Synthesis of 1-arylcyclopropylphosphonates*

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A simple method for the synthesis of 1-arylcyclopropylphosphonates was proposed. The method involves treatment of 1-arylethenylphosphonic acids or their esters with diazomethane followed by thermolysis of intermediate 3-aryl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonates.

Key words: cyclopropylphosphonates, 4,5-dihydro-3*H*-pyrazol-3-ylphosphonates, vinylphosphonates, diazomethane, [2+3] cycloaddition, organophosphorus compounds.

Interest in cyclopropylphosphonates and cyclopropylphosphonic acids is due to their known biological activities. For instance, some compounds of this class have been found to be antagonists for the NMDA receptor,[1] inhibitors of alanine racemase and aminocyclopropanecarboxylate deaminase,[2] and insectoacaricides.[3]

Several approaches to the design of the cyclopropane ring in cyclopropylphosphonates have been documented. This is mostly done *via* reactions of olefins with diazophosphonate.[1,4—17] Reactions of vinylphosphonate with diazo compounds are employed in substantially fewer studies.[18—25] In both cases, the reaction is carried out in both the presence[1,7—17,25] and in the absence of a catalyst.[4,5,18—24]

Other methods include reactions of vinylphosphonates with Fischer carbene complexes,[26,27] dihalocarbenes,[3,28] or sulfur ylides;[24,29—32] nucleophilic addition of substituted α-halomethylphosphonate anions to the Michael acceptors followed by intramolecular S_N2 cyclization;[33—39] intramolecular cyclization of alkylphosphonate anions containing a leaving group in the γ-position;[2,40—44] Lewis acid-promoted [2+1] cycloaddition of 1-seleno-2-silylethene to 1-(methoxycarbonyl)vinylphosphonates.[45]

The proposed synthetic routes lead to a sufficiently broad variety of structures. When choosing target molecules with potential biological activity, two basic principles are guided. First, phosphorus analogs of cyclopropanecarboxylic acids with already known activity are intensively synthesized. For instance, *P*-analogs of (±)-(*Z*)-*N*,*N*-diethyl-2-aminomethyl-1-phenylcyclopropanecarboxamide (antidepressant Minalcipran),[38] chrysanthemic acid,[9] and (—)-*allo*-norcoronamic acid[44] have been obtained.

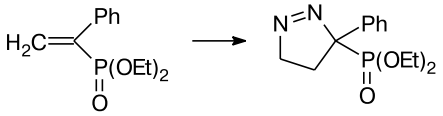
According to the other approach, known biologically active acyclic phosphonates are modified by introduction of the cyclopropane fragment to restrict the skeleton conformationally. For instance, cyclopropyl analogs of D-2-amino-5-phosphonopentanoic acid (NMDA antagonist),[1] 3-amino-2-(4-chlorophenyl)propylphosphonic acid ($GABA_B$ antagonist Phaclophen),[30,32,35] and the nucleotide (*E*)-9-(4-phosphonobut-3-enyl)adenine[31,43] exhibiting antiretroviral activity have been obtained.

In this context, the synthesis of 1-arylcyclopropylphosphonates, which are conformationally constrained analogs of 1-arylethylphosphonic acids, are of interest. The latter are phosphorus analogs of 2-arylpropionic acids (a well-known class of nonsteroidal antiinflammatory and analgesic drugs such as naproxen and ibuprofen) and exhibit negative inotropic,[46] Ca^{2+}-antagonistic,[46,47] neuroprotective,[47] and psychotropic activities,[47] inhibit cyclooxygenase,[48] and serve as haptens of reactive immunization.[49,50] Here we studied the cyclopropanation of 1-arylethenylphosphonic acids[51] with diazomethane as the simplest synthetic route to 1-arylcyclopropylphosphonates.

Results and Discussion

A reaction of diethyl 1-phenylethenylphosphonate (**1a**) with diazomethane (2 equiv.) in ether for 3 h gave diethyl 3-phenyl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (**2a**) as the sole product (Scheme 1). In the ^{31}P NMR spec-

Scheme 1



1a (δ_P 17.7) **2a** (δ_P 19.8)

Reagents and conditions: CH_2N_2, Et_2O, 20 °C, 3 h; ~100% yield.

* Dedicated to Academician G. A. Abakumov on the occasion of his 70th birthday.

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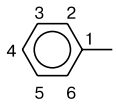
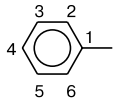
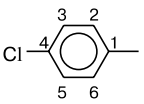
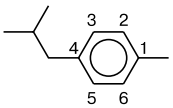
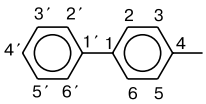
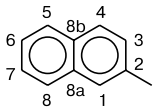
trum of the reaction mixture, the signal of the starting compound **1a** at δ_P 17.7 disappears; instead, a new signal appears at δ_P 19.8.

The structure of product **2a** isolated in quantitative yield was proved by elemental analysis and spectroscopic methods. The IR spectrum exhibits a characteristic set of bands corresponding to the diethoxyphosphoryl fragment: a band at 1260 cm^{-1} (P=O stretching vibrations), a broad band at 980 cm^{-1} (C—C stretch), and two very strong bands at 1030 and 1060 cm^{-1} (O—C stretch).[52] The stretching vibrations of the endocyclic N=N bond give rise to a weak band at 1560 cm^{-1}. 4,5-Dihydro-3*H*-pyrazol-3-ylphosphonates can undergo prototropic isomerization into 4,5-dihydro-1*H*-pyrazol-5-ylphosphonates.[8,19,20,53] However, this is not the case with product **2a** because its IR spectrum contains no intense absorption bands in the range characteristic of ν(N—H) and ν(C=N) (usually, 1595—1635 cm^{-1}).[19,20,53] The ^{13}C (Table 1) and ^1H NMR spectra (Table 2) of product **2a** show two sets of signals for the diastereotopic ethoxy groups. The ^{13}C NMR spectrum exhibits a characteristic doublet at δ_C 98.02 ($^1J_{CP}$ = 148.0 Hz) for the quaternary C atom. Four complex multiplets correspond to the protons of the five-membered heterocycle. The two low-field multiplets (δ_H 4.58 and 4.79) probably relate to the strongly coupled CH_2N protons, while the two high-field multiplets (δ_H 1.84 and 2.67) relate to the CH_2CP protons. The considerable difference in the chemical shifts of the latter is due to the vicinity of the asymmetric center.

Treatment of 1-arylethenylphosphonic acids (**1b—f**) with diazomethane (4—5 equiv.) gave the corresponding dimethyl 3-aryl-4,5-dihydro-3*H*-pyrazol-3-ylphosphon-

Table 1. ^{13}C NMR spectra of 3-aryl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonates **2a—f**

Compound	R	Ar	^{13}C NMR ($CDCl_3$), δ (*J*/Hz)				
			P(O)$(OR)_2$	Pyrazoline ring			Ar*
				$\underline{C}H_2CP$	CH_2N	CP	
2a	CH_2Me		15.89 (Me); 15.94 (Me); 62.86 (d, $^2J_{C,P}$ = 7.7, CH_2); 63.66 (d, $^2J_{C,P}$ = 6.9, CH_2)	27.34	77.36	98.02 (d, $^1J_{C,P}$ = 148.0)	126.93 (d, C(2), C(6), $^3J_{C,P}$ = 4.6); 127.55 (C(4)); 128.04 (C(3), C(5)); 137.55 (d, C(1), $^2J_{C,P}$ = 4.6)
2b	Me		53.75 (d, $^2J_{C,P}$ = 7.6); 54.55 (d, $^2J_{C,P}$ = 7.6)	27.60	77.65	98.22 (d, $^1J_{C,P}$ = 147.5)	127.15 (d, C(2), C(6), $^3J_{C,P}$ = 4.2); 128.01 (C(4)); 128.50 (C(3), C(5)); 137.56 (d, C(1), $^2J_{C,P}$ = 5.1)
2c	Me		53.85 (d, $^2J_{C,P}$ = 5.9); 54.51 (d, $^2J_{C,P}$ = 7.6)	27.56	77.85	97.78 (d, $^1J_{C,P}$ = 148.4)	128.50 (d, C(2), C(6), $^3J_{C,P}$ = 4.2); 128.66 (C(3), C(5)); 134.05 (C(4)); 136.13 (d, C(1), $^2J_{C,P}$ = 6.7)
2d	Me		53.48 (d, $^2J_{C,P}$ = 7.7); 54.40 (d, $^2J_{C,P}$ = 6.9)	27.36	77.43	97.85 (d, $^1J_{C,P}$ = 147.2)	22.08 (Me); 29.88 (CH); 44.73 (CH_2); 126.69 (d, C(2), C(6), $^3J_{C,P}$ = 3.8); 129.04 (C(3), C(5)); 134.49 (d, C(1), $^2J_{C,P}$ = 5.4); 141.38 (C(4))
2e	Me		53.69 (d, $^2J_{C,P}$ = 6.9); 54.43 (d, $^2J_{C,P}$ = 6.9)	27.43	77.60	98.00 (d, $^1J_{C,P}$ = 148.0)	126.82, 126.99 (C(2), C(6), C(2′), C(6′)); 127.36 (C(4′)); 127.43 (d, C(3), C(5), $^3J_{C,P}$ = 4.6); 128.63 (C(3′), C(5′)); 136.38 (d, C(4), $^2J_{C,P}$ = 6.1); 140.06, 140.65 (C(1), C(1′))
2f	Me		53.76 (d,$^2J_{C,P}$ = 6.9); 54.56 (d, $^2J_{C,P}$ = 6.9)	27.70	77.66	98.24 (d, $^1J_{C,P}$ = 148.0)	124.92 (C(3)); 126.04 (d, C(1), $^3J_{C,P}$ = 6.9); 126.35, 126.39, 127.49, 128.18 (2C) (C(4), C(5), C(6), C(7), C(8)); 132.66, 132.87 (C(8a), C(8b)); 134.91 (d, C(2), $^2J_{C,P}$ = 5.4)

* The signals for the C atoms of the aromatic ring were assigned with consideration for known[54] substituent increments.

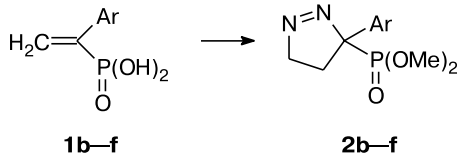
Table 2. ^{1}H and ^{31}P NMR spectra ($CDCl_3$) of 3-aryl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonates **2a—f**

Compound	^{1}H NMR, δ (*J*/Hz)				^{31}P NMR δ
	$P(O)(OR)_2$	Pyrazoline ring		Ar*	
		CH_2CP (m, 1 H)	CH_2N (m, 1 H)		
2a	1.16 (t, 3 H, Me, $^{3}J_{H,H}$ = 7.1); 1.26 (t, 3 H, Me, $^{3}J_{H,H}$ = 7.0); 3.84 (m, 1 H, CH_2); 3.95 (m, 1 H, CH_2); 4.07 (m, 2 H, CH_2)	1.84, 2.67	4.58, 4.79	7.30 (m, 1 H, H(4)); 7.38 (t, 2 H, H(3), H(5), $^{3}J_{H,H}$ = 7.2); 7.69 (m, 2 H, H(2), H(6))	19.8
2b	3.58 (d, 3 H, $^{3}J_{P,H}$ = 10.6); 3.70 (d, 3 H, $^{3}J_{P,H}$ = 10.7)	1.87, 2.67	4.61, 4.80	7.33 (m, 1 H, H(4)); 7.40 (m, 2 H, H(3), H(5)); 7.69 (m, 2 H, H(2), H(6))	22.1
2c	3.62 (d, 3 H, $^{3}J_{P,H}$ = 10.7); 3.74 (d, 3 H, $^{3}J_{P,H}$ = 10.7)	1.80, 2.66	4.61, 4.83	7.38 (d, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.7); 7.63 (dd, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.7, $^{4}J_{HP}$ = 2.4)	21.6
2d	3.56 (d, 3 H, $^{3}J_{P,H}$ = 10.5); 3.71 (d, 3 H, $^{3}J_{P,H}$ = 10.7)	1.86, 2.63	4.59, 4.77	0.89 (d, 6 H, CH_3, $^{3}J_{H,H}$ = 6.6); 1.86 (m, 1 H, CH); 2.47 (d, 2 H, CH_2, $^{3}J_{H,H}$ 7.1); 7.17 (d, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.1); 7.59 (dd, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.1, $^{4}J_{HP}$ = 2.1)	22.3
2e	3.64 (d, 3 H, $^{3}J_{P,H}$ = 10.6); 3.76 (d, 3 H, $^{3}J_{P,H}$ = 10.7)	1.91, 2.69	4.64, 4.83	7.36 (m, 1 H, H(4′)); 7.45 (m, 2 H, H(3′), H(5′)); 7.60 (m, 2 H, H(2′), H(6′)); 7.64 (d, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.5); 7.76 (dd, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.5, $^{3}J_{P,H}$ = 2.3)	22.1
2f	3.56 (d, 3 H, $^{3}J_{P,H}$ = 10.6); 3.75 (d, 3 H, $^{3}J_{P,H}$ = 10.7)	1.96, 2.74	4.65, 4.81	7.47—7.51 (m, 2 H); 7.79—7.90 (m, 4 H); 8.14 (br.s, 1 H, H(1))	21.9

* The signals for the protons of the aromatic ring were assigned with consideration for known[54] substituent increments.

ates (**2b—f**) (Scheme 2) also isolated in quantitative yields. Their compositions and structures were confirmed by elemental analysis and spectroscopic methods (see Experimental and Tables 1, 2).

Scheme 2



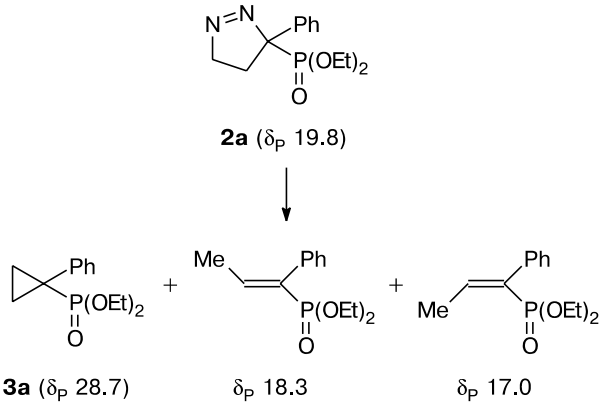
1b—f **2b—f**

Ar = Ph (**b**), 4-ClC_6H_4 (**c**), 4-$Bu^iC_6H_4$ (**d**), 4-PhC_6H_4 (**e**), 2-naphthyl (**f**)

Reagents and conditions: CH_2N_2, Et_2O, 20 °C, 3 h; ~100% yield.

Photolysis[4,5,19,20,24] or thermolysis[18,20] of 4,5-dihydro-3*H*-pyrazol-3-ylphosphonates produces cyclopropylphosphonates through liberation of nitrogen. Compound **2a** was quantitatively decomposed in boiling *o*-xylene over 1 h (Scheme 3). The ^{31}P NMR spectrum of the reaction mixture shows, along with a signal at δ_P 28.7 for diethyl 1-phenylcyclopropylphosphonate (**3a**), signals at δ_P 18.3 and 17.0 assigned to by-products: *E*- and *Z*-isomers of diethyl 1-phenylprop-1-enylphosphonate (the integral intensity ratio is 88 : 4 : 8).

Scheme 3



2a (δ_P 19.8)

3a (δ_P 28.7) δ_P 18.3 δ_P 17.0

Reagents and conditions: Δ, 1 h, *o*-xylene.

The ^{1}H NMR spectrum contains signals for the *Z*-isomer at δ_H 6.54 (dq, H_{olefin}, $^{3}J_{H,H}$ = 7.3 Hz, $^{3}J_{P,H}$ = 48.4 Hz) and 2.25 (dd, $H_{allylic}$, $^{3}J_{H,H}$ = 7.3 Hz, $^{4}J_{P,H}$ = 3.5 Hz) and signals for the *E*-isomer at δ_H 6.98 (dq, H_{olefin}, $^{3}J_{H,H}$ = 6.9 Hz, $^{3}J_{P,H}$ = 23.1 Hz) and 1.73 (dd, $H_{allylic}$, $^{3}J_{H,H}$ = 6.9 Hz, $^{4}J_{P,H}$ = 3.3 Hz). Note that the thermolysis of 4,5-dihydro-3*H*-pyrazol-3-ylphosphonates sometimes leads only to acyclic unsaturated products.[22]

In boiling toluene, compound **2a** decomposed slowly (after 1 h, its conversion was 57%); the selectivity of the process was virtually unchanged.

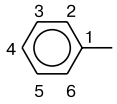
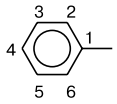
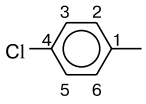
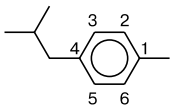
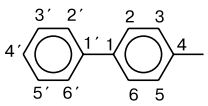
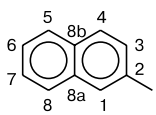
We failed to separate the reaction mixture by distillation; for this reason, unsaturated by-products were removed by treatment with a solution of $KMnO_4$ in aqueous acetone. Subsequent distillation gave the analytically and spectroscopically pure target product **3a** in 78% preparative yield.

The IR spectrum of cyclopropylphosphonate **3a** retains the set of bands of the diethoxyphosphoryl fragment. The band at 1230 cm^{-1} is due to the breathing vibrations of the cyclopropane ring and bands at 840 and 940 cm^{-1} correspond to the deformation vibrations (see Ref. 52). In the ^{13}C (Table 3) and ^1H NMR spectra (Table 4), one set of signals corresponds to equivalent ethoxy groups. The quaternary C atom is manifested as a doublet at δ_C 21.12. The coupling constant $^1J_{C,P}$ = 191.7 Hz is higher than that for compound **2a** in agreement with a known[54] increase in $^1J_{C,P}$ for the C atom with a greater *s*-orbital contribution. The protons of the cyclopropane ring are manifested as two complex multiplets at δ_H 1.06 and 1.49. The signals in the ^1H NMR spectra (see Table 4) were assigned by comparing the coupling constants $J_{H,P}$ with consideration for the known[19,54] ratio $^3J_{HCCP\text{-}cis} > {}^3J_{HCCP\text{-}trans}$. The ^{31}P chemical shift is δ_P 28.7 (see Table 4). This value falls in the range described for cyclopropylphosphonates (δ_P 21—36).[19,20,24,25] The absence of the pronounced anisotropic effect of the α-aromatic substituent is probably associated with a larger bond angle between the exocyclic bonds in cyclopropanes compared to a tetrahedral bond configuration.

A number of dimethyl 1-arylcyclopropylphosphonates (**3b—f**) were obtained and characterized analogously (see Tables 3, 4 and Experimental).

In conclusion, room-temperature reactions of 1-arylethenylphosphonic acids or their esters with diazomethane are regiospecific: [2+3] cycloaddition gives 3-aryl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonates. Thermolysis of the latter leads mainly to 1-arylcyclopropylphosphonates isolated in 53—79% yields (with respect to the two-step

Table 3. ^{13}C NMR spectra of 1-arylcyclopropylphosphonates **3a—f**

Compound	R	Ar	^{13}C NMR ($CDCl_3$), δ (*J*/Hz)			
			$P(O)(OR)_2$	Three-membered ring		Ar*
				CH_2	CP	
3a	CH_2Me		16.24 (d, Me, $^3J_{C,P}$ = 6.1); 62.15 (d, CH_2, $^2J_{C,P}$ =6.9)	11.34	21.12 (d, $^1J_{C,P}$ = 191.7)	127.09 (C(4)); 128.02 (C(3), C(5)); 130.97 (C(2), C(6)); 138.62 (C(1))
3b	Me		52.90 (d, $^2J_{C,P}$ = 6.8)	11.14	20.38 (d, $^1J_{C,P}$ = 191.4)	127.17 (C(4)); 128.10 (C(3), C(5)); 130.80 (C(2), C(6)); 138.29 (C(1))
3c	Me		53.01 (d, $^2J_{C,P}$ = 6.7)	11.28	19.96 (d, $^1J_{C,P}$ = 191.4)	128.31 (C(3), C(5)); 132.14 (d, C(2), C(6), $^3J_{C,P}$ = 3.0); 133.08 (C(4)); 136.96 (C(1))
3d	Me		52.95 (d, $^2J_{C,P}$ = 6.9)	11.21	20.01 (d, $^1J_{C,P}$ = 189.4)	22.26 (Me); 29.99 (CH); 44.94 (CH_2); 128.88 (C(3), C(5)); 130.50 (d, C(2), C(6), $^3J_{C,P}$ = 3.8); 135.44 (C(1)); 140.70 (C(4))
3e	Me		53.11 (d, $^2J_{C,P}$ = 6.8)	11.37	20.18 (d, $^1J_{C,P}$ = 190.5)	126.97 (4 C); 127.26 (C(4′)); 128.68 (2 C); 131.26 (C(3), C(5)); 137.44, 140.20, 140.56 (C(1), C(1′), C(4))
3f	Me		53.03 (d, $^2J_{C,P}$ = 6.1)	11.37	20.66 (d, $^1J_{C,P}$ = 191.7)	125.93, 126.02, 127.46, 127.60, 127.75, 128.70, 129.72 (d, $^2J_{C,P}$ = 4.6); 132.48, 133.05 (C(8a), C(8b)); 135.84 (C(2))

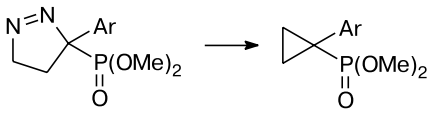
* The signals for the C atoms of the aromatic ring were assigned with consideration for known[54] substituent increments.

Table 4. ^{1}H and ^{31}P NMR spectra ($CDCl_3$) of 1-arylcyclopropylphosphonates **3a—f**

Compound	^{1}H NMR, δ (*J*/Hz)				^{31}P NMR δ
	$P(O)(OR)_2$	Three-membered ring		Ar*	
		trans-HCCP (m, 2 H)	*cis*-HCCP (m, 2 H)		
3a	1.25 (t, 6 H, Me, $^{3}J_{H,H}$ = 7.1); 4.04 (m, 4 H, CH_2)	1.06 ($^{3}J_{H,P}$ = 10.4)	1.49 ($^{3}J_{H,P}$ = 16.4)	7.23 (m, 1 H, H(4)); 7.29 (m, 2 H, H(3), H(5)); 7.42 (m, 2 H, H(2), H(6))	28.7
3b	3.68 (d, 6 H, $^{3}J_{H,P}$ = 10.6)	1.07 ($^{3}J_{H,P}$ = 10.5)	1.50 ($^{3}J_{H,P}$ = 16.4)	7.23 (m, 1 H, H(4)); 7.29 (m, 2 H, H(3), H(5)); 7.41 (m, 2 H, H(2), H(6))	31.4
3c	3.70 (d, 6 H, $^{3}J_{H,P}$ = 10.6)	1.04 ($^{3}J_{H,P}$ = 10.4)	1.50 ($^{3}J_{H,P}$ = 16.3)	7.26 (d, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.6); 7.35 (dd, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.6, $^{4}J_{HP}$ = 2.0)	30.8
3d	3.68 (d, 6 H, $^{3}J_{H,P}$ = 10.6)	1.06 ($^{3}J_{H,P}$ = 10.5)	1.48 ($^{3}J_{H,P}$ = 16.3)	0.89 (d, 6 H, Me, $^{3}J_{H,H}$ = 6.6); 1.84 (m, 1 H, CH); 2.44 (d, 2 H, CH_2, $^{3}J_{H,H}$ = 7.2); 7.07 (d, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.0); 7.31 (dd, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.0, $^{4}J_{HP}$ = 2.0)	31.8
3e	3.73 (d, 6 H, $^{3}J_{H,P}$ = 10.6)	1.12 ($^{3}J_{H,P}$ = 10.4)	1.54 ($^{3}J_{H,P}$ = 16.3)	7.34 (m, 1 H, H(4′)); 7.43 (m, 2 H, H(3′), H(5′); 7.48 (dd, 2 H, H(3), H(5), $^{3}J_{AB}$ = 8.2, $^{4}J_{H,P}$ = 1.3); 7.53 (d, 2 H, H(2), H(6), $^{3}J_{AB}$ = 8.2); 7.57 (m, 2 H, H(2′), H(6′))	31.5
3f	3.71 (d, 6 H, $^{3}J_{H,P}$ = 10.5)	1.18 ($^{3}J_{H,P}$ = 10.4)	1.58 ($^{3}J_{H,P}$ = 16.4)	7.43—7.49 (m, 2 H); 7.56 (d, 1 H, $^{3}J_{H,H}$ = 8.5); 7.77—7.81 (m, 3 H); 7.84 (br.s, 1 H, H(1))	31.4

* The signals for the protons of the aromatic ring were assigned with consideration for known[54] substituent increments.

Scheme 4



2b—f **3b—f**

Conditions: Δ, *o*-xylene.

2, **3**	Ar	Yield (%)	
		From ^{31}P NMR	Preparative
b	Ph	86	53
c	4-ClC_6H_4	86	68
d	4-Bu$^{i}C_6H_4$	90	56
e	4-PhC_6H_4	89	79
f	2-naphthyl	88	66

process). Isomeric 1-arylprop-1-enylphosphonates are detected as by-products.

Experimental

^{1}H, ^{31}P, and ^{13}C NMR spectra were recorded on a Bruker Avance-400 spectrometer (400, 162, and 101 MHz, respectively). ^{1}H chemical shifts are referenced to $SiMe_4$ as the internal standard; ^{31}P chemical shifts are referenced to 85% H_3PO_4 as the external standard; ^{13}C chemical shifts are referenced to $CDCl_3$ (δ 77.0). IR spectra were recorded on a Carl Zeiss UR-20 spectrophotometer. Elemental analysis was carried out on a Carlo Erba automatic analyzer. Melting points were measured with an Electrothermal 9100 melting point apparatus in sealed capillaries.

Diethyl ether and *o*-xylene were dehydrated in a standard way. The starting diethyl 1-phenylethenylphosphonate (**1a**) and 1-arylethenylphosphonic acids (**1b—f**) were prepared as described earlier.[51] A solution of diazomethane in ether was prepared according to a standard procedure.[55]

Diethyl 3-phenyl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2a). A round-bottom flask fitted with a magnetic stirring bar, a dropping funnel, and a drying tube packed with calcium chloride was charged with phosphonate **1a** (1.718 g, 7.15 mmol) and anhydrous diethyl ether (5 mL). A 0.11 *M* solution of diazomethane (127 mL, 14 mmol, 2 equiv.) in anhydrous ether was added dropwise with stirring for 30 min and the solution was stirred for an additional 3 h. Volatile components were removed first in a rotary evaporator and then under high vacuum. Phosphonate **2a** as a pale yellow oil was obtained in quantitative yield. Found (%): C, 55.30; H, 6.56; N, 9.84. $C_{13}H_{19}N_2O_3P$. Calculated (%): C, 55.31; H, 6.78; N, 9.92. IR (thin film), ν/cm^{-1}: 1560 (N=N); 1260 (P=O); 1060 (O—C); 1030 (O—C); 980 (OC—C).

Dimethyl 3-phenyl-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2b) was obtained analogously in quantitative yield from 1-phenylethenylphosphonic acid (**1b**) (1.291 g, 7.01 mmol) and 0.08 *M* diazomethane (350 mL, 28 mmol, 4 equiv.). White crystals turned yellow in air, m.p. 74—75 °C. Found (%): C, 52.14; H, 5.87; N, 11.08. $C_{11}H_{15}N_2O_3P$. Calculated (%): C, 51.97; H, 5.95; N, 11.02. IR (Nujol), ν/cm^{-1}: 1555 (N=N); 1255 (P=O); 1070 (O—C); 1030 (O—C).

Dimethyl 3-(4-chlorophenyl)-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2c) was obtained analogously in quantitative yield from 1-(4-chlorophenyl)ethenylphosphonic acid (**1c**) (2.000 g, 9.15 mmol) and 0.11 *M* diazomethane (325 mL, 36 mmol,

4 equiv.). Cream-colored crystals, m.p. 82—83 °C. Found (%): C, 46.06; H, 5.05; N, 9.47. $C_{11}H_{14}ClN_2O_3P$. Calculated (%): C, 45.77; H, 4.89; N, 9.70. IR (Nujol), ν/cm^{-1}: 1560 (N=N); 1250 (P=O); 1070 (O—C); 1040 (O—C).

Dimethyl 3-(4-isobutylphenyl)-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2d) was obtained analogously in quantitative yield from 1-(4-isobutylphenyl)ethenylphosphonic acid (**1d**) (1.882 g, 7.83 mmol) and 0.1 *M* diazomethane (400 mL, 40 mmol, 5 equiv.). A pale yellow oil. Found (%): C, 58.37; H, 7.58; N, 9.79. $C_{15}H_{23}N_2O_3P$. Calculated (%): C, 58.06; H, 7.47; N, 9.03. IR (thin film), ν/cm^{-1}: 1555 (N=N); 1260 (P=O); 1060 (O—C); 1020 (O—C).

Dimethyl 3-(biphenyl-4-yl)-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2e) was obtained analogously in quantitative yield from 1-(biphenyl-4-yl)ethenylphosphonic acid (**1e**) (1.575 g, 6.05 mmol) and 0.17 *M* diazomethane (144 mL, 24 mmol, 4 equiv.). Pale yellow crystals, m.p. 81—82 °C. Found (%): C, 61.88; H, 5.96; N, 8.59. $C_{17}H_{19}N_2O_3P$. Calculated (%): C, 61.81; H, 5.80; N, 8.48. IR (thin film), ν/cm^{-1}: 1560 (N=N); 1260 (P=O); 1065 (O—C); 1040 (O—C).

Dimethyl 3-(2-naphthyl)-4,5-dihydro-3*H*-pyrazol-3-ylphosphonate (2f) was obtained analogously in quantitative yield from 1-(2-naphthyl)ethenylphosphonic acid (**1f**) (1.906 g, 8.14 mmol) and 0.15 *M* diazomethane (220 mL, 33 mmol, 4 equiv.). A pale yellow oil. Found (%): C, 58.98; H, 5.82; N, 9.08. $C_{15}H_{17}N_2O_3P$. Calculated (%): C, 59.21; H, 5.63; N, 9.21. IR (thin film), ν/cm^{-1}: 1555 (N=N); 1250 (P=O); 1050 (O—C); 1030 (O—C).

Diethyl 1-phenylcyclopropylphosphonate (3a). A solution of compound **2a** (2.019 g, 7.15 mmol) in anhydrous *o*-xylene (160 mL) was refluxed for 3 h. The solvent was thoroughly removed under reduced pressure. The residue was dissolved in acetone (10 mL) and a saturated solution of $KMnO_4$ (50 mL) in aqueous acetone (1 : 5) was added dropwise with stirring for 7 h. The excess of $KMnO_4$ was decomposed by adding saturated aqueous Na_2SO_3 until the violet color vanished. The brown precipitate that formed was filtered off and washed with acetone. The combined filtrates were concentrated and the product was extracted with diethyl ether (3×20 mL). The organic extracts were dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was distilled *in vacuo* under dry argon. The yield of compound **3a** was 1.416 g (78%), a nearly colorless transparent oil, b.p. 140—150 °C (2 Torr). Found (%): C, 61.68; H, 7.48. $C_{13}H_{19}O_3P$. Calculated (%): C, 61.41; H, 7.53. IR (thin film), ν/cm^{-1}: 1260 (P=O); 1230 (cyclopropane); 1070 (O—C); 1040 (O—C); 970 (OC—C); 940 (cyclopropane); 840 (cyclopropane).

Dimethyl 1-phenylcyclopropylphosphonate (3b) was obtained analogously from compound **2b** (1.782 g, 7.01 mmol) in boiling anhydrous *o*-xylene (160 mL). The yield was 0.845 g (53%), a colorless transparent oil, b.p. 136—140 °C (2 Torr). Found (%): C, 61.68; H, 7.48. $C_{13}H_{19}O_3P$. Calculated (%): C, 61.41; H, 7.53. IR (thin film), ν/cm^{-1}: 1255 (P=O); 1220 (cyclopropane); 1070 sh (O—C); 1050 (O—C); 945 (cyclopropane); 845 (cyclopropane).

Dimethyl 1-(4-chlorophenyl)cyclopropylphosphonate (3c) was obtained analogously from compound **2c** (2.000 g, 6.93 mmol) in boiling anhydrous *o*-xylene (165 mL). The yield was 1.223 g (68%), a colorless oil, b.p. 120—130 °C (0.1 Torr). The oil crystallized on storage, m.p. 40—41 °C. Found (%): C, 50.78; H, 5.43. $C_{11}H_{14}ClO_3P$. Calculated (%): C, 50.69; H, 5.41. IR (thin film), ν/cm^{-1}: 1270 (P=O); 1230 (cyclopropane); 1070 (O—C); 1040 (O—C); 935 (cyclopropane); 860 (cyclopropane).

Dimethyl 1-(4-isobutylphenyl)cyclopropylphosphonate (3d) was obtained analogously from compound **2d** (2.431 g, 7.83 mmol) in boiling anhydrous *o*-xylene (165 mL). The yield was 1.229 g (56%), a nearly colorless transparent oil, b.p. 155—160 °C (2 Torr). Found (%): C, 63.72; H, 8.35. $C_{15}H_{23}O_3P$. Calculated (%): C, 63.82; H, 8.21. IR (thin film), ν/cm^{-1}: 1265 (P=O); 1230 (cyclopropane); 1070 (O—C); 1040 (O—C); 935 (cyclopropane); 835 (cyclopropane).

Dimethyl 1-(biphenyl-4-yl)cyclopropylphosphonate (3e) was obtained analogously from compound **2e** (1.978 g, 5.99 mmol) in boiling anhydrous *o*-xylene (100 mL). The product was extracted with toluene (3×50 mL). The solvent was removed under reduced pressure and the residue was kept in high vacuum. The yield of compound **3e** was 1.426 g (79%), cream-colored crystals, m.p. 56—57 °C. Found (%): C, 67.47; H, 6.52. $C_{17}H_{19}O_3P$. Calculated (%): C, 67.54; H, 6.34. IR (Nujol), ν/cm^{-1}: 1260 (P=O); 1225 (cyclopropane); 1070 (O—C); 1040 (O—C); 940 (cyclopropane); 865 (cyclopropane).

Dimethyl 1-(2-naphthyl)cyclopropylphosphonate (3f) was obtained analogously from compound **2f** (2.477 g, 8.14 mmol) in boiling anhydrous *o*-xylene (165 mL). The yield was 1.487 g (66%), a light yellow oil, b.p. 170 °C (0.1 Torr). Found (%): C, 65.13; H, 6.39. $C_{15}H_{17}O_3P$. Calculated (%): C, 65.21; H, 6.20. IR (thin film), ν/cm^{-1}: 1265 (P=O); 1225 (cyclopropane); 1070 (O—C); 1040 (O—C); 940 (cyclopropane); 835 (cyclopropane).

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