salt of an aldimine would afford the precursor of cyclic (alkyl)(amido)carbenes **IV** (Scheme 2.2b). Indeed, when **1** is reacted with the lithium salt of N-(2,6-diisopropylphenyl)-cyclohexylcarbaldimine **2**, the desired precursor **IVa·HCl** is obtained in 52% yield.



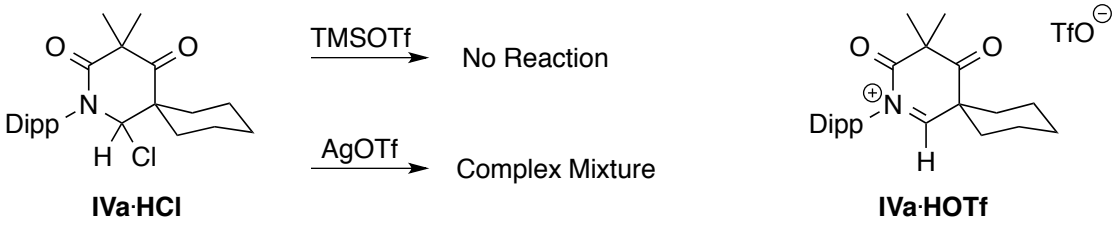
Scheme 2.2: (a) Synthesis of carbenes **I**, and (b) Synthesis of carbene precursor **IVa·HCl**

The neutral nature of **IVa·HCl** is evidenced by its NMR spectra. The ^{13}C NMR spectrum displays signals corresponding to 24 different carbon atoms clearly indicating

the asymmetric nature of **IVa·HCl**. Notably, no signal corresponding to a $C_{carbene}$-H can be found in the typical range for the precursors of carbenes **II** and **III** (160-200 ppm). Instead, the chemical shift of the carbon of the potential carbene center can be found at 85.1 ppm, a much higher filed shift that is inconsistent with a sp^2-hybridized carbon involved in an iminium moiety. Similarly, the ^{1}H NMR spectrum of **IVa·HCl** shows no signal in the typical range for the proton of typical salt precursors (*ca.* 8-11 ppm). Instead, a singlet corresponding to one proton can be found at 5.48 ppm. In addition, all four CH_3 groups from the isopropyl fragments are inequivalent, and the two CH_3 from the malonyl unit are also inequivalent. Such a splitting is characteristic of diastereotopic protons and confirms the asymmetric nature of **IVa·HCl**. Such a covalent nature of the precursor, as opposed to traditional carbenium salts, is a good indication of the potential electrophilicity of the targeted carbene and is reminiscent of the behavior of diamido carbene precursors **I·HCl**.

The precursor **IVa·HCl** in hand, we attempted to generate the free carbene via the classical route of deprotonation with a strong base. To our surprise, all attempts were unsuccessful. Variation of the experimental conditions, be it the base, the solvent (Et_2O, THF, benzene) or the temperature resulted either in the absence of reaction (LiHMDS, NaHMDS, KHMDS) or in complex mixtures (LDA).

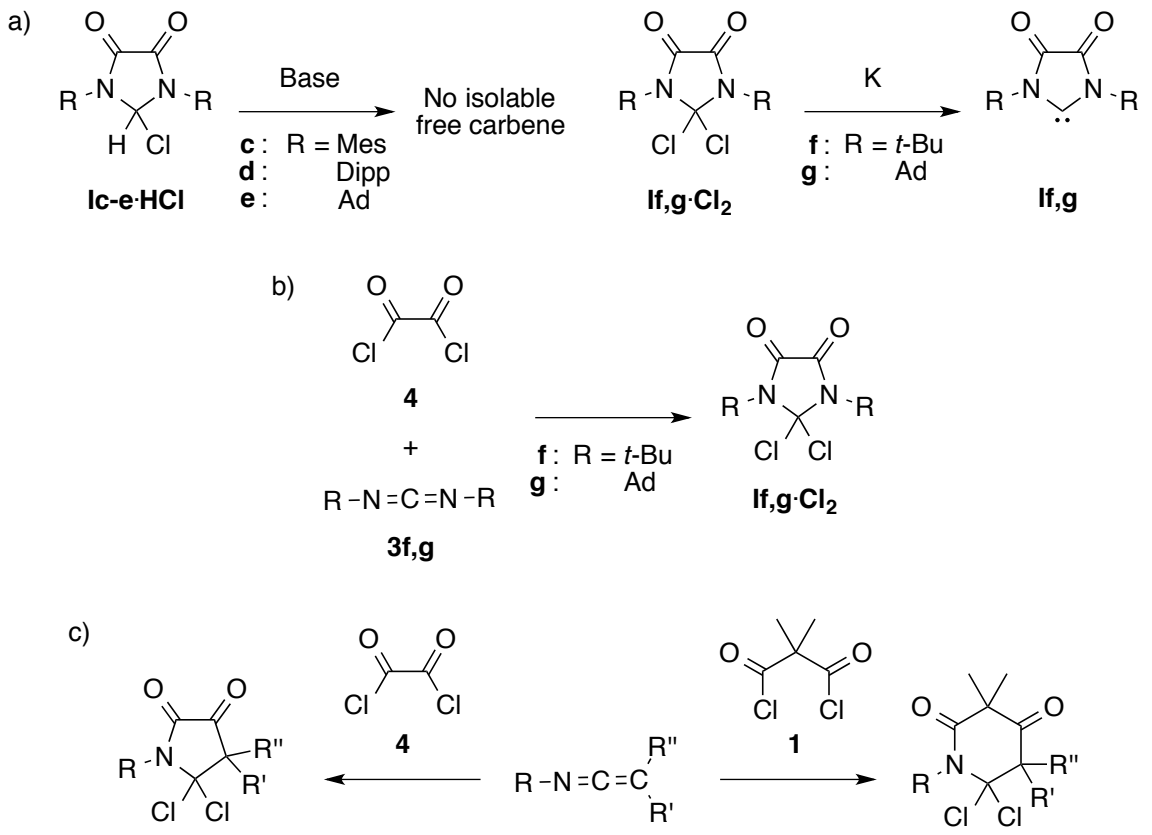
In order to obtain an ionic precursor similar to those of carbenes of type **II** and **III**, we attempted to abstract a chloride from **IVa·HCl** to generate a cationic precursor of type **IVa·HOTf** using TMSOTf or AgOTf resulted in the absence of reaction in the first case or in a complex mixture in the latter (Scheme 2.3).



Scheme 2.3: Attempts toward an activated precursor

3) Conclusion

Based on these results, we can conclude that deprotonation is not a viable route to access free carbenes of type **IV**. Similar issues were observed by Ganter[17] in the case of 5-membered ring diamido carbene precursors **Ic-e.HCl** (Scheme 2.4a). However, in a recent report, Bielawski[18] showed that carbene **If** and **Ig** can be synthesized by reduction of the dichloro precursors **If·Cl$_2$** and **Ig·Cl$_2$** with potassium. These precursors are obtained by the condensation of the corresponding carbodiimide derivatives **3f** and **3g** with oxalyl chloride **4** (Scheme 2.4b). This methodology could be adapted to 5-membered ring carbene precursors of type **IV·Cl$_2$** by substituting the carbodiimide for a ketenimine, and even to 6-membered ring carbene precursors of type **IV·Cl$_2$** by replacing oxalyl chloride **4** by dimethylmalonyl dichloride **1** to access (Scheme 2.4c).

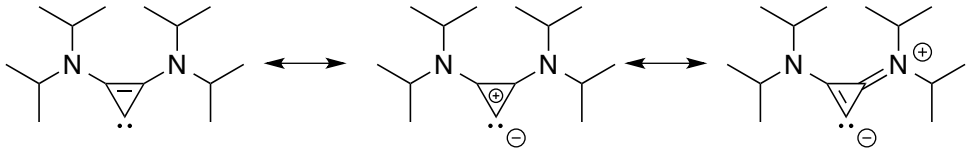


Scheme 2.4: (a) Deprotonation and reduction approaches to 5-membered carbenes **I** reported in the literature, (b) Synthesis of carbene precursors **If·Cl$_2$** and **Ig·Cl$_2$**, and (c) Proposed synthesis of carbene precursors of type **IV·Cl$_2$**

B) Toward new carbenes with remote stabilization

1) Introduction

To this day, isolated free carbenes possess at least one heteroatom substituent directly attached to the carbene center. The only notable exception is the cyclopropenylidene **Va**, which was developed by our group in 2006 (Figure 2.2).[19]



Va

Figure 2.2: Cyclopropenylidene **Va** and its resonance structures showing ring aromaticity and remote stabilization from the nitrogen substituents

In **Va**, the carbene center is included in an all-carbon 3-membered ring and the heteroatomic substituents are found in exocyclic positions. The stability of **Va** was attributed to the combination of the pronounced s-character of its lone pair due to its confinement in a 3-membered ring, the aromaticity of the ring, and through conjugation with the exocyclic dialkylamino substituents (Figure 2.2). The isolation of the free carbene **Va** allowed for the synthesis of several transition metal complexes that were not previously available through traditional methods relying on the oxidative addition of a metal complex to a suitable carbene precursor,[20] for the development and use of similar *bis*-(amino)cyclopropenylidene as organocatalysts,[21] and opened unprecedented reactions between P_4 and carbenes.[13]

Inspired by this work, we decided to investigate the synthesis of other cyclic carbenes with remote stabilization through extended conjugation with π-donating substituents. We reasoned that the stabilizing influence of the dialkylamino substituents of **Va** could be extended to more remote carbene centers trough a properly conjugated system. This reasoning was inspired by the synthesis of allenylidene lithium complex **VIa-Li**.[22] Indeed, in **VIa** two amino substituents are remotely conjugated with the carbene empty orbital as illustrated by resonance form **VIa'**. This zwitterionic resonance

form features a positively charged 5-membered carbenium moiety connected to a negatively charged acetylide anion (Figure 2.3).

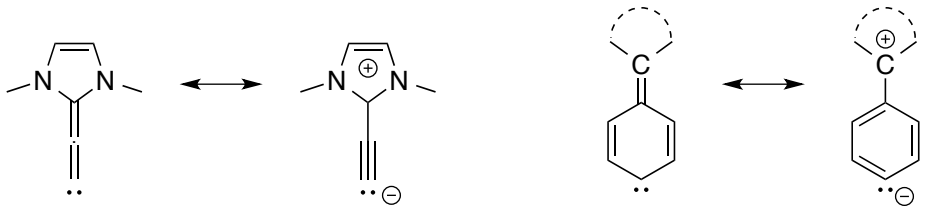


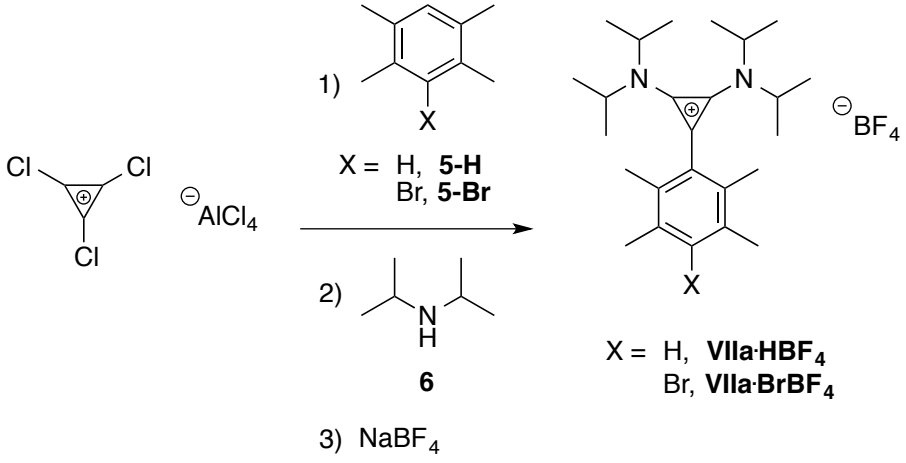
Figure 2.3: Resonance structure of carbene **VIa** and proposed target carbene **VII**

Based on this analysis, we reasoned that carbene **VII** could be attainable (Figure 2.3). Indeed, such a carbene can be described by the zwitterionic resonance structure **VII'** featuring a negatively charged phenylide moiety and a positively charged carbenium substituent (Figure 2.3). This observation encouraged us to attempt the synthesis of such remotely stabilized carbenes.

2) Synthesis of precursors and carbene generation attempts

Close examination of resonance structures **VII** and **VII'** (Figure 2.3) reveals that the stabilization of the empty orbital of the carbene (resonance form **VII**) is intimately linked to the ability of the remote substituent to accommodate a positive charge (resonance form **VII'**). We quickly realized that a cyclopropenylidene unit would not only fully satisfy these requirements, as the cyclopropenium cation is a well-known example of a stable carbenium ion, but also allow an easy access to suitable precursors. Indeed, a Friedel-Crafts alkylation of a carefully chosen benzene derivative by the trichlorocyclopropenium cation followed by the substitution of the cyclopropenium unit with a dialkylamine would provide the desired precursor. Adapting a procedure developed by Regitz,[23] we synthesized precursor **VIIa**$\cdot$**HBF$_4$** from durene **5-H** as the

benzene derivative and diisopropylamine **6** as the amine partner in 91% yield (Scheme 2.5).



Scheme 2.5: Synthesis of precursors **VIIa·HBF$_4$** and **VIIa·BrBF$_4$**

With precursor **VIIa·HBF$_4$** in hand, we attempted its deprotonation in order to obtain the free carbene. Unfortunately, all attempts resulted in complex reaction mixtures out of which no carbene could be isolated. Varying the experimental conditions, be it the solvent, the temperature or the base (KHMDS, *t*BuOK, LDA, TMPLi or *n*-BuLi) did not yield the desired carbene.

To circumvent this issue, we investigated the possibility of generating the carbene through reduction of precursor **VIIa·BrBF$_4$**. This compound was easily obtained in 84% yield using the same methodology as for **VIIa·HBF$_4$** by using bromodurene **5-Br** as the Friedel-Crafts substrate (Scheme 2.5). Unfortunately, all reduction attempts failed to provide the desired carbene, no matter which reducing agent was used.

3) Conclusion

Despite all our attempts, carbenes of type **VII** still elude isolation. The failure of deprotonation approach could be explained by the presence of acidic benzylic proton on the designed precursor, which can compete with the proton on the aromatic 6-membered ring. Replacing durene **5-H** by other aromatic precursors, featuring methoxy or dimethylamino groups in place of the methyl substituents for example, could prevent this issue. However, such precursors are quite tedious and expensive to prepare, which led us to abandon this project.

C) Toward electron rich acyclic carbenes and their potential applications as organic reducing agents

1) Introduction

In 2011, our group reported the synthesis of phosphenium ion **VIIIa** (Figure 2.4).[24] In this molecule, the cationic phosphorus center is stabilized by to π-donating carbene-iminato substituents. We quickly realized that such substituents might prove to be equally efficient at stabilizing species isoelectronic to phosphenium ions and that, as such, carbenes of type **IX** were obvious targets (Figure 2.4).

Carbene-iminato substituents are strongly π-donating as illustrated by resonance structures **VIIIa'**, **VIIIa''**, **IX'** and **IX''**. Indeed, they can be seen as their resonance structure presenting a positively charged carbenium unit and a negatively charged nitrogen center (Figure 2.4).

Considering the 2-electron oxidation of carbenes **IX**, we realized that the resulting product can be seen as dicationic carbodiimides $\mathbf{IX}^{2+}$ where the central NCN fragment is

substituted by two positively charged carbenium groups (Figure 2.5). Such dicationic carbodiimides are not known. However, neutral carbodiimides form a very well known and widely developed family of stable molecules.

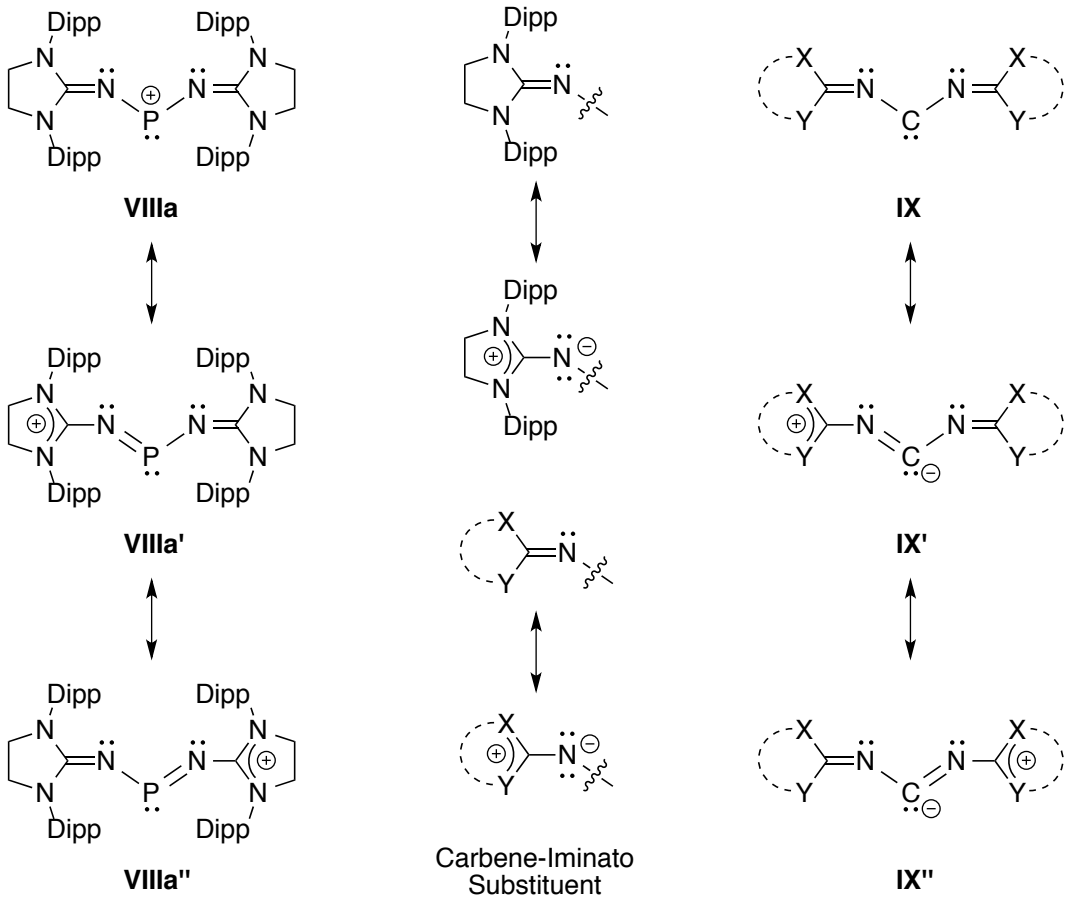


Figure 2.4: Phosphenium cation **VIIIa** and target carbenes of type **IX** and their respective resonance structures illustrating the π-donation of the carbene-iminato substituents.

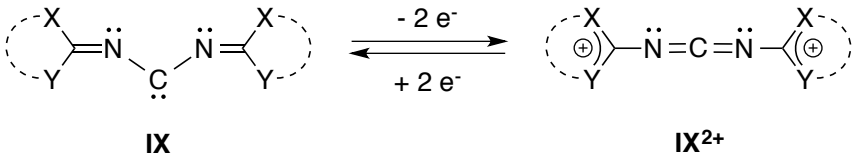
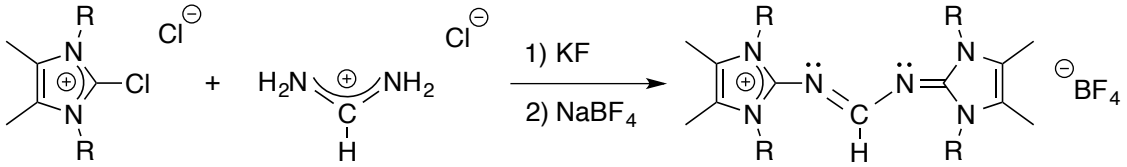


Figure 2.5: Carbenes of type **IX** and carbodiimides $\mathbf{IX}^{2+}$

This observation led us to consider the potential of carbenes of type **IX** as organic reducing agents. Additionally, based on the knowledge of the π-accepting properties of carbenes (see Chapter 1), we reasoned that the variation of the carbene moiety of the carbene-iminato substituents would likely result in carbenes **IX** that are stabilized to different extents, resulting in different respective reductive abilities. Such organic reducing agents are reminiscent of tetraaminoethylenes[25] and would possess similar advantages of ease of handling, solubility, tunability and ease of by-product elimination when compared to classical metallic reducing agents.[26]

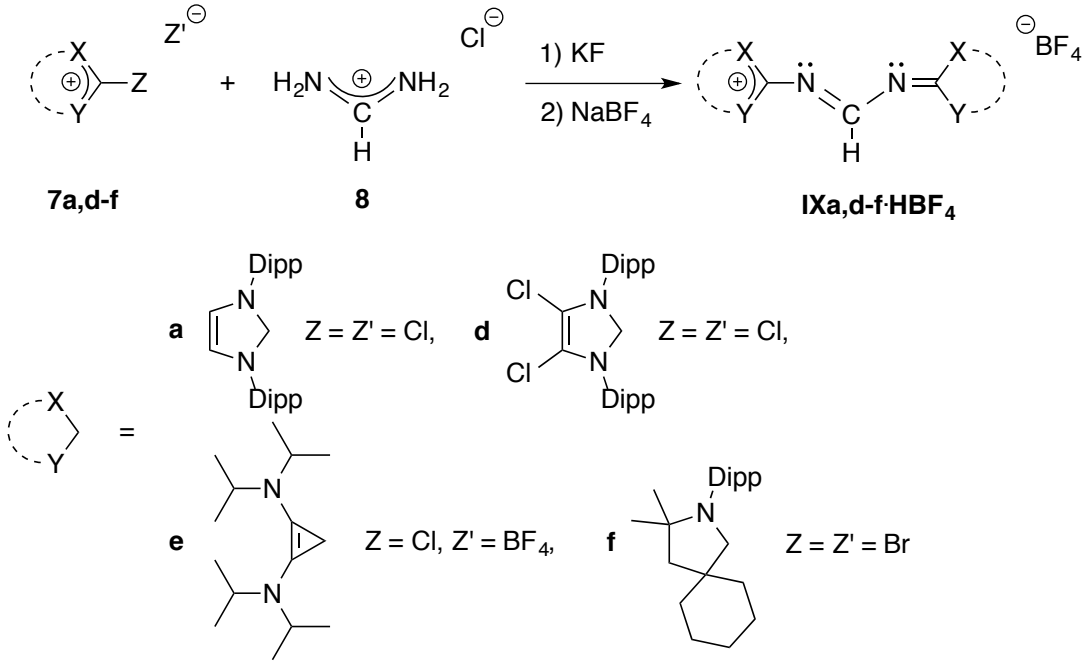
2) Synthesis of precursors and carbene generation attempts

In 2012, Schröder[27] reported the synthesis of compounds **IXa·HBF$_4$** and **IXb·HBF$_4$** and studied their behavior by collision-induced dissociation mass spectrometry (Scheme 2.6).



Scheme 2.6: Synthesis of precursors **IXa·HBF$_4$** and **IXb·HBF$_4$**

We reasoned that those precursors would likely lead to unstable carbenes as the alkyl R substituents could migrate to the carbene center.[28] However, we quickly realized that this synthetic strategy would provide a versatile access to the desired precursors with different carbene-iminato moieties (Scheme 2.7). Indeed, starting from formamidine hydrochloride **8** and appropriate substrates **7c-f**, we were able to synthesize precursors **IXc-f·HBF$_4$** in moderate to good yields (42-91%).



Scheme 2.7: Synthesis of precursors **IXc-f·HBF$_4$**

We first attempted to deprotonate precursor **IXc·HBF$_4$** using KHMDS. However, no clean reaction occurred. Variation of the base and other experimental conditions only resulted in complex mixtures from which no desired carbene could be isolated. We reasoned that the acidic hydrogen atoms which **IXc·HBF$_4$** possesses on its imidazole moieties,[29] could compete with the proton on the central carbon leading to the observed mixtures (Figure 2.6).

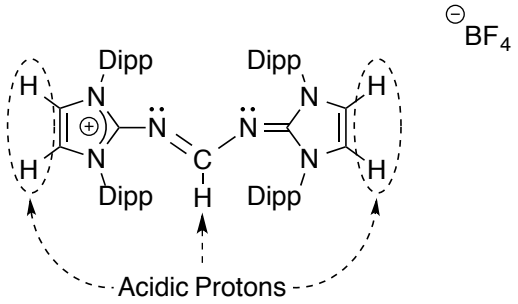
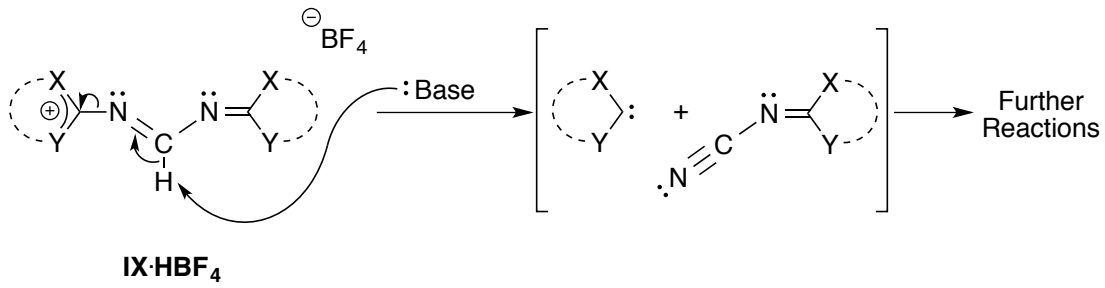


Figure 2.6: Acidic protons of **IXc·HBF$_4$**

In order to eliminate this possibility, we turned our attention to precursor **IXd·HBF$_4$** in which the imidazole protons have been replaced by chlorine atoms. Unfortunately, all attempts at deprotonating **IXd·HBF$_4$** resulted in equally complex mixtures. Precursor **IXe·HBF$_4$**, derived from carbene **Va** proved to be equally unsuitable. We realized that for each of these precursors, the free carbenes (type **X** for **IXc·HBF$_4$** and **IXd·HBF$_4$** and **Va** for **IXd·HBF$_4$**), corresponding to the carbene-iminato substituents were all good leaving groups as illustrated by their use as organocatalysts. [21,30] Suspicions arose that the action of the base on those precursors could result in the departure of the carbene unit of one carbene-iminato substituent, leading to the corresponding free carbene on one hand and a cyanamide on the other (Scheme 2.8). The two newly generated molecules could then react together, leading to various possible products.

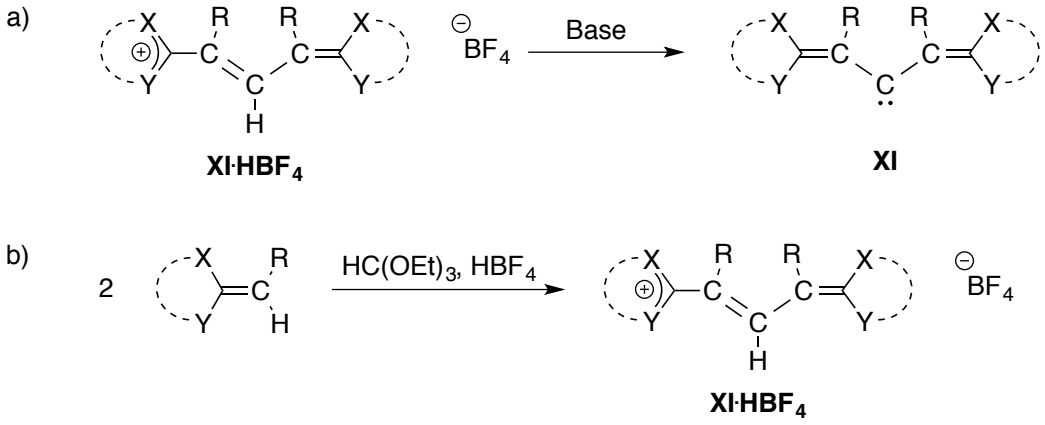


Scheme 2.8: Alternative outcome to the deprotonation of precursors **IX·HBF$_4$**

We decided to consider precursor **IXf·HBF$_4$**. In this precursor, the carbene-iminato substituent is derived from a cyclic (alkyl)(amino)carbene **IIIa**. Carbenes of type **III** are notably stronger σ-donors as well as significantly stronger π-acceptors than carbenes of type **X** or **Va** as demonstrated in Chapter 1, and as such, we can expect them to be poorer leaving group. Unfortunately, the reaction of **IXf·HBF$_4$** also resulted in complex mixtures in all the attempted conditions.

3) Conclusion

Despite all our efforts, carbenes of type **IX** still elude isolation. A possible solution to this problem could be the replacement of the carbene-iminato substituents by N-heterocyclic alkenes, leading to carbenes of type **XI**. The replacement of the nitrogen atom by a carbon atom could result in a structure that is less prone to dissociation and potentially allow for the isolation of the desired carbenes (Scheme 2.9a). Precursors to carbenes of type **XI** could be obtained by adapting the methodology developed by Reichardt (Scheme 2.9b).[31]



Scheme 2.9: Proposed syntheses of (a) carbenes of type **XI** and (b) their precursors **XI·HBF$_4$**

D) Conclusions

With the ultimate goal to extend the scope of known stable carbenes, we synthesized precursors to strongly electrophilic carbenes, to carbenes with remote electronic stabilization and to carbenes of potential interest as organic reducing agents. Unfortunately, all attempts at generating these new carbenes failed to yield the desired compounds. We proposed possible explanations to these results and potential routes to circumvent these issues. Some of these are currently under investigation in our group.

E) Appendix: Experimental section

1) General considerations

All manipulations were performed under an atmosphere of dry argon using standard Schlenk techniques or in an argon filled glove box. Solvents were dried by standard methods and distilled under argon. Imine **2**[32] and precursors **7c**,[33] **7d**,[33] and **7e**[33] were prepared according to literature procedures. **7f** was synthesized starting from carbene **IIIa** by adapting a previously published procedure.[34] Dimethylmalonyl dichloride **1** (TCI America), durene **5-H** (Aldrich), bromodurene **5-Br** (Aldrich), diisopropylamine **6** (Aldrich), formamidine hydrochloride **8** (Aldrich) and $NaBF_4$ (Aldrich) were purchased from commercial sources and used without further purification. KF was purchased from Aldrich and dried under vacuum at 150 ºC overnight prior to use. Deuterated solvents were purchased from Cambridge Isotope Laboratories and distilled over CaH_2. ^1H and ^{13}C NMR spectra were recorded on Varian Inova 300, 400, 500 or Bruker 300, 400, 500 or JEOL 500 MHz spectrometers at 25 °C. Chemical shifts are given in ppm and are referenced to $SiMe_4$ (^1H, ^{13}C). NMR multiplicities are abbreviated as follows: s = singlet, d = doublet, t = triplet, q = quadruplet, quint = quintet, sept = septet, oct = octuplet, m = multiplet, br = broad signal.

2) Synthesis of precursors

a) Toward carbenes with increased electrophilicity

Preparation of precursor IVa·HCl: A solution of 4.10 g (15.1 mmol) of imine **2** in 20 mL Et_2O was slowly added to a solution of 1.70 g of LDA (15.9 mmol, 1.05 eq.) in 20 mL Et_2O. The resulting mixture was stirred at room temperature for 3 hours and then the volatiles were removed under vacuum. The residue was dissolved in 40 mL Et_2O and the

solution was then cooled to -78 ºC. 2 mL (2.56 g, 15.1 mmol) of **1** were added to the solution causing the formation of a white precipitate. The resulting mixture was allowed to warm up to room temperature and stirred overnight. The solvent was removed under vacuum and the residue was extracted with 3 x 10 mL of dichloromethane. The extract was evaporated under vacuum and washed with 10 mL Et_2O, affording **IVa·HCl** as an off-white solid (3.20 g, 52 %). ^{1}H ($CDCl_3$, 300 MHz): δ = 7.40 (t, J = 7.5 Hz, 1H), 7.26 (d, J = 7.5 Hz, 2H), 5.48 (s, 1H), 3.13 (sept, J = 6.8 Hz, 1H), 3.01 (sept, J = 6.8 Hz, 1H), 2.51 (br m, 1H), 2.39 (br m, 1H), 1.10-2.15 (m, 8H), 1.60 (s, 3H), 1.49 (s, 3H), 1.34 (d, J = 6.8 Hz, 3H), 1.26 (d, J = 6.8 Hz, 3H), 1.17 (d, J = 6.8 Hz, 3H), 1.06 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 75.4 MHz): δ = 209.5, 174.8, 148.0, 145.5, 134.9, 129.6, 125.3, 124.5, 85.1, 55.1, 52.0, 33.9, 32.0, 28.9, 27.9, 25.8, 25.6, 25.5, 23.8, 23.5, 23.3, 23.0, 22.3

b) Toward new carbenes with remote stabilization

Preparation of precursor VIIa·HBF$_4$: A suspension of 2.17g (16.3 mmol) of $AlCl_3$ in 30 mL dichloromethane was cooled to -78 ºC. 2mL (2.90 g, 16.3 mmol) of tetrachlorocyclopropene were added dropwise to the suspension. The resulting mixture was then allowed to warm up to room temperature and stirred for a additional 30 min. The reaction medium was then cooled to 0 ºC and a solution of 2.41 g (17.9 mmol, 1.1 eq.) of durene **5-H** in 20 mL dichloromethane was added. The resulting mixture was stirred for 30 min at this temperature, which yielded a clear yellow solution. A solution of 15 mL (10.83 g, 107mmol, 6.6 eq.) of diisopropylamine **6** in 50 mL dichloromethane was added dropwise while keeping the reaction mixture temperature at 0 ºC. The resulting solution was allowed to slowly warm up to room temperature and stirred overnight. A solution of 10 g (91mmol, 5.6 eq.) of $NaBF_4$ in 100 mL H_2O was then added to the

reaction mixture and the resulting biphasic mixture was stirred for an hour. The organic layer was separated, washed with 3 x 25 mL H_2O and then concentrated to dryness using a rotary evaporator. The residue was then dissolved in a minimal amount of dichloromethane and added dropwise to 500 mL Et_2O under vigorous stirring, resulting in the precipitation of a white solid. The precipitate was filtered out and then dried under vacuum to afford **VIIa·HBF$_4$** (6.80 g, 91 %). ^{1}H ($CDCl_3$, 500 MHz): δ = 7.09 (s, 1H), 4.23 (sept, J = 6.8 Hz, 2H), 3.75 (sept, J = 6.8 Hz, 2H), 2.23 (s, 6H), 2.06 (s, 6H), 1.44 (d, J = 6.8 Hz, 12H), 1.11 (d, J = 6.8 Hz, 12H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125.7 MHz): δ = 135.5, 135.4, 133.7, 132.0, 125.7, 109.8, 58.1, 47.7, 22.1, 21.0, 19.9, 18.2

Preparation of precursor VIIa·BrBF$_4$: A suspension of 2.17g (16.3 mmol) of $AlCl_3$ in 30 mL dichloromethane was cooled to -78 ºC. 2mL (2.90 g, 16.3 mmol) of tetrachlorocyclopropene were added dropwise to the suspension. The resulting mixture was then allowed to warm up to room temperature and stirred for a additional 30 min. The reaction medium was then cooled to 0 ºC and a solution of 3.82 g (17.9 mmol, 1.1 eq.) of 3-bromodurene **5-Br** in 20 mL dichloromethane was added. The resulting mixture was stirred for 3 hours at this temperature, which yielded a clear yellow solution. A solution of 15 mL (10.83 g, 107mmol, 6.6 eq.) of diisopropylamine **6** in 50 mL dichloromethane was added dropwise while keeping the reaction mixture temperature at 0 ºC. The resulting solution was allowed to slowly warm up to room temperature and stirred overnight. A solution of 10 g (91mmol, 5.6 eq.) of $NaBF_4$ in 100 mL H_2O was then added to the reaction mixture and the resulting biphasic mixture was stirred for an hour. The organic layer was separated, washed with 3 x 25 mL H_2O and then concentrated to dryness using a rotary evaporator. The residue was then dissolved in a

minimal amount of dichloromethane and added dropwise to 500 mL Et_2O under vigorous stirring, resulting in the precipitation of a white solid. The precipitate was filtered out and then dried under vacuum to afford **VIIa·BrBF$_4$** (7.33 g, 84 %). ^{1}H ($CDCl_3$, 400 MHz): δ = 4.23 (sept, J = 6.7 Hz, 2H), 3.75 (sept, J = 6.7 Hz, 2H), 2.42 (s, 6H), 2.18 (s, 6H), 1.43 (d, J = 6.7 Hz, 12H), 1.11 (d, J = 6.7 Hz, 12H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100.6 MHz): δ = 136.1, 135.3, 133.4, 132.0, 125.4, 108.9, 58.2, 47.6, 22.2, 21.2, 21.0, 20.1

c) Toward electron rich acyclic carbenes and their potential applications as organic reducing agents

7f: 83 % yield, ^{1}H (CD_3CN, 500 MHz): δ = 7.60 (t, J = 7.5 Hz, 1H), 7.52 (d, J = 7.5 Hz, 2H), 2.64 (s, 2H), 2.57 (sept, J = 6.6Hz, 2H), 2.06-1.74 (m, 10H), 1.55 (s, 6H), 1.33 (d, J = 6.6Hz, 6H), 1.20 (d, J = 6.6Hz, 6H). ^{13}C{^{1}H} NMR (CD_3CN, 125.7 MHz): δ = 191.2, 145.3, 133.1, 130.6, 127.3, 85.6, 58.6, 43.5, 36.2, 30.3, 29.1, 26.3, 24.9, 23.5, 21.7

General method for the synthesis of precursors **IXc·HBF4**, **IXd·HBF4**, **IXe·HBF4** and **IXf·HBF4** from compounds **7c**, **7d**, **7e** and **7f** respectively:

25mL of acetonitrile were added to a solid mixture of 5 mmol of **8** (403 mg), 80 mmol of KF (4.65g) and 10 mmol of the appropriate precursor **7**. The reaction medium was then stirred at 50 ºC for 2 days. The mixture was then diluted with 25 mL of chloroform, filtered and the filtrate was evaporated to dryness. The residue was then dissolved in 50 mL chloroform and added to 50 mL of a 2 mol/L solution of $NaBF_4$. The biphasic mixture was then stirred overnight. The organic layer was separated and the aqueous layer washed twice with 25 mL chloroform. The organic layers were combined and evaporated to dryness. The residue was dissolved in a minimal amount of chloroform and the resulting solution was poured onto 250 mL of Et_2O under vigorous stirring, which

resulted in the precipitation of a white solid. If necessary, these precursors can be recrystallized from isopropanol.

Characterization of precursor IXc·HBF4: 81 % yield, ^{1}H ($CDCl_3$, 400 MHz): δ = 7.37 (t, J = 7.8 Hz, 4H), 7.17 (s, 1H), 7.10 (d, J = 7.8 Hz, 8H), 6.82 (s, 8H), 2.44 (sept, J = 6.9 Hz, 8H), 1.06 (d, J = 6.9 Hz, 24 H), 0.78 (d, J = 6.9 Hz, 24 H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100.6 MHz): δ = 154.3, 146.3, 145.6, 130.8, 130.2, 124.8, 119.3, 29.0, 24.0, 23.2

Characterization of precursor IXd·HBF4: 84 % yield, ^{1}H ($CDCl_3$, 500 MHz): δ = 7.51 (t, J = 8.0 Hz, 4H), 7.21 (d, J = 8.0 Hz, 8H), 7.18 (s, 1H), 2.29 (sept, J = 6.3 Hz, 8H), 1.14 (d, J = 6.3 Hz, 24 H), 076 (d, J = 6.3 Hz, 24 H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125.7 MHz): δ = 153.8, 146.2, 144.1, 132.2, 126.6, 125.3, 115.3, 29.5, 23.8, 23.6

Characterization of precursor IXe·HBF4: 42 % yield, ^{1}H ($CDCl_3$, 500 MHz): δ = 8.23 (s, 1H), 3.79 (sept, J = 6.7 Hz, 8H), 1.30 (d, J = 6.7Hz, 48H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125.7 MHz): δ = 162.2, 122.8 (br), 120.3, 51.1 (br), 22.1

Characterization of precursor IXf·HBF4: 91 % yield, ^{1}H ($CDCl_3$, 500 MHz): δ = 8.65 (s, 1H), 7.31 (t, J = 7.8 Hz, 2H), 7.13 (d, J = 7.8 Hz, 4H), 2.64 (sept, J = 6.8 Hz, 4H), 2.33 (s, 4H), 1.85-1.35 (m, 20H), 1.31 (s, 12H), 1.22 (d, J = 6.8 Hz, 12H), 0.81 (d, J = 6.8 Hz, 12H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125.7 MHz): δ = 176.0, 151.9, 146.6, 129.9, 129.1, 124.7, 68.7, 49.9, 46.1, 35.2, 29.4, 25.9, 25.5, 25.0, 23.1, 21.8

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CHAPTER 3:

A Stable Singlet Phosphinonitrene

Adapted from:

F. Dielmann, O. Back, M. Henry-Ellinger, P. Jerabek, G. Frenking, G. Bertrand,

Science, **2012**, *337*, 1526-1528

A) Introduction

Nitrenes are neutral compounds featuring a monovalent nitrogen atom possessing either a lone pair of electron and two singly occupied non-bonding orbitals (triplet state), or two lone pairs and a vacant orbital (singlet state). These molecules are the nitrogen analog of carbenes (Figure 3.1).

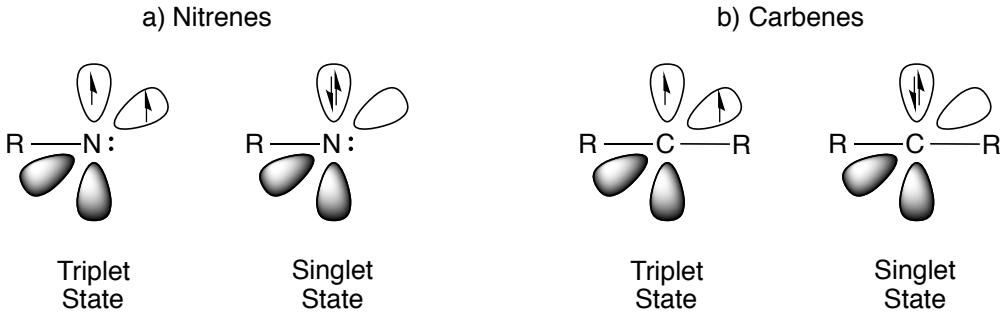


Figure 3.1: Analogy between (a) nitrenes and (b) carbenes

Nitrenes form a family of highly reactive species[1,2] that has so far eluded the synthetic skills of chemists, with the only exception being metallonitrenes **I** (Figure 3.2a).[3-7] The latter can be regarded as metal-nitrido ligands (L_nMN, where L is a ligand and M is a metal) since one contributing resonance structure features a metal-nitrogen triple bond (form **I'**, Figure 3.2a). A M-N σ-bond is formed through the interaction between a p_z or sp-hybridized orbital of the nitrogen atom and an orbital of σ-symmetry of the metal. Additionally, π-bonds can be formed from the interaction of the p_x and p_y orbitals of the nitrogen atom and the appropriate orbitals of π-symmetry of the metal center.

Non-metallic nitrenes, on the other hand, are short-lived intermediates, which have eluded isolation. The most stable non-metallic nitrenes are the aminonitrenes **II** synthesized by Dervan.[8-13] **IIa** and **IIb** are stable enough in solution at -78 ºC to allow

spectroscopic characterization and even purification by low-temperature chromatography at -88 ºC. The relative stability of aminonitrenes **II** can be explained by the π-donation of the lone pair of the nitrogen atom of the amino substituent into the vacant orbital of the nitrene center as illustrated by the 1,1-diazene resonance form **II'** featuring a N-N double bond (Figure 3.2b). The stabilization of the empty orbital of electron deficient centers by two π-donating substituents is a well-known mechanism in carbene chemistry.[14-16]

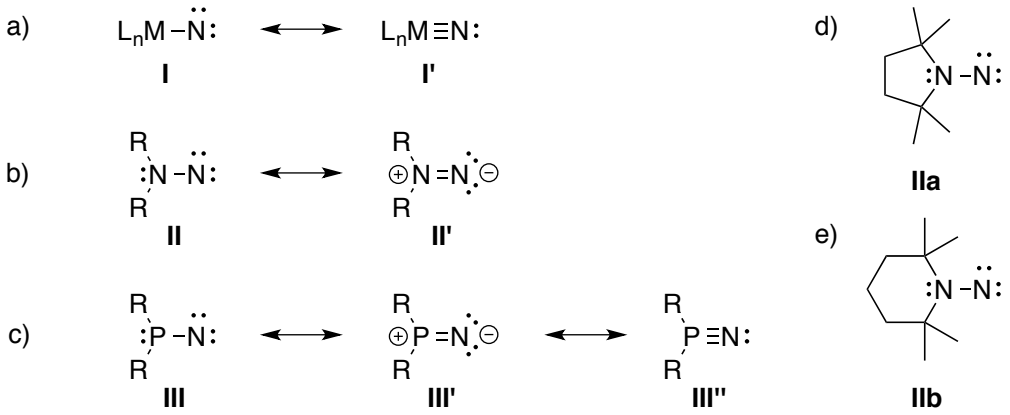


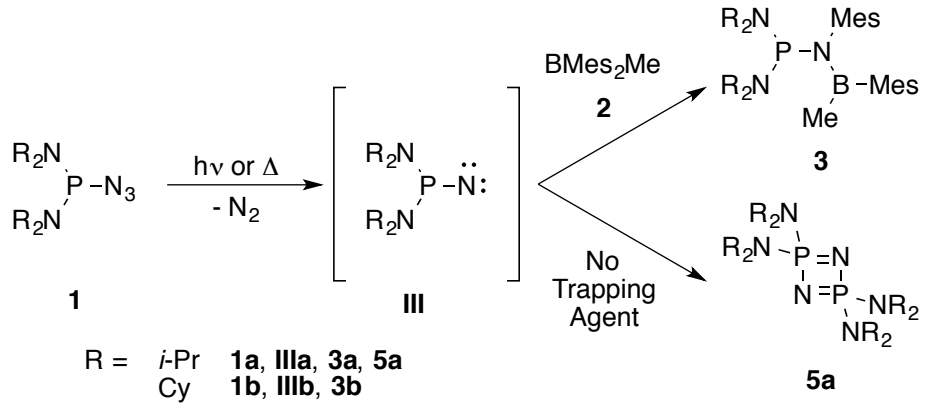
Figure 3.2: (a) Metallonitrenes **I**, (b) aminonitrenes **II**, (c) phosphinonitrenes **III** and their relevant resonance structures. Spectroscopically characterized aminonitrenes (d) **IIa** and (e) **IIb**

Another common stabilization strategy in carbene chemistry is to combine the effect of a π-donating substituent to stabilize the empty orbital and of a π-accepting substituent to stabilize the carbene lone pair.[17,18] However, whereas carbenes possess a dicoordinated carbon atom, nitrenes possess only a monocoordinated nitrogen atom. Consequently, in order to extend the latter strategy to nitrenes, a substituent capable of both π-donation and π-acception is needed. Computational studies showed that a phosphino substituent would satisfy these properties.[19-21] Indeed, the phosphorus atom of a phosphinonitrene **III** can not only donate a lone pair of electrons to stabilize the empty orbital of the nitrene (resonance structure **III'**) but as well, can accept a lone pair of

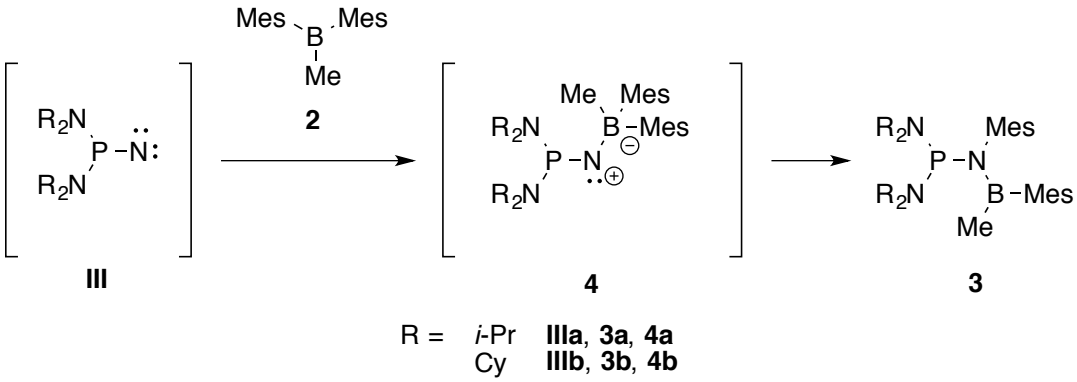
electrons from the nitrogen atom into an empty σ*-orbital (resonance structure **III''**, Figure 3.2c). As such, phosphinonitrenes **III** resemble metallonitrenes **I** since the P-N bond order can approach three.

Phosphinonitrenes **III** have been a long-standing target in our group.[22-25] As early as 1984, it was shown that compounds **IIIa** and **IIIb**, which are generated from either photolysis or thermolysis of azide precursors **1a** and **1b**, exhibit nitrene-like reactivity. Indeed, when **IIIa** and **IIIb** are generated in presence of dimesitylmethylborane **2**, adducts **3a** and **3b** are obtained (Scheme 3.1). The formation of **3** can be explained through the formation of the Lewis acid-nitrene adducts **4** in a first step, followed by the 1,2-migration of a mesityl group in a second step (Scheme 3.2). Despite their encouraging reactivity, compounds **IIIa** and **IIIb** are not stable and it was shown that if **IIIa** is generated in the absence of any trapping agent, dimer **5a** is obtained (Scheme 3.1).[23]

In 2001, a computational study by Schoeller and Rozhenko[21] concluded that the most appropriate substituents for stabilizing phosphinonitrenes are strong p-donors and weak s-acceptors. These authors suggested that "substituents, which bear an imino function in the α-position to the phosphorus atom, e.g., the phosphaniminato group" would be the best choice.



Scheme 3.1: Reactivity of transient phosphinonitrenes **III**



Scheme 3.2: Proposed mechanism for the formation of **3**

Based on this prediction and on the analogy between the phosphaniminato and carbene-iminato groups, we decided to explore the synthesis of *bis*-(carbene-iminato)phosphinonitrenes (Figure 3.3).

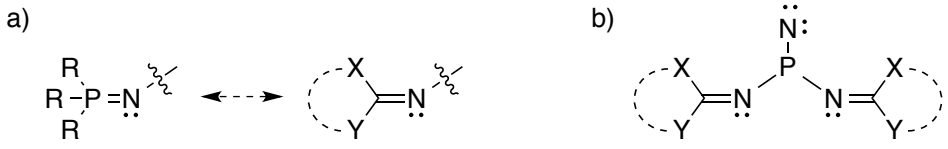
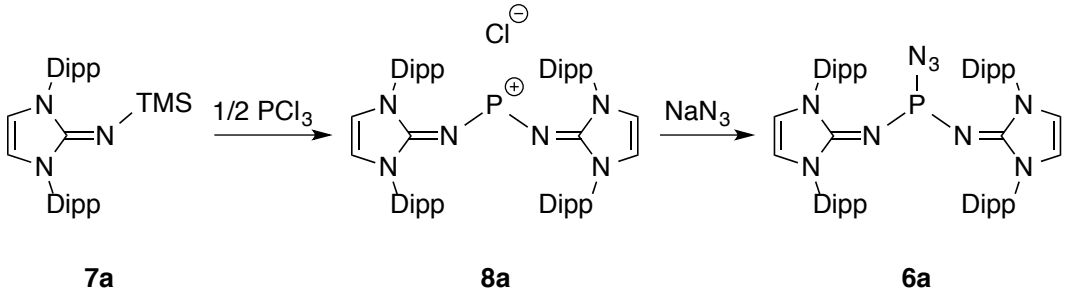


Figure 3.3: (a) Analogy between phosphaniminato and carbene-iminato groups and (b) *bis*-(carbene-iminato)phosphinonitrene

B) Synthesis of a stable singlet phosphinonitrene

We first synthesized the azide precursor **6a**. This compound is easily obtained in two steps from the 2-(trimethylsilylimino)-imidazole derivative **7a**.[26] In a first step, **7a** is reacted with PCl_3 to afford the phosphenium chloride precursor **8a**, which upon reaction with sodium azide produces the desired azide precursor **6a** in 90% overall yield (Scheme 3.3). **6a** was fully characterized by NMR spectroscopy (^{1}H, ^{13}C, ^{31}P). Its ^{31}P NMR spectrum displays a singlet at 111.1 ppm, as expected for such a molecule (for comparison, **1a**: 105.3 ppm).[24]



7a **8a** **6a**

Scheme 3.3: Synthesis of **6a**

At room temperature, **6a** was found to slowly decompose in the solid state but it is stable when stored in solution in benzene or toluene. In line with this observation, thermolysis of **6a**, whether as a solid or in solution, affords complex mixtures and therefore, we investigated the photolysis of **6a**.

A benzene solution of **6a** was irradiated at 254 nm, and the progress of the reaction monitored by ^{31}P NMR spectroscopy. After 15 min, a new signal is observed at 15.8 ppm corresponding to a new compound **9a**, along with the signal corresponding to **6a**. The chemical shift of **9a** is indicative of a hypervalent phosphorus center, which is consistent with a 1,1-phosphazene or phosphinonitride structure (resonance forms **III'**

and **III''** respectively, Figure 3.2c). However, prolonged irradiation resulted in increasingly complex mixtures (Figure 3.4).

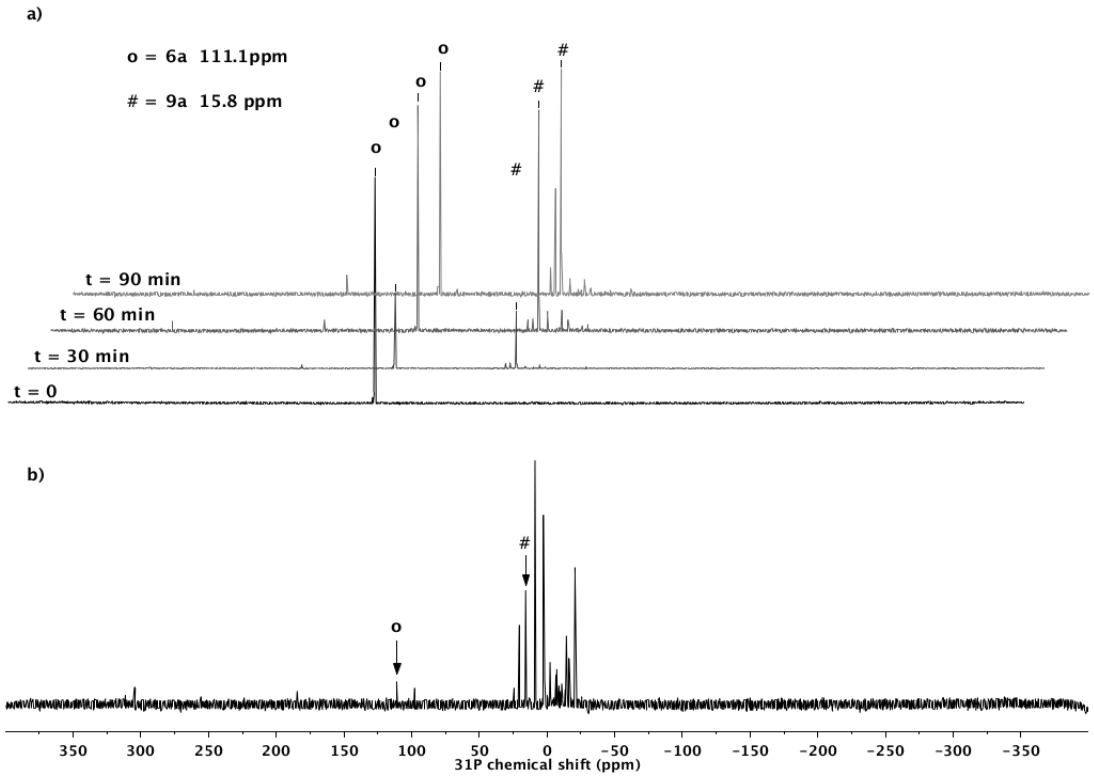


Figure 3.4: (a) Irradiation of **6a** followed by ^{31}P NMR and (b) ^{31}P NMR spectrum after 5 hours of irradiation

Encourage by this result, we turned our attention to azide precursor **6b** (Scheme 3.4). This compound was prepared following the same methodology as **6a**. To our delight, after two hours of irradiation at 254 nm, a much cleaner ^{31}P NMR spectrum is observed. The major product **9b** shows as a singlet at 7.7 ppm, once again suggesting a hypervalent phosphorus atom (Figure 3.5 and Scheme 3.4).

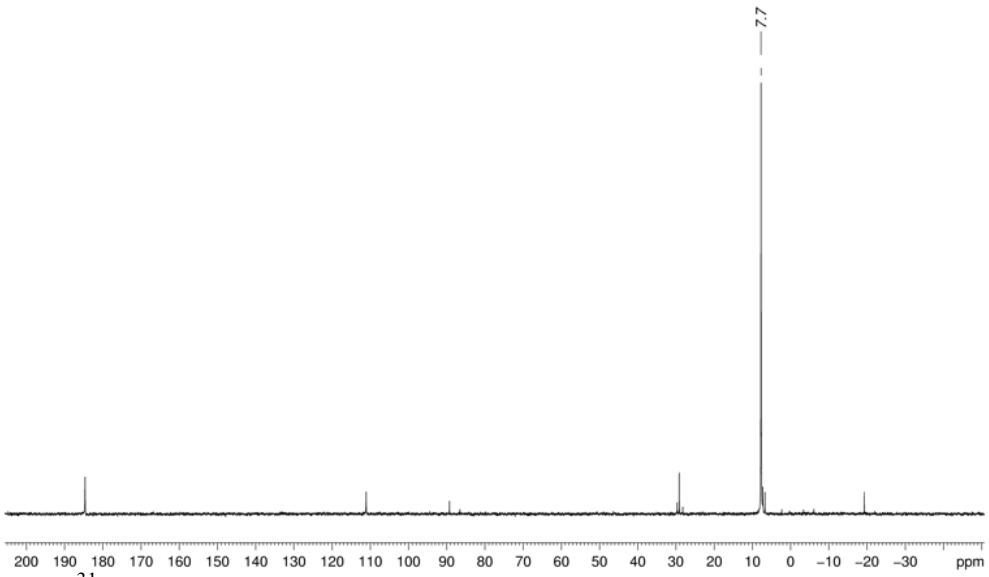
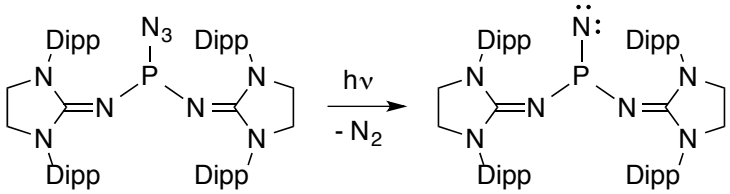


Figure 3.5: ^{31}P NMR spectra of the crude mixture after 2 hours of irradiation (254nm) of **6b**



6b **9b**

Scheme 3.4: Synthesis of nitrene **9b**

Evaporation of the solvent under reduced pressure afforded **9b** as a pale yellow solid, which was fully characterized by NMR spectroscopy. As mentioned previously, the ^{31}P NMR spectrum shows a singlet at 7.7 ppm, shifted high field in comparison to the azide starting material **6b** (111.0 ppm), indicative of a hypervalent phosphorus center. In order to obtain further insight on the nature of **9b**, the ^{15}N enriched azide **6b*** (50:50 mixture of $R_2P^{15}N_\alpha NN_\gamma$ and $R_2PN_\alpha N^{15}N_\gamma$) was prepared using ^{15}N enriched sodium azide ($NaNN^{15}N$) and then irradiated. For **6b***, the N_γ and N_α give a singlet at 196.6 ppm and a doublet at 95.8 ppm (J_{PN} = 103 Hz), respectively. The ^{15}N enriched **9b*** appears as a doublet with a larger PN coupling constant (J_{PN} = 144 Hz), suggesting once again the

presence of a PN multiple bond. This doublet is at 266.0 ppm, shifted to lower field in comparison to **6b***, but is strongly shielded compared to that observed for the nitrene nitrogen of N-(2,2,6,6-tetramethylpiperidy1)nitrene **IIb** (917.0 ppm).[10] The same high field shielding effect is observed when comparing the ^{13}C chemical shift of the carbene carbon of phosphinocarbenes (80-150 ppm) with aminocarbenes (200-400 ppm).[27]

The nitrene nature of **9b** was unequivocally established by a X-Ray diffraction study (Figure 3.6). Single crystals of **9b** were obtained by dissolving the powder in warm hexane, subsequent filtration, and storing the solution at −30 °C. The solid state structure shows that the phosphorus atom is in a planar environment (sum of the angles: 359.9 ^{o}), and a very short P-N1 bond length is 1.458(8) Å. For comparison, the P-N2 and P-N3 bond distances are 1.629(8) and 1.618(8) Å, respectively, and PN double bonds are in the range of 1.50-1.60 Å. All these geometric parameters yet again suggest the presence of a phosphorus-nitrogen multiple bond.[28]

In order to gain further insight into the electronic structure of **9b**, the model compound **9M** (phenyl instead of 2,6-diisopropyl substituents) was studied with quantum chemical methods in collaboration with the group of Prof. Gernot Frenking. At the MO5-2X/TZVPP level of theory, the triplet state features a non-planar phosphorus center, and is 36.0 kcal/mol higher in energy than the singlet state. For the latter, the geometry is in good agreement with experimental findings. The Natural Bond Orbital (NBO) calculations give large negative partial charges for N1 (-1.22 e) and N2, N3 (-0.96 e), while the phosphorous atom carries a large positive charge (+1.92 e). There is a P-N1 σ-bond and an out-of-plane $\pi_{\perp}$-bond, which are clearly polarized towards the nitrogen end; the latter possess one σ and one in-plane $\pi_{\parallel}$ lone-pair orbitals. The Wiberg bond order

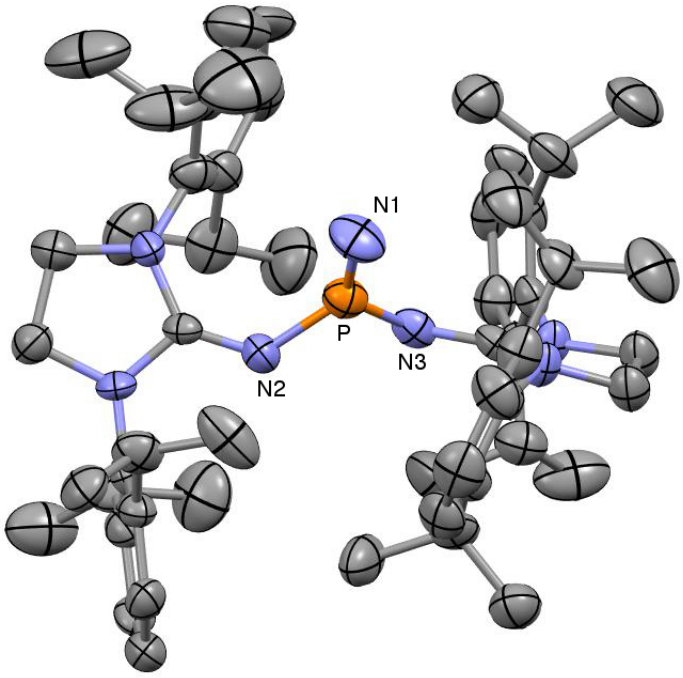
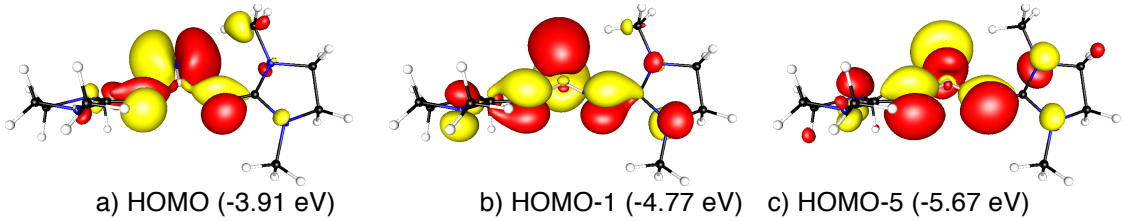


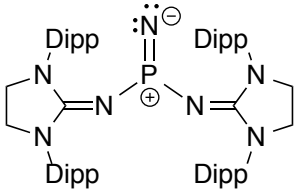
Figure 3.6: Solid-state structure of **9b**. Hydrogen atoms omitted for clarity. Thermal ellipsoids are drawn at 50 % probability.

values suggest a double bond for P-N1 (2.09) and single bonds for P-N2 and P-N3 (0.85). The NBO results are supported by Energy Decomposition Analysis with Natural Orbitals for Chemical Valence (EDA-NOCV) calculations of nitrene **9M'** (methyl instead of 2,6-diisopropyl substituents), using two different fragmentation schemes. The P-N1 bond was broken (a) into neutral fragments (nitrogen atom in the ^{2}P reference state and the phosphinyl fragment in the matching doublet state) and (b) into charged fragments (N^- and the phosphinyl cation in the triplet state). The results show in both cases that the P-N1 covalent bond comes mainly from the σ bond (52% for the neutral fragments, 47% for the charged fragments) and from the $\pi_\perp$-bond (36% for the neutral fragments, 33% for the charged fragments). The contribution of the in-plane $\pi_\parallel$ interactions is much smaller (8%

for the neutral fragments, 11% for the charged fragments). The calculated molecular orbitals of **9M'** comply with the NBO and EDA results. The HOMO is the in-plane $\pi_{\parallel}$ lone-pair orbital at N1 while the HOMO-1 is the polarized out-of-plane P-N1 $\pi_{\perp}$-orbital. The HOMO-5 is mainly the P-N1 σ-bonding orbital. It is interesting to note that there is generally no 1:1 correspondence between the delocalized canonical molecular orbitals and the localized Lewis structure.



a) HOMO (-3.91 eV) b) HOMO-1 (-4.77 eV) c) HOMO-5 (-5.67 eV)



d) Localized Lewis Structure

Figure 3.7: (a) HOMO, (b) HOMO-1, (c) HOMO-5 calculated at the MO5-2X/TZVPP level of theory, and (d) Localized Lewis structure suggested from the NBO analysis and Wiberg bond order values

C) Conclusion

More than two decades after the isolation a the first stable carbene, a phosphino carbene[29] and almost four decades after the first efforts towards stable nitrenes,[8-13] a long-standing target has finally been isolated, namely phosphinonitrene **9b**. This phosphinonitrene features a PN multiple bond as illustrated by its solid-state structure and computational studies. Additionally, phosphinonitrenes are the monomers corresponding to polyphosphazenes, a well-known and widely used family of polymers.[30,31] The reactivity of phosphinonitrene **9b** was investigated in later efforts in our group.[32,33]

Chapter 3 has been adapted from materials published in F. Dielmann, O. Back, M. Henry-Ellinger, P. Jerabek, G. Frenking, G. Bertrand, *Science*, **2012**, *337*, 1526-1528. The dissertation author actively participated in this project.

D) Appendix: Experimental section

1) General considerations

All manipulations were performed under an atmosphere of dry argon using standard Schlenk techniques or in an argon filled glove box. Solvents were dried by standard methods and distilled under argon. 2-(trimethylsilylimino)-imidazole **7a** was prepared according to the procedure of Tamm[26] and 2-(trimethylsilylimino)-imidazoline **7b** was prepared following the same procedure but starting from the previously described corresponding imidazolin-2-ylidene.[34] All other starting materials were purchased from commercial sources. Phosphorus trichloride (Aldrich) was heated under reflux to expel traces HCl and then distilled under vacuum. Sodium azide (Aldrich) was dried under vacuum and washed thoroughly with anhydrous THF. Azido trimethylsilane (Aldrich) was used without further purification. Deuterated solvents were purchased from Cambridge Isotope Laboratories and distilled over CaH_2. ^{1}H, ^{31}P, and ^{13}C NMR spectra were recorded on Varian Inova 300, 400, 500 or Bruker 300, 400, 500 or JEOL 500 MHz spectrometers at 25 °C. ^{15}N NMR spectra were recorded on a Bruker Avance 600 spectrometer at 25 ºC (60.82 MHz for ^{15}N). Chemical shifts are given in ppm and are referenced to $SiMe_4$ (^{1}H, ^{13}C), 85 % H_3PO_4 (^{31}P), and NH_3 (^{15}N). NMR multiplicities are abbreviated as follows: s = singlet, d = doublet, t = triplet, q = quadruplet, quint = quintet, sept = septet, oct = octuplet, m = multiplet, br = broad signal.

2) Synthesis of target compounds

Preparation of phosphenium chloride 8a: PCl_3 (0.126 g, 0.91 mmol) was added to a stirred solution of **7a** (1.0 g, 2.1 mmol) in 25 mL dichloromethane at -78 °C. The resulting bright yellow mixture was then allowed to warm up to room temperature and stirred overnight. The solvent was removed under reduced pressure and the resulting solid was washed with Et_2O (10 mL) and hexanes (2 x 20 mL). Drying the solid under vacuum afforded **8a** as a bright yellow powder in 90 % yield (0.715 g, 0.82 mmol) based on PCl_3. ^{1}H NMR (CD_3CN, 300 MHz): δ = 7.45 (t, J = 7.8 Hz, 4H), 7.19 (d, J = 7.8 Hz, 8H), 7.11 (s, 4H), 2.35 (sept, J = 6.8 Hz, 8H), 1.09 (d, J = 6.8 Hz, 24H), 0.81 (d, J = 6.8 Hz, 24H). ^{13}C{^{1}H} NMR (CD_3CN, 75.5 MHz): δ = 148. (d, J_{PC} = 20.2 Hz), 147.2, 132.1, 125.3, 119.8, 29.7, 24.3, 23.5. ^{31}P NMR (CD_3CN, 121.5 MHz): δ = 309.3

Preparation of phosphino azide 6a: A Schlenk tube containing **8a** (0.600 g, 0.69 mmol) and NaN_3 (60 mg, 0.92 mmol) was cooled to -78 °C and THF (25 mL) was then slowly added. The mixture was allowed to warm up to room temperature and stirred in the dark overnight. The solvent was then removed under reduced pressure. The resulting colorless solid was dried under vacuum and then was extracted with benzene (2 x 10 mL). Removing of the solvent under reduced pressure afforded **6a** as a colorless solid in quantitative yield (0.604 g, 0.69 mmol). ^{1}H NMR (C_6D_6, 300 MHz): δ = 7.27 (t, J = 7.7 Hz, 4H), 7.08 (br m, 8H), 5.86 (s, 4H), 3.01 (br m, 8H), 1.18 (d, J = 6.8 Hz, 24H), 1.14 (d, J = 6.8 Hz, 24H). ^{13}C{^{1}H} NMR (C_6D_6, 75.5 MHz): δ = 148.0, 147.6, 145.9 (d, J_{PC} = 20.8 Hz), 134.3, 123.8, 123.6, 115.1, 28.9, 24.9, 23.5, 23.2. ^{31}P NMR (C_6D_6, 121.5 MHz): δ = 111.1

Characterization of 2-(trimethylsilylimino)-imidazoline 7b: 75 % yield (recrystallization from hexanes). ^{1}H NMR (C_6D_6, 300 MHz): δ = 7.20 (m, 2 H), 7.12 (m, 4 H), 3.43 (s, 4 H), 3.33 (sept, J = 6.9 Hz, 4 H), 1.41 (d, J = 6.9 Hz, 12 H), 1.25 (d, J = 6.9 Hz, 12 H), -0.22 (s, 9 H). ^{13}C{^{1}H} NMR (C_6D_6, 75.5 MHz): δ = 148.9, 147.0, 136.8, 128.7, 124.2, 47.4, 28.9, 25.0, 24.4, 3.4

Preparation of phosphenium chloride 8b: PCl_3 (0.42 g, 3.08 mmol) was added to a stirred solution of **7b** (3.00 g, 6.28 mmol) in THF (25 mL) at -78 °C. The mixture was warmed to room temperature and stirred overnight. During this process, a colorless precipitate of **8b** appeared. The solvent was removed under reduced pressure and the resulting solid was washed with Et_2O (10 mL) and hexanes (2 x 20 mL). Drying the solid under vacuum afforded **8b** as a colorless powder in 91 % yield (2.45 g, 2.80 mmol) based on PCl_3. ^{1}H NMR (CD_3CN, 300 MHz): δ = 7.37 (t, J = 7.7 Hz, 4 H), 7.09 (d, J = 7.7 Hz, 8 H), 3.92 (s, 8 H), 2.80 (sept, J = 6.9 Hz, 8 H), 1.16 (d, J = 6.9 Hz, 24 H), 0.78 (d, J = 6.9 Hz, 24 H). ^{13}C{^{1}H} NMR (CD_3CN, 75.5 MHz): δ = 159.0 (d, J_{PC} = 17 Hz), 148.3, 131.7, 131.3, 125.5, 49.8, 29.4, 24.9, 24.4 (d, J_{PC} = 3 Hz). ^{31}P NMR (CD_3CN, 121.5 MHz): δ = 275.7

Preparation of phosphino azide 6b: A Schlenk tube containing **8b** (1.55 g, 1.77 mmol) and NaN_3 (150 mg, 2.31 mmol) was cooled to -78 °C. THF (25 mL) was slowly added and the mixture was allowed to warm to room temperature with stirring. After stirring in the dark overnight the solvent was removed under reduced pressure, giving a colorless solid, which was dried under vacuum. The residue was extracted with benzene (2 × 10 mL) and filtrated. After removing the benzene under reduced pressure, **6b** was isolated as a colorless solid in quantitative yield (1.56 g, 1.77 mmol). ^{1}H NMR (C_6D_6, 300 MHz): δ

= 7.24 (t, J = 7.7 Hz, 4 H), 7.06 (m, 8 H), 3.28 (m, 16 H), 1.19 (d, J = 6.9 Hz, 36 H), 1.15 (d, J = 6.9 Hz, 12 H); $^{13}C\{^{1}H\}$ NMR (C_6D_6, 75.5 MHz): δ = 152.9 (d, J_{PC} = 19 Hz), 148.6, 148.2, 136.0, 128.5, 124.4, 123.8, 49.3, 28.9, 28.7, 25.7, 25.6, 24.3 (d, J_{PC} = 3 Hz), 23.9. ^{31}P NMR (C_6D_6, 121.5 MHz): δ = 111.0. ^{15}N-enriched (50:50 mixture of $R_2P^{15}NNN$ and $R_2PN^{15}N$) **6b*** was prepared using the same procedure.^{15}N NMR (C_6D_6): δ = 196.6 (s, 1 N, PNN*N*), 95.8 (d, J_{PN} = 103 Hz, P*N*NN). ^{31}P NMR (C_6D_6, 121.5 MHz): δ = 111.0 (d, J_{PN} = 103 Hz)

Preparation of nitrene 9b: A stirred solution of **6b** (500 mg, 0.57 mmol) in toluene (20 mL) in a quartz Schlenk tube was irradiated over 2 h at 254 nm. After removing the solvent under reduced pressure, **9b** was obtained as a slightly yellow solid in 92 % yield (445 mg, 0.52 mmol). Single crystals were obtained by dissolving the powder in warm hexane, subsequent filtration, and storing the solution at -30 °C. ^{1}H NMR (C_6D_6, 300 MHz): δ = 7.22 (t, J = 7.6 Hz, 4 H), 7.07 (d, J = 7.6 Hz, 8 H), 3.27 (s, 8 H), 3.18 (sept, J = 6.9 Hz, 8 H), 1.19 (d, J = 6.9 Hz, 24 H), 1.16 (d, J = 6.9 Hz, 24 H). $^{13}C\{^{1}H\}$ NMR (C_6D_6, 300 MHz): δ = 157.1, 148.4, 134.9, 128.9, 124.4, 49.1, 29.0, 25.4, 25.0. ^{31}P NMR (C_6D_6, 121.5 MHz): δ = 7.7. ^{15}N-labeled ($R_2P^{15}N$) **9b*** was prepared using the same procedure.^{15}N NMR (C_6D_6): δ = 266.0 (d, J_{NP} = 144 Hz). ^{31}P NMR (C_6D_6, 121.5 MHz): δ = 7.7 (d, J_{NP} = 144 Hz)

3) Crystallographic data

Compound	**9b**
CCDC #	884586
Empiric Formula	$C_{54}H_{76}N_7P$
Fw (g/mol)	854.18
Crystal system	Monoclinic
Space group	$P2_1/c$
Radiation, λ (Å)	0.71073
T (K)	100(2)
a (Å)	21.117(5)
b (Å)	12.118(3)
c (Å)	20.092(5)
α (deg)	90
β (deg)	95.920(3)
γ (deg)	90
V ($Å^3$)	5114 (2)
Z	4
d_{calcd} ($g \cdot cm^{-3}$)	1.108
$R1[I>2\sigma(I)]$	0.1161
$wR2[I>2\sigma(I)]$	0.2804
GOF (F^2)	1.098

4) Computational details

Geometry optimizations of the model compound **9M**, which has phenyl groups at the nitrogen atoms instead of 2,6-diisopropyl substituents and **9M'**, which has N-methyl groups were carried out using density functional theory (DFT) at the M05-2X/def2-TZVPP[35,36] level of theory with the program package Gaussian 09, Revision A.02.[37] Natural bond orbital (NBO)[38] calculations were performed using the NBO 3.1 program implemented in Gaussian. The Atom-in-molecules (AIM)[39] analysis of **9M** were carried out with the program AIMAll[40] using the M05-2X/def2-TZVPP wavefunction. Energy-decomposition analyses in conjunction with natural orbitals for chemical valency (EDA-NOCV)[41] were carried out for **9M'** at BP86/TZ2P+[42] at the M05-2X/def2-TZVPP optimized geometry with the ADF(2010.02) program package.[43]

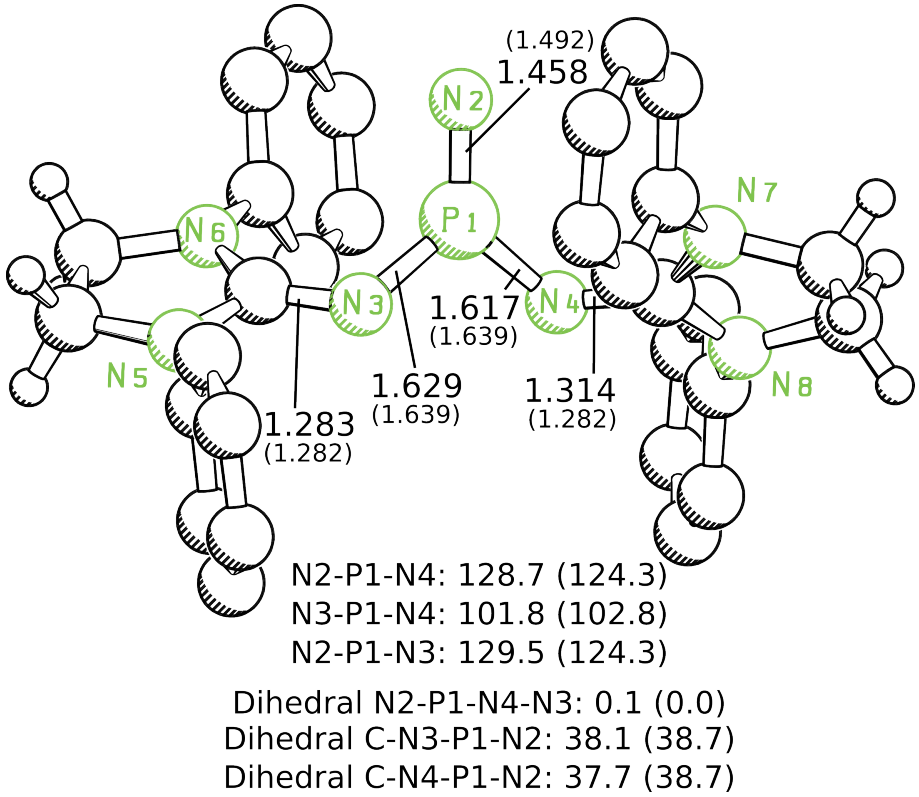


Figure 3.8: Optimized geometry of **9M**. The calculated values of the bond lengths [Å] and angles [degree] are given in parentheses

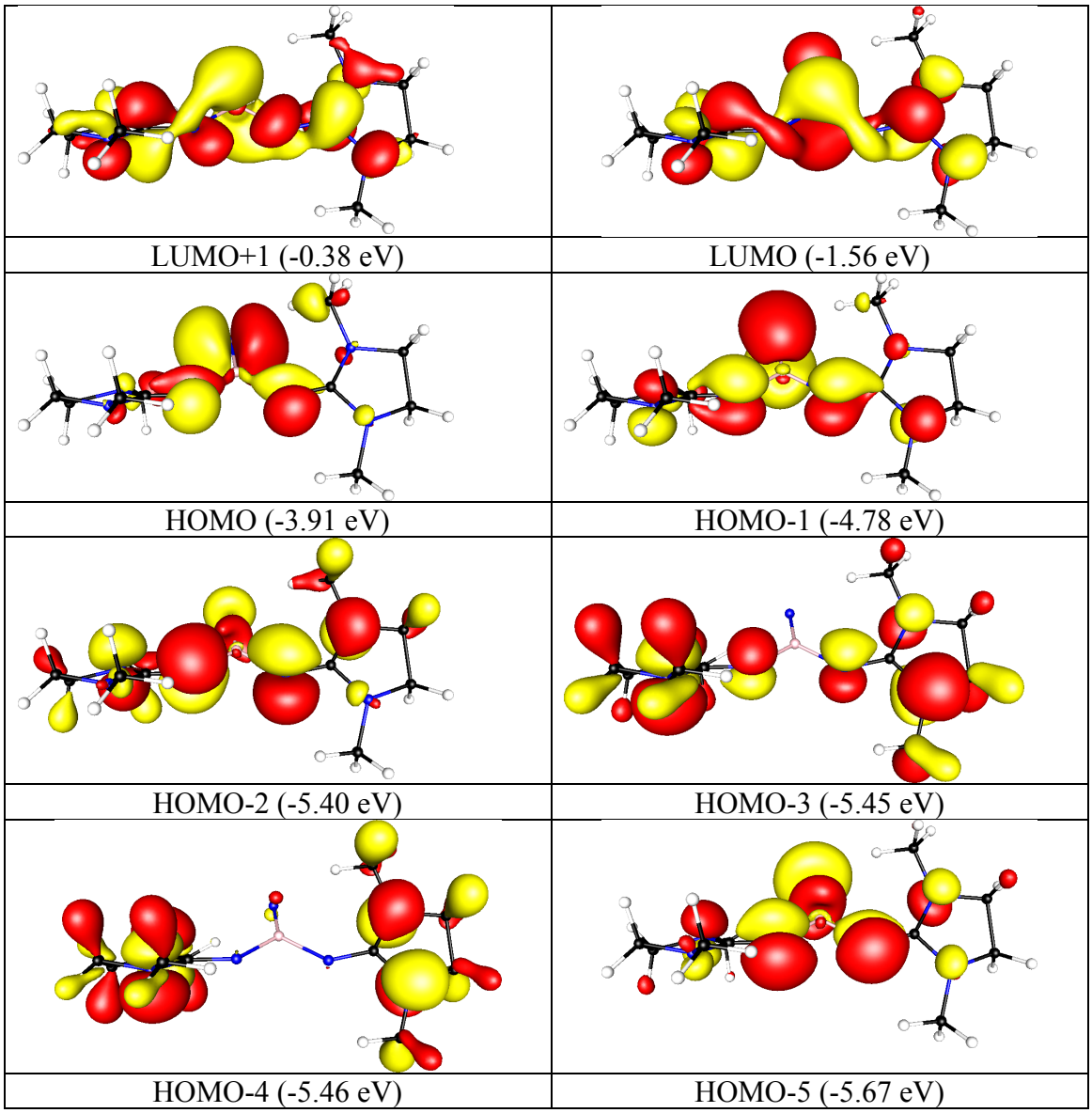


Figure 3.9: Plot of the two lowest lying unoccupied molecular orbitals (LUMO) and the six highest occupied molecular orbitals (HOMO) of the nitrene **9M'** which has N-methyl groups

Table 3.1: EDA-NOCV results in kcal/mol for **9M',** which has N-methyl groups (BP86/TZ2P+//M05-2X/TZVPP). Occupation of the fragments: N: doublet ($s^2p_\sigma^0p_{\pi\perp}^1p_{\pi\parallel}^2$); $P(N{=}NHC^{Me})_2$: doublet

ΔE_{int}	-171.9	
ΔE_{Pauli}	456.1	
ΔE_{elstat}	-154.6 (24.6%)	
ΔE_{orb}	-473.4 (75.4%)	
$\Delta E_{orb,\ \sigma}$	-248.1 (52.4%)	P→N donation
$\Delta E_{orb,\ \pi\parallel}$	-37.3 (8.0%)	P→N donation; N→P backdonation
$\Delta E_{orb,\ \pi\perp}$	-170.7 (36.1%)	N-P electron-sharing bond
$\Delta E_{orb,\ pol}$	-12.7 (2.7%)	Delocalization of nitrogen LPs
$\Delta E_{orb,\ rest}$	-4.6 (1.0%)	

Table 3.2: EDA-NOCV results in kcal/mol for **9M'**, which has N-methyl groups (BP86/TZ2P+//M05-2X/TZVPP). Occupation of the fragments: N^-: triplet ($s^2p_\sigma^1p_{\pi\perp}^1p_{\pi\parallel}^2$); $[P(N{=}NHC^{Me})_2]^-$: triplet

ΔE_{int}	-257.1	
ΔE_{Pauli}	554.4	
ΔE_{elstat}	-370.9 (45.7%)	
ΔE_{orb}	-440.6 (54.3%)	
$\Delta E_{orb,\ \sigma}$	-206.7 (46.9%)	N-P electron-sharing bond
$\Delta E_{orb,\ \pi\parallel}$	-48.5 (11.0%)	P→N donation; N→P backdonation
$\Delta E_{orb,\ \pi\perp}$	-146.5 (33.3%)	N-P electron-sharing bond
$\Delta E_{orb,\ pol}$	-26.7 (6.1%)	Delocalization of nitrogen LPs
$\Delta E_{orb,\ rest}$	-12.2 (2.8%)	

Table 3.3: Coordinates [Å] and energies [Hartrees] at M05-2X/def2-TZVPP of the calculated species **9M**

9M. E = -1885.08536091

P	0.000014	0.000055	0.717168
N	0.000030	0.000147	2.209159
N	-1.161215	0.540240	-0.305211
N	1.161239	-0.540226	-0.305169
N	-3.118453	1.781040	-0.633261
N	-1.515313	2.727911	0.580415
N	1.515311	-2.727876	0.580554
N	3.118443	-1.781074	-0.633191
C	-1.862095	1.596422	-0.110309
C	-3.712409	3.003940	-0.098333
H	-4.347710	2.762900	0.754979
H	-4.302395	3.520345	-0.847636
C	-2.480480	3.792603	0.326923
H	-2.119608	4.438292	-0.475803
H	-2.647797	4.389914	1.216850
C	1.862110	-1.596402	-0.110197
C	2.480462	-3.792587	0.327070
H	2.119577	-4.438284	-0.475646
H	2.647775	-4.389887	1.217005
C	3.712395	-3.003953	-0.098216
H	4.347701	-2.762883	0.755084
H	4.302374	-3.520392	-0.847503
C	-3.974348	0.708959	-0.989984
C	-4.026225	-0.460914	-0.242575
C	-4.933477	-1.448683	-0.590599
H	-4.976618	-2.353914	-0.004762
C	-5.789017	-1.277522	-1.668742
H	-6.495570	-2.050294	-1.928619
C	-5.732118	-0.107935	-2.410890
H	-6.388731	0.032407	-3.255423
C	-4.823445	0.881761	-2.074792
C	-0.157885	3.085457	0.813850
C	0.737786	3.145981	-0.244386
C	2.045054	3.543283	-0.010762
H	2.744742	3.579567	-0.830842
C	1.546725	3.817184	2.325008
H	1.865936	4.059702	3.326316
C	0.244349	3.408298	2.100010
C	0.157871	-3.085424	0.813934
C	-0.244455	-3.408113	2.100103
C	-1.546841	-3.816994	2.325048
H	-1.866128	-4.059387	3.326362
C	-2.447026	-3.886665	1.270639
H	-3.463736	-4.200837	1.452064
C	-2.044997	-3.543385	-0.010794
H	-2.744623	-3.579780	-0.830922
C	-0.737716	-3.146094	-0.244365
C	3.974349	-0.709018	-0.989971
C	4.823371	-0.881845	-2.074834
C	5.732060	0.107820	-2.410981
H	6.388616	-0.032536	-3.255555
C	5.789049	1.277399	-1.668826
H	6.495614	2.050148	-1.928742
C	4.933583	1.448584	-0.590627
H	4.976793	2.353810	-0.004787
C	4.026316	0.460846	-0.242556
C	2.446992	3.886711	1.270660
H	3.463692	4.200891	1.452125
H	-0.456815	3.292830	2.910864
H	0.415026	2.861342	-1.234578
H	-4.757456	1.789294	-2.655681
H	-3.360263	-0.595690	0.595235
H	-0.414882	-2.861568	-1.234566
H	0.456642	-3.292519	2.910996
H	3.360408	0.595638	0.595295
H	4.757312	-1.789372	-2.655722

Table 3.4: Coordinates [Å] and energies [Hartrees] at M05-2X/def2-TZVPP of the calculated species **9M'**

9M'. E = -1117.90151304

P	0.000007	-0.552570	-0.000035	C	4.756920	0.482433	0.511501
N	0.000018	-2.048222	0.000005	H	4.961106	-0.084899	1.424475
N	-1.252049	0.482907	-0.112846	H	5.532696	1.230511	0.377209
N	1.252044	0.482930	0.112770	C	3.090273	1.935163	1.680810
N	-3.441671	1.086171	-0.570114	H	2.071796	2.276971	1.540964
N	-3.180884	-0.743114	0.655428	H	3.160439	1.397300	2.629663
N	3.180891	-0.743146	-0.655360	H	3.763464	2.788033	1.706687
N	3.441660	1.086218	0.570071	C	2.613081	-1.501189	-1.752876
C	-2.517722	0.243892	-0.004307	H	3.338975	-2.256964	-2.039506
C	-4.756934	0.482398	-0.511474	H	1.698962	-1.988990	-1.427313
H	-4.961145	-0.084993	-1.424406	H	2.417185	-0.855674	-2.612116
H	-5.532702	1.230489	-0.377212	C	-3.090307	1.935044	-1.680915
C	-4.602993	-0.442826	0.687707	H	-3.763496	2.787915	-1.706831
H	-4.861244	0.070922	1.617799	H	-2.071826	2.276858	-1.541113
H	-5.192923	-1.350481	0.607071	H	-3.160496	1.397122	-2.629733
C	2.517720	0.243910	0.004289	C	-2.613059	-1.501089	1.752984
C	4.603003	-0.442870	-0.687623	H	-2.417145	-0.855519	2.612180
H	4.861280	0.070813	-1.617744	H	-3.338953	-2.256840	2.039676
H	5.192925	-1.350524	-0.606911	H	-1.698951	-1.988920	1.427438

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CONCLUSION

We have developed a new experimental method to assess the electronic properties of carbenes based on the ^{31}P NMR chemical shifts of carbene-phosphinidene adducts. Strongly π-accepting carbenes will form adducts that are best described as phosphaalkenes, and exhibit a low-field ^{31}P chemical shift, whereas weakly π-accepting carbenes form adducts with a strongly polarized carbene-phosphorus P-C bond, in which the phosphorus atom presents a significant negative charge, resulting in high-field ^{31}P chemical shifts. We also designed and applied a versatile and easy synthesis of such compounds involving free carbenes and dichlorophenylphosphine. This new probe is more spread out and sensitive than traditional probes relying on infrared spectroscopy. In addition, this new probe is insensitive to the influence of the σ-donating properties of carbenes. Consequently, the combination of this new metric with other methods that are indicative of the overall donating properties of carbenes, such as the Tolman Electronic Parameter, allows for the deconvolution of σ-donating and π-accepting properties. Finally, we propose that this concept could be extended to different ligands on the condition that additional computational information confirms the validity of the analogy. An overview of the different class of carbenes according to this new probe is provided in Figure C1.

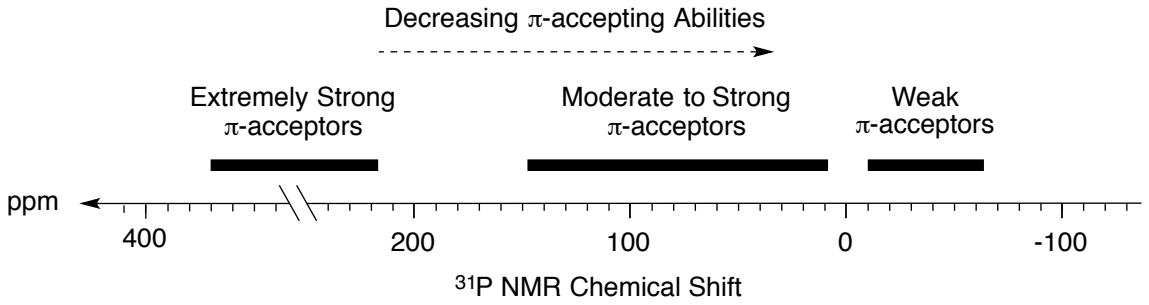

Figure C1: Different π-accepting properties of carbenes according to the ^{31}P NMR chemical shift of their respective carbene-phosphinidene adducts

With this new scale in mind, we attempted to extend the scope of known stable carbenes. We synthesized precursors of strongly electrophilic carbenes, of carbenes with remote electronic stabilization and of carbenes with potential use as organic reducing agents. Unfortunately, all attempts at generating these new carbenes failed to lead results. We proposed possible explanations to these results and potential routes to circumvent them. Some of these are currently under investigation in our group.

In the last part of this thesis, we applied our knowledge of carbene chemistry to their nitrogen analogs, namely nitrenes. More than two decades after the isolation a the first stable carbene, a phosphino carbene, and almost four decades after the first efforts towards stable nitrenes, we report the synthesis of a stable and crystalline representative of these long-sought targets, namely a phosphinonitrene. The bonding situation of this phosphinonitrene was studied by experimental and computational methods. We showed that this compound features a P-N bond with a significant multiple bond character. The isolation of this nitrene paved the path for the investigation of phosphinonitrenes properties as their reactivity and ability to act as a ligand in metal complexes was studied in subsequent efforts in our group.