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Arylation of α-Substituted Diethyl Methylphosphonates with π-Complexes of Haloarenes*

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Abstract—Nucleophilic aromatic substitution of halogen in neutral and cationic π-complexes of haloarenes η^6-(ArF)Cr(CO)$_3$ and $[\eta^6$-(ArHlg)FeCp$]^+[PF_6]^-$ (Hlg = F, Cl) by carbanions derived from α-substituted diethyl methylphosphonates $[CHZP(O)(OEt)_2]^-$ (Z = CN, COOEt), generated *in situ* by the action of Cs_2CO_3, leads to formation of the corresponding arylmethylphosphonate complexes in 78–88% yield. The reaction of the complexes $[\eta^6$-{ArCHZP(O)(OEt)$_2$}FeCp$]^+$ $[PF_6]^-$ with 1,10-phenanthroline in acetonitrile on exposure to daylight yields 32–44% of the free diethyl arylmethylphosphonates.

Reactions of aryl and hetaryl halides with stabilized carbanions containing an α-phosphinoyl group in addition to other electron-acceptor substituents lead to formation of new functionally substituted organic phosphonates and diphosphonates. Such compounds attract interest as potential biologically active substances and new synthons for preparation of aryl- or hetaryl-substituted alkenes by the Horner–Emmons reaction.

In the preceding communication [1] we reported on the arylation of carbanions derived from α-substituted dialkyl methylphosphonates with fairly electrophilic haloarenes, perfluoro- and perchloroaromatic compounds. Arylation of stabilized carbanions with nonactivated haloarenes presents a considerably more difficult problem. A known way for solving this problem is based on catalytic cross-coupling, e.g., arylation of α-phosphinoyl carbanions of the general formula $[CHZP(O)(OEt)_2]^-$ (Z = CN, SO_2R, COOEt) in the presence of an equivalent amount of CuI, which requires fairly severe conditions (DMF or HMPA, 100°C) [2]. Sakamoto *et al.* [3] reported on the only example of Pd(PPh$_3$)$_4$-catalyzed arylation of diethyl cyanomethylphosphonate (DME, 85°C). Another general way of activating haloarenes to nucleophilic attack involves π-coordination of the aromatic substrate to transition metals. This approach was successfully utilized in the arylation of a number of stabilized carbanions derived from β-dicarbonyl compounds [4–6], including diethyl malonate derivatives [7, 8]; here, haloarene complexes with cyclopentadienyliron cation were used as arylating agents.

In the present work we studied the possibility for arylation with neutral and cationic haloarene π-complexes η^6-(ArHlg)Cr(CO)$_3$ and $[\eta^6$-(ArHlg)FeCp$]^+ \cdot [PF_6]^-$ of substituted diethyl methylphosphonates of the general formula $ZCH_2P(O)(OEt)_2$ (**I**–**III**) where Z is an additional electron-acceptor group [**I**, Z = COOEt; **II**, Z = CN; **III**, Z = P(O)(OEt)$_2$]. Preliminary experiments showed that ethyl diethoxyphosphinoyl acetate (**I**) smoothly reacts with *p*-nitrofluorobenzene in DMF at room temperature in the presence of CsF or Cs_2CO_3 as a base. After 3.5 h, the corresponding arylation product was formed in 83% yield (according to the ^{31}P NMR data); the yield of the isolated product was 70% (by chromatography on silica gel). Likewise, *p*-nitrofluorobenzene readily reacted with diethyl cyanomethylphosphonate (**II**). These results led us to expect successful arylation with haloarene complexes of transition metals.

However, ester **I** failed to react with the tricarbonylchromium complex of *p*-chlorotoluene (**IV**-Cl) in the system DMF–Cs_2CO_3. No reaction was also observed with preliminarily prepared sodium salt of **I**, NaCH(COOEt)P(O)(OEt)$_2$. On prolonged heating (30 h at 60°C) in the presence of 18-crown-6, the

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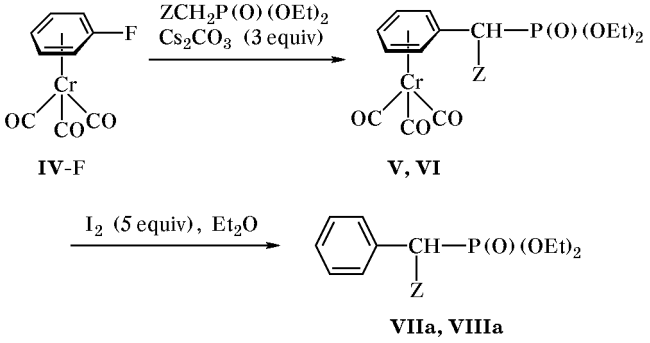
conversion of the initial compound was as low as 10%. The reaction of phosphonate **II** sodium salt $NaCH(CN)P(O)(OEt)_2$ with complex **IV**-Cl was much faster, and the corresponding product was obtained in 75% yield* in 1.5–2 h. Obviously, for the arylation to be successful it is necessary to enhance electrophilicity of the aromatic substrate in one or another way. For example, the higher mobility of fluorine atom as compared to chlorine in arene(tricarbonyl)chromium complexes can be utilized [9–11].

Both CH acids reacted with fluorobenzene–tricarbonylchromium complex **IV**-F even at room temperature in the presence of Cs_2CO_3 as a base (runs. nos. 1 and 2; Table 1). Tetrahydrofuran can be used as solvent in the reaction with cyanomethylphosphonate **II**, which facilitates isolation of the product. According to the TLC data, the reactions are sufficiently fast (in 2 h, the conversion is more than 50%), and only small amounts of by-products are formed. However, the conversion of initial fluorobezene complex **IV**-F is not complete; after 48 h, it remains in the reaction mixture even in the presence of excess (5–10%) CH acid. The products, tricarbonylchromium complexes of benzylphosphonates **V** and **VI** (Scheme 1), were isolated in good yields (77–80%) and were characterized by ^1H and ^{13}C NMR spectra (Tables 1, 2). Complexes **V** and **VI** are very sensitive to oxidation; on exposure to air they are converted into phosphonates **VIIa** and **VIIIa**. Preparative oxidation of **V** and **VI** with excess molecular iodine [11] gave compounds **VIIa** and **VIIIa** in 90% yield (70% after chromatographic purification). However, the application of fluoroarene–tricarbonylchromium complexes as arylating agents is strongly limited by difficulties in the preparation of such complexes (especially of those with fluoroarenes containing acceptor substituents) and their high lability. It is well known that coordination of an aromatic substrate to the cationic species $[C_5H_5Fe]^+$ considerably enhances electrophilicity of the former, as compared with neutral tricarbonylchromium complexes [9, 10, 12]. The complexes $[\eta^6\text{-(ArHlg)FeCp}]^+ [PF_6]^-$ are fairly resistant to oxidation (see, e.g., [12, 13]). They can be synthesized in one step from accessible starting compounds [12, 14], and hence they are free from disadvantages intrinsic to the tricarbonylchromium complexes. In keeping with some published data [9, 10, 12], the activity of such complexes in S_NAr reactions is comparable with the activity of 2,4-dinitrochlorobenzene.

Scheme 1.



V, Z = CN; **VI**, Z = COOEt.

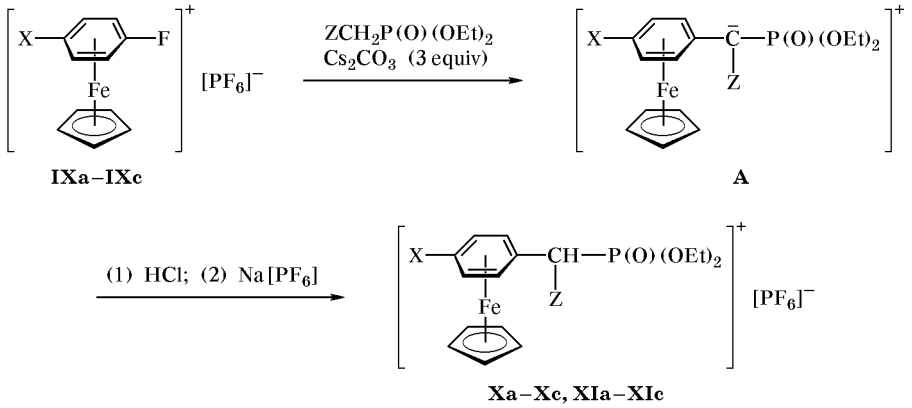
Therefore, we tried haloarene complexes with cyclopentadienyliron cation as arylating agents toward substituted dialkyl methylphosphonates $ZCH_2P(O)(OEt)_2$ [Z = COOEt, CN, $P(O)(OEt)_2$].

Cationic complexes of cyclopentadienyliron with chlorobenzene (**IXa**), *p*-dichlorobenzene (**IXb**), and *p*-fluorotoluene (**IXc**) smoothly reacted with phosphonates **I** and **II** in the presence of excess Cs_2CO_3 as a base (20°C; for the other conditions, see Table 3). The progress of the reaction can be monitored by ^{31}P NMR spectroscopy: signals of the initial CH acids disappear, and those belonging to deprotonated form **A** of the product appear. After acidification, signals from arylated CH acids **X** and **XI** are observed in the spectrum. No by-products were detected. An intense red color develops as the reaction progresses. The corresponding absorption band of complex **A** in the visible region (λ_{max} = 442–452 nm) was also used to monitor the reaction course. The reaction was assumed to be complete when the optical density no longer increased. Cationic benzylphosphonate complexes **Xa**–**Xc** and **XIa**–**XIc** (Scheme 2) were isolated in good yields (78–88%) by acidification and addition of excess $NaPF_6$. They were characterized by ^1H NMR spectra (Table 3) and analytical data.

As well as in the previously studied reactions with polyfluoroaromatic compounds [1] or fluorobenzene–tricarbonylchromium complex, cyanomethylphosphonate **II** turned out to be more reactive than phosphinoylacetate **I**. The reactions with phosphonate **II** occur at a sufficient rate in solvents which are less polar than DMF, e.g., in THF or acetonitrile. Phosphonate **II** also reacts with chlorobenzene complex **IXa** without a solvent, on intermittent grinding with a glass rod of a paste-like mixture of the reactants with Cs_2CO_3, but the process is not complete in 24 h (unlike the reaction in THF; run no. 3, Table 3). It should be noted that the higher reactivity of stronger

* The yield was calculated taking into account that only 50% of the initial CH acid can be consumed in the reaction because of subsequent transmetalation.

Scheme 2.



IXa–IXc **A** **Xa–Xc, XIa–XIc**

IX–**XI**, X = H, Hlg = Cl (**a**); X = Hlg = Cl (**b**); X = CH_3, Hlg = F (**c**); **X**, Z = CN; **XI**, Z = COOEt.

CH acid **II** is consistent with the mechanism involving proton transfer in the rate-determining stage.

p-Fluorotoluene complex **IXc** is more reactive than chloroarene complexes, but the difference is relatively small. According to published data, the presence of a positive charge in complexes like **IX** levels the effect of the ring substituent, as well as the "element effect" (F/Cl) [10].

Cesium fluoride as a base was much less efficient than Cs_2CO_3. In the reactions of complex **IXa** with both CH acids **I** and **II** in the system THF–CsF (2.5–3 equiv) and even in the system THF–DMF (1 : 1)–CsF, the conversion was as low as <5%. Better results were obtained when the reaction was carried out in DMF: the yield of the arylation product attains 40% from cyanomethylphosphonate **II** and 20% from ester **I** (20°C, 6–8 h). On heating the reaction mixtures for 6–8 h at 80°C, signals belonging to the arylation product disappear from the ^{31}P NMR spectrum, presumably because of further reaction with fluoride ion, which leads to formation of diethyl fluorophosphate and $(Ar_2CZ)Cs$ (an analogous process was studied by us in detail previously [1]). Obviously, the arylation of phosphonates $ZCH_2P(O)(OEt)_2$ in the presence of fluoride ions should not be carried out at elevated temperature.

The structure of colored complex **A** is an interesting point. Such complexes are usually represented in the form of canonical zwitterionic and neutral species $\mathbf{A_1}$ and $\mathbf{A_2}$ (Scheme 3). However, the question so as to whether this complex exists as an individual species or as an adduct with inorganic ion (Cs^+, Cl^-, $[PF_6]^-$) was not discussed [5, 7]. We have found that the signal from $[PF_6]^-$ ion decreases in intensity as the reaction progresses and that it disappears almost completely by the end of the process. Presumably, $[PF_6]^-$ ions leave the solution as the salt $CsPF_6$; therefore, addition of a hexafluorophosphate(V) salt is quite necessary for isolation of final products **X** and **XI**. Furthermore, addition of hydrochloric acid to the

Table 1. Reactions of ethyl diethylphosphinoylacetate (**I**) and diethyl cyanomethylphosphonate (**II**) with fluorobenzene–tricarbonylchromium complex **IV**-F in the presence of 3 equiv of Cs_2CO_3; 20°C

Run no.	Z	Reaction conditions	Product	Yield, %	^1H NMR spectrum (acetone-d_6, 20°C), δ, ppm
1	CN	THF, 48 h	**V**	80	1.299 t, 1.310 t (6H, CH_3); 4.17–4.25 m (4H, CH_2); 4.820 d (1H, CH, $J_{H,P}$ = 26 Hz); 5.64–5.80 (5H, C_6H_5)
2	COOEt	DMF, 48 h	**VI**	77	1.253 t, 1.259 t (6H, $POCH_2C\mathbf{H}_3$); 1.298 t (3H, $COCH_2C\mathbf{H}_3$); 4.06–4.16 m (4H, $POC\mathbf{H}_2CH_3$), 4.132 d (1H, PCH, $J_{H,P}$ = 24 Hz); 4.232 q (2H, $COC\mathbf{H}_2CH3$); 5.574 t, 5.630 t, 5.684 t (3H, *m*-H, *p*-H); 5.796 (1H, *o*-H), 6.232 (1H, *o*-H)

Table 2. ^{13}C NMR spectra of α-substituted benzylphosphonates **V**, **VIIa**, and **VIIIa**

Compound	Chemical shifts δ_C, ppm
η^6-[$C_6H_5CH(CN)P(O)(OEt)_2$]$Cr(CO)_3$ (**V**)	16.55 d (CH_3, $J_{C,P}$ = 5.5 Hz); 36.29 d (CH, $J_{C,P}$ = 133 Hz); 65.12 d (CH_2, $J_{C,P}$ = 7 Hz); 65.25 d (CH_2, $J_{C,P}$ = 7 Hz); 93.03 d (C^o, $J_{C,P}$ = 2.5 Hz); 93.94, 94.10, 94.20 (C^m, C^p); 96.08 d (C^o, $J_{C,P}$ = 2 Hz); 101.40 d (C^i, $J_{C,P}$ = 4.5 Hz); 114.82 d (CH, $J_{C,P}$ = 10 Hz), 233.10 (CO)
$C_6H_5CH(CN)P(O)(OEt)_2$ (**VIIa**)	16.48 t (CH_3, $J_{C,P}$ = 5 Hz); 36.52 d (CH, $J_{C,P}$ = 137 Hz); 64.62 t[a] (CH_2, $J_{C,P}$ = 7 Hz); 116.86 d (CN, $J_{C,P}$ = 10 Hz); 129.28 d (C^p, $J_{C,P}$ = 3 Hz); 129.63 d (C^m, $J_{C,P}$ = 3 Hz); 129.70 d (C^o, $J_{C,P}$ = 5 Hz); 129.93 d (C^i, $J_{C,P}$ = 8 Hz)
$C_6H_5CH(COOEt)P(O)(OEt)_2$ (**VIIIa**)	14.32 ($COCH_2\mathbf{C}H_3$); 16.47 d ($POCH_2\mathbf{C}H_3$, $J_{C,P}$ = 6 Hz); 16.62 d ($POCH_2$-$\mathbf{C}H_3$, $J_{C,P}$ = 6 Hz); 52.48 d (CHP, $J_{C,P}$ = 133 Hz); 61.98 ($CO\mathbf{C}H_2CH_3$); 63.22 d ($PO\mathbf{C}H_2CH_3$, $J_{C,P}$ = 6.5 Hz); 63.45 d ($PO\mathbf{C}H_2CH_3$, $J_{C,P}$ = 6.5 Hz); 128.41 d (C^p, $J_{C,P}$ = 2.5 Hz); 128.92 d (C^m, $J_{C,P}$ = 2.5 Hz); 130.68 d (C^o, $J_{C,P}$ = 6.5 Hz); 132.64 d (C^i, $J_{C,P}$ = 8.5 Hz), 168.18 (CO, $J_{C,P}$ = 3.5 Hz)

[a] Superposition of two doublets.

reaction mixture (after filtration) leads to almost quantitative precipitation of CsCl. These findings may be explained on the assumption that complex **A** in the reaction mixture exists in the form of an adduct with CsCl (CsF). Thus zwitterionic structure $\mathbf{A_1}$ is more appropriate for such complexes in solution.

The formation of nucleophilic substitution products as deprotonated species **A** is readily explainable: cationic complexes **X** and **XI** should be very strong CH acids; therefore, they should readily lose a proton by the action of Cs_2CO_3. However, it is more probable that proton abstraction occurs at the stage of formation of the corresponding σ-complex, thus facilitating elimination of halide ion; in other words, complex **A** is formed directly from the σ-complex via β-elimination of hydrogen halide (Scheme 4). This reaction path seems to be preferred to elimination of anionic species (Hlg^-) from the neutral complex, which is unfavorable at least for electrostatic reasons. Elimination of nucleofuge from the *endo*-position of such σ-complexes may also be hindered for steric reasons [10]. According to published data, a relatively high energy barrier to nucleofuge elimination is typical of nucleophilic replacement in haloarenes activated through π-coordination with transition metals, especially in the case of cationic complexes [10].

Let us consider briefly one interesting feature of the ^1H and ^{13}C NMR spectra of complexes **X** and **XI**. Protons in the *ortho*- and *meta*-positions of the aromatic ring are magnetically nonequivalent, as well as the corresponding protons and carbon nuclei in tricarbonylchromium complexes **V** and **VI** (Tables 1–3). The aromatic region of the ^1H NMR spectra of *para*-substituted complexes displays a superposition of two *AB* systems. Sutherland and co-workers [8] described an analogous nonequivalence of the two ethoxycarbonyl groups in complexes of *meta*- and *ortho*-substituted aralalkylmalonic acid esters with the $[CpFe]^+$ cation. The authors erroneously explained the observed pattern by restricted rotation about the Ar–C bond. In fact, this is the result of chiral structure of metal complexes with arenes having at least two different substituents in the *meta*- or *orto*-positions [15]. In our case, molecules **V**, **VI**, **X**, and **XI** already have

Scheme 3.

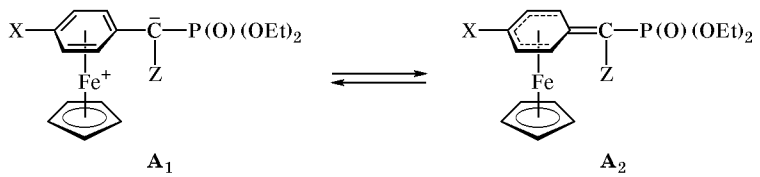


Table 3. Reactions of ethyl diethoxyphosphinoylacetate (**I**), diethyl cyanomethylphosphonate (**II**), and tetraethyl methylenediphosphonate (**III**) with complexes $[CpFeArHal]^+ [PF_6]^-$ (**IXa**–**IXc**) in the presence of Cs_2CO_3 (3 equiv); 20°C

Run no.	Initial complex	Z	Reaction conditions	Product	Yield, %	NMR spectra of **X** and **XI**,[a] δ, ppm	
						δ_P[b]	δ_H (acetone-d_6, 20°C)
1	**IXa**	CN	DMF, 1 h	**Xa**	80	26.1	1.269 t, 1.282 t (6H, CH_3); 4.15–4.26 m (4H, CH_2); 5.326 d (1H, CHP, $J_{H,P}$ = 25 Hz); 5.335 s (5H, C_5H_5); 6.59–6.75 m (5H, C_6H_5)
2			THF, 24 h	**Xa**	78	26.3	
3			No solvent, 24 h	**Xa**	65		
4	**IXa**	COOEt	DMF, 5 h	**XIa**	81	30.1	1.224 t, 1.237 t (6H, $POCH_2C\mathbf{H}_3$); 1.395 t (3H, $COCH_2C\mathbf{H}_3$); 4.109 m (4H, $POC\mathbf{H}_2CH_3$); 4.431 q (2H, $COC\mathbf{H}_2CH_3$); 4.788 d (1H, CHP, $J_{H,P}$ = 24 Hz); 5.157 s (5H, C_5H_5); 6.57 m (4H); 6.86 (1H) (C_6H_5)
5	**IXb**	CN	CH_3CN, 9 h	**Xb**	88	25.5	1.275 t, 1.289 t (6H, CH_3); 4.16–4.25 m (4H, CH_2); 5.313 d (1H, CHP, $J_{H,P}$ = 25 Hz); 5.450 s (5H, C_5H_5); 6.753 t[d] (2H), 7.001 d (1H), 7.038 (1H) (C_6H_4)
6			THF, 24 h	**Xb**	55[c]	26.4	
7	**IXb**	COOEt	DMF, 20 h	**XIb**	84	29.0	1.230 t, 1.246 t (6H, $POCH_2C\mathbf{H}_3$); 1.376 t (3H, $COCH_2C\mathbf{H}_3$); 4.115 m (4H, $POC\mathbf{H}_2CH_3$); 4.402 q (2H, $COC\mathbf{H}_2CH_3$); 4.817 d (1H, CHP, $J_{H,P}$ = 24 Hz); 5.258 s (5H, C_5H_5); 6.682 d (1H); 6.91–6.94 m, 6.969 d (3H) (C_6H_4)
8	**IXc**	CN	THF, 3 h	**Xc**	78	26.2	1.270 t, 1.285 t (6H, $POCH_2C\mathbf{H}_3$); 2.613 s (3H, $ArC\mathbf{H}_3$); 4.15–4.23 m (4H, CH_2); 5.288 d (1H, CHP, $J_{H,P}$ = 25 Hz); 5.285 s (5H, C_5H_5); 6.543 m[e] (2H); 6.578 q (2H, C_6H_4, *AB* system, $J_{A,B}$ = 6.8 Hz)
9	**IXc**	COOEt	CH_3CN, 24 h	**XIc**	83	30.3	1.228 t, 1.237 t (6H, $POCH_2C\mathbf{H}_3$); 1.385 t (3H, $COCH_2C\mathbf{H}_3$); 2.577 s (3H, $ArC\mathbf{H}_3$); 4.06–4.14 m (4H, $POC\mathbf{H}_2CH_3$); 4.417 q (2H, $COC\mathbf{H}_2$); 4.746 d (1H, CHP, $J_{H,P}$ = 24 Hz), 5.095 s (5H, C_5H_5); 6.46–6.50 m (3H); 6.780 d (1H, J = 6.7 Hz) (C_6H_4)
10	**IXa**	$P(O)(OEt)_2$	DMF, 72 h[f]	**XII**	60	29.2	1.275 t, 1.328 t (12H, $POCH_2C\mathbf{H}_3$); 4.05–4.29 m (8H, $POC\mathbf{H}_2CH_3$); 4.371 t (1H, CHP, $J_{H,P}$ = 24 Hz), 5.28 s (5H, C_5H_5); 6.563 br.s (5H, C_6H_5)

[a] ^{31}P NMR spectrum of the $[PF_6]^-$ ion and initial compounds, 20°C, δ_P, ppm (solvent): $[PF_6]^-$, –143.9 (THF), –144.3 (DMF); $CH_2(CN)P(O)(OEt)_2$, 15.8 (THF); $CH_2(COOEt)P(O)(OEt)_2$, 19.5 (DMF); $CH_2[P(O)(OEt)_2]_2$, 19.7 (DMF).

[b] $^{31}P–\{^1H\}$ NMR spectrum of deprotonated form **A** of complexes **X** and **XI** in the same solvent as that used as reaction medium; 20°C.

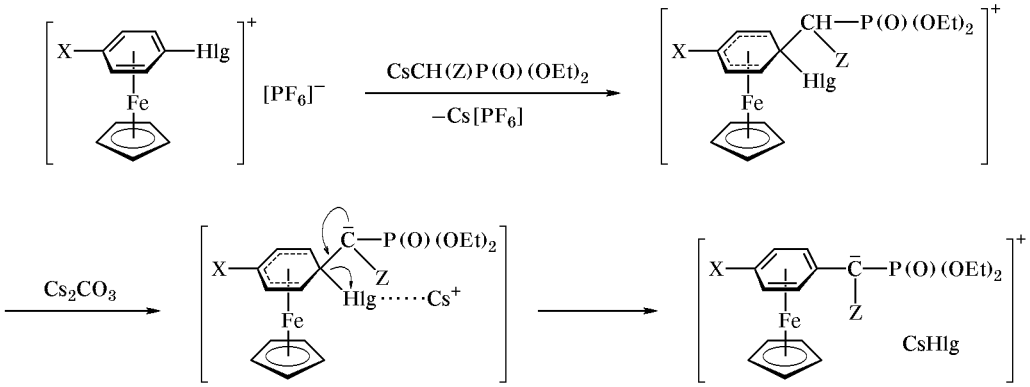
[c] Conversion 75%.

[d] Superposition of two doublets.

[e] Unresolved *AB*-quartet.

[f] The reaction was performed with 2 equiv of preliminarily prepared $NaCH[P(O)(OEt)_2]_2$.

Scheme 4.

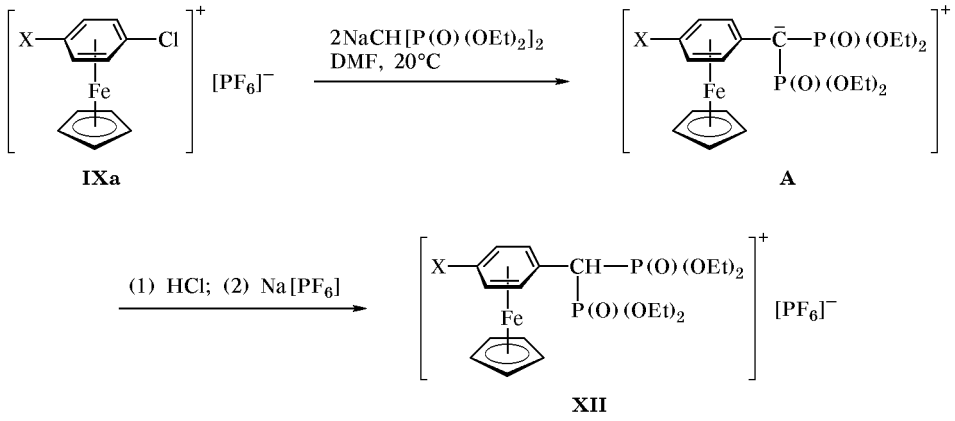


an asymmetric carbon atom [$Ar\overset{*}{C}HZP(O)(OEt)_2$], so that usually equivalent *ortho*- and *meta*-positions of the aromatic ring become diastereotopic [16].

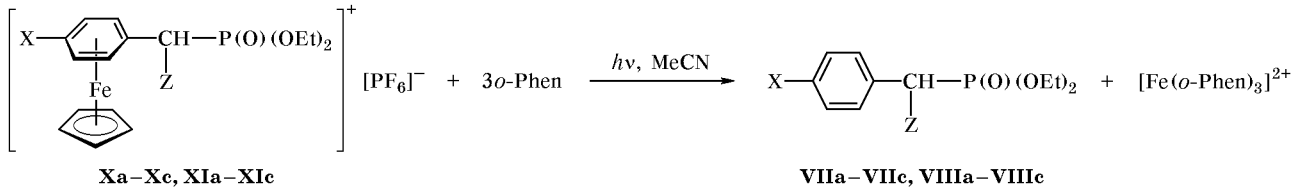
Our attempts to effect arylation of tetraethyl methylenediphosphonate (**III**) with cationic haloarene complexes under conditions of phase-transfer catalysis were unsuccessful. The reaction of bis-phosphonate **III** with *p*-fluorotoluene complex **IXc** in the presence of Cs_2CO_3 (CH_3CN, 20°C, 15 h) gave no arylation product. The ^{31}P NMR spectrum of the reaction mixture contained only the signal from the initial CH acid. Under more severe conditions (DMF, 60°C, 4 h), the yield of the arylation product did not exceed 6% (if it was formed). On the other hand, in the two cases the reaction mixture quickly turned crimson, and the absorption maximum (λ_{max} = 540 nm) was located at longer wavelengths than those typical of type **A** complexes. The $[PF_6]^-$ signal disappeared from the ^{31}P NMR spectrum, and the ^1H NMR spectrum (in CH_3CN) lacked a characteristic singlet from cyclopentadienyl fragment. These findings indicate that some reaction involving initial haloarene **IXc** does occur, but it does not lead to formation of arylation product.

The sodium salt $NaCH[P(O)(OEt)_2]_2$, prepared from phosphonate **III** by the action of NaH, slowly reacts with chlorobenzene complex **IXa** in DMF following Scheme 5. According to the ^{31}P NMR data, the reaction with 2 equiv of $NaCH[P(O)(OEt)_2]_2$ at a concentration of ~0.5 M proceeds by 75% in 18 h at 20°C. On further increase of the reaction time, the signal from complex **A** in the ^{31}P NMR spectrum no longer increases but begins to decrease. At the same time, the intensity of the signal at δ_P ~20 ppm, which belongs to free CH acid **III** or its mixture with unidentified by-products, continuously increases (up to 65% of the overall signal intensity). In addition, broadening of the ^{31}P signals from phosphinoyl groups is observed. The desired product, cationic arylmethylenediphosphonate complex **XII**, was isolated in 60% yield by appropriate treatment of the reaction mixture, and its ^1H NMR spectrum was recorded (run no. 10; Table 3). Strangely enough, carbanion of the weakest CH acid **III** (pK_a 23; calculated by the

Scheme 5.



Scheme 6.



Xa–Xc, XIa–XIc **VIIa–VIIc, VIIIa–VIIIc**

VII, **X**, Z = CN; **VIII**, **XI**, Z = COOEt; *o*-Phen = 1,10-phenanthroline.

Kabachnik equation [17]) turned out to be the least nucleophilic in the series under study. This may be due to strong association of its salts in solution.

An important aspect of using the above reactions as a method of arylation of substituted methylphosphonates is transformation of the resulting complexes **X** and **XI** into free arylmethylphosphonates. A number of procedures were proposed for liberation of arene ligands from their complexes with cyclopentadienyliron cation. These include photolysis in a donor solvent, e.g., acetonitrile [6, 18], vacuum pyrolysis [5, 7], reaction with 1,10-phenanthroline in daylight [18, 19], and treatment with sodium *tert*-butoxide [19]. The latter procedure is efficient even in the case of sterically hindered arene ligands but is totally inapplicable to complexes with arylmethylphosphonates. The latter, as strong CH acids, will react with *t*-BuONa to give less electrophilic neutral type **A** comlexes through elimination of proton. The reaction with *t*-BuONa can also involve ester and CH moieties which are sensitive to bases.

The most widely used procedure for isolation of arylation products of stabilized carbanions (such as malonates and other β-dicarbonyl compounds) from their complexes with $[CpFe]^+$ is vacuum pyrolysis which usually occurs at 200–220°C (0.1–1 mm) [5, 7]. In fact, by vacuum pyrolysis of the complexes $[\eta^6\text{-Ar}\{CH(CN)P(O)(OEt)_2\}FeCp]^+[PF_6]^-$ (**X**) we obtained the corresponding arylmethylphosphonates **VII**, but their yields were poor (10–20%). Moreover, a number of by-products were formed, some of which could not be separated by column chromatography. We succeeded in isolating the whole series of phosphonates **VII** and **VIII**, though in moderate yields (32–44%), by an alternative procedure, namely by treatment of complexes **X** and **XI** with 1,10-phenanthroline under day(sun)light (Scheme 6). It should be noted that decomposition of the complexes was not quantitative. According to the electron absorption spectra in the visible region, the concentration of phenathroline–iron complex $[Fe(o\text{-Phen})_3]^{2+}$ reaches 70% of the theoretically possible one, and it no longer increases. Most arylmethylphosphonates **VII** and **VIII** were reported previously (see, e.g., [2, 3]) and were identified by the ^1H NMR spectra (Table 4) and ^{13}C NMR spectra (for **VIIa** and **VIIIa**; Table 2). Newly synthesized compounds **VIIIb** and **VIIIc** were additionally characterized by elemental analysis.

EXPERIMENTAL

The ^1H (400 MHz), ^{31}P (161.90 MHz), and ^{13}C (100.58 MHz) NMR spectra were recorded on a Varian VXR-400 spectrometer. The ^{31}P NMR spectra were also measured on a Varian FT-80A instrument operating at 32.4 MHz. The ^{31}P chemical shifts were measured relative to 85% H_3PO_4 as external reference. The electron absorption spectra in the visible region were recorded on a Hewlett–Packard 8452A spectrophotometer.

Cesium carbonate and fluoride were dried for 2–4 h at 100–180°C under reduced pressure over P_2O_5. Dimethylformamide, tetrahydrofuran, and acetonitrile were dried and purified by standard procedures; THF was stored over potassium diphenylketyl. π-Complexes **IX** of haloarenes with cyclopentadienyliron cation were synthesized by reaction of ferrocene with the corresponding haloarenes in the presence of $AlCl_3$ and powdered aluminum [12, 14] and were purified by reprecipitation from acetone with excess diethyl ether. Complexes **IXb** and **IXc** were additionally recrystallized from acetone–benzene. Tricarbonylchromium complexes of haloarenes and substituted methylphosphonates **I**–**III** were synthesized by known methods. Their physical properties were in agreement with published data.

Reaction of substituted diethyl methylphosphonates with haloarene π-complexes under conditions of phase-transfer catalysis (*general procedure***).** A flat-bottom Schlenk vessel was charged with preliminarily dried powdered CsF or Cs_2CO_3 and was evacuated for 0.5 h at 180°C. Haloarene complex, CH acid (usually in 5–15% excess), and DMF were added in succession under counterstream of argon, and the

Table 4. Reactions of the complexes $[CpFeArCH(Z)P(O)(OEt)_2]^+ [PF_6]^-$ (**X** and **XI**) with 1,10-phenanthroline (3 equiv) in daylight; CH_3CN, concentration of **X** and **XI** 0.02–0.035 M, 20°C

Initial complex			Product	Yield, %	^{1}H NMR spectrum (acetone-d_6, 20°C), δ, ppm
no.	X	Z			
Xa	H	CN	**VIIa**	32	1.213 t, 1.243 t (6H, CH_3); 3.96–4.15 m (4H, CH_2); 4.903 d (1H, CHP, $J_{H,P}$ = 26.5 Hz); 7.37–7.47 m (3H, *m*-H, *p*-H); 7.49–7.54 m (2H, *o*-H)
XIa	H	COOEt	**VIIIa**	43	1.107 t (3H, $COCH_2CH_3$); 1.229 t, 1.234 t (6H, $POCH_2CH_3$); 3.83–4.24 m (6H, CH_2); 4.360 d (1H, CHP, $J_{H,P}$ = 24 Hz); 7.23–7.37 m (3H, *m*-H, *p*-H); 7.56–7.60 m (2H, *o*-H)
Xb	Cl	CN	**VIIb**	44	1.239 t, 1.257 t (6H, CH_3); 4.00–4.19 m (4H, CH_2); 4.961 d (1H, CHP, $J_{H,P}$ = 26.5 Hz); 7.48–7.54 m (5H, C_6H_4)
XIb	Cl	COOEt	**VIIIb**	40	1.128 t (3H, $COCH_2CH_3$); 1.235 t, 1.242 t (6H, $POCH_2CH_3$); 3.87–4.23 m (6H, CH_2); 4.425 d (1H, CHP, $J_{H,P}$ = 24 Hz); 7.386 d (2H), 7.599 d (2H, C_6H_4)
Xc	CH_3	CN	**VIIc**	42	1.216 t, 1.248 t (6H, $POCH_2CH_3$); 2.332 s (3H, $ArCH_3$); 3.97–4.15 m (4H, CH_2); 4.838 d (1H, CHP, $J_{H,P}$ = 26.5 Hz); 7.249 d (2H), 7.382 d.q (2H, C_6H_4, J_q = 2.3 Hz)
XIc	CH_3	COOEt	**VIIIc**	36	1.119 t (3H, $COCH_2CH_3$); 1.223 t, 1.230 t (6H, $POCH_2CH_3$); 2.299 d (3H, $ArCH_3$, J = 2 Hz); 3.84–4.22 m (6H, CH_2); 4.293 d (1H, CHP, $J_{H,P}$ = 23.5 Hz); 7.152 d (2H), 7.445 d.q (2H, C_6H_4, J_q = 2.3 Hz)

mixture was evacuated. When the reaction was carried out in THF or acetonitrile, the solvent was recondensed through a vacuum line. The mixture was agitated using a magnetic stirrer under argon with protection from direct daylight, for (η^6-arene)(cyclopentadienyl)iron(II) complexes are very sensitive to light [12]. When the reaction was performed without a solvent, the paste-like mixture was intermittently ground with a glass rod. The conditions are given in Tables 1 and 3. The progress of the reactions was monitored by spectrophotometry. For this purpose, 0.02-ml samples were withdrawn and diluted with 500–1250 volumes of acetone, and absorption spectrum of the resulting solution was recorded immediately. When the reaction was complete, a part of the mixture was transferred into an NMR ampule, the ampule was sealed, and ^{31}P NMR spectrum was recorded. To monitor the reaction course by ^{31}P NMR spectroscopy, the reaction was carried out directly in an NMR ampule which was charged with the reactants and solvent in the same order as above; after evacuation, the ampule was sealed. In this case, the mixture was stirred by fixing the ampule at a rotor shaft.

Reactions of haloarene π-complexes with substituted methylphosphonate sodium salts. The reactions were carried out in a device consisting of two reservoirs which were connected through a tube with a built-in glass filter. One reservoir had a side arm separated by a constriction, and an NMR ampule was built in the second reservoir. The latter was charged with initial haloarene π-complex (~0.5 mmol), and the first reservoir (with a side arm) was charged with 1.5–2 equiv of NaH as a 60% suspension in mineral oil. The setup was evacuated, and tetrahydrofuran was recondensed therein to remove mineral oil from NaH. The solution was collected in the side arm which was then sealed off. The solvent was evaporated, the setup was filled with argon, 1.5–2 ml of argon-saturated DMF was added to sodium hydride, 1 equiv of appropriate CH acid was then added, and the mixture instantaneously foamed. It was stirred with a magnetic stirrer with intermittent evacuation until hydrogen no longer evolved (30–40 min), and the resulting colorless solution of CH acid sodium salt was filtered into the second reservoir containing haloarene π-complex; the complex dissolved completely. A part of the solution was placed into the built-in NMR ampule, the latter was sealed off, and ^{31}P NMR spectrum was recorded when necessary.

Isolation of (η^6-diethyl arylmethylphosphonate)-(η^5-cyclopentadienyl)iron(II) hexafluorophosphates(V). The reaction mixture was filtered through

Celite® into 0.2–0.4 ml of concentrated hydrochloric acid, the originally bright red filtrate instantaneously turned pale yellow, and a colorless solid (CsCl) precipitated. The filter was repeatedly washed with acetone, and the solution was separated from the CsCl precipitate by decanting, concentrated to a volume of 1–3 ml, and poured into an aqueous solution of $NaPF_6$ (1.5–2 equiv). A brown–yellow oily liquid separated. The aqueous phase was extracted with 3 portions of methylene chloride, the extracts were compbined with the oily substance, and the mixture was evaporated to dryness on a rotary evaporator. The residue was dissolved in 2–4 ml of acetone, the solution was diluted with a 10–15-fold amount of diethyl ether, and the product, $[\eta^6\text{-Ar}\{CH(Z)P(O)(OEt)_2\}FeCp]^+ [PF_6]^-$ [Z = CN, COOEt, $P(O)(OEt)_2$], was isolated as a brown–yellow oily liquid which foamed on evacuation and solidified to form a pale–yellow foam-like material. The ^1H and ^{31}P NMR spectra of the complexes are given in Table 3.

(η^6-Diethyl α-cyanobenzylphosphonate)(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (Xa) was synthesized from 180 mg of phosphonate **II**, 375 mg of complex **IXa**, and 1.1 g of Cs_2CO_3 in 1.5 ml of THF. Yield 400 mg (78%). Found, %: C 38.91; H 3.87; P 12.01. $C_{17}H_{21}F_6FeNO_3P_2$. Calculated, %: C 39.33; H 4.08; P 11.93.

[η^6-Ethyl diethoxyphosphinoyl(phenyl)acetate]-(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (XIa) was synthesized from 350 mg of phosphonate **I**, 568 mg of complex **IXa**, and 1.46 g of Cs_2CO_3 in 1.6 ml of DMF. Yield 690 mg (81%). Found, %: C 40.16; H 4.51; P 10.70. $C_{19}H_{26}F_6FeO_5P_2$. Calculated, %: C 40.31; H 4.63; P 10.94.

(η^6-Diethyl *p*-chloro-α-cyanobenzylphosphonate)(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (Xb) was synthesized from 235 mg of phosphonate **II**, 520 mg of complex **IXb**, and 1.2 g of Cs_2CO_3 in 2 ml of acetonitrile. Yield 610 mg (88%). Found, %: C 36.91; H 3.36; P 11.18. $C_{17}H_{20}ClF_6FeNO_3P_2$. Calculated, %: C 36.88; H 3.64; P 11.19.

[η^6-Ethyl *p*-chlorophenyl(diethoxyphosphinoyl)-acetate](η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (XIb) was synthesized from 240 mg of phosphonate **I**, 415 mg of complex **IXb**, and 1.05 g of Cs_2CO_3 in 1.3 ml of DMF. Yield 510 mg (84%). Found, %: C 38.36; H 4.21. $C_{19}H_{25}ClF_6FeO_5P_2$. Calculated, %: C 37.99; H 4.20.

(η^6-Diethyl α-cyano-*p*-methylbenzylphosphonate)(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (Xc) was synthesized from 200 mg of phosphonate **II**, 400 mg of complex **IXc**, and 1.12 g of Cs_2CO_3 in 1.5 ml of tetrahydrofuran. Yield 430 mg (77%). Found, %: C 40.24; H 4.17; P 11.52. $C_{18}H_{23}F_6FeNO_3P_2$. Calculated, %: C 40.55; H 4.35; P 11.62.

[η^6-Ethyl diethoxyphosphinoyl(*p*-tolyl)acetate]-(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (XIc) was synthesized from 245 mg of phosphonate **I**, 385 mg of complex **IXc**, and 1.2 g of Cs_2CO_3 in 1 ml of acetonitrile. Yield 460 mg (78%). Found, %: C 40.76; H 5.01. $C_{20}H_{28}F_6FeO_5P_2$. Calculated, %: C 41.40; H 4.86.

[η^6-Tetraethyl benzylidenediphosphonate)(η^5-cyclopentadienyl)iron(II) hexafluorophosphate(V) (XII) was synthesized from 125 mg of bis-phosphonate **III**, 82 mg of complex **IXa**, and 30 mg of NaH in 1 ml of DMF. Yield 81 mg (60%). Found, %: C 38.04; H 4.79. $C_{20}H_{31}F_6FeO_6P_3$. Calculated, %: C 38.12; H 4.96.

Isolation of (η^6-diethyl arylmethylphosphonate)-tricarbonylchromium(0) complexes. Excess hydrochloric acid was added to the reaction mixture, the product was extracted into diethyl ether, the extract was washed with water and evaporated to dryness on a rotary evaporator, and the residue was subjected to column chromatography on silica gel L (40/100 μm). Unchanged (η^6-fluorobenzene)tricarbonylchromuim(0) was eluted with methylene chloride–petroleum ether–ethyl acetate (5:10:1); a number of unidentified products were eluted by gradually increasing the fraction of ethyl acetate in the eluent; and the major fraction was collected when the fraction of ethyl acetate in the eluent attained 20–30%. The NMR spectra of the products are given in Tables 1 and 2.

(η^6-Diethyl α-cyanobenzylphosphonate)tricarbonylchromium(0) (V) was synthesized from 190 mg of phosphonate **II**, 220 mg of complex **III**-F, and 0.95 g of Cs_2CO_3 in 2 ml of tetrahydrofuran. Yield 295 mg (80%).

[η^6-Ethyl diethoxyphosphinoyl(phenyl)acetate]-tricarbonylchromium(0) (VI) was synthesized from 250 mg of phosphonate **I**, 260 mg of complex **III**-F, and 1.1 g of Cs_2CO_3 in 1.6 ml of dimethylformamide. Yield 375 mg (77%).

Vacuum pyrolysis of (η^6-diethyl benzylphosphonate)(η^5-cyclopentadienyl)iron(II) hexafluorophosphates(V). A 100–300-mg portion of the complex was dissolved in 1–3 ml of methylene chloride, and the solution was carefully evaporated in a vacuum sublimator in such a way that the residue formed an even film on the walls. The setup was evacuated to 0.1 mm and was heated to 200–220°C over a period

of 2–3 h. The dark sublimate was washed off from the finger condenser with acetone and was subjected to chromatography on a 15-cm column charged with silica gel L (40/100 μm). The column was eluted first with methylene chloride–petroleum ether (10 : 15), and ethyl acetate was then gradually added to the eluent. Initially, a number of unidentified products were washed off from the column. A fraction containing the major product was collected when the eluent contained 20–30% of ethyl acetate.

Isolation of arylphosphonates by reaction of (η^6-diethyl benzylphosphonate)(η^5-cyclopentadienyl)iron(II) complexes with 1,10-phenanthroline. A 140–500-mg portion (1 equiv) of appropriate complex and 3 equiv of 1,10-phenanthroline were dissolved in acetonitrile to attain an initial complex concentration of 0.02–0.035 M (at higher concentrations the yield of the product was lower). The solution was stirred in a glass flask with a magnetic stirrer on exposure to sunlight. The progress of the reaction was monitored by electron spectroscopy. A 0.02-ml sample of the mixture was diluted with a 100-fold volume of acetone, and the optical density was measured at the absorption maximum of the iron(II) complex with 1,10-phenanthroline $[Fe(o\text{-Phen})_3]^{2+}$, λ_{max} = 508 nm, $\varepsilon \approx 11\,000$. After 2.5–4 h, the optical density no longer increased, and an appreciable amount of a solid separated from the solution. The mixture was kept for an additional 1–2 h on exposure to light and evaporated to dryness. The residue was passed through a short (*h* = 3–4 cm) column charged with silica gel L (40/100 μm) using chloroform as eluent. The eluate was shaken with 0.1–0.2 ml of concentrated hydrochloric acid to remove 1,10-phenanthroline and was filtered again through a similar column (see above). The ^{1}H and ^{13}C NMR spectra of the products are given in Tables 4 and 2, respectively.

Diethyl α-cyanobenzylphosphonate (VIIa) [2, 3] was synthesized from 550 mg of complex **Xa** and 580 mg of 1,10-phenanthroline in 33 ml of acetonitrile. Reaction time 4.5 h. Yield 85 mg (32%). Oily liquid.

Ethyl diethoxyphosphinoyl(phenyl)acetate (VIIIa) [2] was synthesized from 530 mg of complex **XIa** and 530 mg of 1,10-phenanthroline in 35 ml of acetonitrile. Reaction time 4 h. Yield 120 mg (43%). Oily liquid.

Diethyl *p*-chloro-α-cyanobenzylphosphonate (VIIb) [20] was synthesized from 145 mg of complex **Xb** and 155 mg of 1,10-phenanthroline in 13 ml of acetonitrile. Reaction time 5 h. Yield 34 mg (44%). Oily liquid.

Ethyl *p*-chlorophenyl(diethoxyphosphinoyl)acetate (VIIIb) was synthesized from 340 mg of complex **XIb** and 340 mg of 1,10-phenanthroline in 17.5 ml of acetonitrile. Reaction time 7 h. Yield 80 mg (40%). Oily liquid. Found, %: C 50.04; H 6.43; P 9.49. $C_{14}H_{20}ClO_5P$. Calculated, %: C 50.23; H 6.02; P 9.25.

Diethyl α-cyano-*p*-methylbenzylphosphonate (VIIc) [3, 20] was synthesized from 180 mg of complex **Xc** and 185 mg of 1,10-phenanthroline in 14 ml of acetonitrile. Reaction time 5 h. Yield 39 mg (42%). Oily liquid.

Ethyl diethoxyphosphinoyl(*p*-tolyl)acetate (VIIIc) was synthesized from 220 mg of complex **XIc** and 245 mg of 1,10-phenanthroline in 12 ml of acetonitrile. Reaction time 7 h. Yield 43 mg (36%). Oily liquid. Found, %: C 56.84; H 7.54; P 9.65. $C_{15}H_{23}O_5P$. Calculated, %: C 57.32; H 7.38; P 9.85.

REFERENCES

1. Artamkina, G.A., Tarasenko, E.A., Lukashev, N.V., and Beletskaya, I.P., *Tetrahedron Lett.*, 1998, vol. 39, pp. 901–904; Tarasenko, E.A., Artamkina, G.A., Voevodskaya, T.I., Lukashev, N.V., and Beletskaya, I.P., *Russ. J. Org. Chem.*, 1998, vol. 34, no. 10, pp. 1459–1463.
2. Suzuki, H., Watanabe, K., and Yi, Q., *Chem. Lett.*, 1985, pp. 1779–1780; Minami, T., Isonaka, T., Okada, Y., and Ichikawa, J., *J. Org. Chem.*, 1993, vol. 58, no. 25, pp. 7009–7015.
3. Sakamoto, T., Katoh, E., Kondo, Y., and Yamanaka, H., *Heterocycles*, 1988, vol. 27, no. 6, pp. 1353–1356; Sakamoto, T., Katoh, E., Kondo, Y., and Yamanaka, H., *Chem. Pharm. Bull.*, 1990, vol. 38, no. 6, pp. 1513–1517.
4. Moriarty, R.M. and Gill, U.S., *Organometallics*, 1986, vol. 5, no. 2, pp. 253–256.
5. Abd-El-Aziz, A.S., Lee, C.C., Piorko, A., and Sutherland, R.G., *J. Organomet. Chem.*, 1988, vol. 348, pp. 95–107.
6. Abd-El-Aziz, A.S., Boraie, W., Al-Salem, N., Sadek, S.A., and Epp, K.M., *J. Chem. Soc., Perkin Trans. 1*, 1997, pp. 1469–1479.
7. Abd-El-Aziz, A.S., Lee, C.C., Piorko, A., and Sutherland, R.G., *Synth. Commun.*, 1988, vol. 18, no. 3, pp. 291–300.
8. Piorko, A., Abd-El-Aziz, A.S., Lee, C.C., and Sutherland, R.G., *J. Chem. Soc., Perkin Trans. 1*, 1989, pp. 469–475.
9. Nesmeyanov, A.N., Vol'kenau, N.A., Isaeva, L.S., and Bolesova, I.N., *Dokl. Akad. Nauk SSSR*, 1968, vol. 183, no. 4, pp. 834–837.

10. Litvak, V.V. and Shteingarts, V.D., *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Khim.*, 1983, no. 4, pp. 59–68.
11. Semmelhack, M.F. and Hall, H.T., *J. Am. Chem. Soc.*, 1974, vol. 96, pp. 7091–7092.
12. Nikitina, T.V., *Metody elementoorganicheskoi khimii* (Methods of Organometallic Chemistry), Nesmeyanov, A.N. and Kocheshkov, K.A., Eds., Moscow: Nauka, 1985, pp. 371–384.
13. Storm, J.P. and Andersson, C.-M., *J. Org. Chem.*, 2000, vol. 65, no. 17, pp. 5264–5274.
14. Nesmeyanov, A.N., Vol'kenau, N.A., and Bolesova, I.N., *Dokl. Akad. Nauk SSSR*, 1963, vol. 149, no. 3, pp. 607–610.
15. Potapov, V.M., *Stereokhimiya* (Stereochemistry), Moscow: Khimiya, 1988, pp. 19, 433.
16. Ustynyuk, Yu.A., Artamkina, G.A., Luzikov, Yu.N., Grishin, Yu.K., Azizov, A.A., and Beletskaya, I.P., *Zh. Org. Khim.*, 1976, vol. 12, no. 8, pp. 1615–1618.
17. Kabachnik, M.I. and Mastryukova, T.A., *Russ. J. Gen. Chem.*, 1993, vol. 63, no. 1, pp. 1–16.
18. Pearson, A.J., Gelormini, A.M., Fox, M.A., and Natrins, D., *J. Org. Chem.*, 1996, vol. 61, no. 4, pp. 1297–1305.
19. Brown, R.A., Fernando, S.I.S., and Roberts, R.M.G., *J. Chem. Soc., Perkin Trans. 1*, 1994, pp. 197–201.
20. Kim, D.Y. and Oh, D.Y., *Synth. Commun.*, 1987, vol. 17, no. 8, pp. 953–958.