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Constant, Samuel Claude; Lacour, Jérôme

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New Trends in Hexacoordinated Phosphorus Chemistry

Samuel Constant · Jerome Lacour (✉)

Département de Chimie Organique, Université de Geneve, Quai Ernest Ansermet 30,
 1211 Genève 4, Switzerland
jerome.lacour@chiorg.unige.ch

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Abstract Phosphorus derivatives with six substituents at the immediate periphery of the heteroatom are quite common, more than usually imagined, and this review presents some of the novel structures that have been reported in the last 5–10 years. Many derivatives of varied charge and geometry have been synthesized in studies devoted to phosphorus reactivity. A large number of compounds have also been prepared for applications in fields as varied as: (i) classical organic chemistry, (ii) stereoselective synthesis and analysis, (iii) bioorganic chemistry, (iv) electrochemistry, and (v) photochemistry. Selected examples of applied transformations, industrial and academic, have been selected to present a general overview of the new trends in P(VI) chemistry.

Keywords 6-Coordinate · Hypervalent · Octahedral · Chirality · Electrochemistry · Photochemistry

Abbreviations

BINOL	[1,1']Binaphthalenyl-2,2'-diol
BINPHAT	Bis(tetrachlorobenzenediolato)mono([1,1']binaphthalenyl-2,2'-diolato)-phosphate(v)
<i>o</i> -Chloranil	3,4,5,6-Tetrachloro-[1,2]benzoquinone
HYPHAT	Bis(tetrachlorobenzenediolato)mono(1,2-diarylethanediolato)phosphate(v)
LiHMDS	Lithium 1,1,1,3,3,3-hexamethyl-disilazane
TARPHAT	Bis(tetrachlorobenzenediolato)mono(dialkyl 2,3-di(hydroxybutanediolato)-phosphate(v)
TRISPHAT	Tris(tetrachlorobenzenediolato)phosphate(v)

1

Introduction

“Modern” hexacoordinated phosphorus chemistry essentially started in 1963 when Allcock and coworkers studied the reaction of phosphonitrilic chlorides with pyrocatechol and isolated the unexpected tris(benzenediolato)phosphate anion **1** (Fig. 1) which sees a central octahedral phosphorus bound to six oxygen atoms [1–4]. Since this discovery, and now for more than 40 years, chemists interested in organic, inorganic, physical, and applied chemistry have generated compounds based on hexacoordinated phosphorus and studied these many derivatives for a variety of applications. Earlier work was reviewed in 1972 by Hellwinkel [5] and more recent articles are those of Cavell [6] and Holmes [7,8]. Several manuscripts or book chapters have also been written on the topic giving a good – yet slightly outdated – overview of the field [9–12].

The purpose of this chapter will be to describe the structures that have been reported over the last few (5–10) years and detail the synthetic protocols used or developed to make them. The compounds have been classified according to their charge in three categories: anionic, neutral, and cationic. Care has been taken to demonstrate the importance of the relationship between penta- [P(V)]

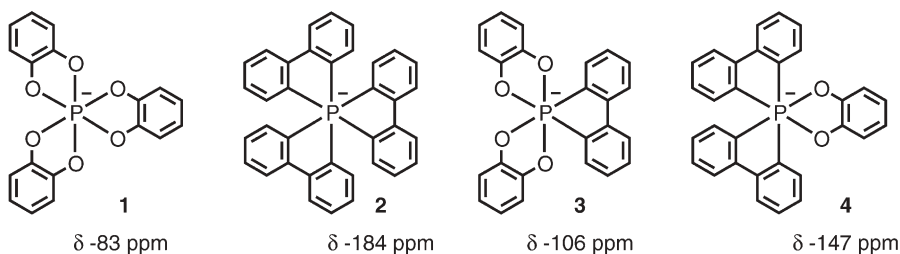


Fig. 1 Selection of “historical” hexacoordinated phosphate anions

and hexacoordinated [P(VI)] phosphorus as the later compounds can be often viewed as Lewis salts arising from a donor group interacting with a 5-coordinate phosphorus. Many of the compounds are chiral and efforts to obtain these derivatives in enantiomerically and/or diastereomerically pure forms has been noted. Then, in the second part, some of the recent uses of P(VI) adducts are detailed as the structural scaffold and reactivity of (pseudo-)octahedral phosphorus allows applications in fields as varied as: (i) classical organic chemistry, (ii) stereoselective synthesis and analysis, (iii) bioorganic chemistry, (iv) electrochemistry, and (v) photochemistry.

2 New Hexacoordinated Phosphorus Derivatives

2.1 Preamble

Hexacoordinated phosphorus centers are formally “hypervalent” and the nature of the bonding (sp^3d^2) in such phosphorus compounds has been debated in the literature, in particular with regards to the involvement of d orbitals [13]. These compounds can be designated as σ^6 , λ^6 in which σ corresponds to the coordination number and λ to the total number of bonds; this last parameter thus representing the valence of phosphorus. In general, hexacoordinated phosphorus adopts (i) an octahedral geometry (Oh) with six identical substituents positioned at same distance and at a 90° angle from each other or (ii) a pseudo-octahedral arrangement ($D4h$) with ligands in two axial and four equatorial positions, respectively. The main criterion for establishing the presence of P(VI) is the observance of lower frequency shifts in ^{31}P NMR relative to analogous P(V). When known, ^{31}P NMR chemical shifts (δ in ppm, usually negative) have been specified.

Chemical assemblies around hexacoordinated phosphorus atoms can be anionic, neutral or cationic depending upon the nature of the ligands. This is described in the following paragraphs.

2.2 Anionic P(VI) Derivatives

2.2.1 Introduction

The flagship of anionic P(VI) chemistry is of course the hexafluorophosphate anion PF_6^- , which is routinely used in all fields of chemistry as a “non-coordinating” counter-ion [14]. In his pioneering work of the 1970s Hellwinkel prepared several anionic phosphates, among which are compounds **1** to **4** (Fig. 1), by combining around an octahedral P atom (i) three benzenediolato ligands

(e.g., 1) [15, 16], (ii) three identical bidentate biphenylidene ligands (e.g., 2) [17–24] and (iii) combinations of the two types of chelating moieties (e.g., 3 and 4) [15]. Since then, the field has evolved towards the formation of more complex and/or more stable derivatives.

Figures 2, 3, 5, and 6 show anionic compounds 5 to 22 and 25 to 30, which have been described in the literature since 1997. In these adducts, as in examples 1 to 4, the P(VI) derivatives have carbon or oxygen atoms in the immediate proximity of the central (pseudo-)octahedral atom. This is probably due to the accessibility of the ligand precursors, the ease of their manipulation and, more importantly, to the sheer strength of the resulting P–C and P–O bonds. They all present tris(bidentate) structures in which the three chelating rings can be identical (Fig. 2 and most of Fig. 6) or of two different types (Fig. 3). The ligands can be monooxo (Fig. 6) or dioxo (Fig. 2 and Fig. 3). These differences in composition have, of course, consequences for the making of the derivatives,

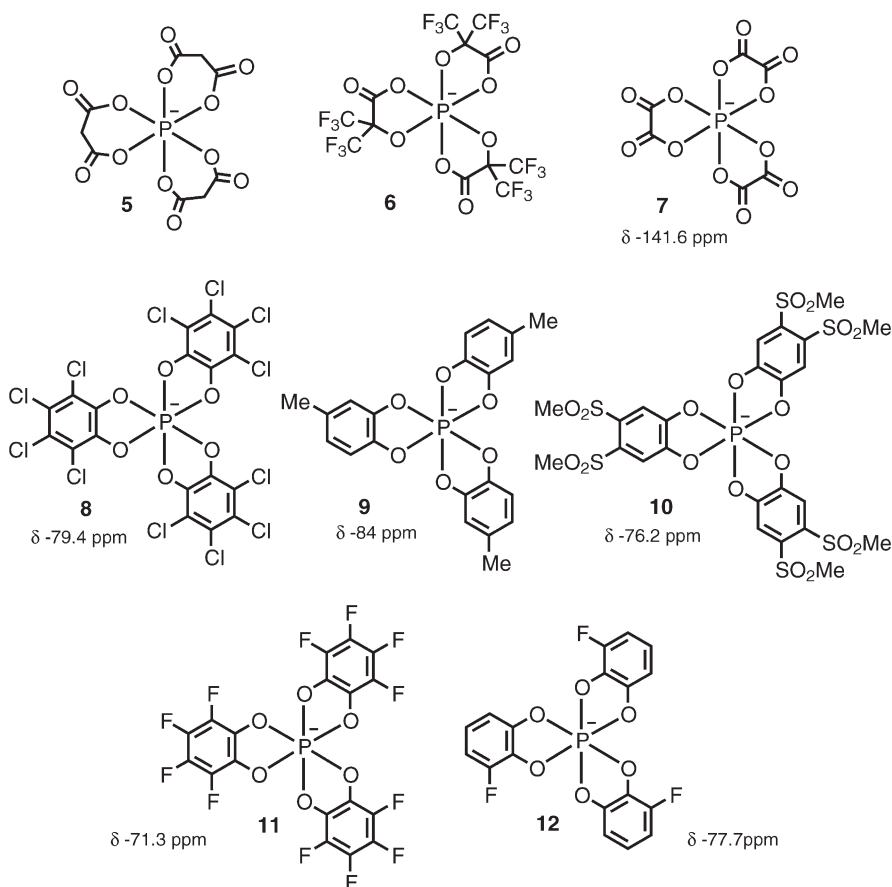


Fig. 2 Recently published anionic P(VI) derivatives of “P(aa)₃” type

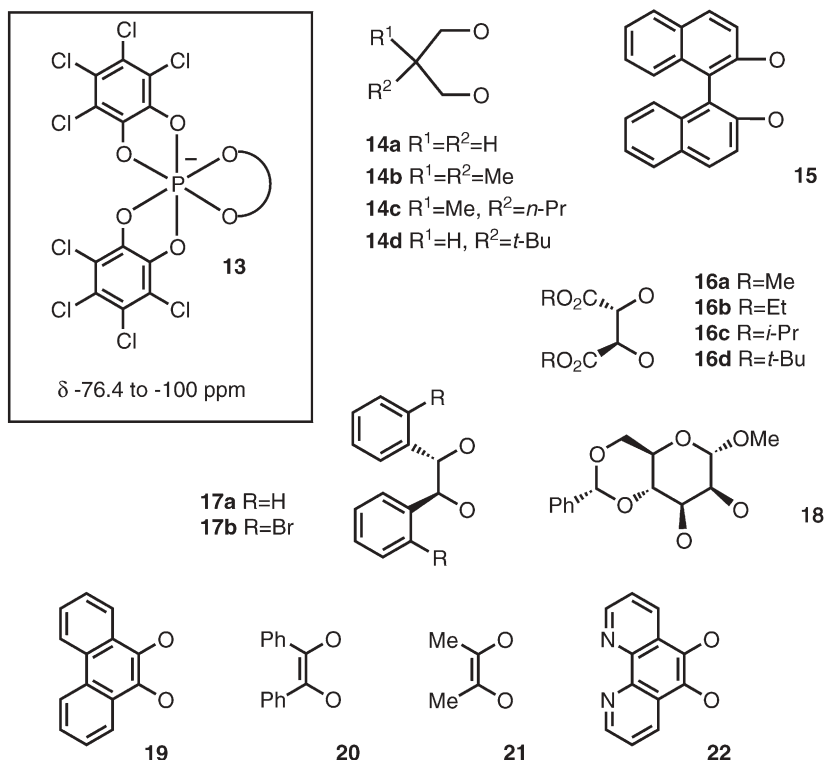


Fig. 3 Recently published anionic P(VI) derivatives of “P(aa)₂(bb)” type

as different synthetic strategies need to be used for their preparation in high yields and analytically pure form. These are detailed in the next section.

2.2.2

Synthesis

Most of the anionic compounds that have been reported contain six oxygen atoms at the periphery of the pseudo-octahedral phosphorus. Two different strategies have been used for the preparation of the moieties depending upon the homogeneous (three times the same chelate) or heterogeneous (two different types) distribution of the bidentate ligands.

When the three ligands are the same, procedures similar to the ones developed by Hellwinkel [16, 17], Koenig [25–28] and coworkers can be utilized – that is the one-time addition of three equivalents of bidentate ligands to PCl_5 to afford the hexacoordinated phosphate anions. Ligands as varied as malonic acid, 3,3,3-trifluoro-2-hydroxy-2-trifluoromethyl-propionic acid or oxalic acid have been used to form 5, 6, and 7, respectively [29]. Aromatic 1,2-diols are also particularly good ligands as tetrachloropyrocatechol [30, 31], 4-methylpyro-

catechol [32], 4,5-bis(methanesulfonyl)catechols [33], tetrafluorocatechol [34] and 3-fluoropyrocatechol [35] afford phosphates **8** (known as TRISPHAT), **9**, **10**, **11**, and **12**, respectively. The process can be easily driven to completion by the addition of a base to the medium (aliphatic amines, lithium salts, etc.). This last step is not always necessary as the phosphate anion is sometimes isolable as its Brønsted acid, as in the case of **7** [29, 36].

However, for the making of anionic phosphates containing different dioxo ligands around the phosphorus, as exemplified by the general structure **13** in Fig. 3, this synthetic protocol is not adapted as it leads to a random distribution of ligands around the phosphorus and to the usually unwanted formation of complex mixtures of products.

For instance, if 1 equivalent of three different bidentate symmetrical ligands are added to 1 equivalent of PCl_5 and 1 equivalent of a base, then a “library” of 10 compounds is likely to be generated. This is represented in Fig. 4, considering the theoretical case of three different ligands (aa), (bb) and (cc) (1:1:1 ratio) which react simultaneously with PCl_5 and subsequent derivatives. A statistical 1:1:1:3:3:3:3:3:6 repartition among 10 possible products is expected; the desired compound $[\text{P}(\text{aa})(\text{bb})(\text{cc})]$ being synthesized with a maximum 22% (6/27) theoretical yield.

To overcome this problem and obtain desired $[\text{P}(\text{aa})_2(\text{bb})]$ or $[\text{P}(\text{aa})(\text{bb})(\text{cc})]$ type products in high yields and to the exclusion of all others, it is necessary to consider a synthetic route that allows the sequential introduction of each of the three ligands in three different and orthogonal chemical steps. This is done by treating PX_3 derivatives ($\text{X}=\text{halogens}, \text{NR}_2, \text{OR}_f$) with diols to form monocyclic adducts, which are in turn oxidized to bicyclic spiroposphoranes using

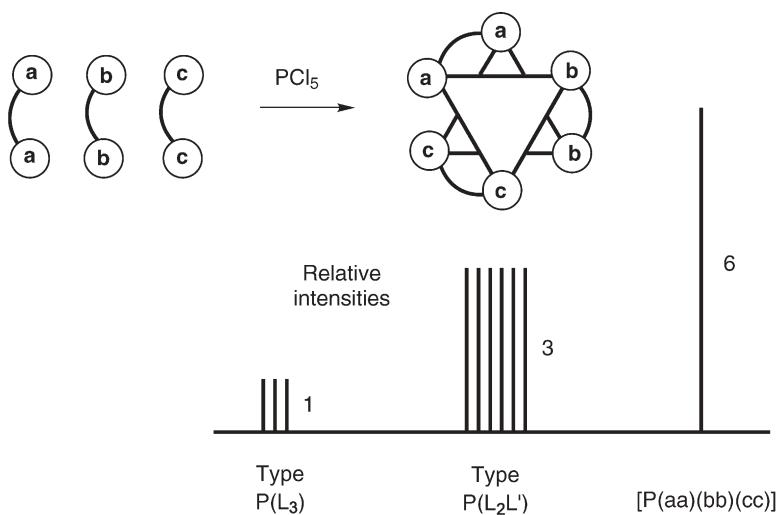
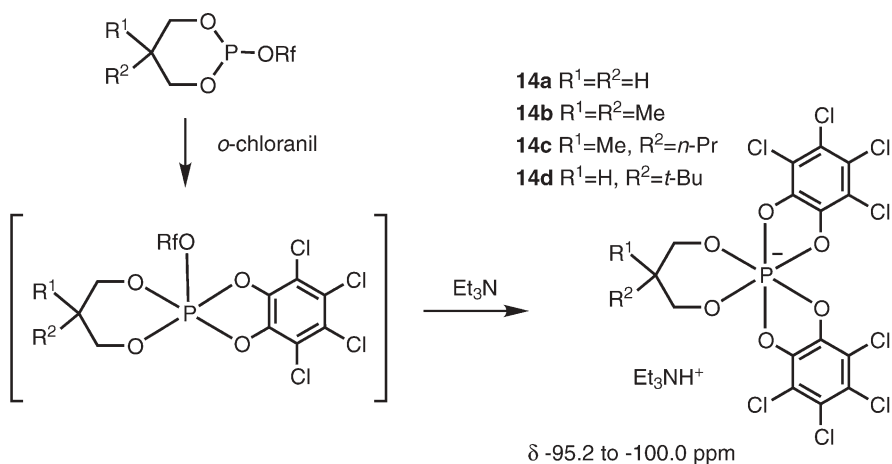


Fig. 4 Statistical distribution among possible hexacoordinated phosphates from the reaction of three different ligands (aa, bb and cc, 1:1:1 ratio) and PCl_5 . L, L'=(aa), or (bb), or (cc)

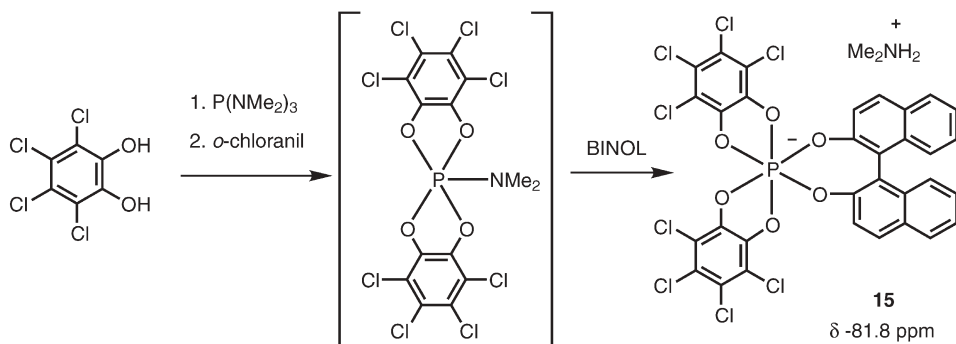
α -diketones or *ortho*-quinones as oxidants, and *o*-chloranil in particular. To carry out the final chelation step, it is sufficient to add a third diol ligand (ligand cc). After nucleophilic displacement of the last substituent X, chelation occurs, usually in the presence of a base, to form the final ring. If substituent X is itself a base – such as an amino group – then the two protons delivered by the last diol are directly scavenged in solution.

This type of process was performed in 2000 by Skowronska and coworkers when studying the formation of hexacoordinated phosphates of type **14** containing 1,3,2-dioxaphosphorinane rings [37]. The starting phosphorinane is substituted by a perfluorinated alcohol and subsequent treatment with *o*-chloranil and addition of tetrachlorocatechol and Et₃N afforded the desired triethylammonium phosphate salts **14** (Scheme 1). Careful monitoring in ³¹P NMR of the reaction medium after the addition of the oxidant allowed the researchers to detect many intermediates shedding light on reaction pathways.



Scheme 1 Synthesis of hexacoordinated phosphates **14** containing 1,3,2-dioxaphosphorinane rings

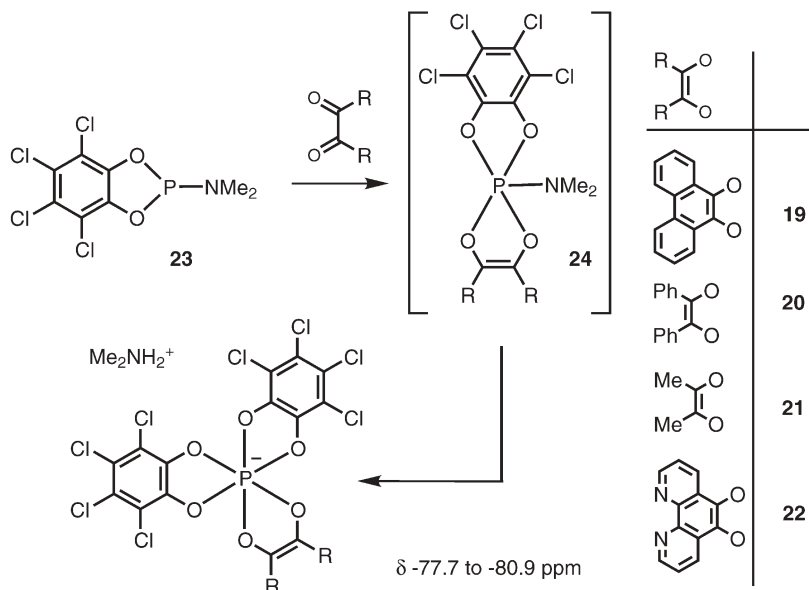
In 2000, Lacour and coworkers reported a similar one-pot three-step protocol to afford phosphate anion **15**, known as BINPHAT, containing a BINOL moiety along with two tetrachlorocatecholate ligands [38]. Starting from tris(dimethylamino)phosphine, subsequent additions of tetrachlorocatechol, *o*-chloranil and BINOL affords anion **15** in good yield and chemical purity (Scheme 2). This procedure was extended to aliphatic 1,2-diols such as tartrate esters, hydrobenzoin and mannose derivatives to afford the corresponding anions in modest to good yields (61–86%): **16a–16d** TARPAT (R=Me, Et, *i*-Pr, *t*-Bu) [39], **17a–17b** HYPHAT (R=H, Br) [40] and **18**, respectively [41] (Fig. 3). In all these examples, the chiral ligands were introduced in the last step in place of the BINOL moiety.



Scheme 2 Synthesis of BINPHAT anion **15** containing a BINOL ligand

Following a similar protocol, novel hexacoordinated phosphate anions **19** to **22** bearing two different dioxo ligands could be simply prepared as their dimethylammonium salts from the reaction of tetrachlorocatechol derived phosphoramidite **23** with a variety of symmetrical diones other than *o*-chloranil (α -diketones or *ortho*-quinones) and subsequent addition of tetrachlorocatechol to the corresponding phosphorane **24** (Scheme 3) [42].

Finally, two more anionic phosphate anions with six oxygen substituents at phosphorus (Fig. 5) were isolated by serendipity. Compound **25** [43] was isolated from the reaction of naphthalene-2,3-diol and phosphonitrilic chloride in



Scheme 3 Possible synthetic route to anionic P(VI) derivatives of “P(aa)₂(bb)” type

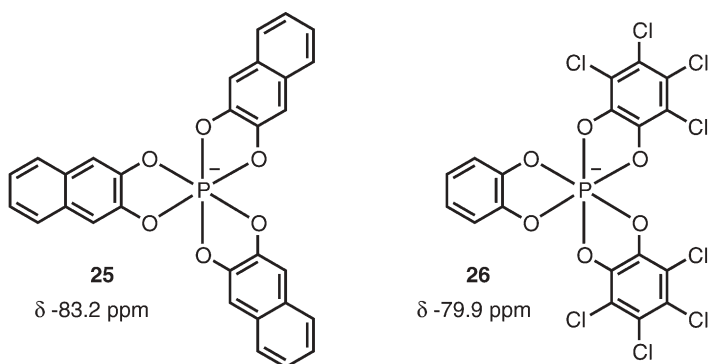


Fig. 5 Anionic hexacoordinated phosphates **25** and **26**

a process analogous to the one observed by Allcock [1]. Compound **26** was isolated as a decomposition product from the oxidation with *o*-chloranil of a bis(4,5-benzo-1,3-dioxo-2-phospholano)dichloromethane [44].

Other anionic phosphates **27a–27e**, **28**, **29**, and **30** (Fig. 6), which contain both P–C and P–O bonds, have been reported since 1997. In these cases, as shown by Akiba, Kawashima and Holmes, the synthetic strategy is slightly different as P–C bonds usually need to be formed prior to P–O ones.

The formation of **27a–27e**, **28**, and **29** makes use of a chemistry developed by Akiba and coworkers in the 1990s for the synthesis and applications of cyclic 10-P-5 phosphoranes made of two Martin ligands. Methyl, benzyl and phenylth-

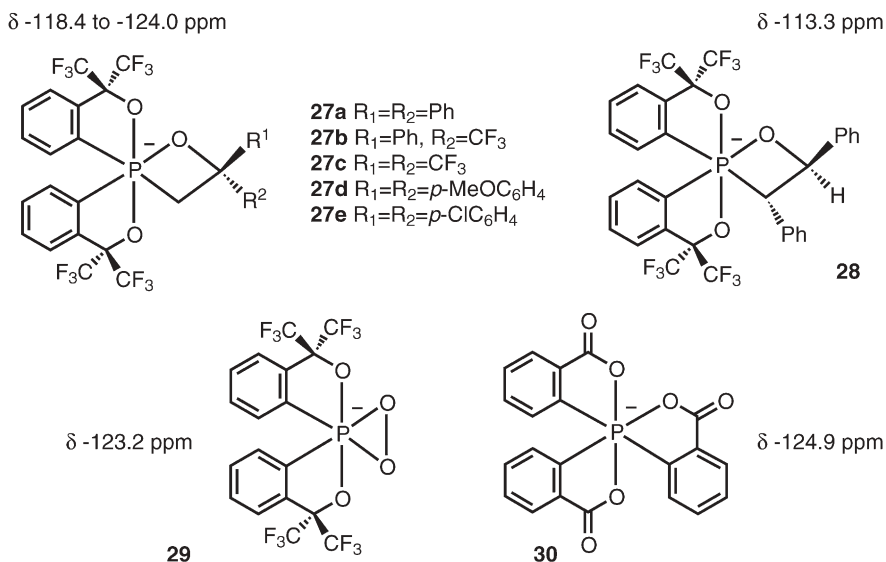
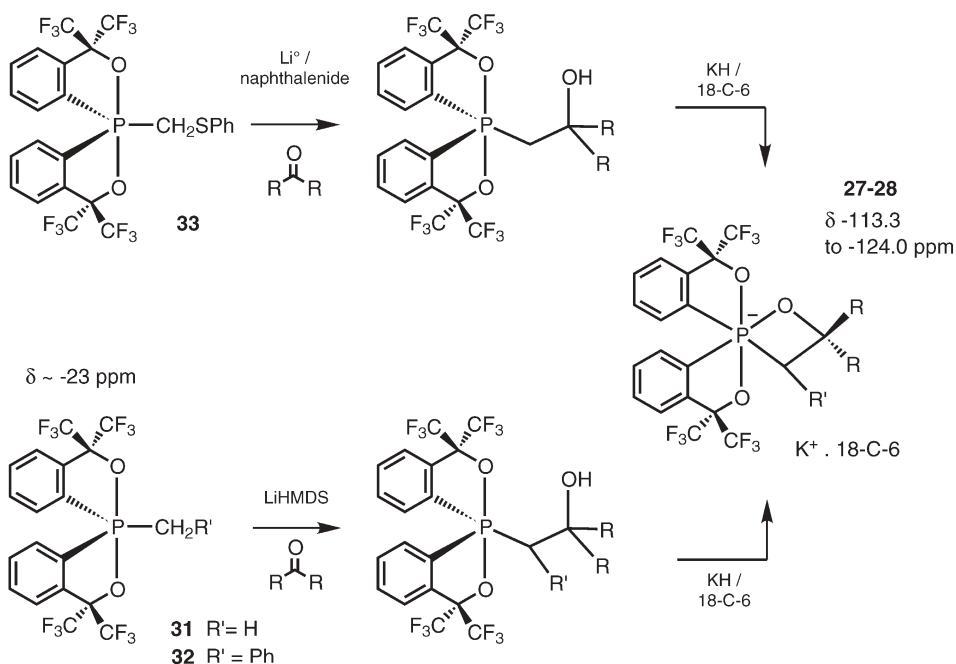


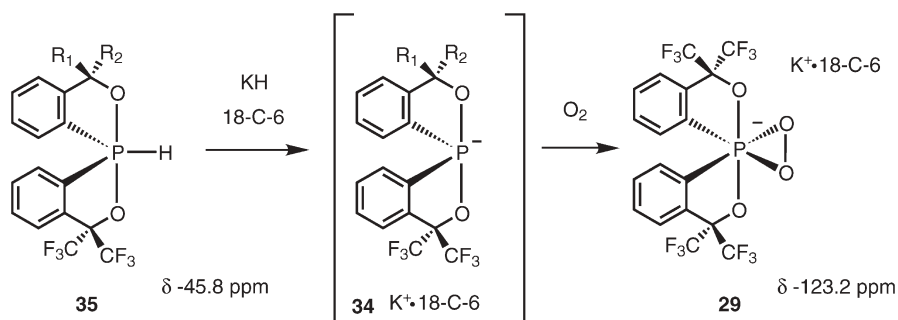
Fig. 6 Isolated anionic hexacoordinated phosphates containing both P–C and P–O bonds

iomethyl phosphoranes, **31**, **32**, and **33**, respectively (Scheme 4), were prepared and studied in the context of P(VI) chemistry. In the case of **33**, reduction of the carbon–sulfur bond in the presence of lithium naphthalenide generated a carbanion, which was reacted with ketones to form the corresponding P(V) β -hydroxyalkylphosphoranes [45]. Similarly, treatment of **31** and **32** with *n*-butyllithium, and quenching with aldehydes and ketones yielded analogous β -hydroxyphosphoranes [46, 47]. Then, reactions of the isolated P(V) alcohols with a combination of KH and 18-crown-6 afforded the hexacoordinated 2-oxaphosphetanides **27a–27e** and **28** in moderate yields (39–49%). It is interesting to note that the lithium salts of the β -hydroxyalkylphosphorane precursors do not undergo cyclization reactions to form P(VI) oxaphosphetanides. These compounds are quite kinetically stable and only the more reactive “naked” potassium salts can form stable hexacoordinated phosphates.



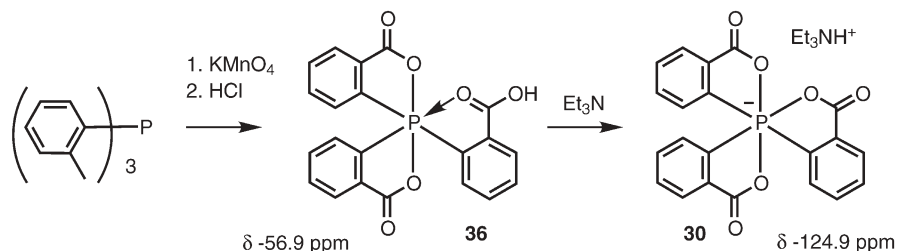
Scheme 4 Synthesis of anionic oxaphosphetanides **27–28**

Akiba and coworkers reported a new type of anionic hexacoordinated phosphorus derivative exemplified by compound **29** bearing a stable three-membered dioxaphosphirane ring [48]. Phosphoranide **34**, generated from P-H phosphorane **35** with KH in the presence of 18-crown-6, was exposed to dioxygen to give crystalline **29** (50%). Phosphate **29** was found to be quite stable as a solid to ordinary room light as well as to the air at ambient temperature for several months (Scheme 5).



Scheme 5 Synthesis of hexacoordinated phosphate **29** containing a dioxaphosphirane ring

Finally, in the case of **30** made by Holmes and coworkers, the starting material was tris(*o*-tolyl)phosphine, which was treated sequentially with potassium permanganate and HCl to generate phosphorane **36**, which was then treated with triethylamine to yield the desired phosphate **30** in 64% yield as its Et_3NH^+ salt [49, 50] (Scheme 6).



Scheme 6 Synthesis of hexacoordinated phosphate **30**

2.3

Neutral P(VI) Derivatives

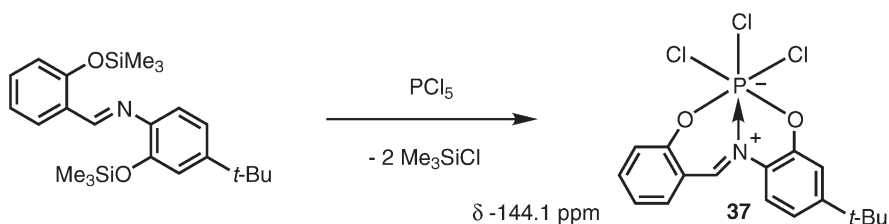
As previously mentioned, the interaction between Lewis acidic 5-coordinate phosphorus centers and a Lewis base donor atom is a simple route to a 6-coordinate phosphorus centers and, if the donor atom is neutral (usually a nitrogen, sulfur or oxygen atom), then the appearance of a positive charge on that atom upon coordination upsets the negative character of the pseudo-octahedral phosphorus and yields a compound with a global charge neutrality. This field of phosphorus chemistry was extensively reviewed, most recently by Cavell and Holmes [6–8], and only novel structures since 1996 are detailed. A different approach to the generation of neutral P(VI) adducts consists in the generation of dinuclear zwitterionic $\lambda^4\text{P}^{(+)}\lambda^6\text{P}^{(-)}$ species. This chemistry will also be presented.

2.3.1

Via P–N Interaction

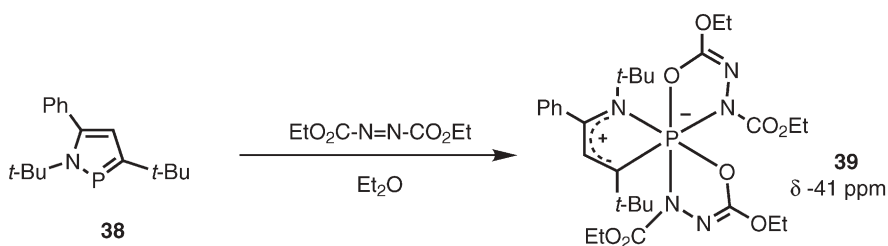
As mentioned, stabilization of neutral hexacoordinated phosphorus via nitrogen donation is possible and this topic has been widely studied in the past few years. As P–N bonds are weaker and longer than those of P–C and P–O, chemists have essentially relied on chelation to enforce their formation. Most structures involve five- and six-membered chelating rings and the compounds that have been reported are described in Schemes 7, 8, and 9 and Figs. 7 and 8.

In 1996, Cavell described the synthesis of neutral P(VI) compound **37** containing a divalent tridentate diphenol imine ligand and three chlorine atoms by the reaction of a bis silylated Schiff base with PCl_5 to give **37** after elimination of two equivalents of Me_3SiCl (Scheme 7) [51].



Scheme 7 Synthesis of neutral P(VI) derivative **37**

Regitz has shown that the reaction of azaphosphole **38** with two equivalents of DEAD furnishes the zwitterionic 2:1 adduct **39** (Scheme 8) [52]. The extreme low frequency shift of the ^{31}P NMR signal by more than 220 ppm in comparison to that of the azaphosphole confirms the formation of a betaine possessing a hexacoordinated phosphorus atom.



Scheme 8 Synthesis of neutral P(VI) betaine **39**

Octaethyl and tris(pentafluorophenyl) corroles, known as oec and tpfc, respectively, are also efficient for the stabilization of P(VI) phosphorus [53, 54]. The electron-rich oec reacts with PCl_3 to form $(\text{oec})\text{P}=\text{O}$ **40** that can be further derived into dihydrido **41a**, dimethyl **41b** and diphenyl **41c** compounds by reduction with LiAlH_4 and reactions with methyl and phenyl Grignard reagents,

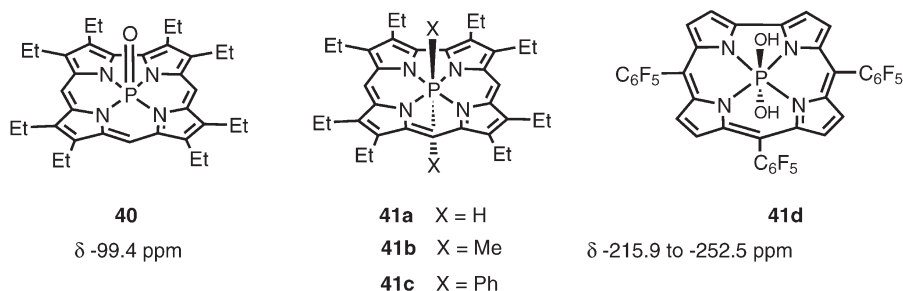
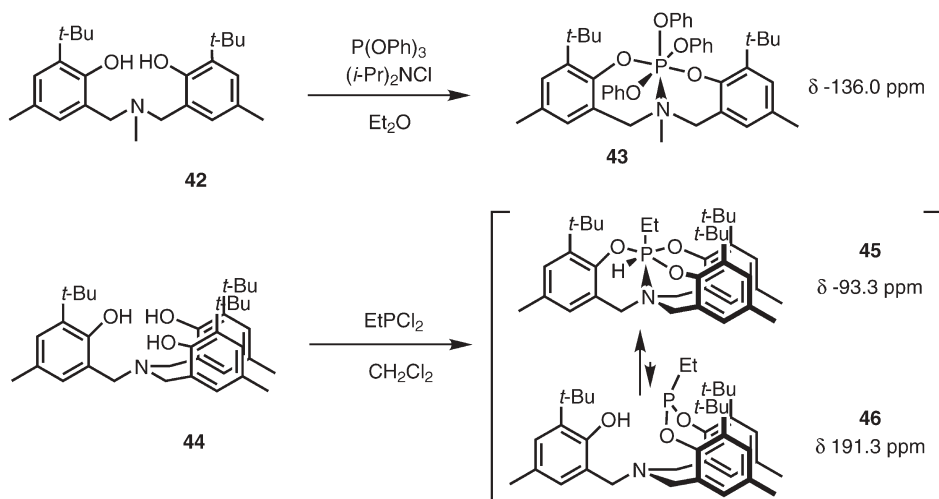


Fig. 7 Corrole-derived neutral P(VI) derivatives **41**

respectively. On the other hand, electron-poor tpfc does not react with PCl_3 but with POCl_3 to directly form the bis(hydroxo) coordinated adduct **41d**.

Most of the work published before 1996 by Holmes and coworkers has concentrated on rigid cyclic systems that exhibited little flexibility, thus strongly fixing the coordination geometry around the phosphorus. By way of contrast, the group of Amherst has recently utilized more flexible ring systems containing a nitrogen donor group, which allows different kinds of geometries and ring conformations. Treatment of nitrogen-containing diphenol **42** with $\text{P}(\text{OPh})_3$, in the presence of *N*-chlorodiisopropylamine, resulted in an oxidative addition to give a pentaoxyphosphorane with a definite P–N coordination (**43**, Scheme 9) [55]. Interestingly, reaction of analogous nitrogen-containing triphenol **44** with EtPCl_2 leads to the formation of a hexacoordinated phosphorane-phosphatane system **45**; a species that exists in solution in equilibrium with its phosphonite form **46**. This is the first example of a direct conversion of 3-coordinate to 6-coordinate phosphorus [56].



Scheme 9 Synthesis of adducts **43** and **45** and equilibrium between P(V) **45** and P(III) **46**

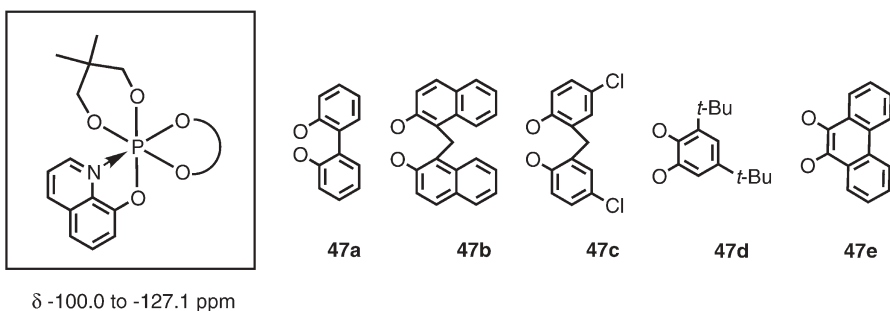


Fig. 8 Some tricyclic neutral hexacoordinated phosphorus derivatives with P–N donations

Finally, new tricyclic hexacoordinated phosphoranes with internal P–N coordination were synthesized by Swamy and coworkers by oxidative addition of cyclic phosphite precursors with quinones or with a combination of diols and (*i*-Pr)₂NCl [57, 58]. Various ring sizes from five to eight membered were obtained showing the generality of the approach. A selection of compounds (47a–47e) is presented in Fig. 8.

2.3.2

Via P–S or P–O–S Interactions

Since 1996, Holmes and coworkers have investigated further the formation of hexacoordinated phosphorus derivatives by virtue of sulfur donation [59–64].

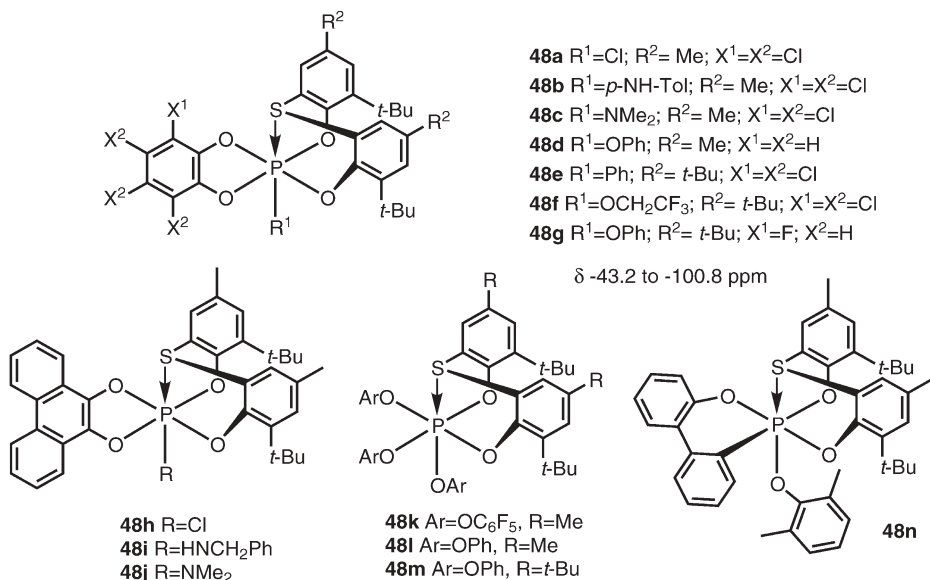
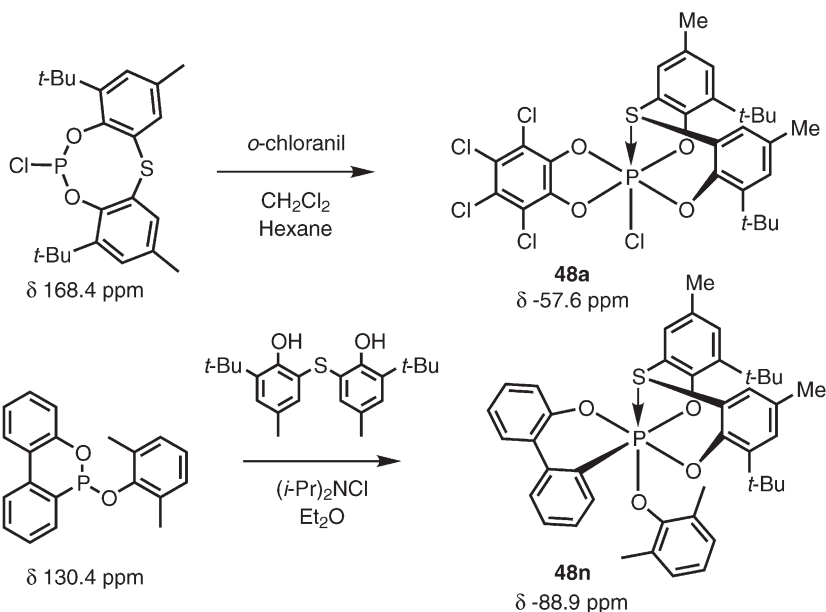


Fig. 9 Tricyclic neutral hexacoordinated phosphorus derivatives (48a–48n) with P–S donation

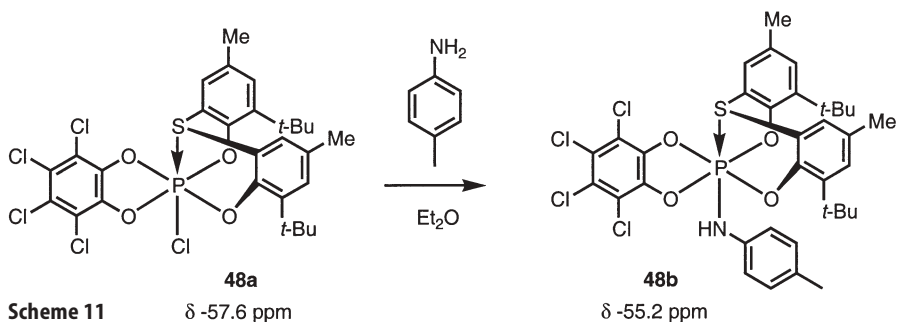
Series of pentaoxyphosphoranes containing a sulfur atom as part of a tricyclic ring have been characterized (**48a–48n**). They are reported in Fig. 9.

X-ray crystallographic analyses of the structures show that the P–S bond distance vary over one-half of an Angstrom (2.36–2.88 Å). The derivatives were generated using procedures similar to those utilized to form pentaoxyphosphoranes with P–N bonds, that is (i) the oxidation of sulfur containing cyclic chlorophosphines with a quinone or (ii) treatment of phosphites with the sulfur-containing diol in presence of *N*-chlorodiisopropylamine. Two typical examples of these synthetic protocols are shown in Scheme 10.



Scheme 10 Principal synthetic routes to compounds **48**

The stability of the resulting P(VI) is emphasized by displacement coordinate experiment as shown in Scheme 11 [59].



Scheme 11

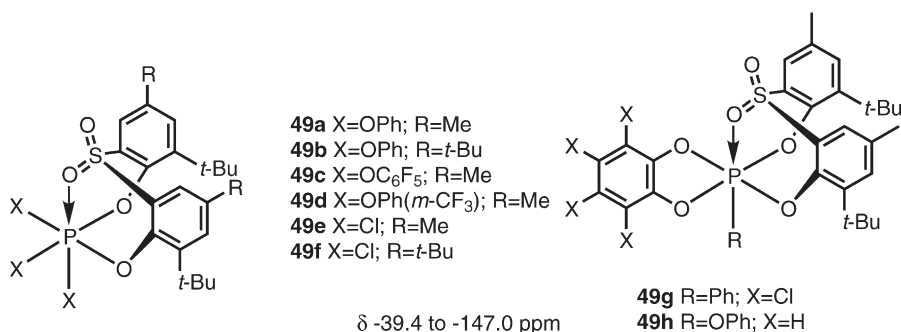


Fig. 10 Tricyclic neutral hexacoordinated phosphorus derivatives with P–O donations

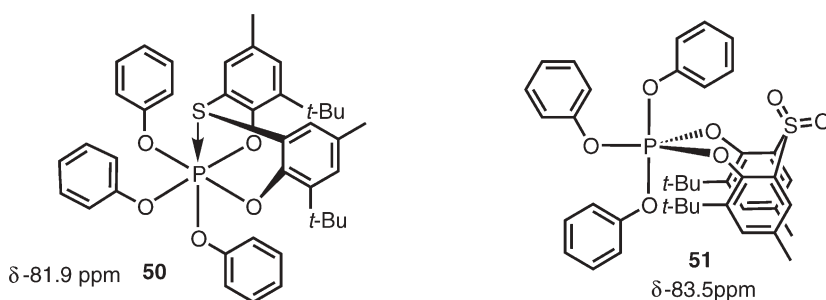


Fig. 11 Neutral hexacoordinated phosphorus derivatives **50** and **51**

If the sulfur atom is oxidized to a sulfonyl moiety, then oxygen donation occurs to the phosphorus as observed in compounds **49a–49h** (Fig. 10) [61, 64–66]. In most examples, the existence of an equilibrium between penta- and hexacoordinated phosphorus was demonstrated in solution. Introduction of electron withdrawing substituents on the ligands around the phosphorus increase its Lewis acidity and consequently enhance the proportion of P(VI) over P(V).

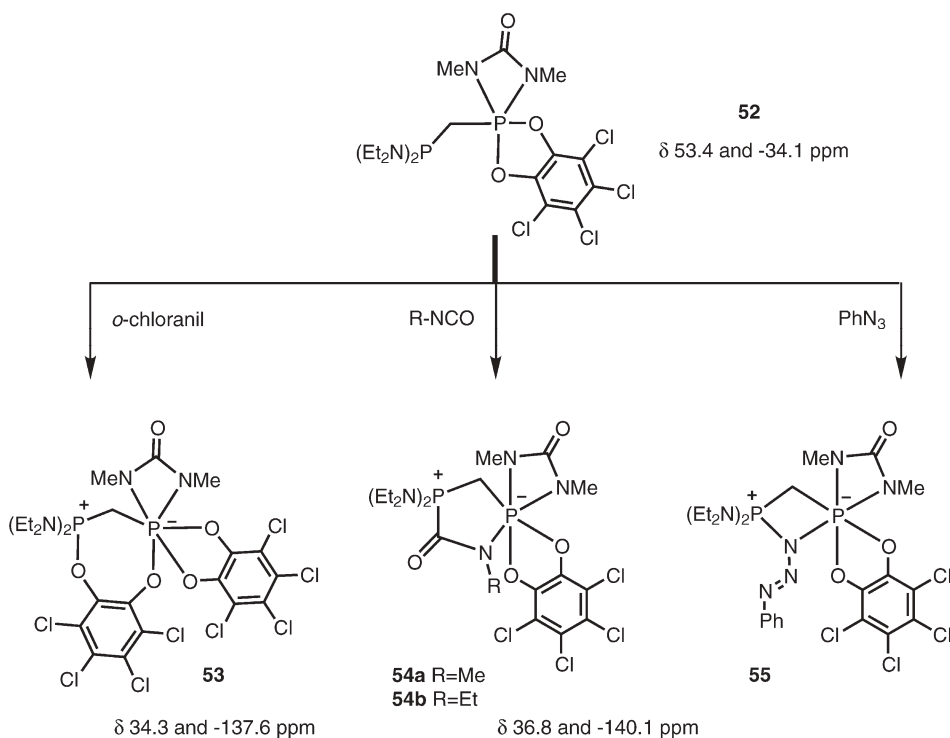
Furthermore, it was determined that sulfur is a stronger coordinating atom than the oxygen of a sulfonyl group. This was established by noting that sulfur coordinates to give phosphorus when the sulfonyl usually does not. This is the case for compounds **50** and **51** (Fig. 11) [64].

2.3.3

Zwitterionic $\lambda^4\text{P}^{(+)}, \lambda^6\text{P}^{(-)}$ Compounds

Zwitterionic heterocyclic compounds with two phosphorus atoms of opposite charge and different coordination were a rarity 10 years ago. This field has emerged recently with the reports of a variety of new structures as shown in Schemes 12, 13, and 14. Schevchenko and Schmutzler described a compound of

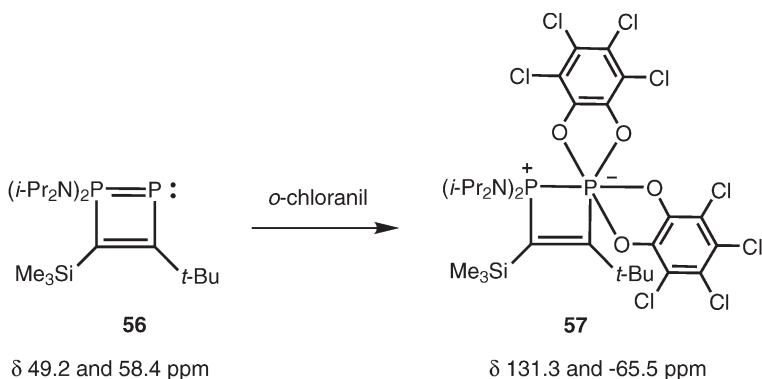
this type in 1993, formed by reaction of methylenephosphinophosphorane **52**, containing a diethylaminophosphine linked to a spiroposphorane via a methylene group, with *o*-chloranil to form the zwitterionic adduct **53** (Scheme 12) [67]. Later, Schevchenko extended the protocol to the reaction of **52** with isocyanates to give 5-membered heterocycles **54a** and **54b** (R=Me and Et, respectively) [68]. In 1999, he and Grützmacher further demonstrated the reactivity of **52** with azides [69]. The organic azide moiety undergoes a Staudinger reaction with the P(III) atom and the distal nitrogen then takes a bridging position between the two phosphorus atoms to give **55**.



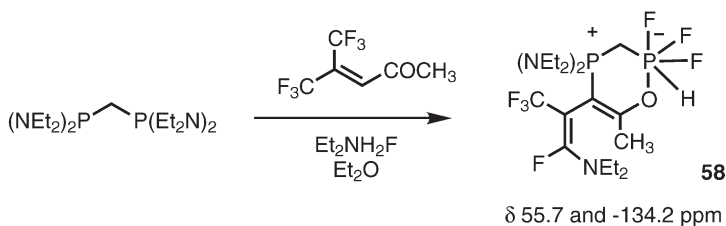
Scheme 12 Synthesis of zwitterionic $\lambda^4\text{P}^{(+)}, \lambda^6\text{P}^{(-)}$ compounds **53**, **54** and **55**

Studying the reactivity of $1\sigma^4, 2\sigma^2$ -diphosphete **56** with *o*-chloranil, Bertrand and coworkers reported the synthesis of zwitterionic **57** in which the two phosphorus atoms are directly linked by a σ bond (Scheme 13). Structural details of **57** were further obtained through a X-ray crystallographic analysis [70].

Finally, Schevchenko and Rosenthaler reported a new type of zwitterionic $\lambda^4\text{P}^{(+)}, \lambda^6\text{P}^{(-)}$ compound through the reaction of a methylenediphosphine with an electron-poor enone giving rise to **58** in the presence of a small amount of $\text{Et}_2\text{NH}_2\text{F}$ [71].



Scheme 13 Synthesis of zwitterionic $\lambda^4\text{P}^{(+)}, \lambda^6\text{P}^{(-)}$ compound **57**



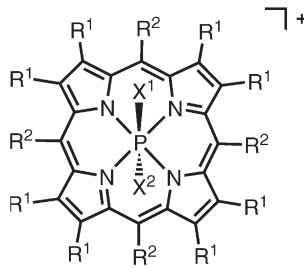
Scheme 14 Synthesis of zwitterionic $\lambda^4\text{P}^{(+)}, \lambda^6\text{P}^{(-)}$ compound **58**

2.4

Cationic P(VI) Derivatives

Four types of cationic hexacoordinated phosphorus compounds have been recently reported and their structures are shown in Figs. 12, 13, and 14 and Scheme 15. In the last 10 years, a large number of substituted porphyrins (**59**) have been described with hexacoordinated phosphorus atoms in the center of the tetracoordinate ligands (Fig. 12) [72–97]. As for the neutral octaethyl corroles, most of these compounds can be prepared by the reaction of the hemes with phosphorus(III) precursors such as PCl_3 or RPCl_2 . The mechanism of the oxidation of the phosphorus(III) to the phosphorus(v) porphyrin is not clear. Peripheral tuning of properties can be achieved through the synthesis of variously substituted porphyrins. Furthermore, due to the high chemical stability of the porphyrinatophosphorus derivatives, “axial” substitutions of labile substituents (e.g., Cl, OH) are conveniently realized and proceed in moderate to good yield. This brings a nice structural diversity, as shown in Fig. 12.

Hexacoordinated phosphorus compounds derived from phthalocyanines have been similarly prepared. Hanack investigated the reaction of metal-free phthalocyanines with POBr_3 or POCl_3 in presence of pyridine [98]. The corresponding dihydroxyphosphorus phthalocyanine hydroxides **60** were characterized.

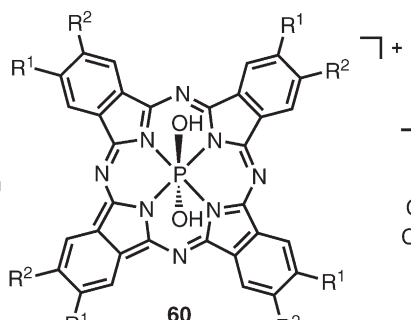


59

δ -159.5 to -229.2 ppm

R ¹	R ²	X ¹	X ²
Et	H	Me	OMe
Et	H	Et	O <i>i</i> Pr
Et	H	Et	OSecBu
Et	H	Et	NEt ₂
Et	H	Et	NHBu
Et	H	Ph	OMe
Et	H	Ph	OEt
Et	H	Ph	OnPr
Et	H	Ph	O <i>i</i> Pr
Et	H	Me	Cl
Et	H	Et	Cl
Et	H	Ph	Cl
Et	H	Me	OH
Et	H	Et	OH
Et	H	Ph	OH
Et	H	Me	F
Et	H	Et	F
Et	H	Ph	F
Et	Ph	Me	OH
Et	Ph	Me	Me
Et	Ph	Me	F
Et	H	Me	OOH
Et	H	Et	OOH
Et	H	Ph	OOH
H	Tol	OH	Tol
H	Tol	OAr	OAr
H	(<i>p</i> -CO ₂ H)Ph	OC ₂ H ₄ OH	OC ₂ H ₄ OH
H	Ph	OPyrene	OPyrene
H	Ph	OC ₂ H ₄ SH	OC ₂ H ₄ SH

Fig. 12 List of some recent cationic phosphorus porphyrins of type 59



60

δ -166 ppm

R ¹	R ²
H	H
H	<i>t</i> -Bu
C ₃ H ₇	C ₃ H ₇
C ₅ H ₁₁	C ₅ H ₁₁

Fig. 13 List of some recent cationic phosphorus phthalocyanines of type 60

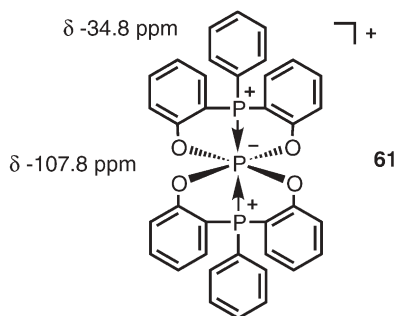
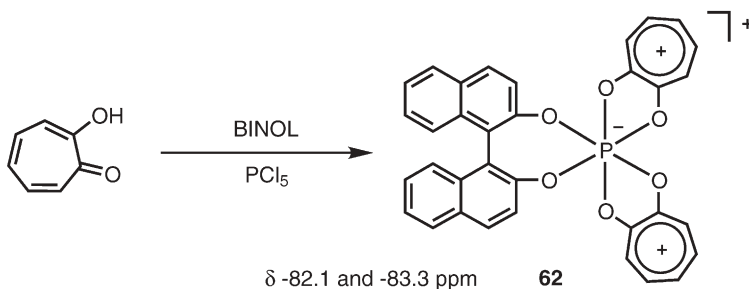


Fig. 14 Cationic P(VI) compound **61** with two axial P^{III}–P^V bonds

Many types of phosphorus–phosphorus bonds are known, but it is rare to find such bonds in hexacoordinated phosphorus compounds (with the exception of **57**). Cavell reported in 1998 the reaction of PCl₅ with phenylbis(*o*-(trimethylsiloxy)phenyl)phosphane, yielding the corresponding bischelate **61** in decent yield (52%) [99]. The octahedral nature of the central phosphorus atom was unambiguously determined by X-ray structural analysis. Two “short” axial P^{III}–P^V bonds (2.202 Å) lie perpendicular to the pseudo-octahedral equatorial plane.

Finally, Lacour and coworkers reported the synthesis of hexacoordinated phosphorus cation **62** [100]. Tropolone, BINOL and PCl₅ react in CH₂Cl₂ at reflux to generate in one step a novel hexacoordinated phosphorus cation.



Scheme 15 One-step synthesis of BINOL-containing P(VI) cation **62**

2.5

Chirality and Isomerism

2.5.1

Preamble

Chirality is an important part of today's chemistry and, in this respect, the pseudo-octahedral geometry of hexacoordinated phosphorus derivatives is interesting as it suffices to coordinate to the central atom three identical sym-

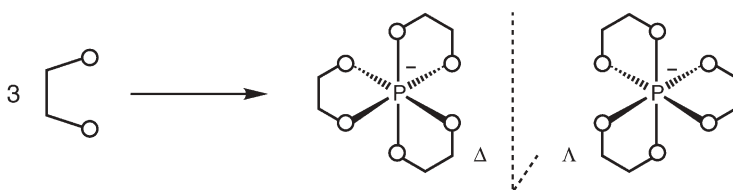


Fig. 15 Enantiomeric Δ and Λ hexacoordinated phosphates of “P(aa)₃” type

metric bidentate ligands to form chiral D_3 -symmetric helical molecules of type P(aa)₃ [101]. Such compounds exist either as Λ (*M*) or Δ (*P*) enantiomers of left- and right-handed propeller shape, respectively (Fig. 15) [102]. Many of the compounds described in Sect. 2.2 belong to this group of molecules (e.g., 5, 7 and 11). To the exception of a few (see below in Sect. 2.5.2), they have been reported only in racemic form (1:1 mixture of enantiomers).

Coordination to the central P atom of two different types of symmetrical bidentate ligands leads to structures of type P(aa)₂(bb), which are this time C_2 -symmetric as detailed in Fig. 16. The same chiral descriptors Λ and Δ apply to these compounds. Derivatives like 3, 4, 14–17 and 19–22 fit this description and have only been reported in racemic form so far. If the ligand bb is itself chiral, then diastereomers are generated. This will be described in the next section.

The presence of substituents on the bidentate ligands often degenerate their local C_2 -symmetry and, as a consequence, further isomerism occurs. This results in trisbidentate derivatives of type P(ab)₃ in the presence of facial or meridional isomers, as depicted in Fig. 17 [102]. Usually, the meridional isomer is preferred over the facial and a statistical 3:1 ratio is observed. Compounds 6, 9, 12 and 30

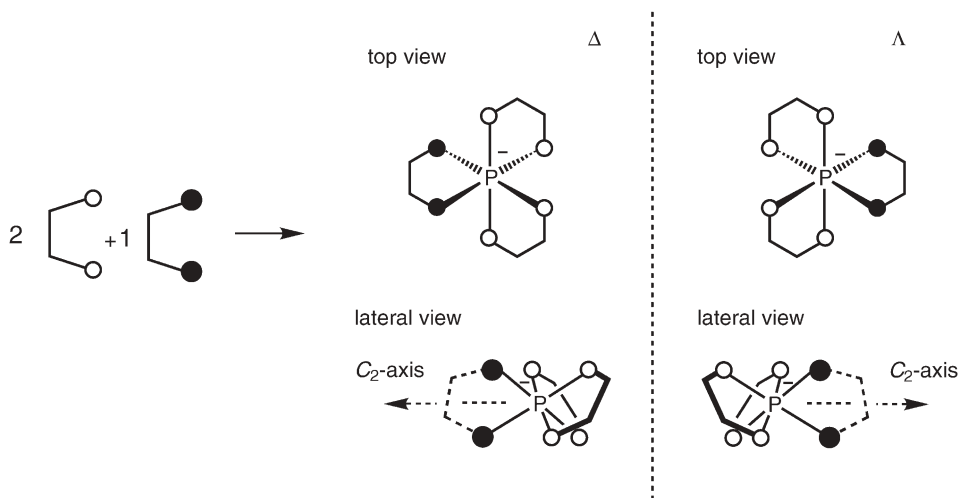


Fig. 16 Enantiomeric Δ and Λ hexacoordinated phosphates of “P(aa)₂(bb)” type

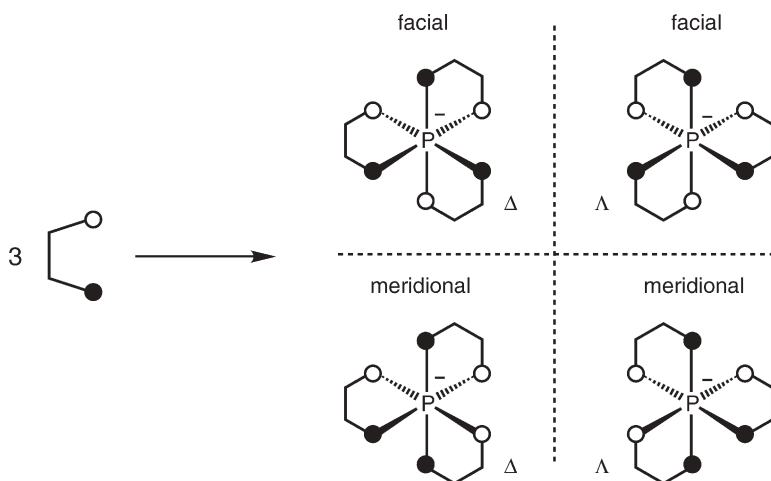


Fig. 17 Enantiomeric (Δ , Δ) and diastereomeric (meridional, facial) hexacoordinated phosphates of “P(ab)₃” type

belong to this group. To our knowledge, the question of their stereochemical integrity has not been studied. For **30**, Holmes and coworkers only report the formation of the meridional isomer (isolated after a crystallization). No mention was made of the presence of the facial derivative.

Finally, the lower symmetry of compounds **27** and **28**, of type P(ab)₂(cd), and **29**, of type P(ab)₂(cc), could have lead to the formation of many (racemic) diastereomers. Interestingly, this is not the case as the configuration of the 10-P-5 phosphorane precursors is translated integrally to the P(VI) derivatives, as shown by Akiba and Kawashima [45–48]. Further manifestation of this phenomenon will be described in Sect. 3.1. A particularly striking example is the exclusive formation of **29** over **29'** and **29''** (Fig. 18) [48].

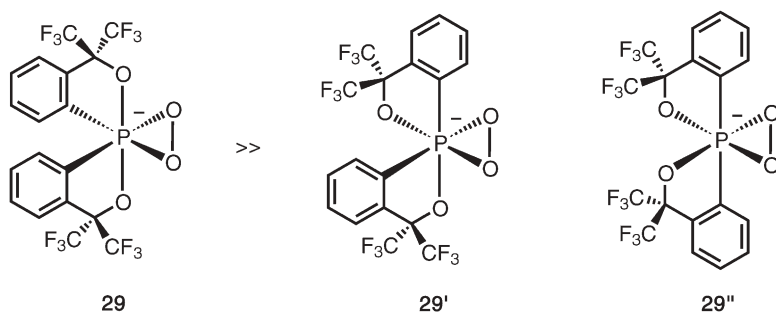


Fig. 18 Diastereomeric phosphates **29**, **29'** and **29''**

2.5.2

Enantiopure (Diastereomerically Enriched) Phosphates

Most of the phosphorus compounds described in the previous sections are chiral *and* racemic. Attempting their resolution – that is a physical separation of the enantiomers – was obviously attractive and this was realized as early as 1965 by Hellwinkel, who obtained both optical antipodes of **2** [18]. A patent on the synthesis and possible applications of enantiopure phosphate **2** was even filed at the time [103].

Tris(benzenediolato)phosphate anion **1**, of particular interest for its simple preparation from pyrocatechol, PCl_5 and an amine, is unfortunately configurationally labile in solution as an ammonium salt. Mechanistic studies by Koenig and coworkers have shown that the racemization of **1** is acid-catalyzed and proposed an intramolecular one-ended dissociation mechanism to explain it [25–28]. In 1997, Lacour and coworkers demonstrated that the introduction of electron-withdrawing chlorine atoms on the aromatic nuclei of the catecholate ligands increases the configurational (and chemical) stability of the resulting tris(tetrachlorobenzenediolato)phosphate(V) derivative (Fig. 19). This D_3 -symmetric TRISPHAT anion **8** can be resolved by an association with a chiral ammonium cation [31]. The Δ enantiomer is isolated as the tri-*n*-butylammonium salt, $[\text{Bu}_3\text{NH}][\Delta\text{-8}]$, which is soluble in pure CDCl_3 and CD_2Cl_2 . The Δ -enantiomer is prepared as the cinchonidium derivative, which is only soluble in polar solvent mixtures (>7.5% DMSO in CDCl_3). Interestingly, pseudo-enantiomeric cinchoninium cation is essentially inefficient for the resolution of the hexacoordinated phosphate [104].

The stereoselective synthesis of hexacoordinated phosphate anions was also reported by the same group. A general one-pot process was developed for the preparation of C_2 -symmetric anions **15**, **16** and **17** containing enantiopure BINOL, hydrobenzoin, and tartrate-derived ligands respectively [38–40]; C_1 -symmetric anion **18** being prepared similarly in two steps from methyl- α -

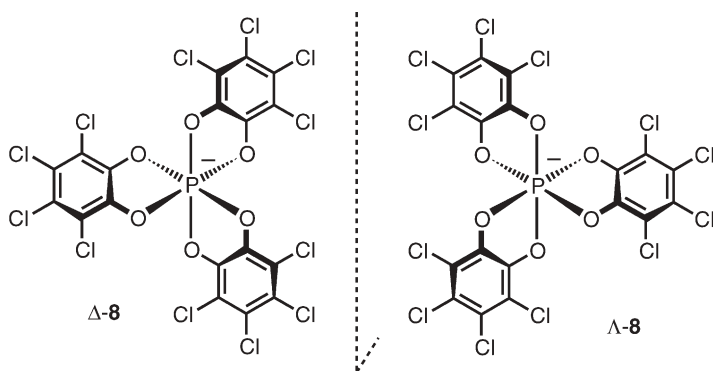


Fig. 19 Δ and Λ enantiomers of TRISPHAT anion **8**

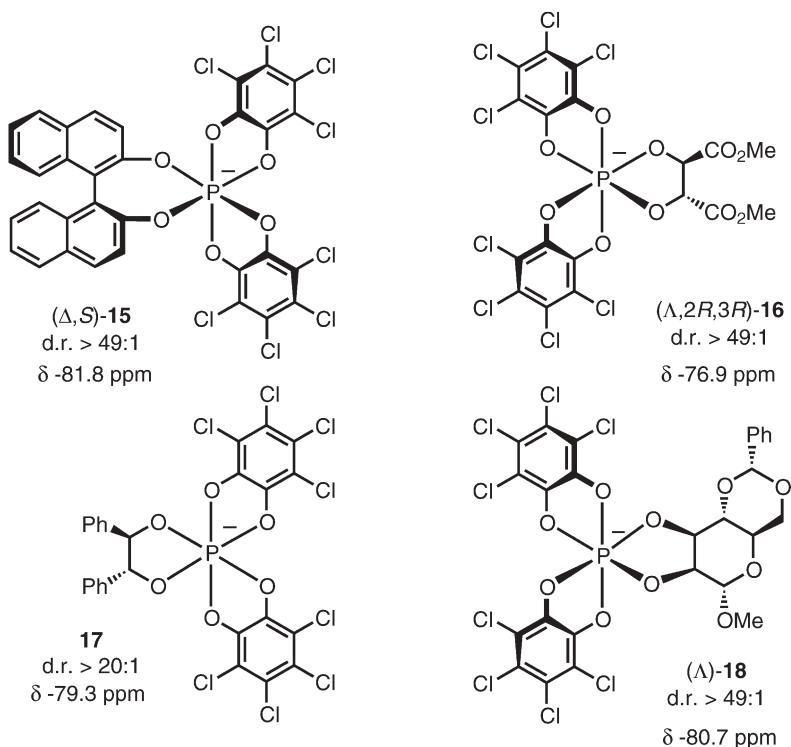
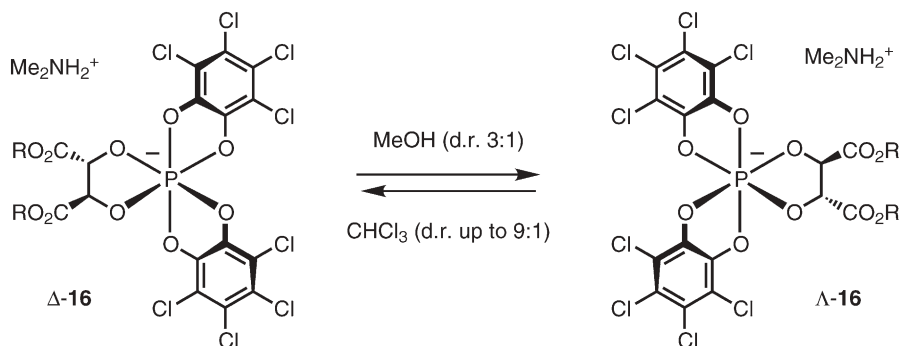


Fig. 20 Diastereomeric purity and relative configuration of enantiopure chiral phosphate anions **15** to **18** isolated after initial precipitation

D-mannopyranoside [41]. All these anions were isolated as their dimethylammonium salts in good yields and chemical purity. The presence of the stereogenic centers of the chiral ligands induces the formation of diastereomers. In essentially all cases, the initial salts are obtained in high diastereomeric purity. Figure 20 shows the diastereomeric ratios and, when known, the relative configuration of the major isolated compounds.

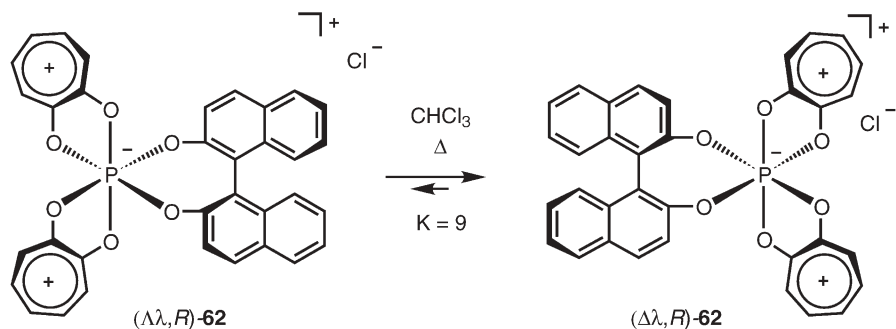
However, upon dissolution, an epimerization of the anions can occur in the presence of acidic counter-ions. This is particularly true for **16a–16d** [39]. The nature of the solvent (MeOH, CHCl₃) plays a crucial role on the kinetics of epimerization and the position of the resulting equilibrium. For anions made with a (2*R*, 3*R*) tartaric backbone, a Λ configuration is always preferred in MeOH; the selectivity, obtained after a slow equilibration, being independent of the nature of the ester alkyl chain (diastereomeric ratio (d.r.) 3:1). However, in chloroform, the Δ diastereomer is rapidly obtained and the selectivity is best if the ester side chain is sterically demanding (d.r. 2:1 to 9:1 from **16a** to **16d**) (Scheme 16).

For the BINPHAT anion **15**, of enantiomeric (Δ,S) or (Δ,R) configuration, no such epimerization occurs. However, due to the strain of the 7-membered ring,



Scheme 16 Solvent-induced (controlled) epimerization of TARPAT anions **16**

a decomposition of the hexacoordinated phosphate anion can happen if the Me_2NH_2^+ cation is not rapidly exchanged in solution for a non-acidic counterion. Finally, if two strongly electron-withdrawing ligands, such as tropyliumdiolato moieties, are introduced along with BINOL around the P atom then the two diastereomers can be observed, isolated and fully characterized [100]. It was shown, using BINOL ligand of same *R* configuration, that the thermodynamic isomer of the cationic derivative **62** has a relative Δ configuration different from the Λ one of BINPHAT anion **15**. This might indicate that the selectivity in favor of the diastereomer (Λ, R)-**15** comes from a kinetic rather than a thermodynamic control (Scheme 17).



Scheme 17 Temperature-induced epimerization of chiral cationic phosphate **62**

3 Applied P(VI) Chemistry

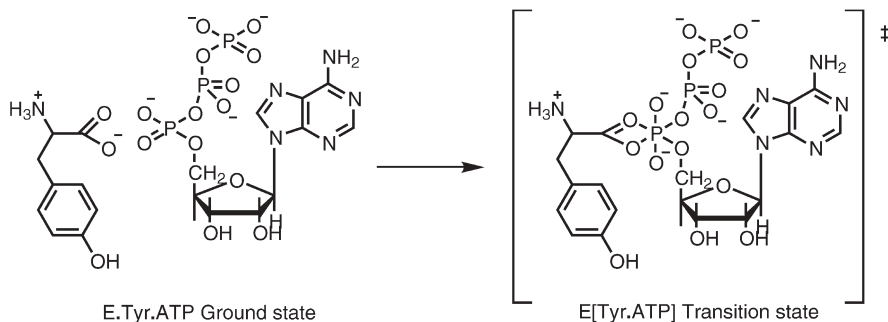
The previous section focused on the structure of novel P(VI) derivatives that have appeared in the literature in recent years. Many of the articles describing these molecules essentially detailed the making and the characterization of the

compounds. However, quite a few reports have dealt more with applications of the derivatives than their characterization since P(VI) compounds find useful roles in fields as varied as: (i) bioorganic chemistry, (ii) classical organic chemistry, (iii) photochemistry, (iv) electrochemistry, and (v) stereoselective synthesis and analysis. A rather broad selection of very diverse applications is therefore presented in the following part.

3.1

P(VI) Derivatives in Bioorganic Studies

Modeling the active site for phosphoryl transfer enzymes represents an important and challenging task for biochemists. Most studies have outlined mechanisms of nucleophilic attack at pseudo-tetrahedral phosphate centers that proceed by in-line displacement reactions. However, due to (i) better understanding of P(V) chemistry, (ii) better understanding of the $P(V) \rightleftharpoons P(VI)$ equilibrium, and (iii) the building of experimental evidence that P(VI) adducts are easily formed, refined mechanistic models taking into account the possible role of high valent phosphorus have been proposed [8, 49, 50]. If the role of P(V) is unambiguously recognized, P(VI) could also intervene. Holmes has recently proposed that a carboxylate group can play a role in the activation of tyrosine in tyrosyl-tRNA synthetase leading to the formation of a P(VI) adduct in the transition state (Scheme 18).



Scheme 18 Possible carboxylate group participation in the activation of tyrosine in tyrosyl-tRNA synthetase

Much effort has also been directed toward mimicking electron transfer on natural photosynthetic systems. Recently, the group of Harada has been able to prepare monoclonal antibodies against metallo porphyrins and show that the biological edifice can control photoinduced electron transfer from the porphyrin to organic acceptor molecules in solution. As it was important to design a biomolecule able to accommodate not only the metalloporphyrin unit but also organic substrates, Harada recently used a hexacoordinated phosphorus

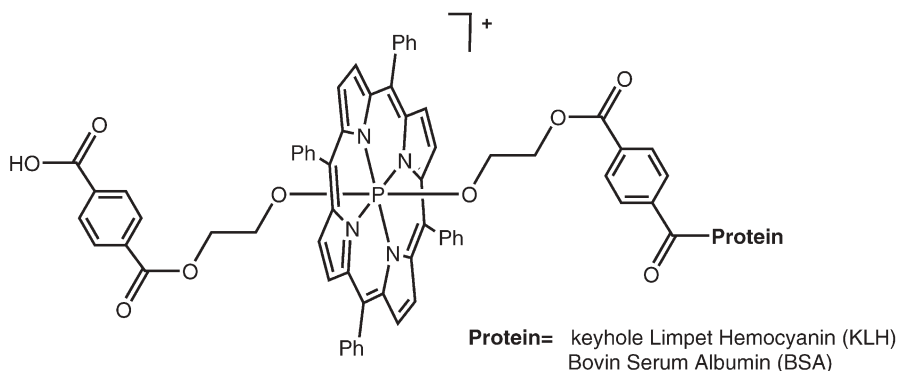


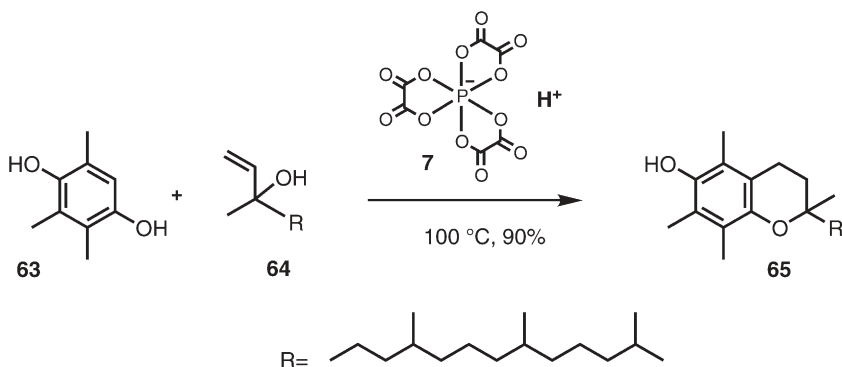
Fig. 21 Cationic P(VI) hapten for biomimetic photosynthetic studies

porphyrin as a hapten because of its ability to form water-stable derivatives with specific ligands attached at the axial positions of the central P atom [90]. The resulting antibodies recognized not only the porphyrin moiety but also the axial ligands. High selectivity, strong coordination and facile electron transfer from the porphyrin to acceptor molecules were then displayed by the bio-assembly. The hapten used is described in Fig. 21.

3.2

P(VI) Derivatives in Organic Chemistry

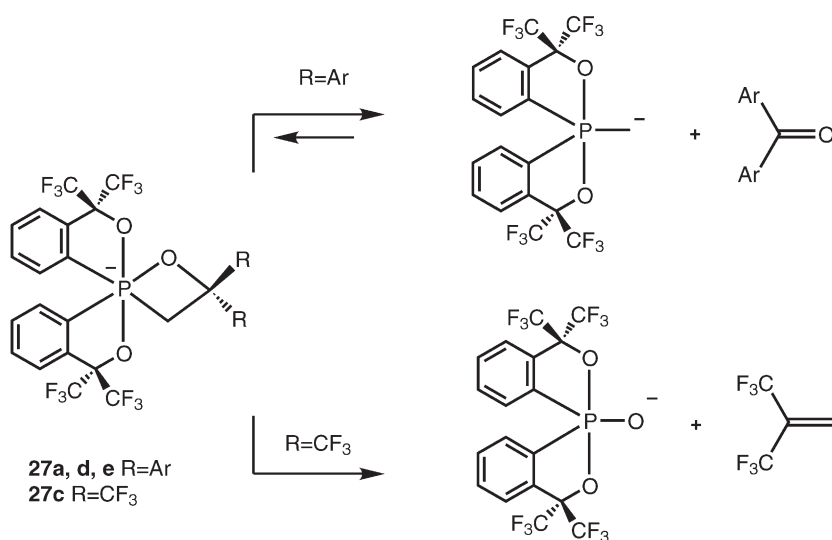
The strong Brønstedt acid nature of some hexacoordinated phosphorus derivatives, $[7^-, H^+] \cdot (Et_2O)_4$ in particular, was recently used within the context of an industrial application [36]. The conjugated acid of tris(oxalato)phosphate anion **7** was found to effectively catalyze the ring-forming reaction of trimethylhydroquinone **63** with isophytol **64** to give (*all rac*)- α -tocopherol **65** (ethylene-carbonate/heptane 1:1, 100 °C, 90%, Scheme 19). This process is particularly



Scheme 19 Tocopherol (**65**) synthesis mediated by the conjugate acid of anion **7**

efficient as it evolves a small amount of catalyst (0.5 mol% or less) and affords low quantities of by-products. Other advantages are the easy and cheap preparation of **7**, and the absence of heavy metals and sulfur- and fluorine-containing compounds in the process.

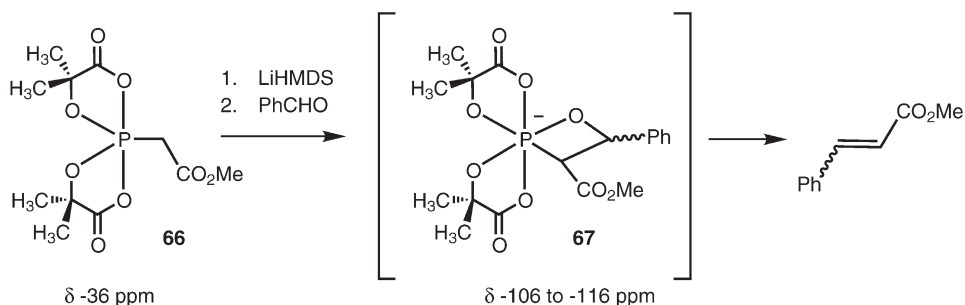
Kawashima [45] and Akiba [46, 47] have reported a possible use of 1,2-oxaphosphetanides **27–28** to generate olefins via a higher-order Horner–Wadsworth–Emmons process. Upon heating at 80–100 °C, derivative **27c** undergoes a cycloreversion reaction to afford the corresponding olefin and a hydroxyphosphorane. However, this process is strongly substrate-dependent as compounds **27a**, **27d** and **27e** react at the same temperature to “form again” benzophenones and methylphosphorane **31**, respectively (Scheme 20).



Scheme 20 Temperature-induced reactions of oxaphosphoranides **27–28**

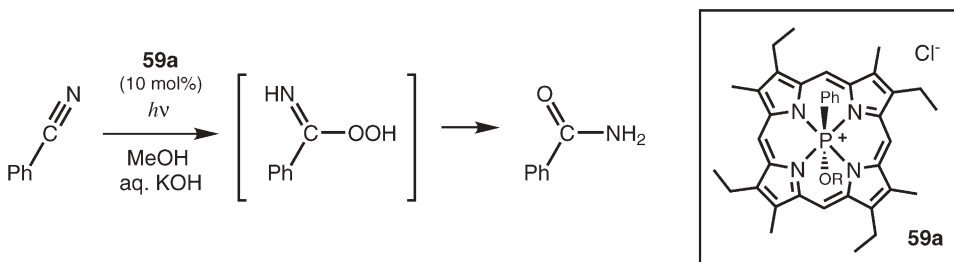
Evans Jr. and coworkers reported a similar olefination reaction employing spirooxyphosphoranes of type **66**. Upon treatment with a strong base (LiHMDS) and subsequent addition of benzaldehyde, the reaction proceeded to form anionic P(VI) intermediates (**67**, δ –106 to –116 ppm) that decomposed at room temperature to form the corresponding olefins and spiropentaoxyphosphoranes [105]. The stereoselectivity (*E:Z* ratio) of the double bond-forming reaction depended upon the conditions; evidence indicated the possibility of kinetic or thermodynamic control (Scheme 21).

Finally, phosphorus porphyrins, such as some of those detailed in Sect. 2.3.1 have attracted attention in organic chemistry for their unique photochemical properties. Aida reported that basic aqueous solutions of benzonitrile in the presence of **59a** undergo under irradiation ($\lambda > 420$ nm) a clean transformation



Scheme 21 Higher order Horner–Wadsworth–Emmons olefination via hexacoordinated intermediates **67**

to benzamide [80]. Most probably, **59a** upon photoexcitation in the presence of OH[−] is reduced to the corresponding anion radical, which then undergoes electron-transfer to existing O₂ to generate O₂[−] (or HO₂[−] in the presence of water); this latter reagent being responsible for the observed reactivity. Obviously, this application of **59a** could have been part of the next paragraph on photochemical applications and it constitutes a good introduction to the next topic (Scheme 22).



Scheme 22 Hydration of benzonitrile catalyzed by cationic porphyrin **59a**

3.3

Photochemical and Photophysical Properties of P(VI) Derivatives

As just mentioned, phosphorus porphyrins have unique photochemical properties. Their photophysics is also interesting. Emitter-quencher assemblies based on porphyrin building blocks have attracted attention due to their potential to serve as models in photosynthetic research (see [90] for an example) or for the development of photoswitches that could be used for the fabrication of molecular electronic/optical devices. In this context, Maiya and coworkers constructed a P(VI) porphyrin system **59b** with two “switchable” azobenzene groups positioned in the “apical” positions of the pseudo-octahedral phosphorus atom [92]. Photoswitch ability (luminescence on/off) was demonstrated as

$R = \text{Ph}, p\text{-NO}_2\text{-Ph}$

$\xrightleftharpoons[\Delta]{h\nu}$

(E)-59b **(Z)-59b**

The ease of introduction of axial substituents on phosphorus porphyrins was also used by Shimidzu and coworkers to link a large number of porphyrin arrays with molecular conducting tetrathiophene wires (Fig. 22) [76, 77]. The P(VI) porphyrin unit tending to be an electron acceptor acts as a photo-induced hole generator. The tetrathiophene tending to be an electron donor is able to transfer the positive hole just as molecular electric wire. The conductivity of this donor-acceptor polymer was shown to be strongly enhanced by photoirradiation, indicating that the formation and transfer occur efficiently along the polymeric chain. This also suggests the possibility of effective photoswitching.

Rao reported measurement of third-order optical non-linearity in the nanosecond and picosecond domains for phosphorus tetratolyl porphyrins bearing two hydroxyl groups in apical position [89]. Strong nonlinear absorption was found at both 532 nm and 600 nm. The high value of nonlinearity for nanosecond pulses is attributed to higher excited singlet and triplet states. Time resolved studies indicate an ultra-fast temporal evolution of the nonlinearity in this compound.

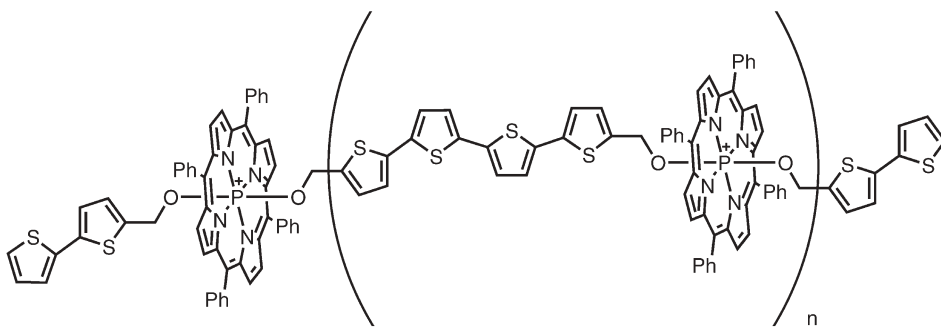


Fig. 22 Phosphorus porphyrin arrays with molecular conducting tetrathiophene wires

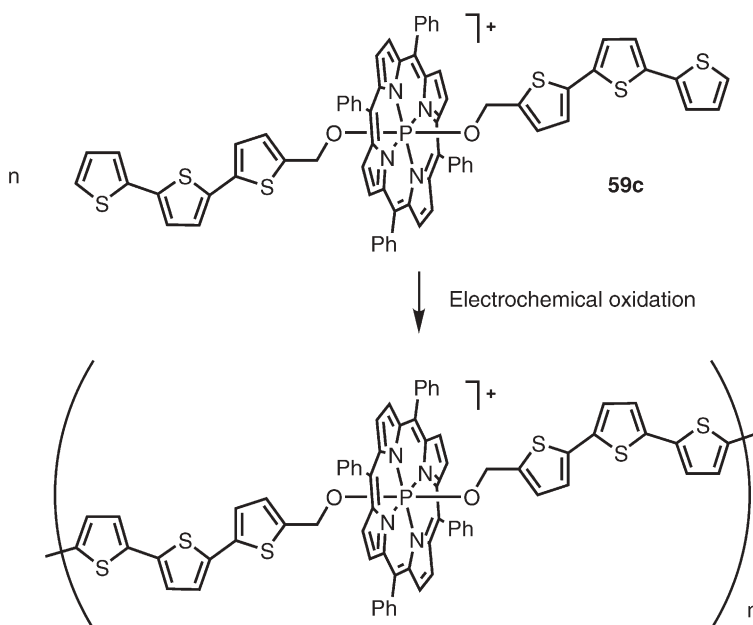
3.4

Electrochemical Applications of P(VI) Derivatives

Numerous investigators have attempted to develop inexpensive, nontoxic, highly soluble and thermally, chemically and electrochemically stable lithium salts to replace the common but problematic LiPF_6 in so-called lithium batteries. In this context, lithium tris[benzenediolato]phosphate or [Li,1] was synthesized and utilized as Li battery electrolytes for $\text{Li}/\text{V}_2\text{O}_5$ cells [106]. The specific conductivity (3.89 mS cm^{-1}) in an ethylene carbonate-tetrahydrofuran binary mixture was somewhat low. It can be explained by the high viscosity of the large anion. In spite of the low conductivity, a rather high cutoff potential of 3.7 V vs Li/Li^+ was measured. For the lithium salt of tris(oxalato)phosphate anion or [Li,7] much higher specific conductivity ($7.0\text{--}9.7 \text{ mS cm}^{-1}$) was measured in a variety of solvent conditions and the cutoff potential was found to be higher ($\sim 4.0 \text{ V}$) [29]. Later, Nanbu investigated the thermal stability and electrolytic properties of tris[4-methyl-1,2-benzenediolato]phosphate or [Li,9] [32]. The specific conductivity of the salt itself is rather modest (2.3 mS cm^{-1}) but the equimolecular mixture of [Li,9] and $[\text{Li}, \text{PF}_6]$ showed – not too surprisingly – an improvement in conductivity (5.3 mS cm^{-1}). However, more importantly, the cyclic efficiencies in the electrolyte solutions containing a mixture of [Li,9] and LiPF_6 were much better than those in LiPF_6 only. Finally, Nanbu, Eberwei and coworkers reported the electrochemical study of [Li,11] and [Li,12] [34, 35]. These two salts presented the very high cutoff potentials vs. Li^+/Li with values of 3.95 and 4.3 V , respectively.

Akiba investigated the electrochemical behavior of a variety of phosphorus octaethylporphyrin derivatives; all compounds showing a single reversible oxidation wave [91]. The absolute difference in potential between the first ring-centered oxidation and reduction varies from 2.19 to 2.36 V in dichloromethane. These values are within the range of the HOMO-LUMO gap observed for most metalloporphyrins.

The synthesis of thin films of organic conducting polymers on a nanometer scale is one of the challenges of nanotechnology. Electrochemical poly-



Scheme 24 Electrochemical Polymerization of “wheel-and-axle” type phosphorus porphyrins

merization is a well-established method for preparation of such films as their thickness can be controlled by limiting the charge passed during the polymerization. Tanaka [81] and Shimidzu [72, 76] and coworkers reported the construction of ultra-thin films by deposition on gold crystals or on electrodes of oxidatively polymerized “wheel-and-axle” type phosphorus porphyrins (**59c**)/oligothienyl units. A selected example of the chemical process is described above (Scheme 24).

3.5

Stereoselective Applications of Enantiopure Anionic P(VI) Derivatives

Many chemical reactions and processes involve cationic reagents, intermediates or products. Cations can be sometimes *prochiral* or *chiral* and most applications that involve these moieties lead to racemic molecular or supramolecular assemblies. To afford instead non-*racemic* or enantiopure products, and benefit from possible new applications, an asymmetric ion pairing with chiral anions can be considered – the counterions behaving as asymmetric auxiliaries, ligands or reagents [107]. Recently, the chemistry of P(VI) phosphate anions has been rejuvenated for exactly this purpose [108, 109]. Applications of anions like **8** and **15** as NMR chiral shift reagents, as resolving agents for organic and inorganic cations and as chiral auxiliaries in stereoselective processes have been reported and some of them are detailed below.

3.5.1

NMR Determination of Enantiomeric Purity

As already mentioned, chiral cations are involved in many areas of chemistry and, unfortunately, only few simple methods are available to determine their optical purity with precision. In the last decades, NMR has evolved as one of the methods of choice for the measurement of the enantiomeric purity of chiral species [110, 111]. Anionic substances have an advantage over neutral reagents to behave as NMR chiral shift agents for chiral cations. They can form diastereomeric contact pairs directly and the short-range interactions that result can lead to clear differences in the NMR spectra of the diastereomeric salts.

An overall efficiency of TRISPHAT **8** and BINPHAT **15** anions as NMR chiral shift agents for chiral cations has been demonstrated over the last few years. Additions of ammonium salts of the Δ or Λ enantiomers of **8** and **15** to solutions of racemic or enantioenriched chiral cationic substrates have generally led to efficient NMR enantiodifferentiations [112–121]. Well-separated signals are usually observed on the spectra of the diastereomeric salts generated in situ.

Sometimes, a direct ion-pairing of the chiral cations and anions **8** or **15** is necessary to maximize the NMR separation of the signals [115, 116]. Cationic species as different as quaternary ammonium, phosphonium, [4]heterohelicene, thiiranium ions, (η^6 -arene)manganese, ruthenium tris(diimine) have been analyzed with success (Fig. 23).

TRISPHAT anion **8** seems to be more particularly efficient with cationic metallo-organic and organometallic substrates. BINPHAT **15** has often superior chiral shift properties than **8** when associated with organic cations such as ammonium cation **68** (Fig. 24). In all these examples, solvent polarity influences the quality of the separation since ion association is crucial. Solvent or solvent mixtures of low polarity are preferred for these experiments.

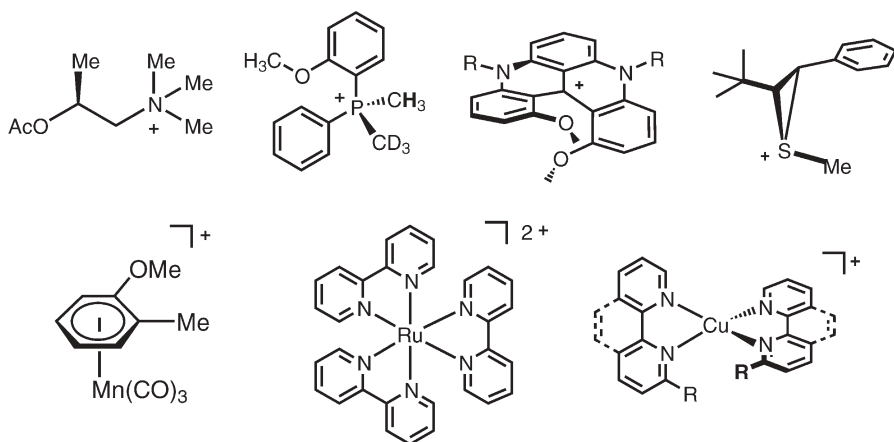


Fig. 23 Selected examples of chiral cations analyzed successfully with anions **8** or **15**

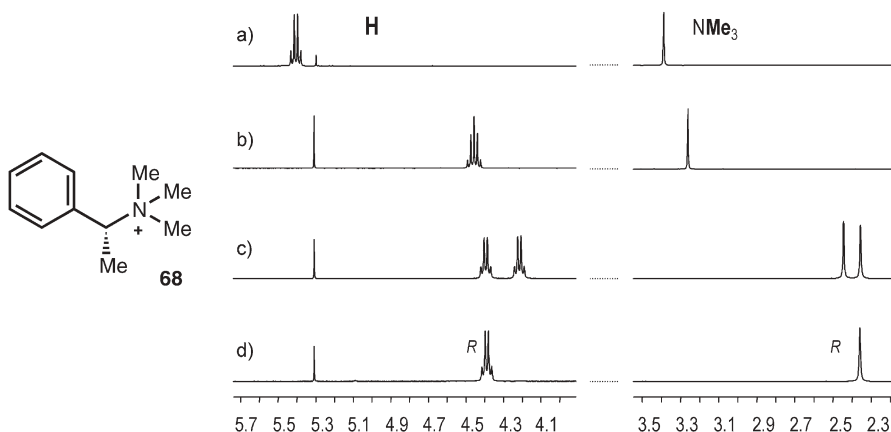


Fig. 24 ^1H NMR spectra (400 MHz, CDCl_3 , parts) of a) [*rac*-**68**][**1**], b) [*rac*-**68**][Δ -**8**], c) [*rac*-**68**][Δ ,*S*]-**15**] and d) [*R*-**68**][(Δ ,*S*)-**15**]

Recently, Lacour, Sauvage and coworkers were able to show that the association of chiral $[\text{CuL}_2]^+$ complexes (L =2-*R*-phen, 6-*R*-bpy and 2-iminopyridine) with TRISPHAT **8** leads to an NMR enantiodifferentiation, which allows the determination of the kinetics of racemization of the complexes (bpy=2,2'-bipyridine; phen=1,10-phenanthroline) [119]. This type of application has recently been reported in conjunction with chiral sandwich-shaped trinuclear silver(I) complexes [122]. Several reports, independent from Lacour's group, have confirmed the efficiency of these chiral shift agents [123–127]. Finally, TRISPHAT can be used to determine the enantiomeric purity of (η^6 -arene)chromium complexes. These results broaden the field of application of **8** to chiral neutral, and not just cationic, species [114, 128, 129].

3.5.2

Resolution of Chiral Cations

Many chemical reactions and processes yield cationic racemic products, and either a resolution or a stereoselective synthesis must be envisaged to obtain the chiral cations in an enantioenriched or enantiopure form. Resolution has been strongly studied [130] and selected representative examples of such processes mediated by chiral P(VI) anions are presented.

Preparative chromatographic resolution procedures have overall freed chemists from the constraint of dependency on crystallization. They are most often performed with covalent diastereomer mixtures but ionic salts can also be separated. Recently, it was found that the lipophilicity of TRISPHAT anion **8** profoundly modifies the chromatographic properties of the cations associated with it and the resulting ion pairs are usually poorly retained on polar chromatographic phases (SiO_2 , Al_2O_3) [131]. Using enantiopure TRISPHAT anion,

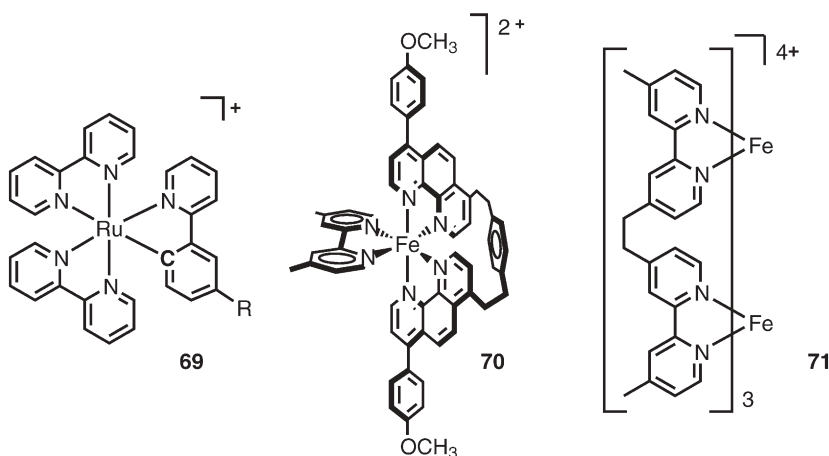


Fig. 25 Chiral cationic coordination complexes **69**, **70** and **71**

accessible from [cinchonidinium][Δ -**8**] or [Bu₃NH][Δ -**8**] salts, the chromatographic resolution of chiral cations is feasible, as the diastereomeric ion pairs often possess rather different retardation factors. For instance, [Ru(bpy)₃]²⁺ and [Ru(Me₂bpy)₃]²⁺ (Me₂bpy: 4,4'-dimethyl-2,2'-bipyridine) complexes were separated into diastereomeric homochiral [Δ -RuL₃][Δ -**8**]₂ and heterochiral [Λ -RuL₃][Δ -**8**]₂ salts by column chromatography over silica gel (eluent CH₂Cl₂) [132]. Rather large differences in retardation factors were observed (ΔR_f 0.10–0.23). The resolution can also be performed on preparative thin-layer chromatographic (TLC) plates. The protocol was extended to monocationic cyclometallated ruthenium complexes **69** and to a configurationally stable mononuclear iron(II) complex **70** (Fig. 25) [116, 133].

The lipophilicity of the TRISPHAT anion **8** also confers to its salts an affinity for organic solvents and, once dissolved, the ion pairs do not partition in aqueous layers. This rather uncommon property was used by Lacour's group to develop a simple and practical resolution procedure of chiral cationic coordination complexes by asymmetric extraction [134, 135]. Selectivity ratios as high as 35:1 were measured for the enantiomers of ruthenium(II) trisdiimine complexes, demonstrating without ambiguity the efficiency of the resolution procedure [134].

An extension of this protocol was further developed for a diiron(II) triple helicate and afforded in separated phases the *P* or *M* enantiomers of the [Fe₂L₃]⁴⁺ helix **71** (Fig. 25) [135].

3.5.3

Stereoselective Chemistry Induced by Chiral Anions

Chiral compounds are sometimes configurationally stable as solids and configurationally labile in solution. When optically active samples of these deriv-

atives are solubilized, a racemization occurs due to the free interconversion of the enantiomers in solution. To obtain these compounds in one predominant configuration over time, a possible strategy is to add stereogenic elements to their backbone; intramolecular diastereoselective interactions happen and favour one of equilibrating diastereomers [136, 137]. If the chiral compounds are charged, an alternative strategy to control their configuration is to consider their asymmetric ion pairing with chiral counter-ions [138]; intermolecular – rather than intramolecular – diastereoselective interactions then control the stereoselectivity (Pfeiffer effect) [139, 140].

Unfortunately, in most of the previous examples, the extent of the asymmetry-induction was determined by chiroptical measurements (ORD, CD) that gave qualitative and not quantitative information. The NMR chiral shift efficiency of TRISPHAT **8** and other hexacoordinated phosphate anions was therefore considered as an excellent analytical tool to provide accurate measurement of the induced selectivity by NMR spectroscopy.

Configurationally labile cations, as varied as $[\text{Fe}(\text{Me}_2\text{bpy})_3]^{2+}$ **72** (Fig. 26), $[\text{Fe}(\text{phen})_3]^{2+}$ and $[\text{Co}(\text{Me}_2\text{bpy})_3]^{2+}$ complexes, dicobalt(II) triple helicates, di-

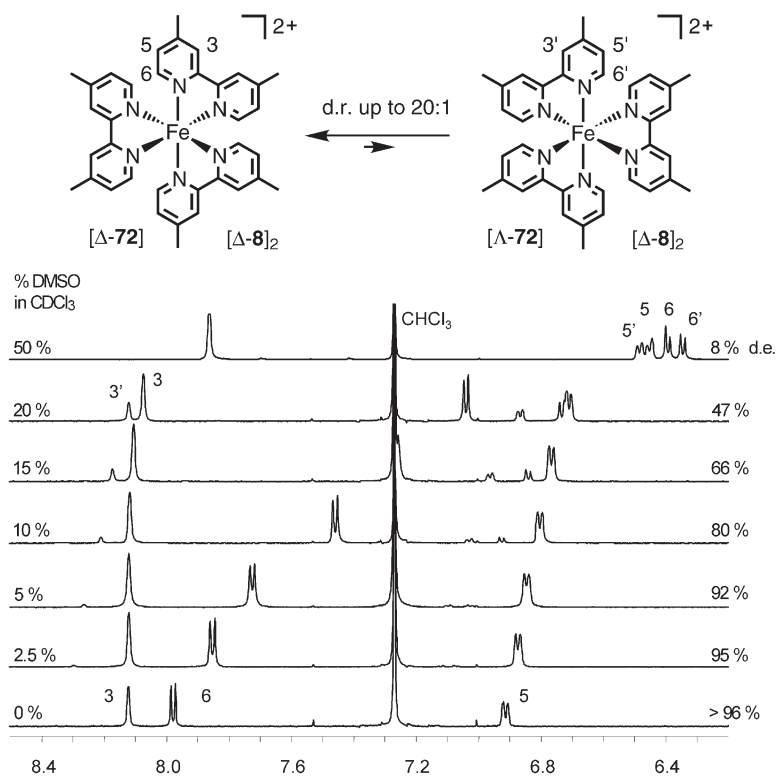


Fig. 26 ^1H NMR spectra (parts) of equilibrating salts $[\Delta\text{-72}][\Delta\text{-8}]_2$ and $[\Lambda\text{-72}][\Delta\text{-8}]_2$ in $[\text{D}_6]\text{DMSO}/\text{CDCl}_3$ and resulting diastereoselectivity

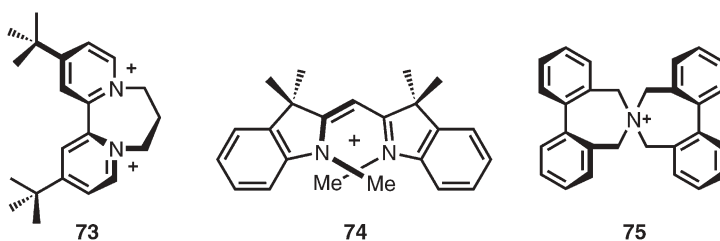


Fig. 27 Chiral configurationally labile cations 73, 74 and 75

quat 73, monomethine dye 74 and quaternary ammonium 75, were paired with enantiopure anions 8 and/or 15 [38, 41, 141–144]. In all cases, an enantiodifferentiation of the interconverting enantiomers of the chiral cations was observed in ^1H NMR spectroscopy. In most cases, the analyses could be performed at room temperature, as the interconversion was slow on the NMR time scale, e.g., 72 (Fig. 26).

For cations 74–75 (Fig. 27), low temperature NMR experiments were necessary to reveal stereodynamical behaviors and allow the observation of split signals for the enantiomers [38, 144]. Stereoselective recognition between the chiral cations and anions was observed in essentially all cases as integration of the split signals revealed the preferential occurrence of one diastereomeric salt over the other.

Diastereomeric ratios as high as 20:1 can be observed for some of the substrates, e.g., salt [72][Δ -8] [41, 141]. The selectivity strongly depends upon the polarity of the solvent medium. An increase in the diastereoselectivity is usually observed upon the decrease of solvent polarity. This is interpreted as the result of closer interactions between the ions. In most cases, induced CD spectra could also be measured allowing the determination of the preferred configuration of the chiral cations.

4

Conclusion

In this review, we hope that we have been able to show the high diversity of P(VI) chemistry in the nature of its derivatives as well as in their subsequent applications. Our feeling is that P(VI) chemistry has strongly matured over the last 5–10 years. However, there is still much ground to be covered and, no doubt, new and more selective P(VI) chemistry will be prepared to achieve new structures and develop more efficient solutions to desired goals.

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