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Review

Protecting groups for stabilization of inter-element linkages

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Dedicated to Prof. Dr Dr h.c. Gerhard Fritz at Universität Karlsruhe on the occasion of his seventy-fifth birthday.

Abstract

Various kinds of protective groups for stabilization of low-coordinated organophosphorus compounds are reviewed, in terms of steric effect and electronic effect, with some typical examples involving diphosphenes, phosphaalkenes, phosphaallenes, phosphabenzoquinones, diphosphinidenecyclobutenes, thioxophosphines, selenoxophosphines, dithioxophosphoranes, diselenoxophosphoranes, and phosphaalkynes. © 2000 Published by Elsevier Science S.A. All rights reserved.

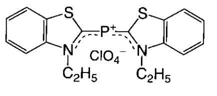
Keywords: Inter-element linkage; Protecting group; Steric protection; Intramolecular coordination; Low coordination; Organophosphorus compounds

1. Introduction

Inter-element linkages are of interest since there are many possibilities for bonding between the heavier main group elements. Low coordinated organophosphorus compounds of coordination number 1 or 2 had long been believed not to exist as stable species. Although some species were postulated as reactive intermediates, only a few examples were known until recently, except for a few delocalized organophosphorus compounds, as exemplified by phosphacyanin (**1**) and phosphabenzene (**2**), reported by Dimroth [1] and Märkl [2], respectively.

Bickelhaupt et al. [3] reported a stable and isolable phosphaalkene (**3**) being protected by the mesityl group in 1978. This was the first example with a localized P=C bond, which is sterically protected. This kind of compound had been commonly believed not to be stable according to the so-called 'double-bond rule', which tells us that multiple bonding involving heavier main-group elements is not strong [4]. However, such multiple bonding becomes stable if electronically delocalized or sterically protected with a built-in auxiliary.

(*E*)-1,2-Bis(2,4,6-tri-*t*-butylphenyl)diphosphene (**4**) was prepared by us in 1981 as the first compound with a localized P=P bond [5] which is kinetically stabilized. This was a 'true' phosphobenzene, which is stable toward moisture or air in the solid state. Furthermore, an unusual phosphaalkyne **5** with P≡C bonding was prepared by Becker et al. in 1981 by using the *t*-butyl group as a protecting group [6]. Since those examples were reported as stable compounds, phosphorus-containing unusual compounds have been of current interest, and many types of compounds with various substituents have been reported so far.



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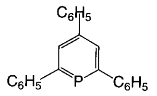

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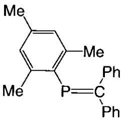

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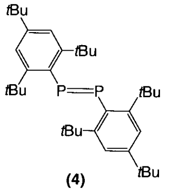

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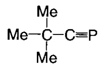

$\mathrm{Me{-}\overset{Me}{\underset{Me}{C}}{-}C{\equiv}P}$

(5)

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2. Protecting groups

In this review, protecting groups for stabilization of inter-element linkage or unusual organophosphorus compounds by steric and/or electronic effects are described [7–9]; they include unusual compounds in low coordination states such as diphosphenes, phosphaalkenes, 1-phosphaallene, 1,3-diphophaallenes, 3-aza-1-phosphaallenes, 1-phosphabutatrienes, 1,4-diphosphabutatrienes, 1,4-diphospha-1,3-butadienes, diphosphabenzoquinones, 3,4-diphosphinidenecyclobutenes, diphospha[4]radialenes, 1,2-diphosphinidenecyclobutanes, 1,3,6-triphosphafulvenes, thioxophosphines, selenoxophosphines, dithioxophosphoranes, diselenoxophosphoranes, and phosphaalkynes (Fig. 1).

2.1. Steric effect

Fig. 2 lists various kinds of sterically protecting groups that have been used for stabilization of organophosphorus compounds in low coordination states. The 2,4,6-tri-*t*-butylphenyl group is one of the most popular protecting groups among those used for such a purpose. The efficiency of this particular substituent is excellent in terms of steric bulkiness, furthermore, the starting material for introduction of this substituent, 2,4,6-tri-*t*-butylbromobenzene, can be prepared easily in large quantities [10]. Since 1981, we have abbreviated this protecting group as 'Ar' to specify this particular aromatic group. On the other hand 'Ttb' was used in Kiev's group [7], as abbreviation of tri-*t*-

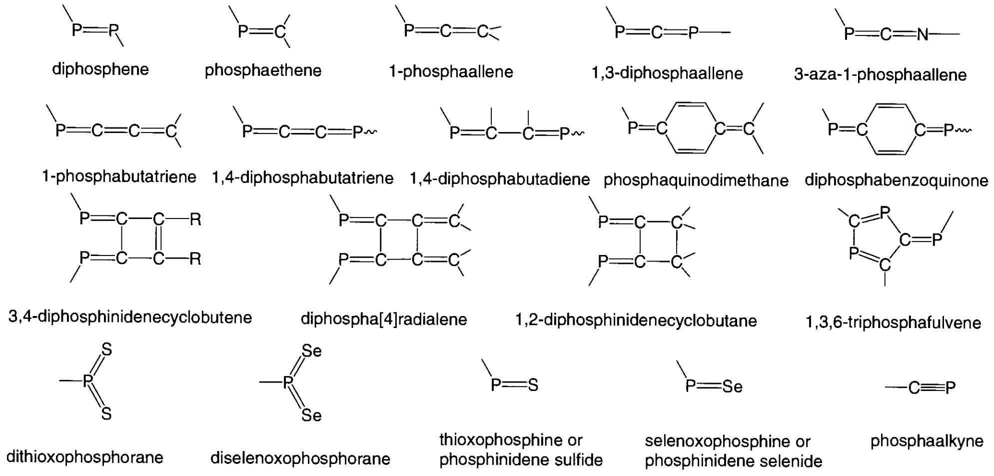


Fig. 1.

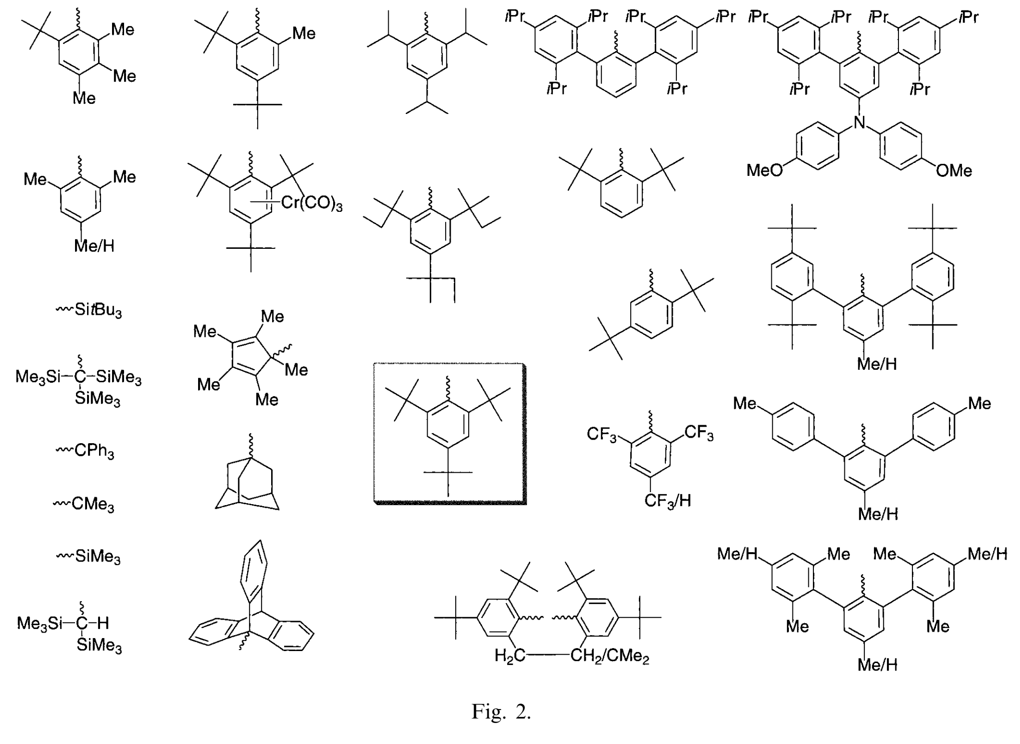


Fig. 2.

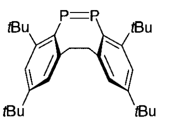
butylphenyl, and even a nickname Yosh was given to this group by Karsch [11] to imply both yielding outstanding steric hindrance and a part of the name of this author. Recently, this protecting group has been widely called the 'super mesityl' group, abbreviated as 'Mes*'. Thus, in this review, we also use the abbreviation Mes* to avoid confusion by use of the term 'Ar', since many similar aromatic protecting groups have been developed by others and ourselves.

2.1.1. Bulky aromatic groups

As has been mentioned above, the 2,4,6-tri-*t*-butylphenyl group (Mes*) is a representative in this category. It is clear that steric bulkiness plays an important role in stabilization of the P=P bond. Unsymmetrical diphosphenes of the type Mes*P=PR can be prepared from 2,4,6-tri-*t*-butylphenylphosphine Mes*PH$_2$ and the corresponding phosphonous dichlorides RPCl$_2$ [12], whereas Mes*P=PMes* can be prepared by the dechlorination reaction of Mes*PCl$_2$ with magnesium metal. Indeed the stability of Mes*P = PR decreases as the bulkiness decreases, as is shown in the order of Mes* > 2,4-di-*t*-butyl-6-methylphenyl > mesityl (Mes or 2,4,6-trimethylphenyl) > phenyl. No significant change in stability was observed between the Mes* group and the 2,4,6-tri-*t*-pentylphenyl group [13]. Furthermore, the *p*-*t*-butyl group in the Mes* group does not seem to affect the stability of the diphosphene, since the 2,6-di-*t*-butylphenyl group can be used in a similar manner to stabilize the corresponding diphosphene [14]. The isopropyl group can be used in place of the *t*-butyl group but the stability of diphosphene carrying the 2,4,6-triisopropylphenyl group (abbreviated as Tip) [15] is not large enough to permit us to handle the corresponding diphosphene as a stable compound at room temperature. A more systematic study on the substituent effect in phosphaalkenes has been carried out by Bickelhaupt [16].

A cyclophane type substituent has been developed for isolation of a *Z*-diphosphene by use of an ethano-bridged bulky aromatic compound **6** [17]. A phosphorus analog of benzoquinone (**7**) and *p*-quinodimethane (**8**) were isolated using the Mes* group as a protecting group [18,19].

2,6-Diarylphenyl or terphenyl groups can serve as a protecting group and the corresponding diphosphenes are isolable as stable compounds [20–23]. Attempts have been made to isolate a mono-coordinate species, phosphinidene (RP:), by using these substituents in order to avoid intramolecular C–H insertion reaction of the ortho alkyl substituents by the highly reactive site [24,25].



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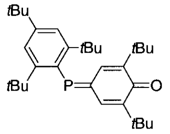

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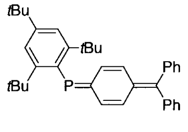

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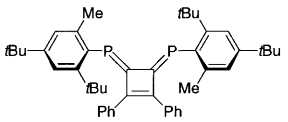
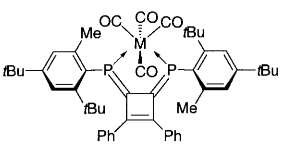
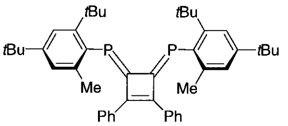


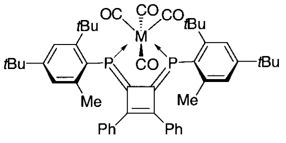
(*anti*-9)



(*anti*-10)



(*syn*-9)



(*syn*-10)

2.1.2. Bulky alkyl and related groups

Bulky alkyl groups, such as *t*-butyl [6], adamantyl [26], triptycenyl [27], tris(trimethylsilyl)methyl [28], bis(trimethylsilyl)methyl [29] groups, and tri-*t*-butylsilyl [30] can serve as a protecting group to stabilize unusual organophosphorus compounds. The triphenylmethyl and trimethylsilyl groups are also known as protecting groups. The pentamethylcyclopentadienyl group, which is not only bulky but also stabilizes itself as an anion of the 6-π electron system, has also been used as a substituent for such a purpose by Jutzi et al. [31].

On the other hand, the 2,4-di-*t*-butyl-6-methylphenyl group (abbreviated as Dbt) is useful to stabilize the diphosphinidenecyclobutene system, where conformational isomerism was observed due to the restricted rotation around the two P–Dbt bonds at the edges of the system. The compound **9** consists of two rotamers, *syn*-**9** and *anti*-**9**, according to NMR studies. After addition of [M(CO)$_5$(THF)] to this mixture, where M is Cr (**A**), Mo (**B**), and W (**C**), the ^{31}P-NMR of the reaction products showed the formation of *syn*-**10** and *anti*-**10** with complete retention of conformation. The compounds **10A**–**10C** were purified by column chromatography to give dark purple complexes and the structure of *syn*-**10C** was determined unambiguously by X-ray analysis. On the other hand, *anti*-**10C** was analyzed by HPLC using a chiral HPLC column and a baseline separation was attained; each separated enantiomer showed the symmetrical CD spectrum. These results indicate that an asymmetric environment can be created in the diphosphinidenecyclobutene–transition metal complex system [32].

2.2. Electronic effect

The electronic effect is also useful in stabilization of phosphorus-containing unusual compounds. Fig. 3 depicts some protecting groups, which might cause an

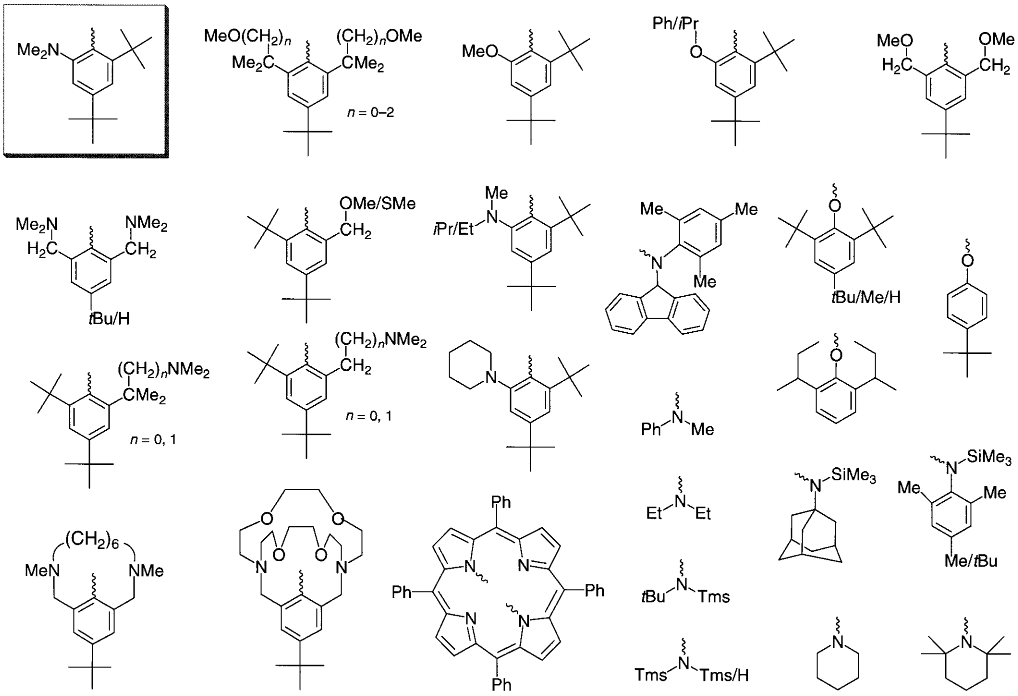
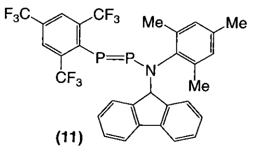


Fig. 3.

electronic effect for stabilization of unusual phosphorus compounds, as listed in Fig. 1. Very early examples of low coordinated organophosphorus compounds have shown that stabilization can be gained by delocalization within the system, effective for compounds of coordination number 2 such as **1** [1] or **2** [2]. A diphosphene bearing the tris(trifluoromethyl)phenyl and fluorenylmesitylamino groups with push-pull type substitution as in compound **11** was analyzed by X-ray crystallography. The X-ray structure and ^{31}P-NMR analysis indicate that the P–N bond length is very much shortened, suggesting a contribution of the P=N form by a mesomeric effect [33]. Bulky phenoxy groups can also serve as a protecting group for stabilization of diphosphenes such as **12** [34,35]. On the other hand, intramolecular coordinative stabilization can be used for stabilization of the electron-accepting part of the molecule. As some early examples, van Koten [36] and Corriu [37] have shown that dimethylphenylstannyl bromide (**13**) and thioxo- and selenoxo-silanes (**14**) are stabilized with the lone-pair electrons of the dimethylamino group, respectively. Similarly, the P(=S)$_2$, P(=Se)$_2$, or P(=Se)(=S) group can be stabilized with the lone-pair electrons of the amino groups, as in compounds **15**, as the P=S and P=Se groups in compound **16** [38]. The 2,4-di-*t*-butyl-6-dimethylaminophenyl group can serve as a protecting group [39] of the P=S moiety, as does the 2,4-di-*t*-butyl-6-(dimethylaminomethyl)phenyl group [40]. The corresponding dimethylaminoethyl group [41] also serves as a protecting group of the P=S and P=Se moieties. The stability caused by the intramolecular coordination is quite efficient and the corresponding compounds without such stabilization are mostly too reactive to be isolated. The internal coordination seems to be strong according to X-ray analyses of such compounds, indicating that the lone-pair electron orients to the phosphorus atom making the bond between phosphorus and the aromatic ring decrease from 120° to 95° to accept coordination, even in the case of four-membered type coordination with the 2,4-di-*t*-butyl-6-dialkylaminophenyl group [42,43]. The 2,4-bis(dimethylaminomethyl)phenyl group has been applied for stabilization of the P(=S)$_2$ moiety [44], which can be coordinated from above and below to form a hypervalent phosphorus.

Yamamoto and Akiba used porphyrin as a ligand of 'PhP=O' to give the six-coordinated phosphorus compound **17** and were successful in using X-ray analysis to confirm the structure [45]. For their further investigation on stabilization of the 'transition state' of S$_N$2 reaction at the carbon atom, **18** was accomplished by ethereal coordination [46].

On the other hand, intramolecular coordination by the ethereal oxygen appears to be less effective than that of the amino groups. The alkoxy groups caused elimination of alkyl halides upon preparation of the corresponding phosphonous dichlorides [47]. The corresponding dithioxophosphorane carrying the 2,4-di-*t*-butyl-6-methoxyphenyl group [48] can be observed only in



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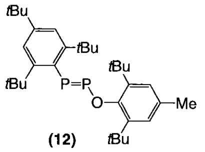

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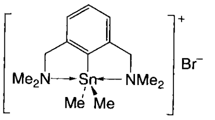

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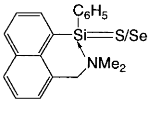

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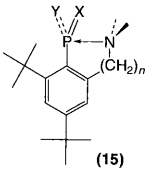

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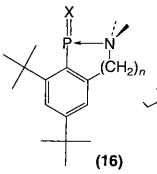

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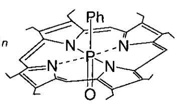

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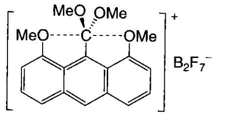


(18)

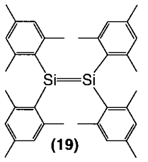
solution but it dimerized to give a Lawesson reagent type compound [49] on concentration or on heating the solution. The compound can be used in the sulfurization reaction of ketones to thioketones as a synthetic reagent. By using a methylthiomethylphenyl protecting group, attempted generation of the corresponding thioxophosphine resulted in trimerization [50]. Similar attempts to prepare the corresponding diselenoxophosphoranes with the 6-alkoxyphenyl groups resulted in the formation of 1,2,3,5,7-pentaselena-4,6,8-triphosphocanes, which served as a selenation reagent of amides to selenoamides [51,52].

3. Further examples other than phosphorus

In 1981, West et al. [53] reported the first stable disilene with Si=Si bond with four mesityl groups (**19**), when almost at the same time the first stable diphosphene with P=P bond with two very bulky Mes* groups was reported by us [5].

On the other hand, Sekiguchi and Sakurai [54] showed that tetrahedrane, prismane (**20**) [55], and cubane (**21**), with the Group 14 elements on each corner, such as silicon, germanium, or tin, can be stabilized with a protecting group such as *t*-butyldimethylsilyl, 2,6-diethylphenyl, 2,6-diisopropylphenyl [56], 1-ethyl-1-methylpropyl [57], bis(trimethylsilyl)methyl, and trimethylsilyl. Only the tri-*t*-butylsilyl group among the other commonly used bulky substituents for that purpose is effective for stabilizing tetrasilatetrahedrane (**22**), as reported by Wiberg et al. [30,58].

The 2,4,6-tris(bistrimethylsilylmethyl)phenyl group [59] is a unique bulky substituent for protecting ‘heavy’ ketones, containing the Group 14 elements [60]. Tokitoh and Okazaki reported compound **23** with the Ge=Se bond [61] stabilized with a combination of that group and the 2,4,6-triisopropylphenyl group, and the Ge=Te bond (**24**) [62] with the 2,6-bis(2-isopropylphenyl)phenyl group. Furthermore, the Bi=Bi bond as in **25** can be stabilized with the 2,4,6-tris(bistrimethylsilylmethyl)phenyl group as the most ‘heavy’ double bond [63]. With a similar substituent, they were successful in isolation of a Bi=Sb compound [64].



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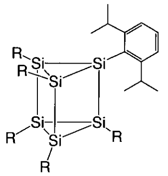

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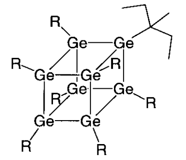

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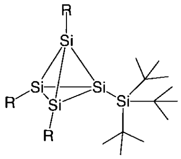

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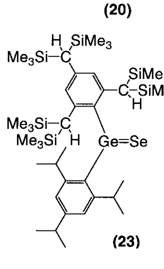

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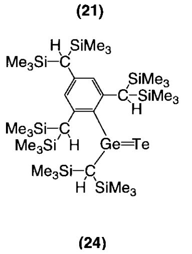

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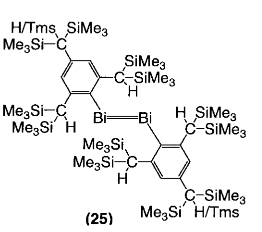

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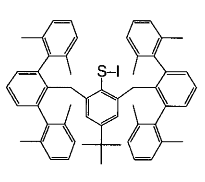

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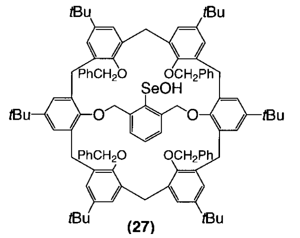

(27)

A bowl-shaped protective effect has been proposed by Goto and Okazaki and **26** with S–I bonding as well as **27** with the SeOH bond were isolated as stable compounds [65,66].

4. Conclusion and outlook

As has been shown for almost two decades, various kinds of unusual compounds have been isolated and characterized, not only phosphorus but also Group 14 and 16 elements, utilizing bulky substituents, as well as special substituents with electronic effect. According to a so-called ‘lock and key’ theory, fine-tuning of shape as well as the electronic effect of protective groups is important to stabilize highly reactive species. Even a theoretical prediction for a suitable substituent has been proposed by Nagase to stabilize the silicon–silicon triple bond [67]. Thus tailor-made protecting groups are a key to design and isolate unusual compounds with their own protecting group.

Acknowledgements

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References

[1] K. Dimroth, P. Hoffmann, Angew. Chem. 76 (1964) 433.
[2] G. Märkl, Angew. Chem. 78 (1966) 907.
[3] Th. Klebach, R. Lourens, F. Bickelhaupt, J. Am. Chem. Soc. 100 (1978) 4886.
[4] H.A. Staab, Einfürung in die theoretische organische Chemie, Verlag Chemie, Weinheim, IVth ed., 1964, p. 76.
[5] M. Yoshifuji, I. Shima, N. Inamoto, K. Hirotsu, T. Higuchi, J. Am. Chem. Soc. 103 (1981) 4587; 104 (1982) 6167.
[6] G. Becker, G. Gresser, W. Uhl, Z. Naturforsch. Teil B 36 (1981) 16.
[7] L.N. Markovski, V.D. Romanenko, A.V. Ruban, Chemistry of Acyclic Compounds of Two-Coordinated Phosphorus, Naukova Dumka, Kiev, 1988, p. 199.
[8] M. Regitz, O.J. Scherer (Eds.), Multiple Bonds and Low Coordination in Phosphorus Chemistry, Georg Thieme Verlag, Stuttgart, 1990.
[9] M. Yoshifuji, Main Group Chem. News 6 (1998) 20.
[10] M. Yoshifuji, in: W.A. Herrmann, H.H. Karsch (Eds.), Synthetic Methods in Inorganic and Organometallic Chemistry 3, Phosphorus, Arsenic, Antimony, and Bismuth, Thieme Verlag, Stuttgart, 1996, pp. 118–125.
[11] H.H. Karsch, F.H. Köhler, H.-U. Reisacher, Tetrahedron Lett. 25 (1984) 3687.
[12] M. Yoshifuji, K. Shibayama, N. Inamoto, T. Matsushita, K. Nishimoto, J. Am. Chem. Soc. 105 (1983) 2495.
[13] M. Yoshifuji, S. Sasaki, N. Inamoto, J. Chem. Soc. Chem. Commun. (1989) 1732.
[14] M. Yoshifuji, T. Niitsu, D. Shiomi, N. Inamoto, Tetrahedron Lett. 30 (1989) 5433.
[15] Th. A. van der Knaap, F. Bickelhaupt, Chem. Ber. 117 (1984) 915.
[16] C.N. Smit, Th. A. van der Knaap, F. Bickelhaupt, Tetrahedron Lett. 24 (1983) 2031.
[17] M. Yoshifuji, N. Shinohara, K. Toyota, Tetrahedron Lett. 37 (1996) 7815.
[18] G. Märkl, R. Hennig, K.M. Raab, J. Chem. Soc. Chem. Commun. (1996) 2057.
[19] S. Sasaki, F. Murakami, M. Yoshifuji, Angew. Chem. Int. Ed. Engl. 38 (1999) 340.
[20] B. Twamley, P.P. Power, Chem. Commun. (1998) 1979.
[21] S. Shah, S.C. Burdette, S. Swavey, F.L. Urbach, J.D. Protasiewicz, Organometallics 16 (1997) 3395.
[22] K. Tsuji, Y. Fujii, S. Sasaki, M. Yoshifuji, Chem. Lett. (1997) 855.
[23] K. Tsuji, S. Sasaki, M. Yoshifuji, Tetrahedron Lett. 40 (1999) 3203.
[24] M. Yoshifuji, T. Sato, N. Inamoto, Chem. Lett. (1988) 1735.
[25] K. Tsuji, S. Sasaki, M. Yoshifuji, Heteroatom Chem. 9 (1998) 607.
[26] T. Allspach, M. Regitz, G. Becker, W. Becker, Synthesis (1986) 31.
[27] G. Märkl, H. Sejpka, Tetrahedron Lett. 26 (1985) 5507.
[28] A.H. Cowley, J.E. Kilduff, T.H. Newman, M. Pakulski, J. Am. Chem. Soc. 104 (1982) 5820.
[29] A.H. Cowley, J.E. Kilduff, S.K. Mehrotra, N.C. Norman, M. Pakulski, J. Chem. Soc. Chem. Commun. (1983) 528.
[30] N. Wiberg, Coord. Chem. Rev. 163 (1997) 217.
[31] P. Jutzi, U. Meyer, B. Krebs, M. Dartmann, Angew. Chem. Int. Ed. Engl. 25 (1986) 919.
[32] M. Yoshifuji, Y. Ichikawa, K. Toyota, E. Kasashima, Y. Okamoto, Chem. Lett. (1997) 87.
[33] M. Abe, K. Toyota, M. Yoshifuji, Heteroatom Chem. 4 (1993) 427.
[34] D.-L. An, K. Toyota, M. Yasunami, M. Yoshifuji, Heteroatom Chem. 6 (1995) 33.
[35] D.-L. An, K. Toyota, M. Yasunami, M. Yoshifuji, J. Organomet. Chem. 508 (1996) 7.
[36] G. van Koten, J.T.B.H. Jastrzebski, J.G. Noltes, A.L. Spek, J.C. Schoone, J. Organomet. Chem. 148 (1978) 233.
[37] P. Arya, J. Boyer, F. Carré, R. Corriu, G. Lapasset, M. Perrot, C. Priou, Angew. Chem. Int. Ed. Engl. 21 (1982) 215.
[38] M. Yoshifuji, M. Hirano, K. Toyota, Tetrahedron Lett. 34 (1993) 1043.
[39] M. Yoshifuji, S. Sangu, M. Hirano, K. Toyota, Chem. Lett. (1993) 1715.
[40] M. Yoshifuji, K. Kamijo, K. Toyota, Tetrahedron Lett. 35 (1994) 3971.
[41] M. Yoshifuji, K. Kamijo, K. Toyota, Chem. Lett. (1994) 1931.
[42] M. Yoshifuji, S. Sangu, K. Kamijo, K. Toyota, Chem. Ber. 129 (1996) 1049.
[43] M. Yoshifuji, S. Sangu, K. Kamijo, K. Toyota, J. Chem. Soc. Chem. Commun. (1995) 297.
[44] M. Yoshifuji, A. Otoguro, K. Toyota, Bull. Chem. Soc. Jpn. 67 (1994) 1503.
[45] Y. Yamamoto, R. Nadano, M. Itagaki, K.-Y. Akiba, J. Am. Chem. Soc. 117 (1995) 8287.
[46] K.-Y. Akiba, M. Yamashita, Y. Yamamoto, S. Nagase, J. Am. Chem. Soc. 121 (1999) 10644.
[47] M. Yoshifuji, M. Nakazawa, T. Sato, K. Toyota, Tetrahedron 56 (2000) 43.
[48] M. Yoshifuji, D.-L. An, K. Toyota, M. Yasunami, Chem. Lett. (1993) 2069.
[49] M. Yoshifuji, D.-L. An, K. Toyota, M. Yasunami, Tetrahedron Lett. 35 (1994) 4379.
[50] K. Kamijo, K. Toyota, M. Yoshifuji, Chem. Lett. (1999) 567.
[51] D.-L. An, K. Toyota, M. Yasunami, M. Yoshifuji, Chem. Lett. (1995) 199.
[52] M. Yoshifuji, N. Higeta, D.-L. An, K. Toyota, Chem. Lett. (1998) 17.
[53] R. West, M.J. Fink, J. Michl, Science 214 (1981) 1343.
[54] A. Sekiguchi, H. Sakurai, Adv. Organomet. Chem. 37 (1995) 1.
[55] A. Sekiguchi, A. Yatabe, C. Kabuto, H. Sakurai, J. Am. Chem. Soc. 115 (1993) 5853.
[56] A. Sekiguchi, C. Kabuto, H. Sakurai, Angew. Chem. Int. Ed. Engl. 28 (1989) 55.
[57] A. Sekiguchi, A. Yatabe, H. Kamatani, C. Kabuto, H. Sakurai, J. Am. Chem. Soc. 114 (1992) 6260.

[58] N. Wiberg, C.M.M. Finger, K. Polborn, Angew. Chem. Int. Ed. Engl. 32 (1993) 1054.
[59] R. Okazaki, M. Unno, N. Inamoto, Chem. Lett. (1987) 2293.
[60] N. Tokitoh, R. Okazaki, Main Group Chem. News 3 (1995) 4.
[61] T. Matsumoto, N. Tokitoh, R. Okazaki, Angew. Chem. Int. Ed. Engl. 33 (1994) 2316.
[62] N. Tokitoh, T. Matsumoto, R. Okazaki, J. Am. Chem. Soc. 119 (1997) 2337.
[63] N. Tokitoh, Y. Arai, R. Okazaki, S. Nagase, Science 277 (1997) 78.
[64] N. Tokitoh, Pure Appl. Chem. 71 (1999) 495.
[65] T. Saiki, K. Goto, R. Okazaki, Angew. Chem. Int. Ed. Engl. 36 (1996) 2223.
[66] K. Goto, R. Okazaki, Liebigs Ann./Rec. (1997) 2393.
[67] K. Kobayashi, S. Nagase, Organometallics 16 (1997) 2489.