Synthesis of polyfunctionalized methylphosphine oxides

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N,N-Dialkylamino(diphenylphosphoryl)chloromethanes, a new type of organophosphorus compounds, were synthesized. On dissolving in polar and low polar solvents, *N,N*-dialkylamino(diphenylphosphoryl)chloromethanes dissociate spontaneously with the P—C bond cleavage to form the diphenylphosphinite anion Ph_2PO^-. This was confirmed by the reaction of *N,N*-dimethylamino(diphenylphosphoryl)chloromethane with electrophilic substrates to form the corresponding addition or substitution products of Ph_2PO^-. The capability of spontaneous generating the diphenylphosphinite anion considers accessible *N,N*-dimethylamino(diphenylphosphoryl)chloromethane as a synthetic equivalent of the diphenylphosphinite anion.

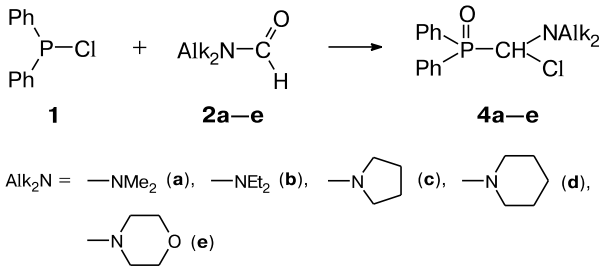
Key words: functionalized phosphine oxides, diphenylchlorophosphine, *N,N*-dialkylamino(diphenylphosphoryl)chloromethanes, *N,N*-dialkylaminobis(diphenylphosphoryl)methanes, *N,N*-dialkylchloromethylideneiminium chloride, diphenylphosphinite anion, dissociation.

Tris-substituted methanes functionalized by diphenylphosphoryl and dialkoxyphosphoryl groups are highly reactive. The phosphorus—carbon bond[1] is cleaved upon the reaction of functionalized methanes with strong acids and bases, which found use in the modern synthetic chemistry. For instance, dialkoxy(diphenylphosphoryl)methanes react with aldehydes and ketones in the Horner—Wadsworth—Emmons reaction to form ketene acetals.[2] Dialkoxy(dialkoxyphosphoryl)methane derivatives are presently used in bioorganic and medicinal chemistry for the temporal protection of the hydrophosphoryl group[3] and as synthetic equivalents (synthones) of phosphinic acids[3a,b,e,4] and formyl anion in the synthesis of carbonyl compounds.[5]

It has previously been reported[6] that the reaction of diphenylchlorophosphine Ph_2PCl (**1**) with *N,N*-dialkylformamides $Alk_2NC(H)O$ (**2**) in the presence of catalytic amounts (5—15 mol.%) of *N,N*-dialkylchloromethylideneiminium chlorides $[Alk_2N{=}C(H)Cl]^+Cl^-$ (**3**) affords *N,N*-dialkylamino(diphenylphosphoryl)chloromethanes **4a**,**e** (Scheme 1). Compounds **4b**—**d** were synthesized in the present work.

N,N-Dialkylchloromethylideneiminium chlorides **3** can be synthesized directly in the reaction medium[6] by the reaction of *N,N*-dialkylformamides **2** with $PhP(O)Cl_2$ (**5**), $(COCl)_2$ (**6**), PCl_5 (**7**), and $SOCl_2$ (**8**). Compounds **3** were shown to be reactant-catalysts recoverable during the reaction, and their formation in the reaction medium allows the synthesis of *N,N*-dialkylamino(diphenylphosphoryl)chloromethanes **4** to occur (see Scheme 1), as it has been proposed earlier[6] and then experimentally confirmed.[7]

Scheme 1



It has been shown[6b] that the ^{31}P NMR spectra of compounds **4a** and **4e** recorded in $CDCl_3$ contain two signals of phosphorus atoms: for **4a**, at δ_P 25.9 (80%) and 21.1 (20%) and for **4e**, at δ_P 34.9 (11%) and 25.9 (89%). At the moment, we would not be able to explain this phenomenon.

Dissociation of *N,N*-dialkylamino(diphenylphosphoryl)-chloromethanes 4 at the P—C bond. The unusual behavior of dialkylamino(diphenylphosphoryl)chloromethanes was studied by ^1H and ^{31}P NMR spectroscopy using phosphine oxide **4a** as the most accessible derivative of compounds **4** as an example. It turned out that the ^1H and ^{31}P NMR spectra of compound **4a** detected in $CDCl_3$ changed substantially with time.

The ^{31}P NMR spectrum (without ^1H decoupling) detected immediately after the dissolution of compound **4a** in $CDCl_3$ exhibits the signal at δ_P 22.0 with the far-range spin-spin coupling constant $^2J_{P,H}$ = 11 Hz, which confirms the presence of the P—C—H fragment in the compound, and the corresponding to $^2J_{P,H}$ of the

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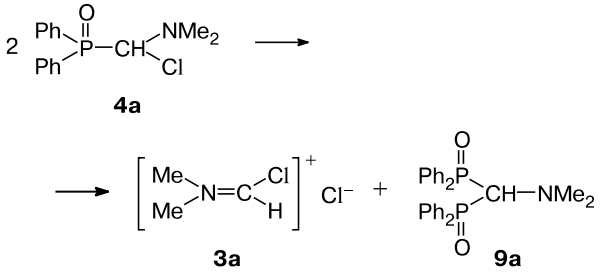
same fragment appeared in the ^{1}H NMR spectrum as a doublet at δ_H 7.89. Thus, the ^{1}H and ^{31}P NMR spectra of compound **4a** correspond to its structural formula, as well as the X-ray diffraction[6] and elemental analyses results.

Ten minutes after the dissolution of compound **4a** in $CDCl_3$ at 5 °C, a signal of another compound appears in the ^{31}P NMR spectrum at δ_P 26.0, whose intensity increases with time. The intensity of the ^{31}P signal of the initial **4a** at δ_P 22.0 simultaneously decreases. After 18 h, the ^{31}P NMR spectrum of the reaction system contains only a signal at δ_P 26.0. The signal at δ_P 26.0 appears as a singlet in the ^{31}P NMR spectrum detected without ^{1}H decoupling. In this case, the ^{1}H NMR spectrum of the reaction mixture contains two signals as singlets at δ_H 11.14 and 3.85 with the 1 : 6 intensity ratio, which is close to the ^{1}H NMR spectrum of *N*,*N*-dimethylchloromethylideneiminium chloride $[Me_2N{=}C(H)Cl]^+Cl^-$ (**3a**, Vilsmeier–Haak reagent) synthesized by a described procedure[8] for comparison. The ^{1}H NMR spectrum of compound **3a** also exhibits two signals: at δ_H 11.18 (H—C(Cl) group) and 3.91 ($N(CH_3)_2$ group) with the 1 : 6 intensity ratio. This indicates the presence of the *N*,*N*-dimethylchloromethylideneiminium cation $[Me_2N{=}C(H)Cl]^+$ (**3´a**) in the reaction mixture. After the work-up of the reaction mixture, *N*,*N*-dimethylaminobis(diphenylphosphoryl)methane (**9a**) was isolated in high yield (85%), and its ^{31}P NMR spectrum exhibits a signal at δ_P 26.0.

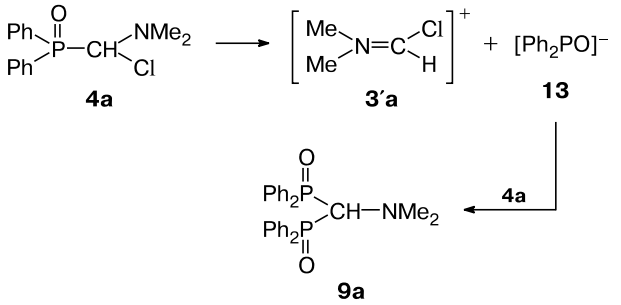
The change observed in the spectra can be explained by the fact that in solution two molecules of **4a** can interact with each other (Scheme 2) to form *N*,*N*-dimethylchloromethylideneiminium chloride (**3a**) and *N*,*N*-dimethylaminobis(diphenylphosphoryl)methane (**9a**).[9]

Scheme 2



In turn, the transformation considered can be explained by the fact that in solutions compound **4a**, by analogy to dialkoxy(dialkoxyphosphoryl)methanes $(AlkO)_2P(O)C(H)(OAlk)_2$ (**10**),[1] (diphenylphosphoryl)diethoxymethane $Ph_2P(O)C(H)(OEt)_2$ (**11**),[5b,e] and benzyl (diphenylphosphoryl)formate $Ph_2P(O)C(O)OBn$ (**12**),[10] can decompose with the P—C bond cleavage (Scheme 3) to form the *N*,*N*-dimethylchloromethylideneiminium cation (**3´a**) and diphenylphosphinite anion Ph_2PO^- (**13**). The latter further readily substitutes the chlorine atom in the initial **4a** to form compound **9a**.

Scheme 3



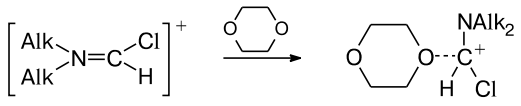
However, unlike compounds **10**, **11**, and **12**, neither heating with hydrochloric acid[1,3] or a solution of NaI,[10] nor lithiation at low temperatures[5b,e] are required for the P—C bond cleavage in compound **4a**. The dissociation of compound **4a** at the P—C bond followed by the formation of compounds **3´a** and **13** occurs simultaneously upon dissolution in low polar ($CHCl_3$) or polar (DMF) solvents.

It can be assumed that in DMF (more polar solvent than $CHCl_3$) the dissociation of compound **4a** to compounds **3´a** and **13** with the subsequent formation of compound **9a** is faster than the same process in $CHCl_3$. Therefore, the ^{31}P NMR spectra detected immediately after the dissolution of compound **4a** in DMF exhibit only one signal[6] at δ_H 26.0 corresponding to compound **9a** as a final product (see Scheme 2).

Synthesis of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes 4b—d. To confirm that the ability of molecules of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4** to react between each other is a common property, we synthesized a series of compounds in which the Alk_2N substituent is the diethylamino group (*N*,*N*-diethylamino(diphenylphosphoryl)chloromethane (**4b**)), pyrrolidino group ((diphenylphosphoryl)pyrrolidinochloromethane (**4c**)), piperidino group ((diphenylphosphoryl)-piperidinochloromethane (**4d**)), and morpholino group ((diphenylphosphoryl)morpholinochloromethane (**4e**)) (see Scheme 1). It was shown that the presence of a catalytic amount of 1,4-dioxane (**14**) in the reaction mixture exerts a substantial effect on the reaction course. In the presence of **14**, the synthesis of compounds **4a** and **4e** occurs more rapidly than in the absence of **14**.[6b] Moreover, it turned out that it is impossible to synthesize compounds **4b—d** under the reaction conditions[6] in the absence of dioxane (**14**) (see Scheme 1). The activating (promoting) effect of compound **14** in the synthesis of compounds **4a—e** can be explained by its ability to solvate the *N*,*N*-dialkylchloromethylideneiminium cation $[Alk_2N{=}C(H)Cl]^+$ (**3´a**) with the formation of the oxoni-

um cation (**3″a**) (see Scheme 4). The electrophilic center of the latter, *viz.*, N,Cl-disubstituted carbocation, is more accessible for the nucleophilic attack of diphenylchlorophosphine **1** by the phosphorus atom compared to iminium cation **3´a**. As a result, this accelerates the synthesis of compounds **4a** and **4e** and makes it possible to synthesize compounds **4b**—**d**.

Scheme 4



3´a **3″a**

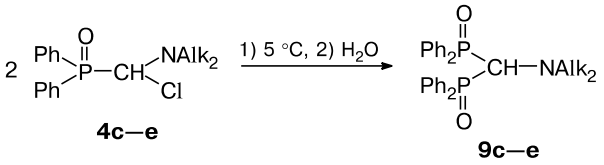
This, in turn, confirms the key role of *N*,*N*-dialkylchloromethylideneiminium chlorides **3** as reactant-catalysts[7] in the synthesis of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4** from *N*,*N*-dialkylformamides **2** and **1**.

N,*N*-Dialkylamino(diphenylphosphoryl)chloromethanes **4b**—**d** are precipitated from the reaction mixture as compounds of nonstoichiometric compositions with hydrogen chloride (the content of HCl was 0.15—0.5 mole (mole of **4b**—**d**)$^{-1}$). Perhaps, this is caused by the higher basicity of the diethylamino-, pyrrolidino-, and piperidino groups of compounds **4b**—**d** compared to the dimethylamino- and morpholino groups of compounds **4a** and **4e**. However, after keeping *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4b**—**d** over fresh NaOH *in vacuo* for 2 days, their elemental analysis becomes consistent with the empirical formula.

Synthesis of *N*,*N*-dialkylaminobis(diphenylphosphoryl)methanes 9c—e. Of the synthesized *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes, molecules of compounds **4c**—**e** also interact with each other. After dissolution in $CHCl_3$, they are rapidly transformed into bis(diphenylphosphoryl)pyrrolidinomethane (**9c**), bis(diphenylphosphoryl)piperidinomethane (**9d**), and bis(diphenylphosphoryl)morpholinomethane (**9e**). Thus, it can be assumed that, upon dissolution of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4** in aprotic low polar ($CHCl_3$, CH_2Cl_2) and polar (DMF) solvents, their molecules, similarly to compound **4a**, react with each other to form *N*,*N*-dialkylaminobis(diphenylphosphoryl)methanes **9** (Scheme 5).

Only *N*,*N*-diethylamino(diphenylphosphoryl)chloromethane (**4b**) does not enter the reaction. Perhaps, this is explained by greater steric hindrances caused by the diethylamino group upon the attack of the diphenylphosphinite anion Ph_2PO^- (**13**) on the tris-substituted carbon atom of compound **4b** as compared to **4a** and compounds **4c**—**e** containing the *N*-heterocyclic fragment. It can be assumed

Scheme 5



4c—e **9c—e**

that the reaction of molecules of compounds **4** between each other is sterically controlled.

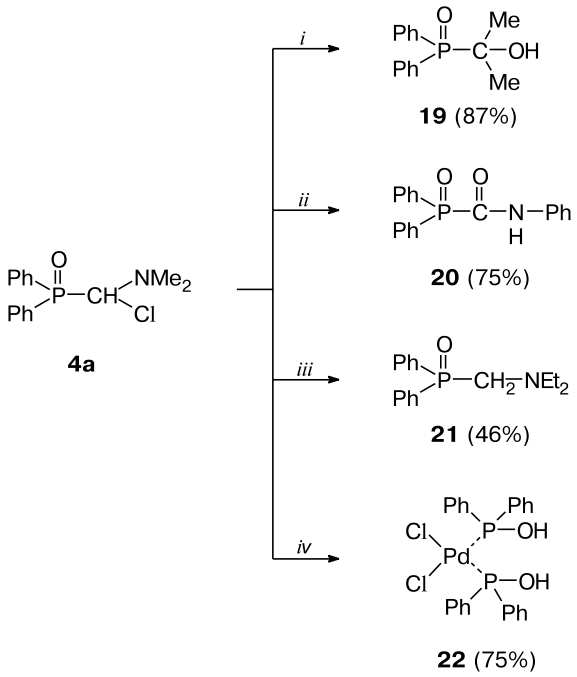
It should be mentioned that the ^{1}H and ^{13}C NMR spectra of *N*,*N*-dialkylaminobis(diphenylphosphoryl)methanes **9a**,**c**—**e** have a number of specific features. For example, in the ^{1}H NMR spectra of compounds **9a**,**c**—**e** the signals of the hydrogen atoms in the *ortho*-positions of the phenyl substituents at the phosphoryl groups appear as two groups of signals at δ_H 8.04—7.98 and 7.82—7.75. Similarly, the *ipso*-carbon atoms of the phenyl substituents at the phosphoryl groups appear as two doublets of doublets with nearly coinciding chemical shifts at δ_C 133.3—132.1 and different spin-spin coupling constants $J_{P,C}$. For *N*,*N*-dimethylaminobis(diphenylphosphoryl)methane **9a**, the first doublet of doublets is observed at δ_C 133.3 ($^1J_{P,C}$ = 118.4 Hz and $^3J_{P,C}$ = 11.0 Hz) and the second doublet is observed at δ_C 133.1 ($^1J_{P,C}$ = 97.1 Hz and $^3J_{P,C}$ = 10.3 Hz). A similar, although less pronounced pattern is observed for signals of the carbon atoms in the *ortho*- and *meta*-positions of the phenyl substituents. The ^{13}C NMR spectra of other *N*,*N*-dialkylaminobis(diphenylphosphoryl)methanes **9c**—**e** are also similar to the ^{13}C NMR spectrum of compound **9a**. This is due to diastereotopicity of the phenylic hydrogen and carbon atoms in molecules of compounds **9a**,**c**—**e**, resulting in their magnetic nonequivalence, which is observed in the ^{1}H and ^{13}C NMR spectra. In these spectra, the nonequivalent hydrogen atoms in the *ortho*-positions and the *ipso*-carbon atoms (and the carbon atoms in the *ortho*- and *meta*-positions) of the phenyl substituents at the phosphoryl groups appear as particular groups of signals.

Reactions of *N*,*N*-dimethylamino(diphenylphosphoryl)chloromethane (4a) with electrophilic substrates. We failed to detect a signal from diphenylphosphinite anion **13** in the ^{31}P NMR spectra of the reaction mixtures. Therefore, to check the assumption about the existence of nucleophilic diphenylphosphinite anion **13** in solutions of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4**, the most accessible of them, namely, *N*,*N*-dimethylamino(diphenylphosphoryl)chloromethane **4a**, was reacted with acetone (**15**), phenyl isocyanate (**16**), and bis(*N*,*N*-diethylamino)methane (**17**), which are pronounced electrophilic substrates, and also with the acetonitrile complex of Pd^{+2}, $PdCl_2 \cdot (CH_3CN)_2$ (**18**).

In all cases, compound **4a** reacted in such a way as it could be expected from the assumption that diphenylphos-

phinite anion **13** exists in the reaction medium (Scheme 6). The corresponding products of addition or substitution of the diphenylphosphinite anion were obtained: 2-(diphenylphosphoryl)propan-2-ol (**19**) (see Ref. 11), *N*-phenyl-(diphenylphosphoryl)formamide (**20**) (see Ref. 12), *N*,*N*-diethylaminomethyldiphenylphosphine oxide (**21**) (see Ref. 13), and *cis*-bis(P-hydroxydiphenylphosphine)palladium(II) chloride (**22**) (see Ref. 14), which confirms the existence of diphenylphosphinite anion **13** in the reaction medium and spontaneous dissociation of compound **4a** as well as, obviously, other *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes **4** at the P—C bond.

Scheme 6



i. $Me_2C{=}O$ (**15**); *ii*. Ph—N=C=O (**16**); *iii*. $(Et_2N)_2CH_2$ (**17**); *iv*. $PdCl_2(MeCN)_2$ (**18**).

Spontaneous dissociation of *N*,*N*-dialkylamino(diphenylphosphoryl)chloromethanes (**4a**,**c**—**e**) in solutions with the P—C bond cleavage makes it possible to consider them as a hidden form of the diphenylphosphinite anion Ph_2PO^- (**13**). This allows the most accessible of them, *N*,*N*-dimethylamino(diphenylphosphoryl)chloromethane (**4a**), to be used in organic and organoelement syntheses as a synthetic equivalent (synthone) of diphenylphosphinite anion **13** instead of the traditional source of the diphenylphosphinite anion, diphenylphosphine oxide (**15**), which requires a strong base[15] in the reaction medium for the generation of Ph_2PO^- (**13**) and tends to oxidation and disproportionation.[16]

Experimental

^1H, ^{31}P, and ^{13}C NMR spectra were recorded on a Bruker Avance 300 spectrometer with working frequencies of 300.11, 121.50, and 75.45 MHz, respectively. The ^1H and ^{31}P NMR spectra of individual compounds were detected in $CDCl_3$; the ^{31}P NMR spectra of the reaction mixtures were also recorded in DMF, $CHCl_3$, and CH_2Cl_2 using 85% H_3PO_4 as an external standard. Melting points were determined on a PTP instrument in a sealed capillary. Elemental analyses to C, H, and N were carried out on a Carlo Erba 1106 automated analyzer. Elemental analysis to P was performed spectrophotometrically on a Cary 100 Scan instrument. Elemental analysis to Cl was conducted by titration with 1 m*M* $AgNO_3$.

N*,*N*-Dimethylamino(diphenylphosphoryl)chloromethane (4a).** Oxalyl chloride $COCl_2$ (**6**) (0.17 g, 0.12 mL, 1.3 mmol) and five—seven droplets of dioxane **14** were slowly added dropwise to a mixture of DMF (**2a**) (6 mL) and benzene (2 mL) at 0 °C with stirring. Then Ph_2PCl (**1**) (2 g, 9.1 mmol) was added under inert atmosphere with stirring at 20 °C. After 0.5 h, the reaction mixture turned red-brown and analytically pure **4a began to precipitate. Benzene (10 mL) was added to the reaction mixture 8 h after, and the mixture was stirred for 5 min. The reaction mixture was kept for 1 h at 0 °C, and the precipitate was filtered off, washed with benzene (3×5 mL), and dried for 2 days *in vacuo* (1 Torr) over P_2O_5. Compound **4a** was obtained in a yield of 2.42 g (91%). Colorless hygroscopic needles, m.p. 92—94 °C (with decomp.). ^{31}P NMR, δ: 22.0 (d, $^2J_{P,H}$ = 11.0 Hz). ^1H NMR, δ: 8.00—7.93 (m, 4 H, *o*-H, Ph); 7.89 (d, 1 H, CH, $^2J_{P,H}$ = 11.0 Hz); 7.56—7.49 (m, 6 H, *m*-H, *p*-H, Ph); 3.08 (s, 6 H, $N(CH_3)_2$). Found (%): C, 61.44; H, 5.79; N, 4.68; P, 10.40. $C_{15}H_{17}ClNOP$. Calculated (%): C, 61.34; H, 5.83; N, 4.77; P, 10.55.

Compounds **4b—e** were synthesized similarly.

***N*,*N*-Diethylamino(diphenylphosphoryl)chloromethane (4b).** The reaction time was 3 days. The yield was 47%. Light yellow hygroscopic substance, m.p. 74—77 °C (with decomp.). $^{31}P\{^1H\}$ NMR, δ: 18.8 (s). ^1H NMR, δ: 10.48 (d, 1 H, CH, $^2J_{P,H}$ = = 23.0 Hz); 8.25—8.19 (m, 4 H, *o*-H, Ph); 7.62—7.53 (m, 6 H, *m*-H, *p*-H, Ph); 4.21 (q, 4 H, 2 CH_2, $^3J_{H,H}$ = 6.0 Hz); 1.34 (br.s, 6 H, 2 CH_3, $\Delta\nu_{1/2}$ = 24 Hz). Found (%): C, 61.65; H, 6.31; N, 4.28; P, 9.21; Cl, 13,05. $C_{17}H_{21}NClOP \cdot 0.25HCl$. Calculated (%): C, 61.70; H, 6.40; N, 4.23; P, 9.35; Cl, 13.39. After drying *in vacuo* (1 Torr) over NaOH, found (%): C, 63.46; H, 6.74; N, 4.31; P, 9.55; Cl, 10.94. $C_{17}H_{21}NPClO$. Calculated (%): C, 63.45; H, 6.58; N, 4.35; P, 9.62; Cl, 11.02.

(Diphenylphosphoryl)pyrrolidinochloromethane (4c). The reaction time was 2 days. The yield was 72%. Pale orange hygroscopic substance, m.p. 79—82 °C (with decomp.). $^{31}P\{^1H\}$ NMR, δ: 19.3 (s). ^1H NMR, δ: 10.31 (d, 1 H, CH, $^2J_{P,H}$ = 23.0 Hz); 8.20—8.13 (m, 4 H, *o*-H, Ph); 7.61—7.49 (m, 6 H, *m*-H, *p*-H, Ph); 4.22 (s, 4 H, 2 NCH_2); 2.03 (br.s, 4 H, 2 CH_2, $\Delta\nu_{1/2}$ = = 15 Hz). Found (%): C, 62.39; H, 6.07; N, 4.23; P, 9.47; Cl, 11.93. $C_{17}H_{19}NClOP \cdot 0.15HCl$. Calculated (%): C, 62.85;

* It is impossible to purify compound **4a** by recrystallization, reprecipitation, or chromatography, because in solutions the compound reacts with another molecule of **4a**. Therefore, analytically pure **4a** was isolated carrying out the reaction in a DMF—benzene mixture used for the recrystallization of structurally similar compounds.

H, 5.93; N, 4.31; P, 9.53; Cl, 12.44. After drying *in vacuo* (1 Torr) over NaOH, found (%): C, 63.19; H, 5.90; N, 4.43; P, 9.47. $C_{17}H_{19}NClOP$. Calculated (%): C, 63.85; H, 5.99; N, 4.38; P, 9.69.

(Diphenylphosphoryl)piperidinochloromethane (4d). The reaction time was 3 days. The yield was 65%. Light yellow hygroscopic substance, m.p. 85—88 °C (with decomp.), $^{31}P\{^1H\}$ NMR, δ: 20.2 (s). ^1H NMR, δ: 9.78 (d, 1 H, CH, $^2J_{P,H}$ = 21.0 Hz); 8.17—8.09 (m, 4 H, *o*-H, Ph); 7.62—7.51 (m, 6 H, *m*-H, *p*-H, Ph); 4.12 (t, 4 H, 2 NCH_2, $^3J_{H,H}$ = 6.0 Hz); 1.82 (br.s, 4 H, $C\underline{H}_2CH_2C\underline{H}_2$, $\Delta\nu_{1/2}$ = 11 Hz); 1.64 (q, 2 H, $CH_2C\underline{H}_2CH_2$, $^3J_{H,H}$ = 6.0 Hz). Found (%): C, 61.64; H, 6.46; N, 3.85; P, 9.17. $C_{18}H_{21}NClOP \cdot 0.5HCl$. Calculated (%): C, 61.72; H, 6.16; N, 3.98; P, 8.80. After drying *in vacuo* (1 Torr) over NaOH, found (%):C, 64.84; H, 6.48; N, 3.95; P, 9.26. $C_{18}H_{21}NClOP$. Calculated (%): C, 64.77; H, 6.34; N, 4.20; P, 9.28.

(Diphenylphosphoryl)morpholinochloromethane (4e). The reaction time was 18 h. The yield was 86%. Colorless hygroscopic needles, m.p. 70—71 °C (with decomp.). $^{31}P\{^1H\}$ NMR, δ: 27.9 (s). ^1H NMR, δ: 7.91—7.81 (m, 4 H, *o*-H, Ph); 7.61—7.54 (m, 2 H, *m*-H, Ph); 7.52—7.45 (m, 4 H, *p*-H, Ph); 6.19 (d, 1 H, CH, $^2J_{P,H}$ = 4.0 Hz); 3.61—3.55 (m, 4 H, OCH_2); 3.08 (t, 4 H, NCH_2, $^3J_{H,H}$ = 5.0 Hz). Found (%): C, 60.32; H, 5.90; N, 4.10; P, 9.11. $C_{17}H_{19}NPClO_2$. Calculated (%): C, 60.71; H, 5.70; N, 4.17; P, 9.22.

***N,N*-Dimethylaminobis(diphenylphosphoryl)methane (9a).** A solution of **4a** (3.4 g, 11.6 mmol) in 20 mL of $CHCl_3$ freshly distilled over P_2O_5 was kept for 18 h at 5 °C. The solution was diluted with CH_2Cl_2 (30 mL) and washed with water (4×5 mL). The organic layer was separated and dried with $MgSO_4$. The drying agent was filtered off and washed with CH_2Cl_2 (4×5 mL). The filtrate was evaporated to a volume of ~5 mL. Hexane (40 mL) was added, and the mixture was cooled to −10 °C. After 18 h, the precipitate formed was filtered off, washed with hexane (4×5 mL) cooled to 0 °C, and doubly reprecipitated with hexane from CH_2Cl_2. Compound **9a** was obtained in a yield of 2.25 g (85%). Colorless needles, m.p. 207—210 °C (*cf.* Ref. 9: m.p. 210–212 °C). $^{31}P\{^1H\}$ NMR, δ: 27.3 (s). ^1H NMR, δ: 8.04—7.98 (m, 4 H, *o*-H, Ph); 7.82—7.76 (m, 4 H, *o*-H, Ph); 7.47—7.37 (m, 8 H, *m*-H, Ph); 7.33–7.28 (m, 4 H *p*-H, Ph); 4.63 (t, 1 H, CH, $^2J_{P,H}$ = 18.0 Hz); 2.50 (s, 6 H, $N(CH_3)_2$). ^{13}C NMR, δ: 133.3 (dd, PC, Ph, $J_{P,C}$ = 118.4 Hz, $J_{P,C}$ = 11.0 Hz); 133.1 (dd, PC, Ph, $J_{P,C}$ = 97.1 Hz, $J_{P,C}$ = 10.3 Hz); 131.9 (dddd, *o*-C, Ph, $J_{P,C}$ = 16.1 Hz, $J_{P,C}$ = 4.8 Hz, $J_{P,C}$ = 6.3 Hz, $J_{P,C}$ = 5.0 Hz); 131.6 (s, *p*-C, Ph); 128.1 (ddd, *m*-C, Ph, $J_{P,C}$ = 5.8 Hz, $J_{P,C}$ = = 6.0 Hz, $J_{P,C}$ = 11.8 Hz); 69.2 (t, CH, $J_{P,C}$ = 62.5 Hz); 45.1 (t, NCH_3, $J_{P,C}$ = 3.3 Hz). Found (%): C, 70.07; H, 5.95; N, 2.82; P, 13.34. $C_{27}H_{27}NO_2P_2$. Calculated (%): C, 70.58; H, 5.92; N, 3.05; P, 13.48.

Compounds **9c—e** were synthesized similarly.

Bis(diphenylphosphoryl)pyrrolidinomethane hemihydrate (9c). The yield was 34%. White substance, m.p. 156—159 °C. $^{31}P\{^1H\}$ NMR, δ: 28.6 (s). ^1H NMR, δ: 8.04—7.98 (m, 4 H, *o*-H, Ph); 7.82—7.76 (m, 4 H, *o*-H, Ph); 7.47—7.37 (m, 8 H, *m*-H, Ph); 7.36—7.27 (m, 4 H, *p*-H, Ph); 4.97 (t, 1 H, CH, $^2J_{P,H}$ = 17.4 Hz); 2.90 (br.s, 4 H, 2 NCH_2, $\Delta\nu_{1/2}$ = 15 Hz); 1.43 (br.s, 4 H, CH_2CH_2, $\Delta\nu_{1/2}$ = 10 Hz). ^{13}C NMR, δ: 133.3 (dddd, PC, Ph, $J_{P,C}$ = 120.4 Hz, $J_{P,C}$ = 14.9 Hz, $J_{P,C}$ = 110.9 Hz, $J_{P,C}$ = 15.8 Hz); 131.8 (dd, *o*-C, Ph, $J_{P,C}$ = 4.3 Hz, $J_{P,C}$ = 4.6 Hz); 131.5 (s, *p*-Ph); 128.2 (q, *m*-C, Ph, $J_{P,C}$ = 5.8 Hz); 65.2 (t, CH, $J_{P,C}$ = 63.2 Hz); 51.8 (s, NCH_2); 24.8 (s, CH_2CH_2). Found (%): C, 70.44; H, 6.15; N, 2.59; P, 12.47. $C_{29}H_{29}NO_2P_2 \cdot 1/2H_2O$. Calculated (%): C, 70.44; H, 6.12; N, 2.83; P, 12.52.

Bis(diphenylphosphoryl)piperidinomethane (9d). The yield was 53%. White substance, m.p. 187—189 °C. $^{31}P\{^1H\}$ NMR, δ: 27.9 (s). ^1H NMR, δ: 8.01 (br.s, 4 H, *o*-H, Ph, $\Delta\nu_{1/2}$ = 18 Hz); 7.78 (br.s, 4 H, *o*-H, Ph, $\Delta\nu_{1/2}$ = 18 Hz); 7.50–7.26 (m, 12 H, *m*-H, *p*-H, Ph); 4.64 (br.s, 1 H, CH, $\Delta\nu_{1/2}$ = 45 Hz); 2.92—2.86 (m, 4 H, 2 NCH_2); 1.20 (br.s, 6 H, $CH_2CH_2CH_2$, $\Delta\nu_{1/2}$ = 27 Hz). ^{13}C NMR, δ: 133.3 (dd, PC, Ph, $J_{P,C}$ = 95.1 Hz, $J_{P,C}$ = 7.5 Hz); 133.0 (dd, PC, Ph, $J_{P,C}$ = 119.0 Hz, $J_{P,C}$ = 7.5 Hz); 131.8 (ddd, *o*-C, Ph, $J_{P,C}$ = 4.6 Hz, $J_{P,C}$ = 4.9 Hz, $J_{P,C}$ = 8.9 Hz); 131.5 (s, *p*-C, Ph); 128.1 (dddd, *m*-C, Ph, $J_{P,C}$ = 25.0 Hz, $J_{P,C}$ = 6.0 Hz, $J_{P,C}$ = 13.2 Hz, $J_{P,C}$ = 5.8 Hz); 70.6 (t, CH, $J_{P,C}$ = 61.8 Hz); 53.9 (s, NCH_2); 26.1 (s, $\underline{C}H_2CH_2\underline{C}H_2$); 23.3 (s, $CH_2\underline{C}H_2CH_2$). Found (%): C, 71.82; H, 6.06; N, 2.97; P, 12.25. $C_{30}H_{31}NO_2P_2$. Calculated (%): C, 72.13; H, 6.26; N, 2.80; P, 12.40.

Bis(diphenylphosphoryl)morpholinomethane (9e). The yield was 41%. White substance, m.p. 172—174 °C. $^{31}P\{^1H\}$ NMR, δ: 28.3 (s). ^1H NMR, δ: 7.99—7.93 (m, 4 H, *o*-H, Ph); 7.93—7.72 (m, 4 H, *o*-H, Ph); 7.40—7.24 (m, 12 H, *m*-H, *p*-H, Ph); 3.61 (t, 1 H, CH, $^2J_{P,H}$ = 17.0 Hz); 3.15 (t, 4 H, 2 OCH_2, $^2J_{H,H}$ = = 4.0 Hz); 2.83 (br.s, 4 H, 2 NCH_2, $\Delta\nu_{1/2}$ = 22 Hz). ^{13}C NMR, δ: 132.9 (dd, PC, Ph, $J_{P,C}$ = 115.5 Hz, $J_{P,C}$ = 29.8 Hz); 132.1 (dd, PC, Ph, $J_{P,C}$ = 98.5 Hz, $J_{P,C}$ = 26.7 Hz); 131.7—131.5 (m, *o*-C, *p*-C, Ph); 128.3 (dddd, *m*-C, Ph, $J_{P,C}$ = 18.3 Hz, $J_{P,C}$ = = 5.8 Hz, $J_{P,C}$ = 6.3 Hz, $J_{P,C}$ = 6.0 Hz); 69.4 (t, CH, $J_{P,C}$ = = 61.5 Hz); 67.3 (s, OCH_2); 52.9 (s, NCH_2). Found (%): C, 69.23; H, 5.96; N, 2.71; P, 12.15. $C_{29}H_{29}NO_3P_2$. Calculated (%): C, 69.45; H, 5.83; N, 2.79; P, 12.35.

2-(Diphenylphosphoryl)propan-2-ol (19). Acetone (**15**) (3.0 mL, 2.4 g, 40 mmol) was added with stirring to a solution of **4a** (0.3 g, 1 mmol) in CH_2Cl_2 (1.5 mL). The mixture was kept for 18 h at 20 °C. The precipitate that formed was dissolved in CH_2Cl_2 (10 mL) without separating from the solution and washed with water (4×5 mL). The organic layer was separated and dried with K_2CO_3. The drying agent was filtered off, and the filtrate was washed with CH_2Cl_2 (2×5 mL) and concentrated to a volume of ~1 mL. Hexane (8 mL) was added, and the precipitate formed was double reprecipitated with hexane from a solution in $CHCl_3$. Compound **19** as colorless needles was obtained in a yield of 0.26 g (87%), m.p. 137—139 °C (*cf.* Ref. 11: m.p. 141—143 °C). $^{31}P\{^1H\}$ NMR, δ: 34.4 (s). ^1H NMR, δ: 8.04—7.97 (m, 4 H, *o*-H, Ph); 7.53—7.43 (m, 6 H, *m*-H, *p*-H, Ph); 2.75 (d, 1 H, OH, $^3J_{P,H}$ = 3.0 Hz); 1.44 (d, 6 H, 2 CH_3, $^3J_{P,H}$ = 15.0 Hz). Found (%): C, 68.97; H, 6.28; P, 11.63. $C_{15}H_{17}O_2P$. Calculated (%): C, 69.22; H, 6.59; P, 11.90.

(Diphenylphosphoryl)-*N*-phenylformamide (20). Phenyl isocyanate (**16**) (0.4 g, 3.5 mmol) was added to **4a** (0.5 g, 1.7 mmol) partially dissolved in CH_2Cl_2 (2 mL). The mixture was stirred at 20 °C. Compound **4a** was entirely dissolved within 48 h. The mixture was stirred for 10 h more, diluted with CH_2Cl_2 (10 mL), and washed with water (4×5 mL). The organic layer was separated and dried with K_2CO_3. The drying agent was filtered off and washed with CH_2Cl_2 (2×5 mL), and the filtrate was concentrated to a volume of ~2 mL. Hexane (8 mL) was added. The precipitate formed was doubly reprecipitated with hexane from a solution in CH_2Cl_2. Compound **20** was obtained as colorless needles in a yield of 0.41 g (75%), m.p. 160—162 °C (*cf.* Ref. 12: m.p. 161—162 °C). $^{31}P\{^1H\}$ NMR, δ: 15.9 (s). ^1H NMR, δ: 9.55 (s, 1 H, NH); 7.98—7.91 (m, 4 H, *o*-H, PhP); 7.64 (d, 2 H, *p*-H, PhP); 7.61—7.56 (m, 2 H, *m*-H, PhN); 7.52—7.46 (m, 4 H, *m*-H,

PhP); 7.36—7.28 (m, 2 H, *o*-H, PhN); 7.18—7.16 (m, 1 H, *p*-H, PhN). Found (%): C, 70.95; H, 5.01; N, 4.39; P, 9.55. $C_{19}H_{16}NPO_2$. Calculated (%): C, 71.02; H, 5.02; N, 4.36; P, 9.64.

Diphenyl(*N*,*N*-diethylaminomethyl)phosphine oxide (21). Bis(*N*,*N*-diethylamino)methane (**17**) (0.53 g, 3.4 mmol) was added with stirring to a suspension of **4a** (0.5 g, 1.7 mmol) in benzene (5 mL). The reaction mixture was warmed to 40 °C, after which a system of two immiscible liquid phases was formed. The system was stirred for 2 h at 20 °C, then diluted with CH_2Cl_2 (10 mL) and washed with water (4×5 mL). The organic layer was separated and dried with K_2CO_3. The drying agent was filtered off and washed with CH_2Cl_2 (2×5 mL), the filtrate was concentrated to a volume of ~2 mL, and hexane (8 mL) was added. The precipitate formed was doubly reprecipitated with hexane from a solution in benzene. Compound **21** was obtained as a white crystalline substance in a yield of 0.23 g (46%), m.p. 88—90 °C (*cf.* Ref. 13: m.p. 89—90 °C). $^{31}P\{^1H\}$ NMR, δ: 27.5 (s). ^1H NMR, δ: 7.84—7.77 (m, 4 H, *o*-H, Ph); 7.50—7.41 (m, 6 H, *m*-H, *p*-H, Ph); 3.29 (d, 2 H, PCH_2, $^2J_{P,H}$ = 7.0 Hz); 2.63 (q, 4 H, 2 $NC\underline{H}_2CH_3$, $^3J_{H,H}$ = 7.0 Hz); 0.88 (t, 6 H, 2 $NCH_2C\underline{H}_3$, $^3J_{H,H}$ = 7.0 Hz). Found (%): C, 71,21; H, 7.69; N, 4.77; P, 10.77. $C_{17}H_{22}NOP$. Calculated (%): C, 71.10; H, 7.72; N, 4.88; P, 10.78.

***cis*-Bis(*P*-hydroxydiphenylphosphine)palladium(II) chloride (22).** Compound **4a** (0.57 g, 2 mmol) was added with stirring under inert atmosphere at 20 °C to a solution of $PdCl_2 \cdot (CH_3CN)_2$ (**18**) (0.25 g, 1 mmol) in CH_2Cl_2 (40 mL). A red solution was formed within 20 min. The solution was stirred for 2 h and water (22 mmol) was added. After stirring for 15 min, the organic layer was separated and dried with $MgSO_4$. The drying agent was filtered off, the filtrate was washed with CH_2Cl_2 (4×5 mL), and concentrated to a volume of ~3 mL. Benzene (15 mL) was added. A dark red oil that formed was gradually dissolved for 3 days at 20 °C and a yellow crystalline precipitate was formed. The filtrate was decanted, and the precipitate was washed by decantation with benzene (4×5 mL) and hexane (2×5 mL), dried *in vacuo* (12 Torr), and reprecipitated with benzene from a solution in CH_2Cl_2. After drying *in vacuo* (1 Torr), *cis*-bis(*P*-hydroxydiphenylphosphine)palladium(II) chloride (**22**) was obtained as a light yellow crystalline substance in a yield of 0.27 g (75%), m.p. 125—127 °C (with decomp.). $^{31}P\{^1H\}$ NMR, δ: 78.5 (s). ^1H NMR, δ: 7.57—7.51 (m, 8 H, *o*-H, Ph); 7.40—7.35 (m, 4 H, *p*-H, Ph); 7.26—7.21 (m, 8 H, *m*-H, Ph); 5.29 (s, 2 H, OH). Found (%): C, 49.28; H, 3.83; P, 10.61; Cl, 12.45. $C_{24}H_{22}Cl_2O_2P_2Pd$. Calculated (%): C, 49.59; H, 3.82; P, 10.66; Cl, 12.20.

References

1. (a) A. I. Razumov, V. V. Moskva, *Zh. Obshch. Khim.*, 1965, **35**, 1595 [*J. Gen. Chem. USSR* (*Engl. Transl.*), 1965, **35**, 1599]; (b) H. Gross, B. Costisella, W. Burger, *J. Prakt. Chem.*, 1969, **311**, 563; (c) H. Gross, B. Costisella, *J. Prakt. Chem.*, 1971, **313**, 265; (d) B. Costisella, I. Keitel, *Phosphorus, Sulfur Silicon Relat. Elem.*, 1988, **40**, 161.
2. (a) T. A. M. van Schaik, A. V. Henzen, A. van der Gen, *Tetrahedron Lett.*, 1983, **24**, 1303; (b) T. H. Kim, D. Y. Oh, *Tetrahedron Lett.*, 1986, **27**, 1165; (c) S. Hackett, T. Livinghouse, *J. Org. Chem.*, 1986, **51**, 879; (d) B. E. Maryanoff, A. B. Reitz, *Chem. Rev.*, 1989, **89**, 863; (e) H. E. Zinneman, M. R. Baker, R. C. Bottner, M. M. Morrisey, S. Murphy, *J. Am. Chem. Soc.*, 1993, **115**, 253.
3. (a) F. Reck, S. Marmor, S. Fisherb, M. A. Wuonolaa, *Bioorg. Med. Chem. Lett.*, 2001, **11**, 1451; (b) C. Alstermark, K. Amin, S. R. Dinn, T. Elebring, O. Fjellstrom, K. Fitzpatrick, W. B. Geiss, J. Gottfries, P. R. Guzzo, J. P. Harding, A. Holmén, M. Kothare, A. Lehmann, J. P. Mattsson, K. Nilsson, G. Sundén, M. Swanson, S. von Unge, A. M. Woo, M. J. Wyle, X. Zheng, *J. Med. Chem.*, 2008, **51**, 4315; (c) L. Coudray, A. F. Pennebaker, J.-L. Montchamp, *Bioorg. Med. Chem. Lett.*, 2009, **17**, 7680; (d) L. Coudray, J.-L. Montchamp, *Eur. J. Org. Chem.*, 2009, **27**, 4646; (e) C. Fougere, E. Guenin, J. Hardouin, M. Lecouvey, *Eur. J. Org. Chem.*, 2009, **34**, 6048.
4. W. Froestl, S. J. Mickel, G. von Sprecher, P. J. Diel, R. G. Hall, L Maier, D. Strub, V. Melillo, P. A. Baumann, R. Bernasconi, C. Gentsch, K. Hauser, J. Jaekel, G. Karlsson, K. Klebs, L. Máitre, C. Marescaux, M. F. Pozza, M. Schmutz, M. W. Steinmann, H. van Riezen, A. Vassout, C. Mondadori, H.-R. Olpe, P. C. Waldmeier, H. Bittiger, *J. Med. Chem.*, 1995, **38**, 3313.
5. (a) A. Kirschning, G. Drager, A. Jung, *Angew. Chem.*, *Int. Ed.*, 1997, **36**, 253; (b) H. Monenschein, G. Drager, A. Jung, A. Kirschning, *Chem. — Eur. J.*, 1999, **5**, 2270; (c) H. Monenschein, M. Brunjes, A. Kirschning, *Synlett*, 2002, **3**, 525; (d) M. Brunjes, C. Kujat, H. Monenschein, A. Kirschning, *Eur. J. Org. Chem.*, 2004, **5**, 1149; (e) A. Kirschning, C. Kujat, S. Luiken, E. Schaumann, *Eur. J. Org. Chem.*, 2007, **15**, 2387.
6. (a) V. P. Morgalyuk, *Abstr. 15th Intern. Conf. on Chemistry of Phosphorus Compounds (ICCPC-XV), (St. Petersburg, Russia, May 25—30, 2008)*, St. Petersburg, 2008, 183; (b) V. P. Morgalyuk, P. V. Petrovsky, K. A. Lyssenko, E. E. Nifant´ev, *Izv. Akad. Nauk*, *Ser. Khim.*, 2009, **58**, 245 [*Russ. Chem. Bull., Int. Ed.*, 2009, **58**, 248].
7. V. P. Morgalyuk, T. V. Strelkova, *Zh. Obshch. Khim.*, 2011, **81**, 1643 [*Russ. J. Gen. Chem.* (*Engl. Transl.*), 2011, **81**, 2096].
8. H. H. Bosschard, R. Mory, M. Schmidt, H. Zollinger, *Helv. Chim. Acta.*, 1959, **42**, 1659.
9. H. Gross, B. Costisella, L. Haake, *J. Prakt. Chem.*, 1969, **311**, 577.
10. (a) S. Warren, M. R. Williams, *J. Chem. Soc., Chem. Commun.*, 1969, 180; (b) P. F. Cann, S. Warren, M. R. Williams, *J. Chem. Soc., Perkin Trans. 1*, 1972, 2377.
11. K. Issleib, B. Walther, *J. Organomet. Chem.*, 1970, **22**, 375.
12. R. C. Schulz, H. Hartmann, *Monatsch. Chem.*, 1962, **93**, 905.
13. L. Maier, *Helv. Chim. Acta*, 1968, **51**, 1608.
14. R. B. Bedford, S. L. Hazelwood, M. E. Limmert, J. M. Brown, S. Ramdeehul, A. R. Cowley, S. J. Coles, M. B. Hursthouse, *Organometallics*, 2003, **22**, 1364.
15. *Methoden der organischen Chemie (Houben-Weil)*, 4 Aufl., B. **XII/2**, Georg Thieme Verlag, Stuttgart, 1964, S. 41.
16. *Methoden der organischen Chemie (Houben-Weil)*, 4 Aufl., B. **XII/1**, Georg Thieme Verlag, Stuttgart, 1964, S.S. 64, 193, 222.

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