Journal of Organometallic Chemistry, 193 (1980) 191—200

MECHANISTIC AND SYNTHETIC ASPECTS OF THE REACTION OF ALKYL ESTERS OF PHOSPHORUS WITH TRIMETHYLSTANNYL HALIDES

J. KOWALSKI and J. CHOJNOWSKI

Centre of Molecular and Macromolecular Studies, Polish Academy of Sciences, Boczna 5, 90 362 Łódź (Poland)

(Received January 4th, 1980)

Summary

The reaction of trimethylstannyl halides with trialkyl phosphates has been studied. The results are interpreted in terms of a mechanism involving a trimethylstannyloxyphosphonium salt intermediate. The much lower reactivity of the stannyl halides compared with their silicon analogs is explained by the lower ionization of the stannyl halide phosphate complexes and the unfavourable direction of the decomposition of the phosphonium salt intermediate. The reaction may be useful in synthesis of phosphates containing only one *O*-stannyl group, which can be used in generation of the acid function or replaced in reactions with compounds containing active halogen.

Introduction

There has been a recent growth of interest in the synthesis and chemistry of the stannyl esters of phosphorus. Some unusual chemical properties of these compounds render them useful as polymer additives [1,2] and as components of catalytic systems [3,4]. Biological studies suggest that these esters also possess effective antimicrobial activity [5,6]. Recently, trialkylstannyl esters of phosphorus were used in synthesis of other bioactive systems [7]. There are several methods of obtaining stannyl esters of oxyphosphoric acids [5,6—16], and one convenient way is the reaction of trialkylstannyl halides with alkyl esters of phosphorus, which leads to the replacement of the alkyl ligand by the stannyl group. This reaction was first reported by Malatesta in the course of his studies of the abnormal course of the Arbuzov reaction between trialkylstannyl iodide and phosphite [8]. He found that the action of triethylstannyl iodide on diethyl ethylphosphonate leads to the formation of (triethylstannyl)ethyl ethylphosphonate. Our aim was examine the possibility of using this type of reaction for the synthesis of stannyl esters of phosphorus as well as to compare its mechanism to that of the analogous reaction of silyl halides with esters of phosphorus, which was the object of recent studies at this Institute [17]. A comparison of this nature should help elucidate the differences in nucleophilic substitution at tin and at silicon centres.

Results and discussion

The reaction of trimethylstannyl halides (I) with triethyl phosphate (II) was studied as the model. The reaction resulted in the replacement of one ethyl group by a stannyl group according to equation (1).

$$\underset{\text{(Ic)}}{Me_3SnI} + \underset{\text{(II)}}{(EtO)_3PO} \rightarrow \underset{\text{(IIIa)}}{(EtO)_2(Me_3SnO)\,PO} + EtI \qquad (1)$$

The same product, diethyl(trimethylstannyl) phosphate, was also obtained by another route involving the reaction of the sodium salt of diethyl phosphate with Me_3SnCl (Ia).

The reactivity of the stannyl halides with triethyl phosphate falls in the sequence $Me_3SnI > Me_3SnBr > Me_3SnCl$. When the reaction was carried out at 85°C without solvent with a 1 : 1 molar ratio of reagents over a 17 h period, the yield, as monitored by ^{31}P NMR spectra, was 95% for the reaction of the Ic but only 2% for the reaction of the Ia. Qualitatively this reaction is similar to the analogous reaction of silyl halides [17]. However, substitution with the silyl group generally occurs much faster, e.g. trimethyliodosilane reacts with triethyl phosphate vigorously at room temperature, and in order to obtain the same rate for the reaction of tin analogue it is necessary to carry out the process at temperatures about 150°C higher. The silylation process leads also to successive replacement of all three alkyl group [17]. The introduction of one stannyl group to the phosphate, in contrast, strongly deactivates this ester towards further stannylation. The ester containing one *O*-stannyl group in addition to one or two *O*-alkyl groups may be thus obtained in almost quantitative yield. Substitution by a second trimethylstannyl group can be achieved by prolonged heating of the monosubstituted derivative with a large excess of the Me_3SnI, but the yield is poor. Thus, heating II with a 6 molar equivalents of Ic at 140°C for about 20 h yields only about 5% of the disubstituted ester along with 95% of the monosubstituted product. The low yield of the distannyl ester is not only a result of an unfavourable equilibrium position as longer heating gave more substitution, the reaction being carried out in an apparatus which prevented escape of EtI from the reaction system. However, the overall-reaction is reversible, as was demonstrated by heating tris(trimethylstannyl) phosphate (IIId) with a large excess of ethyl iodide at 85°C in a closed system. After some time the disubstituted bis(trimethylstannyl)ethyl phospate as well as small amounts of the monosubstituted product (IIIa) appeared *. However, no triethyl phosphate was detected even after prolonged heating.

The thioalkyl group in thiolophosphates does not react with trimethyl-

---

* The reaction proceeded in the two phase crystal-liquid system.

TABLE 1

PHYSICAL DATA FOR STANNYL ESTERS OF PHOSPHORUS

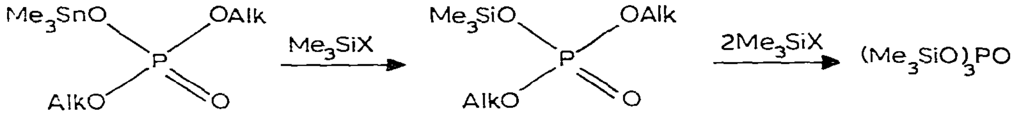
No	Compound	M.W.		Yield (%)	Analyses, found (calcd.) (%)			M.p. (deg.)	^{31}P NMR, δ [b] (ppm)
		calcd.	found [a]		C	H	S		
IIIa	$(EtO)_2(Me_3SnO)PO$	316.9	1318	98 [c]	26.62 (26.53)	6.14 (6.04)		57–62	−9.1
IIIb	$(EtO)(MeS)(Me_3SnO)PO$	318.9	1473	95 [c]	22.15 (22.79)	5.39 (5.37)	9.34 (10.05)	52–56	+14.8
IIIc	$(MeO)(PhS)(Me_3SnO)PO$	366.9	1201	90 [c]	32.76 (32.73)	4.77 (4.67)	8.58 (8.74)	112–115	+10.2
IIId	$(Me_3SnO)_3PO$	586.4	1262	98	17.37 (18.44)	4.46 (4.64)		155–160	−4.4

[a] by vapor-pressure osmometry in benzene, conc. range 0.1–0.02 g/10^{-3} l. [b] in methylene chloride solution. [c] Reaction with one molar equivalent of Me_3SnI.

stannyl halides, and is fully retained during the substitution of the alkyl bound to oxygen. *O*,*S*-Dimethyl-*O'*-trimethylstannyl phosphorothiolate, MeO(MeS)(Me_3SnO)PO (IIIb) and *O*-methyl-*S*-phenyl-*O'*-trimethylstannyl phosphorothiolate, MeO(PhS)(Me_3SnO)PO (IIIc) were obtained in almost quantitative yields by substitution of the methyl group by the trimethylstannyl group using Ic and the appropriate thiolophosphates.

Thionophosphate apparently does not react with trimethylstannyl iodide. The small amount of product which was observed when triethyl phosphorothionate was heated at 100° C in the presence of Ic for a long time (20 h) can presumably be attributed to the products of the Pishchimuka rearrangement [18].

Although the *O*-stannyl *O*-dialkyl phosphate reluctantly reacts further with stannyl halides it readily undergoes reactions with silyl halides. Trimethyliodosilane reacts at temperatures as low as —30° C and at ambient temperature reaction is violent. First, the stannyl group is substituted exclusively, and the remaining silyl iodide replaces the remaining alkyl ester groups, according to the mechanism postulated earlier [17].

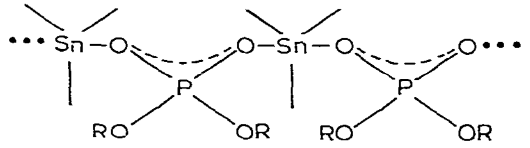


(2)

When trimethylchlorosilane is used, the first step is much faster than the subsequent steps, thus making it possible to obtain the monosilyl ester in almost quantitative yield even in the presence of an excess of trimethylchlorosilane. This reaction was recently used by Hata in the synthesis of some bioactive systems [7].

The properties of new trimethylstannyl esters of phosphorus reported here are shown in Table 1. These compounds are mostly crystalline, though some of them crystallize reluctantly to yield wax-like crystals with broad melting points. In the liquid state they show unusually high viscosity, which implies a high degree of association. Molecular weight measurements with a vapor pressure osmometer disclosed that the (trimethylstannyl)diethyl phosphate exists as a tetramer in benzene (0.1 to 0.05 g cm^{-3}) at ambient temperature. ^{31}P NMR spectrum of the solution (ca. 20% in CH_2Cl_2) taken at room temperature showed only one signal without tin satellites. These satellites could, however, be observed at lower temperatures (—80° C), and on further cooling the signal was split into two signals in the ratio of 2 : 1 (Fig. 1), showing the existence of two nonequivalent phosphorus atoms in the polymeric complex. Presumably one belongs to a cyclic and the other to an open chain species.

Integration demonstrated that the coupling satellites came from both the ^{117}Sn and ^{119}Sn nuclei of two equivalent tin atoms. Thus, the coordination of the phosphoryl oxygen by tin is so strong that both tin atoms bridged to the same phosphorus atom become equivalent, which is in agreement with the structure of polymeric complexes (3) postulated earlier for an analogous sys-



(3)

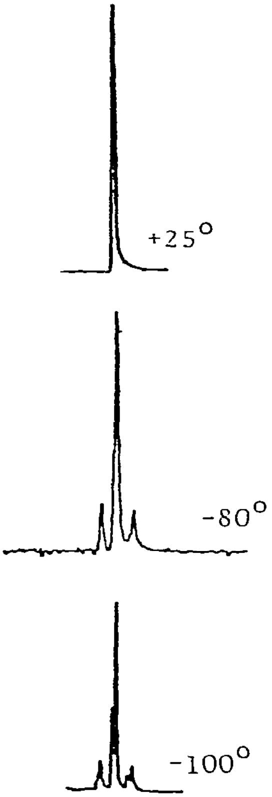


Fig. 1. ^{31}P NMR spectra of $(EtO)_2(Me_3SnO)PO$, ^1H decoupled. (in CH_2Cl_2, ca. 20%).

tem [9]. At room temperature the system is mobile. The polymeric species undergo scrambling which is fast on the NMR time scale.

A similar phosphoryl—tin interaction must exist between ester substrate and ester product as well as between ester product and stannyl halide. They both compete with the complexation of the ester substrate with the stannyl halide, which is the first step of the stannylation process. However, preliminary kinetic studies of the reaction of triethyl phosphate with Ic (1 : 1 molar ratio of the substrates in dioxane) showed that the reaction is not strongly impeded by this type of association. Also, the rate was found to increase considerably as the initial concentration of the phosphate was increased (see Table 2).

TABLE 2

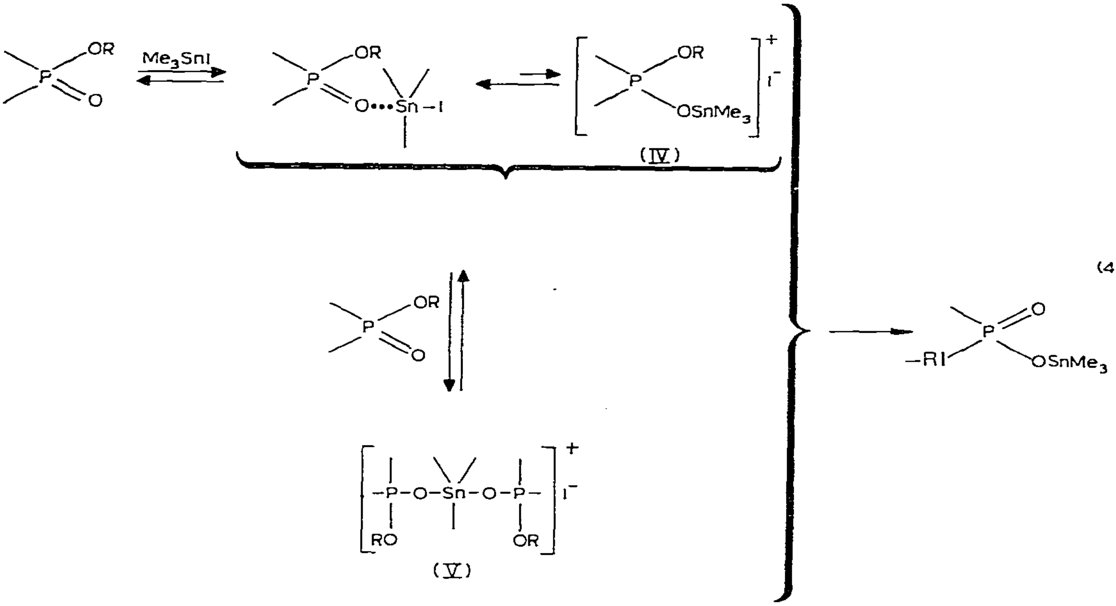
HALF-TIME OF THE STANNYLATION IN DIOXANE AT 85°C

$[(EtO)_3PO]_0$ (*M*)	$[Me_3SnI]_0$ (*M*)	$t_{1/2}$
0.39	0.32	65 h [a]
1.95	0.32	180 min [b]
1.95	0.49	170 min [b]

[a] Determined by ^{31}P NMR spectroscopy for $(EtO)_3PO$. [b] Determined by titration of Me_3SnI.

The mechanism

The results obtained could be explained on the basis of a mechanism similar to that operating in the analogous reactions of silyl halides, involving the formation of a phosphonium salt intermediate (eq. 4) [17]. The ionization of trimethylstannyl halides as a result of interaction with phosphoryl nucleophiles is well documented [19,20]. Two features of the reaction require closer attention: the much lower reactivity of the stannyl halides as compared to their silyl analogs and the considerable difficulty with which more than one stannyl group is introduced into the ester. We believe that the origin of both of these features lies in the more positive character of the tin atom and its high ability to coordinate electron rich species. The positive charge in the stannyloxyphosphonium cation (IV) is concentrated on the tin atom which constitutes the centre strongly interacting with the counter ion. The cations are presumably stabilized by complexation with another phosphate molecule. The stannyl product appears as a result of the dealkylation of the phosphonium intermediate IV or V. Attack of iodide on the ethyl group of the phosphonium species IV is unlikely because of its preferential attack on the tin atom, which results in the formation of starting materials. However, attack of iodide on ethyl group is most likely to occur in structure V, since the tin is five coordinated and the positive charge is delocalized among the tin atom and two phosphonium components, rendering the cation less reactive towards nucleophiles. On the basis of the above argument it can be seen that as the number of tin centers involved in this type of cationic complex increases, the less likely is the formation of the desired products.



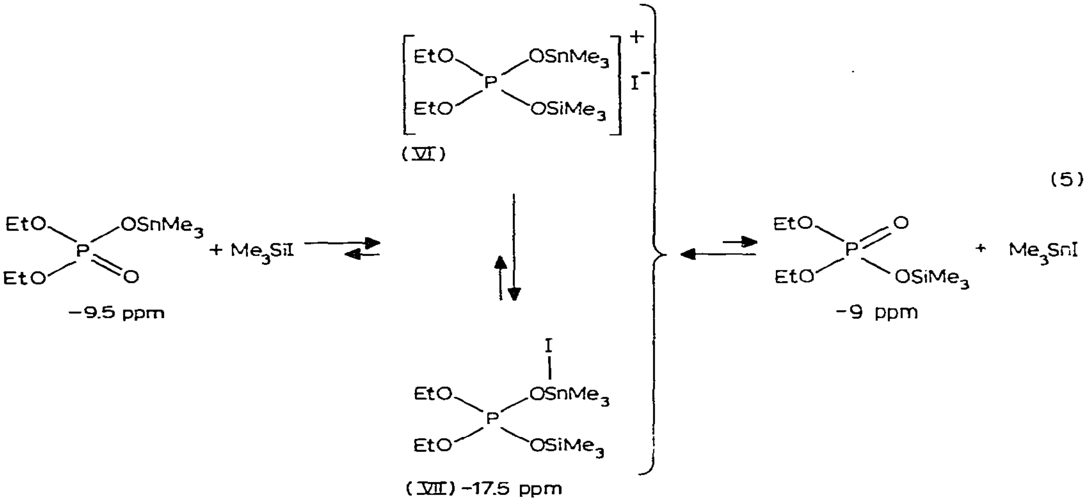
(4)

Apparently, the phosphoryl species does not induce ionization of stannyl halides as readily as it does that of the silyl halides. This can be explained in terms of the ability of the phosphorus center to sustain the positive charge induced by tin and silicon. In the case of the ionization of tin halides the phosphorus center accepts less of the positive charge from the tin moiety as compared to the same situation with silicon, because of the lower electronegativity of the tin and its softer character, and so the degree of ionization of the phosphate-stannyl complexes will be lower. The formation of an ionic phosphate complex with trimethyliodosilane is accompanied by a considerable deshielding of the phosphorus nucleus as the ^{31}P NMR signal shifts about 10 ppm downfield [17]. In contrast, the interaction of the phosphate with trimethylstannyl iodide shifts the signal about 4 ppm upfield (for $(EtO)_3PO$ $\delta = -0.96$ ppm, for $(EtO)_3PO + Me_3SnI$, 1 : 1, $\delta = -5.08$ ppm). About the same change in chemical shift is observed as a result of interaction with stannyl chloride (for $(EtO)_3PO + Me_3SnCl$, 1 : 1, $\delta = -4.67$ ppm).

The conductivity of a 0.1 *M* methylene chloride solution of an equimolar mixture of triethyl phosphate and trimethylstannyl iodide is at least two orders of magnitude lower than that of the corresponding silyl system. These observations are consistent with only partial ionization of the stannyl halide-phosphate complex, though some contribution may come from the lower value of the dissociation constant of the stannyloxy-phosphonium salt ion pair and the lower mobility of the cation due to its complexation with other phosphate molecules.

The lower ability of the tin—halide bond to undergo ionization as a result of interaction with a nucleophile as compared to the ability of the silicon—halide bond contrasts with the well known easier ionization of the Sn—X bond under the action of Lewis acids.

The predominance of nucleophilic attack at the tin atom in the stannyloxy—phosphonium halides is reflected in the very fast reaction of stannyl phosphate with trimethylsilyl halides. The phosphate is able to bring about complete ionization of trimethyliodosilane at temperatures as low as —80°C [17], but the iodide ion immediately adds to the tin atom. The over-all process occurs according to the following scheme:



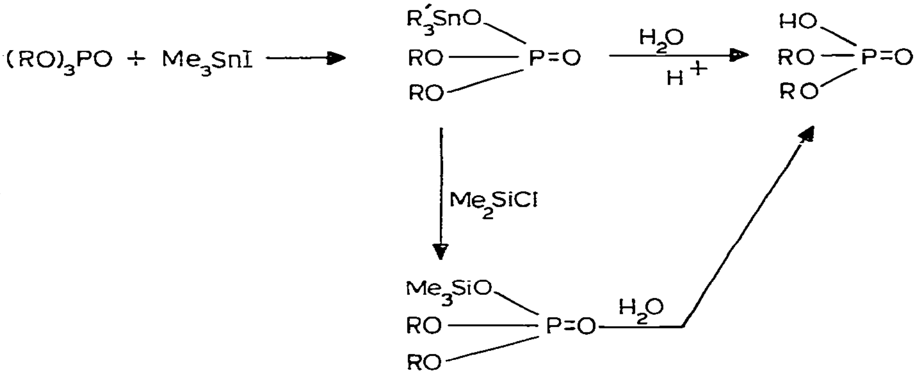
(5)

An equilibrium is established in which the structure VII dominates, as ^{31}P NMR in CH_2Cl_2 in —80°C shows that the signal is shifted from —9.5 ppm to

—17.5 ppm. The same equilibrium was immediately reestablished when appropriate amounts of diethyl(trimethylsilyl) phosphate were mixed with trimethylstannyl iodide.

Synthesis aspects

The reaction of stannyl halides with an alkyl esters of oxyphosphorus acid, in particular with phosphates or phosphonates, could be a convenient method for removing only one ester group, leaving the other ester groups intact;



(6)

The reaction may give almost quantitative yields, and the tin group can be removed by hydrolysis or alcoholysis in acidic medium. Another advantage is that many of the compounds can be purified by crystallization. They also show greater hydrolytic stability than the corresponding silyl derivatives. The stannyl esters group can also be easily replaced by a silyl group when treated with trimethylchlorosilane, as was recently shown by Hata [7]. The affinity of the stannyl group for halogen may be further exploited in reactions of the stannyl esters of phosphorus with other compounds having active halogen atoms.

Experimental

Trimethylstannyl halides were obtained by the disproportionation of tetramethyltin with $SnCl_4$ or with the appropriate halides [21]. Esters of phosphorus were synthesized by standard methods and purified by distillation. In all the syntheses described below atmospheric moisture was excluded.

Preparation of stannyl phosphates

Triethyl phosphate (7.32 g, 0.04 mol) was placed in a 25 ml round-bottom flask equipped with a magnetic stirrer and reflux condenser. 11.62 g (0.04 mol) of trimethylstannyl iodide (Ic) was introduced through the condenser and a slight exothermic effect was observed. The flask was heated to 85°C and the progress of the reaction was monitored by ^{31}P NMR spectroscopy. When the reaction was complete, the volatiles were removed on a vacuum line and the resulting residue eventually crystalized, giving *O,O'*-dimethyl-*O''*-trimethylstannyl phosphate (IIIa). *O,S*-dimethyl-*O'*-trimethylstannyl phosphorothiolate (IIIb) and *O*-methyl-*S*-phenyl-*O'*-trimethylstannyl phosphorotiolate (IIIc) were obtained analogously. The properties and analyses of new compounds are listed in Table 1. The same product (IIIa) was synthesized by the reaction of the sodium salt of diethyl phosphate (obtained by alkaline hydrolysis of 5.5 g (0.03 mol) of triethyl phosphate with 1.2 g (0.03 mol) NaOH in 85% ethanol). After removing the solvents, 6 g (0.03 mol) of trimethylstannyl chloride (Ia) in 20 ml benzene was added. The mixture was stirred for 2 h than filtered, and the filtrate was washed with water and dried over Na_2CO_3, and volatiles were removed under vacuum.

Preparation of tris(trimethylstannyl) phosphate (IIId)

This compound was obtained by the reaction of freshly prepared Ag_3PO_4 (4.2 g; 0.01 mol) with 11.6 g (0.04 mol) with trimethylstannyl iodide (Ic) in benzene as described in ref. 14 for $(Ph_3SnO)_3PO$.

^{31}P NMR studies

^{31}P NMR spectra were recorded on a Jeol JNM-Fx-60-FT instrument at 24.2 MHz. The computer resolution was 1.6 Hz.

For the comparison of the reactivities of the trimethylstannyl halides (chloride, bromide and iodide) with triethyl phosphate reactions were carried out in a 10 mm O.D. NMR tubes. Both substrates (molar ratio 1 : 1) were placed in tubes and heated in an oil bath at 85°C. NMR spectra were recorded every 3 h.

Similarly, reaction of trimethylstannyl iodide (Ic) with triethyl phosphate (molar ratio 6 : 1) at 140°C and reaction of tris(trimethylstannyl) phosphate with ethyl iodide (molar ratio 1 : 7) at 85°C were observed in sealed NMR tubes.

Low temperature silylation experiments of trimethylstannyl esters of phosphorus with trimethylsilyl iodide were performed as described earlier [17].

Half-time of the stannylation

An aliquot of triethyl phosphate and trimethylstannyl iodide in dioxane were mixed to obtain the desired concentration. The solution was transferred into tubes, which were sealed under nitrogen and heated to 85°C. After an appropriate time the tube was broken and the concentration of unreacted trimethylstannyl iodide was determined potentiometrically by titration with $AgNO_3$ solution [22]. In the first experiment shown in Table 2 the progress of reaction was determined by ^{31}P NMR spectroscopy. Conductometric studies were carried out as previously reported [17].

References

1 G.A. Razuvaev, B.B. Troicki, O.S. Diakhovska, L.S. Troicka, I.P. Malysheva and A.F. Lepaev, Eur. Polym. J., 10 (1974) 211.
2 A.J. Ejk and R.C. Ringwood, Jr., M&T Chemicals Inc., U.S. Pat. 4010183, through Chem. Abstr., 86 (1977) 122403.
3 T. Nakata and K. Kawamate, Osaka Soda Co., Ltd., Ger. Pat. 1941690, through Chem Abstr., 72 (1970) 133372.
4 T. Usui, H. Komai, H. Hosozawa, N. Kimura, H. Tamamoto, T. Nakata, T. Kaith and T. Go, Japanese Geon. Co., Ltd., Osaka Soda Co., Ltd.) Ger. Pat. 2128755, through Chem. Abstr., 76 (1972) 127812.
5 M. Kubo, Agr. Biol. Chem. (Yokyo), 29 (1965) 43, through Chem. Abstr., 63 (1965) 7032.
6 Pfizer, Chas and Co. Inc., Brit. Pat. 1163738, through Chem. Abstr., 72 (1970) 2550.
7 T. Hata, Internat. Symposium on Phosphorus Chemistry Directed Towards Biology, Burzenin 1979, Poland.
8 L. Malatesta, A. Sacco and L. Ormezzano, Gazz. Chim. Ital., 80 (1950) 658.

9 R.E. Ridenour and E.E. Flagg, J. Organometal. Chem., 16 (1969) 393.
10 G.A. Lapitski, L.S. Granenkina, P.S. Khokhlov and N.K. Bliznuk Zh. Obshch. Khim., 38 (1968) 2787.
11 C.J. Stern, Jr., Nease Chemical Co., Inc. U.S. Pat. 3179676, through Chem. Abstr., 63 (1965) 2999.
12 K. Issleib and B. Walther, J. Organometal. Chem., 10 (1967) 177.
13 I.G.M. Campbell, G.W.A. Fowles and L.A. Nixon, J. Chem. Soc., (1964) 1389.
14 T.N. Srivastava and S.K. Tandon, Indian J. Appl. Chem., 26 (1963) 171.
15 N.K. Bliznyuk, L.D. Protasova, Z.N. Kvasha and S.L. Varshavski, Pat. USSR 242332, through Chem. Abstr., 72 (1970) 55659.
16 G. Avar and W.P. Neumann, J. Organometal. Chem., 16 (1969) 393.
17 B. Borecka, J. Chojnowski, M. Cypryk, J. Michalski and J. Zielińska, J. Organometal. Chem., 171 (1979) 17.
18 P.S. Pishchimuka, J. Russ. Phys. Chem. Soc., 44 (1912) 1406.
19 V. Gutmann and U. Mayer, Monatsh. Chem., 100 (1969) 2048.
20 V. Gutmann, Angew. Chem. Int. Ed., 9 (1970) 843.
21 D. Seyferth and N. Kahlen, J. Org. Chem., 25 (1960) 809.
22 G.J.M. Van der Kerk and J.G.A. Luijten, J. Appl. Chem., 6 (1956) 49.