A Novel Isomerization of Certain Substituted 1,2,6-Triphenyl-4-phosphorinanones. Stereochemical and Conformational Analysis of Substituted 1,2,6-Triphenyl-4-phosphorinanones and 2,6-Diphenyl-4-thianones via Ultraviolet Spectrometry, ^{13}C NMR Spectroscopy, and Liquid Crystal Circular Dichroism Spectropolarimetry

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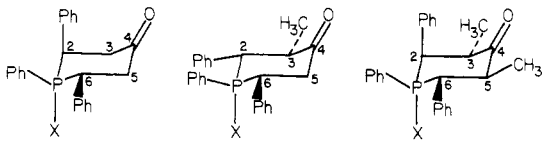
Abstract: A series of 1,2,6-triphenyl-substituted phosphorinan-4-ones with methyl substituents at C(3) or with two methyl substituents at C(3,5) have been prepared via a condensation of the appropriate 1,5-diphenylpentadien-3-one and bis(hydroxymethyl)phenylphosphine. By use of benzaldehyde-α-^{13}C, it was possible to enhance the ^{13}C content of C(2) or C(2,6) in the systems. This permitted the unequivocal identification of the ^{13}C NMR signals for the specific carbons in the phosphorinan-4-ones. It was discovered that *r*-1,*cis*-2(*a*),*trans*-6(*e*)-triphenyl-4-phosphorinanone could be thermally converted to the all equatorially substituted isomer, namely, *r*-1,*trans*-2(*e*),6(*e*)-diphenyl-4-phosphorinanone, in the absence of solvent under nitrogen. The corresponding C(3)-methylated derivative as well as the C(3,5)-dimethylated phosphine behaved similarly. In addition, certain phosphine oxide and phosphine sulfide relatives also were found to undergo this novel thermal isomerization. These are the first reported examples of this type of isomerization in phosphorinanones which could be monitored via ^{31}P NMR analysis of the starting material and product. Both ^{13}C and ^{31}P NMR data are also recorded for all examples and confirm previous suggestions regarding chemical shift assignments in related analogues especially in terms of the C(α) resonances. Another unusual observation was made regarding the use of ultraviolet spectroscopy for identification purposes as related to the relative positions of the two phenyl groups at C(2,6). The "cis isomers" (both C–C_6H_5 bonds equatorial) display considerable fine structure in the ultraviolet spectra. This was demonstrated in the phosphorinan-4-ones, several 4-thianones, and one bispidinone as well as in *cis*-3,5-diphenylcyclohexanone. The corresponding *trans*-2,6-diphenyl isomers showed only a broad curve. Thus, the ultraviolet spectra give every indication of being highly dependent upon the position of the phenyl ring, and, on the basis of reasonable conclusions from the X-ray analysis of several of the systems examined, upon the relative alignments of the rings (this assumes some restricted rotation in these systems which has been inferred from the previous X-ray data) which are also believed to be biased. These observations appear to be the first recorded for arylcyclohexanones with or without a heteroatom. It was also observed for the first time that the above heterocycles displayed different liquid-crystal circular dichroism (LCCD) spectra. In fact, again a plot of ellipticity vs. λ revealed sharp contrasts between the cis and trans isomers [this refers to the phenyl groups at C(2,6) in the systems examined]. Fine structure was detected in the cis isomers with only a broad band revealed in the spectra of the trans isomers. In the cis isomers, which have the phenyl rings probably in a more nearly planar arrangement, the ring transitions may be distinct (as in benzene) and may therefore be cumulative. In the trans isomers, the rings are probably nearly perpendicular to each other, assuming restricted rotation of the C–C_6H_5 bonds in these biased systems. Possibly the *apparent* loss in vibrational structure may be a consequence of noncoincidence in the frequencies of vibrational modes because the transition moments of the two rings are not parallel. This is a tentative conclusion since the use of LCCD to determine stereochemistry in heterocycles is virtually heretofore unexplored.

Six-membered carbon–phosphorus (C–P) heterocycles have been of active interest in recent years.[1] In our previous papers[2,3] we reported that in phosphorinones **1a–c** and **3a–c**, the C(2)–C_6H_5 bond is axial while the C(6)–C_6H_5 bond is in an equatorial orientation. The trans arrangement of the C(2)–C_6H_5 bond and the C(6)–C_6H_5 bond has been established by X-ray techniques for **1c**.[2] In **2a–c** both phenyl groups occupy equatorial positions as



1 2 3

a, X = lone pair; b, X = =O; c, X = =S

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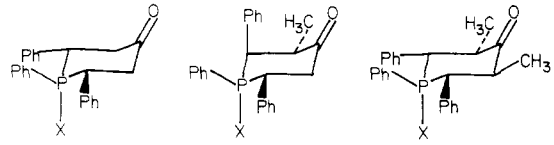
Table I. Physical Properties of the Phosphorinanone and Derivatives

compd	mp, °C	yield, (%)	peak matching, M^+ calcd	peak matching, M^+ found
4a	181-182	51.0	344.1329	344.1329
4b	286-287	60.0	360.1279	360.1286
4c	205-206	41.0	376.1056	376.1039
5a	175-176	14.8	358.1486	358.1484
5b	279-281	50.0	374.1435	374.1431
5c	230-232	51.0	390.1207	390.1213
6a	224-226	75.0	372.1642	372.1651
6b	302-303	56.6	388.1592	388.1580
6c	291-292	56.0	404.1363	404.1371

determined by ^{13}C, ^{1}H, and ^{31}P NMR spectroscopy.[3] We report herein the synthesis and conformational analysis of **4a** and **6a** and



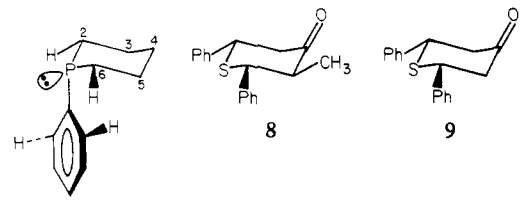
4 **5** **6**

a, X = lone pair; b, X = =O; c, X = =S

their derivatives (Table I) formed via *thermal isomerization* of phosphines **1a** and **3a**, respectively, and the synthesis of phosphorinanone **5a** and its derivatives **5b** and **5c** which have an axial C(2)–C_6H_5 bond. Moreover, ^{13}C NMR chemical shifts and the $^{1}J_{PC}$ values of C(2) and C(6) in **1–6** have now been confirmed by synthesis of the ^{13}C-enriched phosphorinanones via condensation of ^{13}C-enriched distyryl ketones with $C_6H_5P(CH_2OH)_2$ (see Experimental Section).[2,3] Treatment of 2-methyl-1,5-diphenyl-1,4-pentadien-3-one[4] with bis(hydroxymethyl)phenylphosphine[5] in pyridine (under N_2) at room temperature gave the *trans*-2,6-diphenyl-3-methylphosphorinanone **5a**. Oxidation of **5a** with *m*-chloroperbenzoic acid (MCPA) in acetone (0 °C) gave oxide **5b**. Sulfurization of **5a** gave sulfide **5c** at room temperature. One ^{31}P NMR signal (Table II) was recorded at −20.80 ppm for **5a** and at +31.57 ppm for **5b** (relative to 85% H_3PO_4). ^{31}P NMR analysis of sulfide **5c** revealed a strong signal at +45.87 ppm. The use of ^{31}P NMR analysis to follow the thermal isomerization will be discussed shortly.

Surprisingly, heating *trans*-2,6-diphenyl-4-phosphorinanones **1a**,[2] **3a**,[3] and **5a** under N_2 in sealed-glass ampules (for optimum temperature and time, see the Experimental Section) offered *cis*-2,6-diphenyl-4-phosphorinanones **4a**, **6a**, and **2a**,[3] respectively, in moderate yields. Oxidation of **2a**, **4a**, and **6a** with MCPA in acetone (0 °C) gave oxides **2b**, **4b**, and **6b**, respectively. Sulfurization of **2a**, **4a**, and **6a** afforded the corresponding sulfides **2c**, **4c**, and **6c**.

^{13}C NMR Analysis. ^{13}C NMR analysis (Table III) was quite useful in the elucidation of the stereochemistry of the highly substituted phosphorinanones **4a–c**, **5a–c**, and **6a–c**. Moreover, ^{13}C chemical shifts and coupling constants for C(2) and/or C(6) for **4a–c**, **5a–c**, and **6a–c**, as well as those previously found for **1a–c**,[2] **2a–c**,[3] and **3a–c**,[3] are confirmed by the ^{13}C-labeling experiments. The ^{13}C analysis (Table III) of phosphorinanones **4a–c** and **6a–c** suggests a cis arrangement of the two phenyl groups at C(2,6) regardless of the configuration at phosphorus. When the C(2,6)–C_6H_5 bonds [and the C(3,5)–CH_3 bonds] are equatorial as in **4a–c** and **6a–c**, it is assumed that C(2) and C(6) (and C(3,5)) are magnetically equivalent, as are C(3,5). In fact, ^{13}C analysis of ketophosphine **4a** revealed two signals, a doublet in each case for C(2,6) and C(3,5) at 44.76 ppm ($^{1}J_{PC}$ = 13.26 Hz) and 48.54 ppm ($^{2}J_{PC}$ = 14.04 Hz), respectively. For compound **6a**, the carbon signals paralleled those found in **4a**, as seen in Table III. ^{13}C chemical shifts and coupling constants for C(3)–CH_3 and C(5)–CH_3 appeared at 13.44 ppm ($^{3}J_{PC}$ = 6.40 Hz) for **6a**. The $^{2}J_{PC(3,5)}$ coupling constants for several phosphorus-containing six-membered heterocycles have been useful in the determination of the configuration at phosphorus in simple phosphorinane systems.[1e,g,j,6] The large $^{2}J_{PC(3,5)}$ values (14.04 Hz and 14.68 Hz) for **4a** and **6a** suggest *equatorial* C_6H_5–P bonds. It has also been observed by Quin and co-workers[1] that an axial P–C_6H_5 bond in phosphorinane **7** would likely have interaction between the ortho

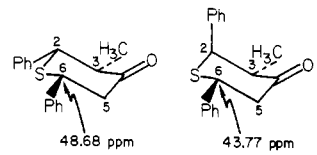


7 **8** **9**

hydrogens and the equatorial H(2) and H(6) protons. Similarly, ^{13}C analysis of oxides **4b** and **6b** and sulfides **4c** and **6c** revealed the presence of equatorial bonds for C(2)–C_6H_5 and C(6)–C_6H_5. The P=S bond is most likely in an axial orientation in **4c** and **6c**.

A ^{13}C NMR signal for carbonyl carbon C(4) in **6a–c** is shifted downfield by 4.77, 4.68, and 4.50 ppm, respectively, compared to the corresponding signal for C(4) in **4a–c** (see Table III). This downfield shift of C(4) may be attributed to the 3,5-dimethyl groups. Interestingly, this deshielding effect is comparable in magnitude to that found[7] for C(4) in *r*-2,*cis*-6-diphenyl-*trans*-3-methyl-4-thianone (**8**) and *r*-2,*cis*-6-diphenyl-4-thianone (**9**). It is also observed that the presence of methyl groups at C(3,5) in **6a–c** causes a β-deshielding effect on C(2,6) by 7.81, 7.96, and 7.94 ppm, respectively, comparable in magnitude to that in **4a–c** (Table III). A similar effect has been observed in several six-membered carbocyclic and heterocyclic ketones.[7-9] A downfield shift of 1.35, 1.61, and 1.70 ppm was observed for C(3,5) carbons in **6a–c** compared to the corresponding signal for C(3,5) in **4a–c** (Table III). Similar effects can be noticed in comparing the ^{13}C analysis of **2a–c**[3,10] and **4a–c**.

^{13}C NMR analysis of **5a** was quite complex in comparison to that for **4a–c** and **6a–c** due to the disymmetry of the molecule. To be sure, we suggest that the C(2)–C_6H_5 and the C(6)–C_6H_5 bonds are in axial and equatorial positions, respectively, since, when **5a** was heated, the thermodynamically more stable *cis*-2,6-diphenylphosphorinanone **2a** was formed. Although there are no model systems for comparison in highly substituted phosphorinanones, a similar situation appears to persist in *r*-2,*trans*-$6_{(e)}$-*diphenyl-cis*-$3_{(e)}$-methyl-4-thianone (**10**) which has been examined by X-ray diffraction and ^{13}C NMR analysis.[4a,7] The axial C_6H_5–C bond and the equatorial C–CH_3 bond were on the same side of the ring in **10**, as is true in phosphorinanones **5a–c**. The ^{13}C NMR shifts for C(6) in **8** and **10** were assigned 48.68 and



8 **10**

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Table II. IR, ^{1}H NMR, and ^{31}P NMR Data

compd	IR, cm^{-1} [a]	^{1}H NMR[b,c]	^{31}P NMR[c,d]
4a	1710, 1495, 745, 695	2.60–4.05 [m, 6 H, H(2), H(3), H(5), H(6)], 6.65–7.45 (m, 15 H, Ar-H)	−2.79
4b	1715, 1440, 1190, 700	2.70–3.20 [d, d, 2 H, H(3)(a), H(5)(a)], 3.50–4.10 [m, 4 H, H(2)(a), H(3)(e), H(5)(e), H(6)(a)], 6.80–8.15 (m, 15 H, Ar-H)	+32.46
4c	1715, 1437, 1105, 692	2.60–3.15 [2 d, 2 H, H(3)(a), H(5)(a)], 3.60–4.30 [m, 4 H, H(2)(a), H(3)(e), H(5)(e), H(6)(a)], 6.75–7.85 (m, 15 H, Ar-H)	53.28
5a	1709, 1452, 790, 750, 760, 700	1.35 (d, 3 H, CH_3, J = 6 Hz), 2.60–3.85 [m, 5 H, H(2), H(3), H(5), H(6)], 6.75–7.54 (m, 15 H, Ar-H)	−20.80
5b	1710, 1440, 1180, 700	1.56 (d, 3 H, CH_3, J = 6.5 Hz), 2.65–4.25 [m, 5 H, H(2), H(3), H(5), H(6)], 7.00–7.62 (m, 15 H, Ar-H)	+31.57
5c	1705, 1450, 1440, 1107, 790, 740, 700	1.57 (d, 3 H, CH_3, J = 6 Hz), 2.60–4.30 [m, 5 H, H(2), H(3), H(5), H(6)], 6.70–7.75 (m, 15 H, Ar-H)	45.87 (1.00),[e] 53.68 (0.15)
6a	1705, 1455, 683	0.95 (d, 3 H, CH_3, J = 6 Hz), 2.92–3.16 [d, d, 2 H, H(2), H(6), J_{HH} = 13 Hz), 3.18–3.58 [m, 2 H, H(3), H(5)] (m, 15 H, Ar-H)	−0.17
6b	1712, 1190, 1115, 683	0.99 (d, 3 H, CH_3, J = 6 Hz), 3.18 [d, d, 2 H, H(2)(a), H(6)(a), J_{HH} = 13 Hz], 3.75–4.15 [m, 2 H, H(3)(e), H(5)(e)], 6.95–7.50 (m, 15 H, Ar-H)	+31.78
6c	1703, 1437, 1100, 697	1.02 (d, 3 H, CH_3, J = 6 Hz), 3.67 [d, d, 2 H, H(2), H(6), J_{PH} = 6 Hz, J_{HH} = 13 Hz], 6.86–7.75 (m, 15 H, Ar-H)	+53.07

[a] KBr pellets. [b] Ppm from Me_4Si. [c] In $DCCl_3$. [d] Ppm from 85% H_3PO_4. [e] Some isomerization of the precursor phosphine **5a** to phosphine **2a** appears to have occurred prior to sulfurization of **5a** to give sulfide **5c**. Therefore the signal at 45.87 ppm is undoubtedly for the P nucleus in *P*-sulfide **5c**.

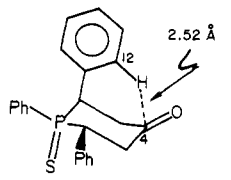
Table III. ^{13}C NMR Data in $DCCl_3$ [from $(CH_3)_4Si$][a]

compd	C(2,6)	C(3,5)	C(4)	CH_3
4a	44.76 (13.26)	48.54 (14.04)	207.00 (0.00)	
4b	44.78 (60.31)	44.80 (4.98)	205.80 (2.87)	
4c	45.57 (44.23)	44.54 (2.36)	205.57 (0.00)	
5a	47.73 (14.66), 44.82 (12.43)	52.14 (7.44), 44.31 (13.16)	212.02 (0.00)	13.81 (11.19)
5b	46.87 (61.79), 45.24 (61.04)	52.75 (4.41), 40.73 (4.50)	210.20 (3.60)	14.57 (2.37)
5c	47.55 (44.89), 45.78 (44.92)	51.80 (2.24), 40.61 (3.00)	209.60 (3.01)	14.01 (3.66)
6a	52.57 (13.12)	49.89 (14.68)	211.77 (2.17)	13.44 (6.40)
6b	52.74 (59.50)	46.41 (3.51)	210.48 (2.96)	13.39 (10.26)
6c	53.51 (43.95)	46.24 (0.00)	210.07 (0.00)	13.08 (10.84)

[a] In ppm; J_{PC} values in parentheses.

43.77 ppm, respectively, on the assumption that the γ_a effect due to the axial phenyl group in **10** would shield C(6).[7] This assumption was verified by preparing (see Experimental Section) ^{13}C-enriched *r*-2,*trans*-6-diphenyl-*cis*-3-methyl-4-thianone-*6*-^{13}*C*. Thus, the ^{13}C signals at 47.73 ($^2J_{PC}$ = 14.66 Hz) and 44.82 ppm ($^2J_{PC}$ = 12.43 Hz) are assigned to C(2) and C(6), respectively, in **5a**. Similar trends were observed for **5b** and **5c** (Table III).

Inspection of the ^{13}C data in Tables III and IV reveals that the carbonyl carbon C(4) resonance in the *cis*-2,6-diphenylphosphorinanones **2a–c**,[3] **4a–c**, and **6a–c** is always upfield (1.0 to 2.70 ppm) in comparison to that in *trans*-2,6-diphenylphosphorinanones **1a–c**,[2] **3b–c**,[3] and **5a–c**. The H(12)–C(4) distance (2.52 Å) in **1c**[2] indicates that the axial phenyl ring is



1c

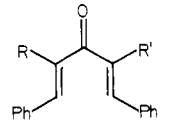
directed with a side toward C(4); presumably, this may cause deshielding at C(4). It is not unreasonable to expect such an effect in all the trans isomers which accounts for the deshielding of C(4) in comparison with the corresponding cis isomers. A similar trend has been observed in 4-thianone analogues.[4a,7]

Table IV. ^{13}C NMR Shifts for C(4) and ^{31}P NMR Shifts in Substituted Phosphorinanones[2,3]

compd	C(4)[a]	^{31}P NMR shifts
1a	209.70 (0.00)	−6.04
1b	207.14 (6.44)	+33.91
1c	207.16 (5.45)	+47.92
2a	209.65 (2.15)	−0.92
2b	209.19 (7.10)	+32.30
2c	207.84 (1.40)	+53.70
3a	213.69 (0.00)	−21.34
3b	212.00 (0.00)	+31.67
3c	211.90 (3.71)	+44.85

[a] In $DCCl_3$, ppm from Me_4Si. $^3J_{PC}$ in parentheses are in Hz. [b] In $DCCl_3$, ppm from 85% H_3PO_4.

To simplify the ^{13}C NMR spectra of several phosphorinanones, we examined the spectra of ^{13}C-enriched **1a–c**, **2a–c**, **3a–c**, **4a–c**, **5a–c**, and **6a–c**. The mixture of labeled ^{13}C and unlabeled distyryl ketones **11a–c** (with labels at positions 1 and/or 5) were condensed



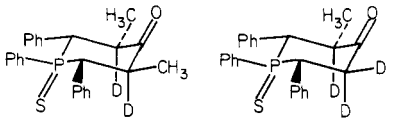
11a, R = R′ = H
b, R = CH_3; R′ = H
c, R = R′ = CH_3

with bis(hydroxymethyl)phenylphosphine to obtain the phosphorinanones which were later thermally isomerized. ^{13}C NMR analysis was performed on all systems to confirm the assignments for C(2) and C(6).

^1H NMR Analysis. X-ray analysis of a few unsubstituted[1a,11] and substituted[2] phosphorinanones has revealed that the ring system is commonly in a chair conformation. We suggest that phosphorinanones **4a–c**, **5a–c**, and **6a–c** exist as chair conformers, regardless of the configuration at phosphorus, and this is supported by ^1H NMR studies of **1a–c**,[2] **2a–c**,[3] and **3a–c**.[3]

^1H NMR data for **4a–c** were very complex due to severe signal overlap and phosphorus coupling. ^1H NMR analysis of **6a–c** was quite informative. One signal each for the C(3,5)–CH_3 protons appeared at δ 0.95, 0.99, and 1.02 for **6a–c**, respectively. We tentatively suggest that all methyl groups are in equatorial positions[1h] in view of the $^3J_{HCCH_3}$ couplings (6 Hz) for **6a–c**. Moreover, irradiations of ^{31}P in **6c** gave a doublet for H(2) and H(6) centered at δ 3.67 ($^3J_{HCCH}$ = 13 Hz) which suggested the trans-diaxial arrangement for protons $H(2)_a$, $H(3)_a$ and $H(5)_a$, $H(6)_a$. A complex multiplet for protons $H(3)_a$ and $H(5)_a$ was observed, obviously the result of vicinal proton coupling as well as coupling with a methyl group, at δ 3.98 for **6c**.

Treatment of **6c** with $D_2O/NaOCH_3$ in dioxane gave the 3,5-dideuterated derivative **12**. ^1H NMR analysis of the latter



12 **13**

showed a doublet at δ 3.70 ($^2J_{PH}$ = 6 Hz) which we have assigned to the axial-positioned $H(2)_a$ and $H(6)_a$. Irradiation of ^{31}P at 58 004 Hz upfield caused the doublet to collapse to a singlet at δ 3.68, confirming that the coupling was due to the phosphorus atom. A singlet was observed for the methyl protons at δ 1.02 for the deuterated derivative **12**. A coupling of similar magnitude was noticed for compound **13** ($^2J_{PH}$ = 5.5 Hz and 6.0 Hz).[3] Hence, ^1H NMR and ^{13}C NMR data strongly support structure **6c**. The ^1H spectra of **6a,b** were similar to that of **6c** (Table II).

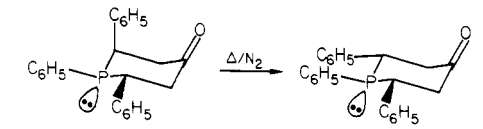
^1H NMR analysis of *trans*-2,6-diphenylphosphorinanones **5a–c** was very complex due to severe signal overlap. Methyl protons appeared at δ 1.35, 1.56, and 1.57 for **5a–c**, respectively. The $^3J_{HCCH_3}$ couplings (6–6.5 Hz) suggested the C(3)–CH_3 bond to be equatorial.[1h,3] The remaining spectrum was quite complex since the signals for the ring protons appeared as an envelope at δ 2.60–4.30 in **5a–c** (Table II).

The ^1H NMR analysis of ketophosphine **4a** gave a very complex pattern for ring protons at δ 2.60–4.05. Oxide **4b** gave a doublet of doublets centered at δ 2.95, which collapsed to a doublet (J_{HH} = 13 Hz) when ^{31}P was irradiated at 58 351 Hz upfield; this was assigned to $H(3,5)_a$. Moreover, signals for $H(3)_a$ and $H(5)_a$ in **4b** should be coupled to $H(2)_a$, $H(6)_a$ and to $H(3)_e$, $H(5)_e$.

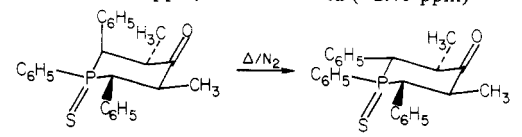
In view of the $^2J_{HH}$ = 13 Hz value, we conclude that the C_6H_5–C(2) bond and the C_6H_5–C(6) bond are both equatorial in **4b** since the vicinal proton coupling is of the correct magnitude. Moreover, the geminal coupling (13 Hz) is also not unreasonable for $^2J_{H(3)_aH(3)_e}$ or $^2J_{H(5)_aH(5)_e}$. The remaining spectrum was complex due to overlapping of signals (see Table II). The ^1H NMR pattern was similar to that observed for phosphorinanone **4c** (Table II).

^{31}P NMR Analysis. In Table II, the ^{31}P NMR revealed one signal for **4a–c**, **5a–b**, and **6a–c**. On the basis of the lone ^{31}P signals as well the ^1H and ^{13}C NMR analysis, we conclude that **4a–c**, **5a–b**, and **6a–c** are highly biased systems in $DCCl_3$. The ^{31}P resonances of *cis*-2,6-diphenylphosphorinanones **2a**,[3] **2c**,[3] **4a**, **4c**, **6a**, and **6c** are shifted downfield compared to the ^{31}P resonances in the *trans*-2,6-diphenylphosphorinanones **1a**,[2] **1c**,[2] **3a**,[3] **3c**,[3] **5a**, and **5c**. However, in the *cis*-oxides **2b**, **4b**, and **6b** and *trans*-oxides **1b**, **3b**, and **5b** not much change in the ^{31}P shifts was observed (see Tables II and IV). A low-temperature study via ^1H NMR analysis (at −78 °C) with **1c** did not reveal any change in the spectrum, and thus we conclude the system is quite biased.

Two ^{31}P NMR signals were recorded for the sulfide **5c**, one at +45.87 and another at +53.68 ppm in the ratio 1:0.15. This may be due to the rearrangement of a small amount of the precursor *trans*-phosphorinanone **5a** into the cis isomer **2a** prior to sulfurization. Indeed the value +45.87 ppm corresponds to the ^{31}P NMR shift for *r*-1,*trans*-2(e),6(e)-triphenyl-*cis*-3(e)-methyl-4-phosphorinanone 1-sulfide at +53.70 ppm,[3] and hence the peak at +45.87 ppm is for the *trans*-phosphorinanone **5c**. Two reactions (**1a** → **4a**; **3c** → **6c**) are illustrated with ^{31}P shifts



1a (−6.04 ppm) **4a** (−2.79 ppm)



3c (+44.85 ppm) 6c (+53.07 ppm)

provided as used to monitor the thermolysis. The conditions for the isomerizations of the trans isomers into the cis forms are given in Table V. Generally, any deviation from the optimum conditions (see Experimental Section) gave only complex mixtures of cis and trans isomers or tarry products and starting material. The ratio of the cis/trans isomers formed under the different conditions could be followed by ^{31}P NMR analysis. It has been noted[3] that if the original condensation of dienone **11b** with bis(hydroxymethyl)-phenylphosphine was carried out at the boiling point of pyridine, only phosphine **2a** formed. Consequently, the latter could be converted to *P*-oxide **2b** and *P*-sulfide **2c** by the methods already described without contamination of the trans isomers **5b** and **5c**, respectively.

Data are insufficient at this time to speculate on the mechanism of isomerization of the trans isomers to the cis isomers. Intuitively one might expect a homolytic C(2)–P bond cleavage to occur initially followed by epimerization of the radical on carbon and then re-formation of the C(2)–P bond. This area requires further study before definitive conclusions are possible.

In addition to the ^{13}C-labeling studies, it was found that the ultraviolet (UV) spectra proved diagnostic for the isomer differentiation. In Table VI can be found the UV_{max} for phosphorus compounds **1c**, **2b**, **3c**, **4a**, **4b**, and **6c** and thianones **9** and **14**. Also included are *r*-2,*trans*-6-diphenyl-*cis*-3-methylthian-4-one (**10**),[4a,7] 2,4,6,8-tetraphenyl-3-aza-7-thiabicyclo[3.3.1]nonan-9-one (**15**),[12]

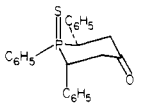
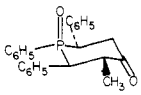
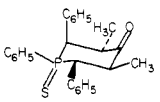
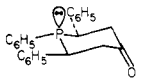
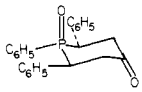
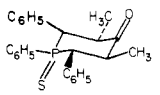
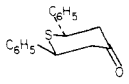
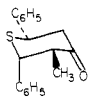
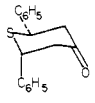
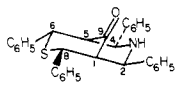
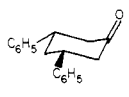
Table V. Data on the Thermal-Catalyzed Rearrangements of the Phosphorinanones

compd (mp, °C)	temp, °C	time, h	cis isomer, %	trans isomer, %	total yield, %
1a (173–174)	200–205	7.0	27.4 (**4a**)	72.6 (**1a**)	70
	220–225	2.5	100	0.0	26
	230–235	5.5	81.5	18.5	62
	240–245	1.5	83.0	17	20
	250–260	2.5	decomposition[a]		
1b (255–256)	280–285	0.5	decomposition[b]		
3a (145–146)	205–210	0.5	100 (**6a**)	0.0 (**3a**)	75
	210–215	0.5	100	0.0	50
3b (296–297)	315–320	0.5	decomposition[b]		
3c (255–256)	265–270	0.5	100 (**6c**)	0.0 (**3c**)	87.5
5a (175–176)	200–210	2	100 (**2a**)	0.0 (**5a**)	72
	230–235	0.5	79.7	20.3	70

[a] Heavy tarring occurred at this temperature or above. [b] Tarring occurred at this temperature, and only complex mixtures with tarring were observed at lower temperatures, with starting ketone also being detected in abundance.

(11) For a review of the X-ray analysis of simple phosphorinanones, see ref 1c.

Table VI. UV and LCCD Data for the Phosphorinanones, Thianones and Models Systems

compd	UV_{max}, nm	$LCCD_{max}$, nm	geometry
 **1c**[2]	broad band[a]	broad band	trans[b]
 **2b**	272, 266, 259, 254	274, 267, 259	cis
 **3c**	broad band	broad band	trans
 **4a**	271, 266 (s), 260	271, 267, 261	cis
 **4b**	272, 265, 258, 253	insoluble	cis
 **6c**	272, 266, 258	276, 265, 262	cis
 **9**	265, 259, 252	266, 260, 253	cis[a]
 **10**[4a]	broad band	broad band	trans[b]
 **14**	broad band	broad band	trans[a]
 **15**[12]	265, 258, 253	265, 258, 251	cis[b]
 **16**[7,13]	268, 265, 262 (s); 259, 252, 248, 243		

[a] Reference compounds of known structure. [b] Compound has been examined by X-ray diffraction techniques on a single crystal.

and *cis*-3,5-diphenylcyclohexanone (**16**).[7,13] It is clear that the fine structure is present in the spectra of the compounds with the phenyl groups at C(2,6) in a cis relationship (i.e., both are bonded via equatorial bonds) in **2b**, **4a**, **4b**, **6c**, **9**, bispidinone **15**, and the cyclohexanone derivative **16**. In contrast, the isomers with a trans arrangement of the C_6H_5–C bonds at C(2,6) have a broad absorption band with little fine structure. In view of X-ray diffraction

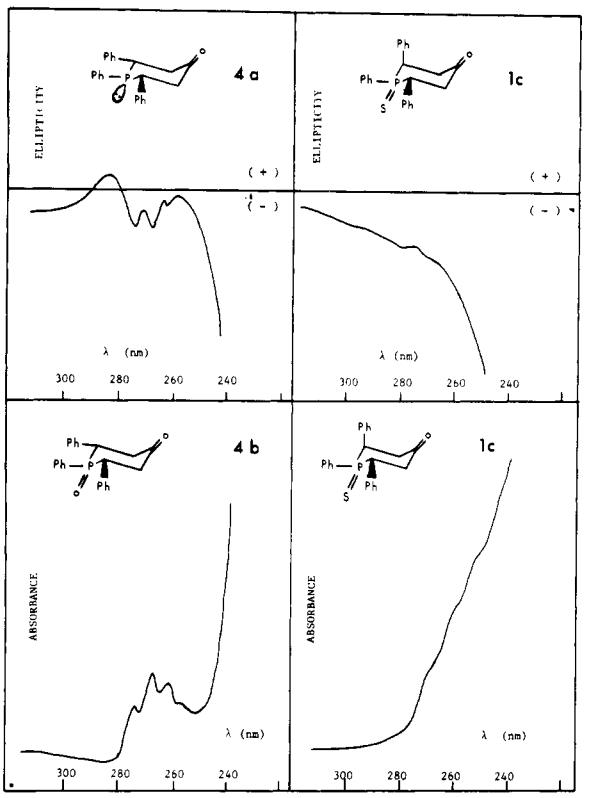


Figure 1. LCCD spectra (upper) and UV absorption spectra (lower) for representative phosphorus derivatives **1c**, **4a**, and **4b**. Ordinate units are arbitrary and solutions are equimolar in each solvent system.

studies on **1c**,[2] **10**,[4a] and bispidinone **15**,[12] there is a firm rational basis for proper correlation of structure with the absorption maxima observed and the positions of the phenyl rings. In solid **1c**[2] and **10**,[4a] the phenyl group attached to the ring by an axial bond is collinear with a plane through P, S, C(4), O and S, C(4), O, respectively. In contrast, the phenyl rings in bispidinone **15** (and presumably in the other "cis isomers" **2b**, **4a**, **4b**, **6c**, and **9**) are situated at sharp angles to the plane through S, C(9), and NH.[12] Thus, it appears that the absorptivity is a function of phenyl-ring alignment assuming the axial C–C_6H_5 bonds have restricted rotation in solution as is implied in the solids **1c**,[2] **10**,[4a] and bispidinone **15**[12] via X-ray analysis.

In view of the known anisotropic structure of the cholesteric solvent systems to induce chirality into optically inactive compounds,[14] it was reasoned that plots of ellipticity vs. λ might also reveal sharp contrasts between the cis and trans isomers. With a 1.63:1 ratio by weight of cholesteryl nonanoate and cholesteryl chloride at 42 °C, a mixture is formed which is a partially compensated cholesteric mesophase with a predominately left-handed helical structure.[14] Solute molecules are preferentially aligned by the solvent and are oriented in the same helical arrangement.[15] Chirality is introduced as a result, and, when the solution is irradiated by circularly polarized light, a liquid-crystal circular dichroism (LCCD) spectrum of the solute is obtained.

Examination of Figures 1 and 2 clearly show fine structure in the LCCD spectra of cis isomers **4a**, **4b**, and **9** and a broad band in the trans isomers **1c** and **14** which are provided as representative examples. Again, it is clear that the cis isomers [equatorial C–C_6H_5 bonds at C(2,6)] can be readily differentiated from the "trans isomers" in these families by LCCD spectral analysis. In

(12) Pantaleo, N. S.; van der Helm, D.; Ramarajan, K.; Bailey, B. R.; Berlin, K. D. *J. Org. Chem.* **1981**, *46*, 4199.
(13) Balasubramanian, M.; D'Souza, A. *Tetrahedron* **1968**, *24*, 5399. Sivakumar, R.; Ph.D. Dissertation, University of Madras, Madras, India, 1979.
(14) (a) Sackmann, E.; Krebs, P.; Rega, H. U.; Voss, J.; Mohwald, H. *Mol. Cryst. Liq. Cryst.* **1973**, *24*, 283. (b) Sackmann, E.; Mohwald, H. *J. Chem. Phys.* **1973**, *28*, 5407. (c) Saeva, F. D.; Sharpe, P. E.; Olin, G. R. *J. Am. Chem. Soc.* **1973**, *95*, 7660. (d) Saeva, F. D.; Olin, G. R. *J. Am. Chem. Soc.* **1976**, *98*, 2709. (e) Eskenazi, C.; Nicoud, J. F.; Kagan, H. B. *J. Org. Chem.* **1979**, *44*, 995.
(15) Bowen, J. M.; Crone, T. A.; Hermann, A. O.; Purdie, N. *Anal. Chem.* **1980**, *52*, 2436.

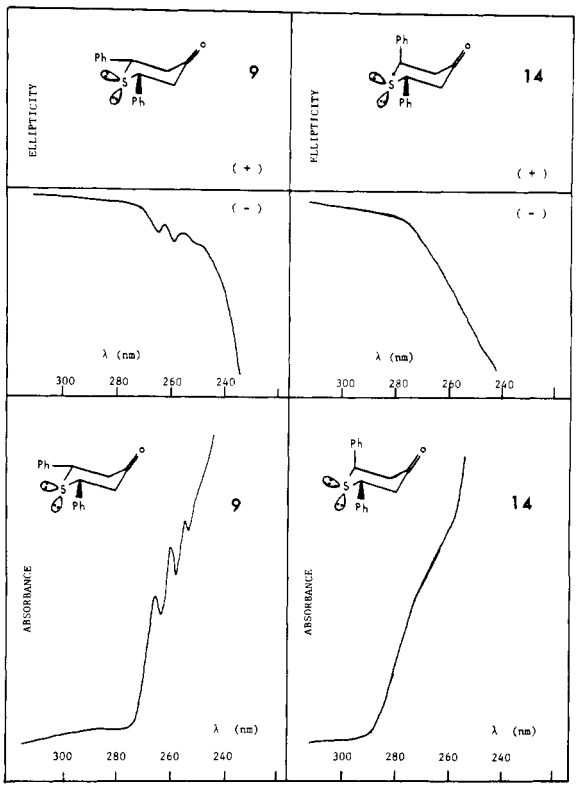


Figure 2. LCCD spectra (upper) and UV absorption spectra (lower) for representative sulfur derivatives **9** and **14**. Ordinate units are arbitrary and solutions are equimolar in each solvent system.

fact the similarity in differences of the LCCD spectra for the cis and trans isomers is reminiscent of the differences noted in the UV spectra since the phenyl ring is the principal chromophore in the systems examined.

There is a tendency toward planarity of the aromatic chromophores in the cis or diequatorial arrangement, which coincides with the retention of vibrational structure typical of benzene. If the ring transitions are distinct, then the effect is *cumulative*. In contrast, in the "trans" arrangement of the aryl rings, the tendency toward coplanarity is lost. The *apparent* loss in vibrational structure may be a consequence of noncoincidence in the frequencies of vibrational modes because the transition moments of the two rings are no longer parallel. Although the use of LCCD in determining the stereochemistry of heterocycles has been essentially unexplored,[16] it appears that the technique has considerable promise in those six-membered ring systems which have an appropriate chromophore group for diagnostic purposes. Since the cyclohexanone system **16** appeared similar to the other "cis isomers", the use of LCCD for stereochemical analysis of carbocycles could also be instructive.

Experimental Section

General Data. Melting points were determined with a Thomas-Hoover capillary apparatus and are uncorrected. The ^1H, ^{13}C, and ^{31}P NMR data were obtained on a Varian XL-100(15) NMR spectrometer equipped with a Nicolet TT-100 PFT accessory operating at 100.1 MHz with tetramethylsilane (Me_4Si) as internal standard for ^1H NMR, at 25.2 MHz (with Me_4Si) for ^{13}C NMR, and at 40.5 MHz (with 85% H_3PO_4) for ^{31}P NMR spectroscopy. The ^{13}C and ^{31}P NMR spectra were obtained with the instruments operating in the FT mode utilizing broad-band proton decoupling and off-resonance decoupling. Infrared spectral data were obtained on a Beckman IR-5A unit. Mass spectral data were collected on a CEC Model 21-110B HR mass spectrometer.

UV-absorption spectra were obtained from a Cary 14 spectrometer. Reagent grade methanol was used in solution preparations. LCCD spectra were obtained from a Cary 61 spectropolarimeter. Data were obtained over the spectral range 350–230 nm. The phenyl ring is the principal chromophore in these compounds over this range of wavelengths. Absorption due to the ketone chromophore is less distinctive at the concentrations used, which were ca. 0.001–0.04 m.

Cholesteryl nonanoate (97%, Aldrich Chemical Co.) and cholesteryl chloride (98%, Aldrich Chemical Co.) were used without further purification. Homogeneous distribution of the solutes in the liquid crystal was assured by dissolving all ingredients in chloroform which was subsequently removed by slow evaporation with vigorous stirring.[15] Each sample used 0.25 g of solvent and ca. 1 mg of ketone. For preparation of the sample cell, a 20-μL aliquot of the solution is pressed between quartz plates. Loading is done with the solution above the isotropic transition temperature to ensure uniformity in the sample. A sample-cell thickness of 12.5 μm is established by a self-adhesive spacer. Provided the cell temperature is adequately controlled, a readily reproducible sample can be prepared and maintained for a number of hours.

The P–C_6H_5 bond in the phosphine **1a** may be assumed to be an equatorial one[2] as it is true in **2a** and **3a**.[3] The configuration and conformation of **1c** have been clearly established via single-crystal X-ray analysis and ^{13}C NMR and ^1H NMR spectra,[2] and the phosphine **1a** and the corresponding sulfide **1c** may now be named more precisely *r*-1,*cis*-2(*a*),*trans*-6(*e*)-triphenyl-4-phosphorinanone and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-triphenyl-4-phosphorinanone 1-sulfide, respectively. All other compounds for which the structures have been clearly established have now been assigned specific names which replace all previous nomenclature employed.

Starting Materials. Reagents (commercially available) were purified before use where necessary. Solvents were reagent grade and were dried over sodium where required. Bis(hydroxymethyl)phenylphosphine was prepared by a known method,[5] and benzaldehyde-α-^{13}C (90 atom % ^{13}C) was obtained from Merck, Sharp, and Dohme.

Preparation of Dibenzalacetone and Dibenzalacetone-*1*-^{13}C (11a). Benzalacetone (3.65 g, 0.025 mol) and a mixture of benzaldehyde (2.56 g, 0.024 mol) and benzaldehyde-α-^{13}C (0.088 g, 0.830 mmol) were dissolved in ethanol (15 mL) and kept at 0 °C. To this was added aqueous NaOH (25%, 12 mL). The remaining procedure was as described in the literature[17] and gave 4.9 g (84.62%) of **11a**, mp 109–110 °C (lit.[17] mp 112 °C).

Peak matching for $^{12}C_{17}H_{14}O$ gave *m/e* (M^+) 234.1044; found, 234.1042; for $^{13}C^{12}C_{16}H_{14}O$, 235.1078; found, 235.1071.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone-2,6-$^{13}C_2$ (1a). To a mixture of dibenzalacetone and dibenzalacetone-*1*-^{13}C (2.70 g, 0.116 mmol) in dry pyridine (25 mL) was added bis(hydroxymethyl)phenylphosphine.[5] The remaining procedure was that already known.[2,18] There was obtained 2.6 g of **1a** (65.6%), mp 173–174 °C (lit.[1p] mp 176–177 °C).

Peak matching for $^{12}C_{23}H_{21}OP$ gave *m/e* (M^+) 344.1329; found, 344.1331; for $^{13}C^{12}C_{22}H_{21}OP$, 345.1365; found, 345.1365.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone 1-Oxide and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone-2,6-^{13}C 1-Oxide (1b). Ketophosphine **1a** (0.45 g, 1.41 mmol) was dissolved in acetone (15 mL). This solution was cooled in ice, and then 0.29 g (1.69 mmol) of MCPA in 3 mL of dry ether was added dropwise with stirring; the remaining procedure was followed as described[3] to give 0.216 g (45%) of **1b**, mp 255–256 °C (lit.[3] mp 253–254 °C).

Peak matching for $^{12}C_{23}H_{21}O_2P$ gave *m/e* (M^+) 360.1279; found, 360.1265; for $^{13}C^{12}C_{22}H_{21}O_2P$, 361.1321; found, 361.1305.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone 1-Sulfide and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-4-phosphorinanone-2,6-^{13}C 1-Sulfide (1c). Ketophosphine **1a** (0.4 g, 0.096 mmol) and sulfur (0.04 g, 1.25 mmol) were dissolved in dry benzene (25 mL), and use of the remaining known method[3] gave 0.3 g (69.1%) of **1c**, mp 239–240 °C (lit.[3] mp 240–242 °C).

Peak matching for $^{12}C_{23}H_{21}OPS$ gave *m/e* (M^+) 376.1050; found, 376.1064; for $^{13}C^{12}C_{22}H_{21}OPS$, 377.1084; found, 377.1071.

Preparation of 2-Methyl-1,5-diphenyl-1,4-pentadien-3-one and 2-Methyl-1,5-diphenyl-1,4-pentadien-3-one-*5*-^{13}C (11b). A solution of sodium hydroxide (2.5 g, 0.063 mol) in water (10 mL) was added slowly to an ice-cold solution of 4.0 g (0.025 mol) of 3-methyl-4-phenyl-3-buten-2-one,[4b] benzaldehyde (2.56 g, 0.024 mol), and benzaldehyde-α-^{13}C (0.088 g, 0.830 mmol) in ethanol (15 mL). The remaining procedure was followed as described in literature[4] to give 6.0 g (96.77%) of **11b**, bp 181–182 °C (0.5 mm) (lit.[4] bp 180–182 °C (0.45 mm)).

Peak matching for $^{12}C_{18}H_{16}O$ gave *m/e* (M^+) 248.1201; found, 248.1212; for $^{13}C^{12}C_{17}H_{16}O$, 249.1235; found, 249.1239.

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Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone and *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C (2a). To a mixture of 2-methyl-1,5-diphenyl-1,4-pentadien-3-one and 2-methyl-1,5-diphenyl-1,4-pentadien-3-one-5-^{13}C (3.30 g, 0.133 mol) in dry pyridine (25 mL) was added bis(hydroxymethyl)phenylphosphine[5] (2.30 g, 01013 mol), and the known procedure was followed[3] to give 1.10 g (23.11%) of **2a**, mp 210–211 °C (lit.[3] mp 210–211 °C).

Peak matching for $C_{24}H_{23}OP$ gave *m/e* (M^+) 358.1486; found, 358.1489; for $^{13}C^{12}C_{23}H_{23}OP$, 359.1520; found, 359.1526.

Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Oxide and *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C 1-Oxide (2b). This oxide was prepared in 50% yield from ketone **2a** (0.1 g, 0.28 mmol) and *m*-chloroperbenzoic acid (0.06 g, 0.35 mmol) as reported;[3] mp 289–291 °C (lit.[3] mp 289–291 °C).

Peak matching for $C_{24}H_{23}O_2P$ gave *m/e* (M^+) 374.1435; found, 374.1430; for $^{13}C^{12}C_{23}H_{23}O_2P$, 375.1468; found, 375.1490.

Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Sulfide and *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C 1-Sulfide (2c). Ketophosphine **2a** (0.1 g, 0.28 mmol) and sulfur (0.011 g, 0.34 mmol) were dissolved in toluene (12 mL), and use of the remaining known procedure[3] gave 0.073 g (67%) of **2c**, mp 246–247 °C (lit.[3] mp 246–247 °C).

Peak matching for $C_{24}H_{23}OPS$ gave *m/e* (M^+) 390.1207; found, 390.1213; for $^{13}C^{12}C_{23}H_{23}OPS$, 319.1241; found, 391.1247.

Preparation of 2,4-Dimethyl-1,5-diphenyl-1,4-pentadien-3-one and 2,4-Dimethyl-1,5-diphenyl-1,4-pentadien-3-one-1,5-^{13}C (11c). The procedure adopted for the preparation of this compound was essentially that of Japp and Maitland[19a] with subsequent modifications reported.[19b] Potassium hydroxide pellets (3.50 g, 0.063 mol) were added to a solution of pentan-3-one, benzaldehyde (7.82 g, 0.074 mol), benzaldehyde-α-^{13}C (0.18 g, 1.68 mmol), and water (18.0 g, 1.0 mol) in ethanol (20 mL) in 0.5-g quantities over a period of 2 h. The mixture was stirred at room temperature for 5 days. The solid that formed was filtered, washed with water, dried, and recrystallized from methanol, yielding 3.0 g (34.5%) of *r*-2,*cis*-6-diphenyl-*trans*-3,5-dimethyl-4-oxanone, mp 112–113 °C (lit.[19b] mp 113.5–114 °C).

To a solution of the above oxanone (2.7 g, 9.64 mmol) in absolute ethanol (100 mL) was added solid KOH (10.0 g, 0.18 mol) in one lot, and the mixture was stirred for 1 week at room temperature and left for another week with occasional stirring. A shining solid formed and was filtered, washed with absolute alcohol (5 mL), and dried. Recrystallization from methanol gave the title compound as colorless plates, 0.6 g (24%), mp 127–128 °C (lit.[19b] 127–128 °C).

Peak matching for $C_{19}H_{18}O$ gave *m/e* (M^+) 262.1358; found, 262.1361; for $^{13}C^{12}C_{18}H_{18}O$, 263.1391; found, 263.1383.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-^{13}C (3a). To a mixture of 2,4-dimethyl-1,5-diphenyl-1,4-pentadien-3-one and 2,4-dimethyl-1,5-diphenyl-1,4-pentadien-3-one-1,5-$^{13}C_2$ (0.3 g, 1.15 mmol) in dry pyridine (5 mL) was added bis(hydroxymethyl)phenylphosphine[5] (0.25 g, 1.47 mmol), and the reported procedure was adopted[3] to yield 0.24 g (57.14%) of **3a**, mp 145–146 °C (lit.[3] 145–146 °C).

Peak matching for $C_{25}H_{25}OP$ gave *m/e* (M^+) 372.1643; found, 372.1627; for $^{13}C^{12}C_{24}H_{25}OP$, 373.1677; found, 373.1673.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone 1-Oxide and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-$^{13}C_2$ 1-Oxide (3b). The oxide was obtained in 76% yield from ketophosphine **3a** (0.04 g, 0.11 mmol) and MCPA (0.035 g, 0.20 mmol) in acetone medium as reported,[3] mp 296–297 °C (lit.[3] 296–297 °C).

Peak matching for $C_{25}H_{25}O_2P$ gave *m/e* (M^+) 388.1592; found, 388.1602; for $^{13}C^{12}C_{24}H_{25}O_2P$, 389.1625; found, 389.1626.

Preparation of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone 1-Sulfide and *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-$^{13}C_2$ 1-Sulfide (3c). Phosphine **3a** (0.04 g, 0.11 mmol) and sulfur (0.004 g, 0.13 mmol) were dissolved in benzene (3 mL) and stirred at 60–65 °C for 6 h under N_2. The product was worked up as reported[3] and gave 0.025 g (58.14%) of **3c**, mp 255–256 °C (lit.[3] mp 255–256 °C).

Peak matching for $C_{25}H_{25}OPS$ gave *m/e* (M^+) 404.1364; found, 404.1373; for $^{13}C^{12}C_{24}H_{25}OPS$, 405.1397; found, 405.1398.

Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-4-phosphorinanone (4a). Ketophosphine **1a** (0.10 g, 0.29 mmol) was placed in a sealed glass tube under N_2. This system was heated in an oil bath (235–240 °C) for 2.5 h. After cooling, the sealed glass tube was opened under N_2. A brown mass was observed and was dissolved in CH_3CN (10 mL). The solution was filtered and cooled to give a light-yellow crystalline product. Recrystallization (H_3CCN) gave **4a** (0.051 g, 51%), mp 180–182 °C. Analytical and spectral data are given in Tables I–III.

A similar procedure was adopted to prepare the ^{13}C-labeled compound *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-4-phosphorinanone-2,6-$^{13}C_2$ (**4a**) from the corresponding ^{13}C-enriched distyryl ketone **11a**.

Peak matching for $C_{23}H_{21}OP$ gave *m/e* (M^+) 344.1330; found, 344.1331; for $^{13}C^{12}C_{22}H_{21}OP$, 345.1364; found, 345.1363.

Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-4-phosphorinanone 1-Oxide (4b). Ketophosphine **4a** (0.018 g, 0.52 mmol) was dissolved in acetone (10 mL). This solution was cooled in an ice bath, and then to this was added, dropwise with stirring, 0.01 g (0.636 mmol) of MCPA in 3 mL of dry ether. This new solution was stirred at 0 °C for 0.5 h followed by stirring at room temperature for another 0.5 h. Evaporation of the solvent left a solid mass which was washed with ether (3 × 3 mL portions) to remove excess MCPA and benzoic acid formed. The residue was recrystallized (abs CH_3OH) to give 0.011 g (60%) of **4b**, mp 286–287 °C. Analytical and spectral data are given in Tables I–III.

The ^{13}C-labeled oxide *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-4-phosphorinanone-2,6-$^{13}C_2$ 1-oxide (**4b**) was prepared similarly.

Peak matching for $C_{23}H_{21}O_2P$ gave *m/e* (M^+) 360.1279; found, 360.1265; for $^{13}C^{12}C_{22}H_{21}O_2P$, 361.1313; found, 361.1305.

Preparation of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-4-phosphorinanone 1-Sulfide (4c). Ketone **4a** (0.06 g, 0.17 mmol) and sulfur (0.006 g, 0.19 mmol) dissolved in toluene (15 mL) were placed in a 50-mL flask. The solution was boiled for 16 h under N_2. The new solution was filtered, and evaporation of the solvent gave a solid mass. Recrystallization (abs CH_3OH) gave 0.034 g (52.3%) of **4c**, mp 205–206 °C. Spectral data are given in Tables I–III.

An identical procedure was employed to prepare *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-4-phosphorinanone-2,6-$^{13}C_2$ 1-sulfide (**4c**).

Peak matching for $C_{23}H_{21}OPS$ gave *m/e* (M^+) 376.1051; found, 376.1064; for $^{13}C^{12}C_{22}H_{21}OPS$, 377.1084; found, 377.1071.

Synthesis of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone (5a). Bis(hydroxymethyl)phenylphosphine (1.03 g, 6.06 mmol) and 1.5 g (6.0 mmol) of 2-methyl-1,5-diphenyl-1,4-pentadien-3-one (**11b**)[4a] were dissolved in dry pyridine (5 mL) under N_2. The solution was stirred at room temperature for 30 h and at 43–45 °C (oil bath) for 2 h. Stirring was continued at room temperature for another 15 h. Evaporation of pyridine under vacuum (0.25 mm (40 °C oil bath)) gave a residue which was washed with petroleum ether (3 × 5 mL portions) to remove the last traces of pyridine. Solution of this solid occurred in hot CH_3CN (10 mL), and the new solution was filtered while hot. The filtrate upon cooling gave a white crystalline product which was recrystallized (CH_3CN) to give 0.35 g (14.81%) of **5a**, mp 175–176 °C. Spectral data are given in Tables I–III.

r-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C was prepared by mixing bis(hydroxymethyl)phenylphosphine (1.03 g, 6.06 mmol) and 1.5 g (6.0 mmol) of 2-methyl-1,5-diphenyl-1,4-pentadien-3-one and 2-methyl-1,5-diphenyl-1,4-pentadien-3-one-5-^{13}C (**11b**). The remaining procedure was as discussed above and gave ^{13}C-enriched phosphorinanone, 0.32 g (13.54%).

Peak matching for $C_{24}H_{23}OP$ gave *m/e* (M^+) 358.1486; found, 358.1489; for $^{13}C^{12}C_{23}H_{23}OP$, 359.1520; found, 359.1533.

Synthesis of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Oxide (5b). Ketone **5a** (0.05 g 0.165 mmol) was dissolved in acetone (10 mL), and the solution was cooled in ice. To this was added, dropwise with stirring, 0.03 g (0.175 mmol) of MCPA in 3 mL of dry ether. The reaction mixture was stirred at 0 °C for 0.5 h and then at room temperature for another 0.5 h. Evaporation of the solvent left a solid mass which was washed with ether (3 × 3 mL portions) to remove excess MCPA. Recrystallization (absolute CH_3OH) gave 0.026 g (50%) of **5b**, mp 279–281 °C. Analytical and spectral data are given in Tables I–III.

r-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C 1-oxide (**5b**) was similarly prepared.

Peak matching for $C_{24}H_{23}O_2P$ gave *m/e* (M^+) 374.1435; found, 374.1424; for $^{13}C^{12}C_{23}H_{23}O_2P$, 375.1468; found, 375.1470.

Synthesis of *r*-1,*cis*-2(*a*),*trans*-6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Sulfide (5c). Ketone **5a** (0.04 g, 0.116 mmol) and sulfur (0.04 g, 0.12 mmol) dissolved in dry benzene (10 mL) were stirred at room temperature for 44 h and for another 30 h at 50 °C (water bath). Evaporation of the solvent gave a solid mass, which was recrystallized (absolute CH_3OH) to give 0.022 g (51.1%) of **5c**, mp 230–232 °C. Analytical and spectral data are given in Tables I–III.

The corresponding ^{13}C-labeled compound *r*-1,*cis*-2(*a*),*trans*-6(*e*)-triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone-6-^{13}C 1-sulfide (**5c**) was obtained as described above.

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Peak matching for $C_{24}H_{23}OPS$ gave m/e (M^+) 390.1207; found, 390.1176; for $^{13}C^{12}C_{23}H_{23}OPS$, 391.1241; found, 391.1262.

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone (2a). Ketophosphine **5a** (0.03 g, 0.14 mmol) was placed in a sealed glass tube under N_2. This system was heated on an oil bath (200–210 °C) for 2 h. The remaining procedure was that described previously to prepare **4a**. The solid was recrystallized (CH_3CN) to give a white crystalline ketone **2a** (0.036 g, 72%), mp 210–211 °C (lit.[3] mp 210–211 °C).

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Oxide (2b). Ketophosphine **2a** (0.2 g, 0.58 mmol) was dissolved in acetone (25 mL), and this solution was cooled in ice. To this was added, dropwise with stirring, 0.12 g (0.70 mmol) of MCPA in 5 mL of dry ether. The remaining procedure paralleled that for **4b**. The residue was recrystallized (abs C_2H_5OH) to give 0.11 g (52.6%) of **2b**, mp 289–291 °C (lit.[3] mp 289–291 °C).

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*)-methyl-4-phosphorinanone 1-Sulfide (2c). Ketone **2a** (0.2 g, 0.58 mmol) and sulfur (0.02 g, 0.62 mmol) were dissolved in toluene (25 mL). The reaction mixture was gently boiled for 8 h under N_2, and the remaining procedure was the same as that described for **4c**. The residue was recrystallized (absolute C_2H_5OH) to give 0.17 g (78%) of **2c**, mp 246–247 °C (lit.[3] mp 246–247 °C).

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone (6a). Ketophosphine **3a** (0.10 g, 0.27 mmol) was placed in a sealed glass tube under N_2. This was heated on an oil bath (210–215 °C) for 0.5 h. The remaining procedure was the same as that described for **4a**. The solid was recrystallized (CH_3OH) to give **6a** (0.75 g, 75%), mp 224–226 °C. Spectral data are given in Tables I–III.

A similar procedure was adopted to prepare *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-$^{13}C_2$ (**6a**).

Peak matching for $C_{25}H_{25}OP$ gave m/e (M^+) 372.1643; found, 372.1640; for $^{13}C^{12}C_{24}H_{25}OP$, 373.1677; found, 373.1689.

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone 1-Oxide (6b). Ketone **6a** (0.04 g, 0.108 mmol) was dissolved in acetone (10 mL). To the ice-cooled solution was added, dropwise with stirring, 0.02 g (0.116 mmol) of MCPA in 3 mL of dry ether. The remaining procedure was as for **4b**. The solid was recrystallized (abs CH_3OH) to give 0.023 g (56.6%) of **6b**, mp 302–303 °C. Spectral data are given in Tables I–III.

The corresponding ^{13}C-labeled oxide, *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-^{13}C 1-oxide, was prepared in a similar fashion.

Peak matching for $C_{25}H_{25}O_2P$ gave m/e (M^+) 388.1592; found, 388.1585; for $^{13}C^{12}C_{24}H_{25}O_2P$, 389.1625; found, 389.1646.

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone 1-Sulfide (6c). Ketophosphine **6a** (0.05 g, 0.134 mmol) and sulfur (0.0043 g, 0.134 mmol) were dissolved in toluene (15 mL). The remaining procedure was as that for **4c**. The solid mass was recrystallized (absolute CH_3OH) to give 0.03 g (56%) of **6c**, mp 291–292 °C. Spectral data are given in Tables I–III.

An identical method was utilized to prepare *r*-1,*trans*-2(*e*),6(*e*)-triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-4-phosphorinanone-2,6-$^{13}C_2$ 1-sulfide (**6c**).

Peak matching for $C_{25}H_{25}OPS$ gave m/e (M^+) 404.1364; found, 404.1368; for $^{13}C^{12}C_{24}H_{25}OPS$, 405.1397; found, 405.1391.

Synthesis of *r*-1,*trans*-2(*e*),6(*e*)-Triphenyl-*cis*-3(*e*),5(*e*)-dimethyl-3,5-dideuteriophosphorinan-4-one 1-Sulfide (12). Ketone **6c** (0.03 g, 0.074 mmol) was dissolved in dry dioxane (3 mL), and to this was added deuterium oxide (6.5 mL, Aldrich Gold Label) and K_2CO_3 (0.012 g, 0.087 mmol). The mixture was boiled with stirring under N_2 for 36 h. Upon cooling, the new mixture was extracted with $HCCl_3$ (3 × 10 mL). The $HCCl_3$ layer was washed with deuterium oxide (10 mL) and dried (Na_2SO_4). Evaporation of the $HCCl_3$ left a solid mass which was recrystallized (CH_3OH) to give 0.027 g (89.4%) of the deuterated analogue **12**, mp 290–291 °C; calcd for $C_{25}H_{23}D_2OPs$, 406.1489; found, 406.1472.

Preparation of *r*-2,*trans*-6-Diphenyl-*cis*-3-methyl-4-thianone and *r*-2,*trans*-6-Diphenyl-*cis*-3-methyl-4-thianone-6-^{13}C (10). Michael addition of hydrogen sulfide to 2-methyl-1,5-diphenyl-1,4-pentadien-3-one and 2-methyl-1,5-diphenyl-1,4-pentadien-3-one-5-^{13}C (2.0 g, 8.07 mmol) in methanol (40 mL) containing sodium acetate trihydrate (4.0 g, 0.029 mol) as reported[4a] gave 0.40 g (17.33%) of the title compound, mp 151–152 °C (lit.[4a] 151–152 °C); calcd for $C_{18}H_{18}OS$, 282.1078; found, 282.1079; for $^{13}C^{12}C_{17}H_{18}OS$, 283.1112; found, 283.1112.

Acknowledgment. We gratefully acknowledge the support of the work by the National Institutes of Health, U.S.P.H.S., via a grant from the National Cancer Institute, CA 22770-03.

Nuclear Magnetic Resonance Investigation of the Spontaneous Decarboxylation of 2-Oxalopropionic Acid. 2. Species in Solution

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Abstract: The kinetics of the spontaneous decarboxylation of 2-oxalopropionic acid (OPA) to the enolate intermediate of α-ketobutyric acid (AKBA) with subsequent ketonization, and β-deuteration via enolization, have been studied by NMR in aqueous solution at 31 °C. The rate constants for the decarboxylation of the fully protonated, monoprotonated, and fully deprotonated species of OPA were found to be 1.67×10^{-5} s^{-1}, 13.5×10^{-5} s^{-1}, and 7.75×10^{-5} s^{-1}, respectively. The rate constant for the ketonization of the intermediate was found to be 3.25×10^{-4} s^{-1} while the rate constant for the enolization of OPA was found to 2.70×10^{-4} s^{-1}. The ketonization and enolization processes exhibited specific acid catalysis and the second-order rate constants were found to be 1.60×10^{-1} M^{-1} s^{-1} and 1.20×10^{-1} M^{-1} s^{-1}, respectively. The first pK_a of OPA, involving the carboxyl adjacent to the keto function, was found to be 1.75, while the second pK_a for the remaining carboxyl group was determined to be 4.18. In D_2O the p*K*'s were calculated as 2.38 and 4.50, respectively. Under the reaction conditions employed the hydrate species exists in appreciable concentrations at low pH while the concentration of the enol species was not significant.

The spontaneous,[1–9] metal-catalyzed,[5–18] and enzymatic[19] decarboxylation of α-keto diacids in which the second carboxyl function is located at the β carbon, along with the corresponding enolization[20–22] and dehydration[20,21] reactions, have been the subject of detailed kinetic studies and still continue to be of widespread scientific interest. Substrates which have been involved in these studies are oxaloacetic acid (OAA), dimethyloxaloacetic

† Abstracted in part from a dissertation to be submitted by Gregory Kubala to the Faculty of Texas A&M in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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