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# CONFIGURATION OF OPTICALLY ACTIVE PHOSPHORUS THIOACIDS—II

## CHIROPTICAL PROPERTIES OF O-ALKYL ALKYLPHOSPHONOTHIOIC ACIDS, ALKYLPHENYLPHOSPHINOTHIOIC ACIDS AND THEIR DERIVATIVES[1–5]

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**Abstract**—Rotations at the NaD line, CD and UV spectra of a series of O-alkyl alkylphosphonothioic acids, two alkylphenylphosphinothioic acids and their respective derivatives were measured. In the case of the phosphonothioic acid derivatives containing the P=S bond the correct sign of rotation at the NaD line could be predicted by the application of Brewster's conformational asymmetry rule. A simple rule is given for correlating the sign of the Cotton effect around 200–230 nm with the configuration. In the CD spectra of the aromatic phosphinothioic acid derivatives at least four bands have been found whose assignments are discussed. The CD of the nondissociated acid (in nonpolar solvents) is analogous to that of homochiral ester derivatives; it is different in water solution, where the dissociated acid forms a new chromophore. According to the CD, the P(=S)OH tautomeric form is preferred for the phosphono- and phosphinothioic acids.

THERE is an increasing interest in optically active phosphorus thioacids, as they are very useful key compounds for synthetic as well as mechanistic studies. An important recent advance in this field was the stereospecific conversion of phosphonothiolates into phosphinates. Benschop, *et al.*[6] were able to correlate the configuration of optically active (+)-O-isopropyl methylphosphonothioic acid with that of S-(−)-methylpropylphenylphosphine oxide and assigned the *R*-configuration to this (+)-acid. On the basis of this result we have assigned the absolute configuration to other O-alkyl alkylphosphonothioic acids by chemical correlations,[2] asymmetric reduction of sulfoxides[7] and NMR spectroscopy.[8]

In continuation of our studies on the configuration of optically active phosphorus thioacids we have investigated their chiroptical properties with the aim of finding perhaps a more convenient correlation method and of confirming the earlier assignments.

### CHEMICAL CORRELATIONS

All the optically active phosphorus thioacids examined here were resolved by salt formation with quinine or α-phenylethylamine according to procedures described in

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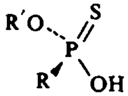
the literature.[9–13]. The compounds thus obtained belong in part to the (+)-, in part to the (−)-series.

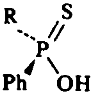
Taking into account the work of Benschop *et al.*,[6] biochemical tests carried out by Aaron *et al.*[10] and our own recent results,[2] the chirality of the P atom in the dextrorotatory phosphonothioic acids **1**–**10** is *R*.



*R*-(+)

| | R | R' | | R | R' |
|---|---|---|---|---|---|
| **1** | Me | Me | E-**6*** | Et | Me |
| **2** | Me | Et | **7**† | Et | Et |
| **3** | Me | Pr$^n$ | E-**8*** | Pr$^i$ | Me |
| **4** | Me | Pr$^i$ | E-**9*** | Pr$^i$ | Et |
| E-**5*** | Me | Bu$^n$ | **10** | Bu$^t$ | Me |

For the (+)-phosphinothioic acid **11** the *R*-configuration has been proven, too,[6,14] the corresponding dextrorotatory homologue **12**, however, was assigned the *S*-configuration on the basis of mechanistic reasoning.[14] As such arguments are rather questionable and the CD results (see later) contradict the assignment based on them, we believe now that (+)-**12** is homochiral[15] to (+)-**11**.



**11**: R = Me
E-**12**:* R = Et

For comparison various derivatives of O-alkyl alkylphosphonothioic acids and alkylphenylphosphinothioic acids containing the >P(=O)S— or >P(=S)O— grouping have been investigated. Most of them had been prepared previously from the corresponding thioacids by stereospecific reactions whose stereochemistry was well proven.

The (+)-phosphonothiolates **13**[16] and **18**,[6] and (+)-phosphinothiolates **21**[6] and **22**[17] have the same absolute configuration as the parent (+)-thioacids **7**, **4**, **11** and **12**, respectively, since the center of chirality is not involved in the alkylation reaction, the sign of rotation did not change in this reaction. The absolute configurations of the thiono-compounds may be deduced from the literature as follows: *S*-(−)-**14**[16,18], *R*-(−)-**15**,[19] *s*-(+)-**16**,[20] *s*-(+)-**17**,[20] *R*-(+)-**19**,[6] *S*-(+)-**20**.[21]

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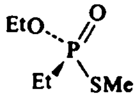
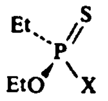
* In order to simplify the discussion, in the case of compounds **1**–**10** we refer only to the *R*-series. If actually the other enantiomer has been measured, this is, as usual, indicated by "E". Thus E-X is the enantiomer of X.

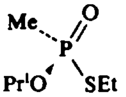
† Both enantiomers have been measured.



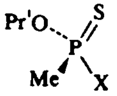
*S*-**13***



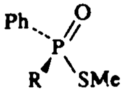
**14**: X = OMe
E-**15**: X = Cl
**16**: X = SEt
**17**: X = $NEt_2$



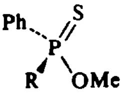
**18**



**19**: X = OMe
E-**20**: X = SEt

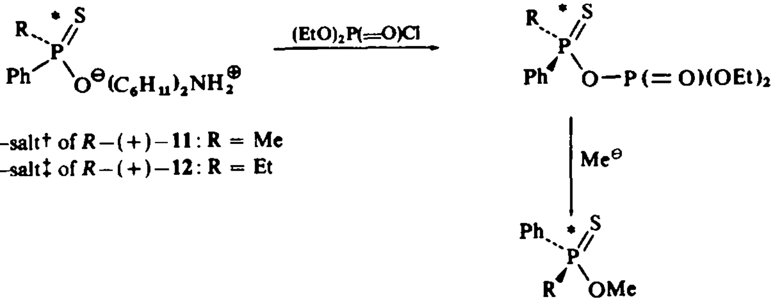


**21** : R = Me
**22** : R = Et



**23**: R = Me
**24**: R = Et

The O-methyl alkylphenylphosphinothionates **23** and **24** were synthesized from alkylphenylphosphinothioic acids **11** and **12** by a sequence of two reactions. Treatment of the dicyclohexylammonium salts of the above acids with diethyl phosphorochloridate affords the corresponding thiopyrophosphinates which subsequently, without isolation, were degraded by sodium methoxide to give the desired thionoesters.



DCHA-salt† of *R*-(+)-**11**: R = Me
DCHA-salt‡ of *R*-(+)-**12**: R = Et

*S*-(+)-**23**: R = Me
*S*-(+)-**24**: R = Et

Since the first reaction proceeds without change of configuration at the P atom and since for the second reaction inversion at the center of chirality is assumed,[22] the chirality of the P atom in (+)-O-methyl methylphenylphosphinothionate **23** and its ethyl homologue **24** should be *S*.

### *Chiroptical properties of O-alkyl alkylphosphonothioic acids and derivatives*

In the CD spectra of compounds **1–10** one observes only one intense Cotton effect

* Both enantiomers of 13 have been measured.
† $[\alpha]_D$ + 7·83 (MeOH).
‡ $[\alpha]_D$ + 11·44 (MeOH).

around 200 nm which is strongest in nonpolar solvents. The band position is nearly independent of the solvent, only in water is there a pronounced bathochromic shift (Table 1; Fig 1 shows the CD spectra of **10**). The intense UV maximum lies at a shorter wavelength than the CD maximum in each case (Table 1). The strong shift in water solution may be due to dissociation of the P(=S)OH grouping. The magnitude of the CD in most cases increases with the size of the substituents R and R′.

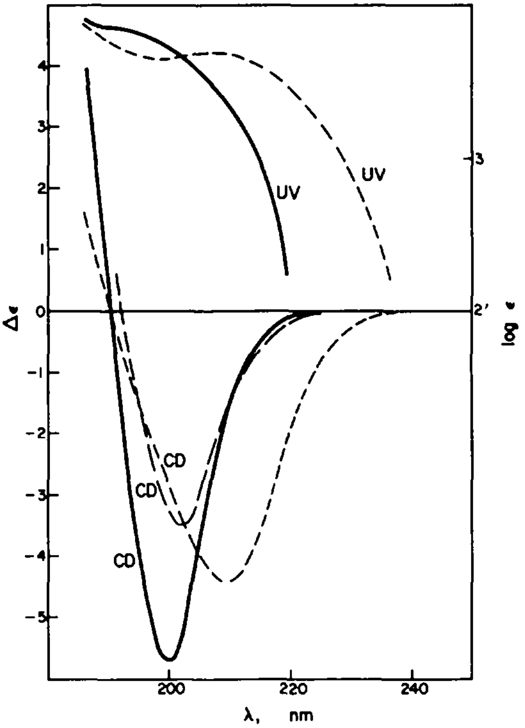
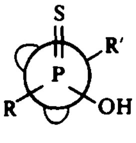


FIG 1. CD of *R*-**10** in isooctane (———), ethanol (— — —) and water (-----); and UV (at the top) in isooctane (———) and water (-----).

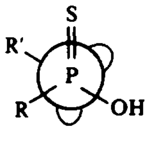
The Cotton effect at about 200 nm is negative for *R*-configuration, a stronger positive CD band must, therefore, be present at shorter wavelengths to explain the positive rotations at the NaD line. Indeed, in some cases a part of this second Cotton effect can just be seen in the CD spectrum.

In order to rationalize the chiroptical data of the monoesters **1**–**10** as well as those of the various diesters **13**, **14**, **16**, **18**–**20**, the chloro compound **15** and the amide **17**, they were subjected to Brewster's method[23,24] in a simplified form using polarizability values from the literature[25] as well as Brewster's more refined conformational asymmetry rule.[23,24] The latter has already been applied earlier to two phosphorus compounds.[26,27] These calculations gave the correct results and the same is true in all our cases except for **15**.

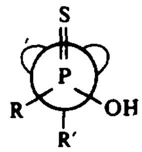
The three rotamers of lowest energy of *R*-(+)-**1**–**10** are as follows:[28]



I



II

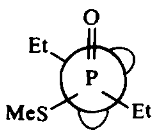


III

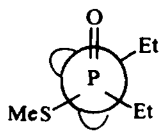
With increasing size of R or/and R' conformation I should become more populated relative to II and III. As $[M]_D$ in general increases in the same sense (*cf* Table 1), conformation I must give a positive rotation. Applying the conformation asymmetry rule[24] and using $E$ for the effect of a free electron pair[27] the molar rotation of I becomes $k(S_dC - CO + OE - CE + CE - S_dE)$[*] $= k(S_d - O)(C - E)$; $(C - E)$ is positive[27] and $(S_d - O)$ is also positive,[25] regardless of what are the exact values of the polarizabilities in the case of these phosphonothoic acid derivatives. The sign of $[M]_D$ of conformer I is, therefore, correctly predicted.

In this treatment we took into account only those rotamers which differ in the torsion angle around the P—O(R') bond. It can easily be shown that the allowed[23, 24] rotamers around the P—C and O—C bonds *in toto* do not contribute to the rotation.

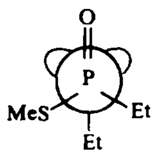
Looking along the P—O bond of *R*-**13** again three preferred rotamers IV, V and VI are possible. Rotamer IV containing the two alkyl groups in anti periplanar conformation should be the most preferred one (lone pair interactions are similar in all three cases), and this leads to $[M]_{D(PO)} = k(C - E)(S - O_d) > 0$. The same treatment when applied to the P—S bond, gives $[M]_{D(PS)} = k(C - E)(O_d - O) > 0$. The rotation is, therefore, predicted to be positive which agrees with the experimental. According to this Brewster treatment **18** should also be dextrorotatory, as indeed it is.



IV



V



VI

As this method does not differentiate between the contributions of different O-alkyl moieties, for **14** and **19** no prediction can be made. These two compounds which are "quasi-achiral" show indeed only very small rotational values.

For **16** again both projections, (a) that along the P—O and (b) that along the P—S bond have to be used and as in the case of **13** the combination of both calculations gives $[M]_D = k(C - E)(S - O) > 0$ in agreement with the experimental. The same is true for **20**.

The calculation for the amide **17** was done in the same way by projecting once along the P—O, once along the P—N bond giving $[M]_D = k(C - E)(N - O) > 0$. Here also the correct sign is predicted.

The chloride **15** is an exception, because the calculation leads to $[M]_D = k(C - E)(S_d - Cl) > 0$, whereas **15** is laevorotatory. One should, however, be aware of the fact that this treatment is very crude, especially as regards the conformational analysis of all these compounds.

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[*] S and O stand for single bonded atoms, $S_d$ and $O_d$ for doubly bonded ones.

TABLE 1. SPECIFIC ROTATIONS, CD AND UV DATA OF THE INVESTIGATED COMPOUNDS

| Compound | $[\alpha]_D$[a] | Solvent[b] | CD : $\lambda_{max}(\Delta\varepsilon)$[f] | UV : $\lambda_{max}(\varepsilon)$[f] |
|---|---|---|---|---|
| (*R*)-1 | +2·8 | isooctane | 197 (−1·3) | |
| | | water | 202 (−2·3) | |
| (*R*)-2 | +9·5 | isooctane | 196 (−2·9) | |
| | | water | 205 (−2·3) | |
| (*R*)-3[d] | +1·3 | isooctane | 195 (−0·86) | |
| | | water | 201 (−0·66) | |
| (*R*)-4 | +14·7 | isooctane | 196 (−3·3) | |
| | | acetonitrile | 197 (−1·5) | |
| | | ethanol | 197 (−1·8) | |
| (*S*)-5 | −12·6 | isooctane | 198 (+4·4) | |
| | | water | 204 (+2·8) | |
| (*S*)-6 | −8·3 | isooctane | 199 (+5·2) | 190! (9900) |
| | | ethanol | 200 (+1·8) | 190! (10500) |
| | | water | 205 (+3·4) | 206 (5600) |
| | | | | 190! (6100) |
| | | 0·5N-HCl | 200 (+2·7) | |
| (*R*)-7 | +12·9 | isooctane | 197 (−2·3) | |
| (*S*)-7 | −13·9 | isooctane | 197 (+2·3) | |
| | | ethanol | 198 (+1·4) | |
| | | water | 205 (+1·5) | |
| | | water-KOH (pH 12) | 213 (+1·3) | |
| (*S*)-8 | −17·0 | isooctane | 198 (+2·9) | |
| | | water | 204 (+1·8) | |
| (*S*)-9 | −21·3 | isooctane | 198 (+4·2) | |
| | | water | 205 (+2·6) | |
| (*R*)-10 | +13·2 | isooctane | 200 (−5·7) | 190i (7150) |
| | | | | 185! (8200) |
| | | ethanol | 202 (−3·5) | 196 (5800) |
| | | water | 210 (−4·4) | 207 (4950) |
| | | | | 185! (7700) |
| (*R*)-11 | +14·4[e] | isooctane | 274 (−0·51) | 272 (880) |
| | | | 268 (−0·39) | 266 (1200) |
| | | | 261 (+0·05) | 258i (1450) |
| | | | 254 (+0·56) | 221i (6500) |
| | | | 233 (+2·7) | 215i (8800) |
| | | | 216 (−3·8) | 190 (41000) |
| | | | 196 (−3·6) | |
| | | | 188 (+14) | |
| | | acetonitrile | 273 (−0·64) | |
| | | | 266 (−0·67) | |
| | | | 260 (−0·46) | |
| | | | 253 (−0·11) | |
| | | | 227 (+2·11) | |
| | | ethanol | 273 (−0·64) | |
| | | | 266 (−0·71) | |
| | | | 260 (−0·47) | |
| | | | 253 (−0·17) | |
| | | | 225 (+2·0) | |
| | | methanol | 272 (−0·53) | |
| | | | 266 (−0·58) | |
| | | | 260 (−0·44) | |
| | | | 251i (−0·15) | |
| | | | 224 (+1·7) | |

TABLE 1—*continued*

| | | | | |
|---|---|---|---|---|
| | | water | 271 (−0·29) | 272i (500) |
| | | | 264 (−0·59) | 265i (780) |
| | | | 258 (−0·81) | 235i (3800) |
| | | | 242 (−1·78) | 215i (10400) |
| | | | 213 (+3·2) | 205i (13700) |
| | | | 193 (+9·0) | 187 (42500) |
| | | ethanol–KOH | 272 (−0·55) | |
| | | | 265 (−0·68) | |
| | | | 258 (−0·72) | |
| | | | 251 (−0·72) | |
| | | | 221 (+1·7) | |
| | | ethanol–water (1 :1) | 272 (−0·42) | |
| | | | 265 (−0·57) | |
| | | | 258 (−0·54) | |
| | | | 247 (−0·62) | |
| | | | 216 (+1·5) | |
| | | methanol–water (1 :1) | 272 (−0·44) | |
| | | | 265 (−0·57) | |
| | | | 258 (−0·58) | |
| | | | 247 (−0·68) | |
| | | | 216 (+1·5) | |
| | | water–KOH (pH 12) | 270 (−0·30) | |
| | | | 263 (−0·50) | |
| | | | 256 (−0·77) | |
| | | | 241 (−1·59) | |
| | | | 215 (+2·15) | |
| (*S*)-**12** | −12·9[e] | isooctane | 274 (+0·33) | 272 (460) |
| | | | 267 (+0·28) | 266 (660) |
| | | | 260 (+0·07) | 258i (810) |
| | | | 232 (−1·45) | 237i (1360) |
| | | | 216 (+2·1) | 215i (7800) |
| | | | 204 (+2·7) | 195! (26600) |
| | | | 186! (−6) | |
| | | water | 271 (+0·31) | 272 (400) |
| | | | 264 (+0·43) | 264 (630) |
| | | | 257 (+0·50) | 238i (2470) |
| | | | 243 (+0·95) | 218 (11600) |
| | | | 220 (−1·8) | 195! (28000) |
| | | | 211 (−2·5) | |
| (*R*)-**13** | +75·0 | isooctane | 230 (−0·24) | 221 (170) |
| | | | 215 (+0·22) | 185! (5200) |
| | | | 187! (+9·7) | |
| | | dioxane | 232 (−0·12) | 219 (200) |
| | | | 216 (+0·47) | |
| | | acetonitrile | 236 (−0·01) | |
| | | | 217 (+0·85) | |
| | | ethanol | 217 (+0·87) | 218 (200) |
| | | | 190! (+1·7) | 195 (2300) |
| | | water | 216 (+0·91) | 216 (200) |
| | | | 190! positive | 185! (2200) |
| (*S*)-**13**[f] | −39·9 | isooctane | 229 (+0·13) | 221 (180) |
| | | | 213 (−0·12) | 190! (4100) |
| | | | 190! (−4·5) | |

Table 1—*continued*

| Compound | $[\alpha]_D$[a] | Solvent[b] | CD: $\lambda_{max}(\Delta\varepsilon)$[c] | UV: $\lambda_{max}(\varepsilon)$[c] |
|---|---|---|---|---|
| (*S*)-**14** | −2·6 | isooctane | 201 (+1·1)? | 195! (10000) |
|  |  |  | 186! (+5)? | 185! (15000) |
| (*R*)-**15** | −70·0 | isooctane | 226 (−1·7) | 220 (3000) |
|  |  |  | 193 (+4·0) | 190 (8700) |
|  |  | acetonitrile | 224 (−1·5) |  |
|  |  |  | 192 (+1·6) |  |
| (*S*)-**16** | +37·6 | isooctane | 245 (+1·04) | 220 (3490) |
|  |  |  | 226 (+2·05) | 195! (9700) |
|  |  |  | 197 (−2·8) |  |
|  |  | ethanol | 250 (+0·40) | 220 (3200) |
|  |  |  | 245 (+0·52) | 195! (8550) |
|  |  |  | 222 (+2·30) |  |
|  |  |  | 200 (−1·8) |  |
| (*S*)-**17** | +50·3 | ethanol | 215 (+0·3)? | 191 (7900) |
|  |  |  | 195 (+1·8)? |  |
|  |  | water–ethanol (2:1) | 213 (+0·2) |  |
|  |  |  | 188 (+4·0)? |  |
| (*R*)-**18** | +82·0 | isooctane | 227 (−0·61) | 220 (195) |
|  |  |  | 209 (+0·07) | 200! (485) |
|  |  |  | 186! (+13) |  |
|  |  | dioxane | 229 (−0·41) |  |
|  |  |  | 212 (+0·20) |  |
|  |  | acetonitrile | 235 (−0·07) |  |
|  |  |  | 216 (+0·60) |  |
|  |  |  | 200 (0) |  |
|  |  |  | 186! (+4) |  |
|  |  | ethanol | 235 (−0·05) | 219 (205) |
|  |  |  | 216 (+0·56) | 200! (335) |
|  |  |  | 198 (0) | 195! (570) |
|  |  |  | 197! (+2·4) |  |
|  |  | water | 217 (+0·82) | 220 (195) |
|  |  |  | 192 (−1·3) | 200! (485) |
| (*R*)-**19** | +1·1 | isooctane | 201 (+0·5)? | 200! (6050) |
|  |  |  | 190 (−0·5)? |  |
| (*S*)-**20** | +61·5 | isooctane | 245 (+1·37) | 220i (3300) |
|  |  |  | 229 (+1·82) | 195! (9000) |
|  |  |  | 196 (−4·65) |  |
|  |  |  | 188 (0) |  |
|  |  |  | 186 (+3) |  |
|  |  | ethanol | 245 (+0·70) | 220i (2850) |
|  |  |  | 222 (+2·14) | 195! (8000) |
|  |  |  | 197 (−3·45) |  |
|  |  |  | 189 (0) |  |
| (*R*)-**21** | +115·0 | isooctane | 274 (+0·30) | 272 (860) |
|  |  |  | 268 (+0·30) | 266 (1070) |
|  |  |  | 264i (−0·10) | 258 (1100) |
|  |  |  | 257i (−0·36) | 251i (1280) |
|  |  |  | 245 (−0·95) | 246i (1550) |
|  |  |  | 220 (+14·5) | 239i (1770) |
|  |  |  | 193 (+17) | 218 (10000) |
|  |  |  |  | 190 (47000) |

TABLE 1—*continued*

| | | | | |
|---|---|---|---|---|
| | | ethanol | 275 (+0·44) | 273 (830) |
| | | | 268 (+0·46) | 266 (1070) |
| | | | 262 (+0·13) | 260 (1060) |
| | | | 257i (−0·30) | 253i (1150) |
| | | | 241 (−1·8) | 240i (1770) |
| | | | 219 (+11·5) | 218 (9500) |
| | | | | 200! (18000) |
| | | water | 274 (+0·38) | 272 (770) |
| | | | 267 (+0·41) | 265 (1130) |
| | | | 262 (+0·19) | 259 (1040) |
| | | | 256i (−0·16) | 218 (9200) |
| | | | 238 (−1·72) | 190 (41300) |
| | | | 218 (+10) | |
| | | | 195 (+22) | |
| (*R*)-**22** | +100·0 | isooctane | 274 (+0·27) | 272 (480) |
| | +118·0[e] | | 267 (+0·23) | 266 (615) |
| | | | 262 (−0·02) | 259 (610) |
| | | | 256 (−0·39) | 238 (1240) |
| | | | 245 (−0·92) | 217 (7500) |
| | | | 220 (+10·0) | 190! (30300) |
| | | | 190 (+13) | |
| | | water | 274 (+0·31) | 273 (570) |
| | | | 267 (+0·31) | 266 (710) |
| | | | 261 (+0·12) | 259 (630) |
| | | | 256 (−0·17) | 252 (650) |
| | | | 237 (−1·40) | 218 (9200) |
| | | | 218 (+6·8) | 195! (34000) |
| | | | 196 (+15) | |
| (*S*)-**23** | +24·5 | isooctane | 275 (+0·44) | 273 (1040) |
| | | | 269 (+0·15) | 266 (1420) |
| | | | 264i (−0·44) | 259 (1810) |
| | | | 256i (−1·00) | 245i (2600) |
| | | | 247i (−1·51) | 220i (7500) |
| | | | 230 (−2·6) | 215i (10800) |
| | | | 215 (+3·5) | 204i (14800) |
| | | | 190 (+10) | 190 (56200) |
| | | ethanol | 275 (+0·43) | 273 (860) |
| | | | 268 (+0·63) | 266 (1170) |
| | | | 263i (−0·08) | 259i (1410) |
| | | | 257i (−0·48) | 235i (3300) |
| | | | 246i (−1·22) | 211 (7300) |
| | | | 230 (−2·27) | 216i (9300) |
| | | | 215 (+2·3) | 195! (36000) |
| | | | 200! (+3·7) | |
| | | water | 274 (+0·30) | 274 (720) |
| | | | 268 (+0·30) | 266 (970) |
| | | | 264i (−0·10) | 260 (1080) |
| | | | 257i (−0·36) | 220i (7600) |
| | | | 245 (−0·95) | 190 (47000) |
| | | | 220 (+14·5) | |
| | | | 193 (+17) | |
| (*S*)-**24** | +25·1 | isooctane | 275 (+0·61) | 273 (680) |
| | | | 269 (+0·32) | 266 (950) |
| | | | 263 (−0·38) | 259i (1200) |
| | | | 257 (−0·93) | 243 (1630) |

TABLE 1—*continued*

| Compound | $[\alpha]_D$[a] | Solvent[b] | CD: $\lambda_{max}(\Delta\varepsilon)$[c] | UV: $\lambda_{max}(\varepsilon)$[c] |
|---|---|---|---|---|
| | | | 245 (−1·54) | 220i (6250) |
| | | | 231 (−2·4) | 215i (8600) |
| | | | 214 (+3·8) | 207i (10200) |
| | | | 197 (−2·2) | 195i (27800) |
| | | | 189 (+6·6) | 190! (46500) |
| | | water | 274 (+0·41) | 273 (480) |
| | | | 267 (+0·46) | 266 (640) |
| | | | 261 (+0·24) | 259 (670) |
| | | | 254 (0) | 218 (6780) |
| | | | 250 (−0·13) | 195i (30800) |
| | | | 229 (−1·08) | 190! (42000) |
| | | | 218 (+1·0) | |
| | | | 209 (−1·3) | |
| | | | 196 (−2·2) | |
| | | | 187! (+5) | |

[a] For the pure liquid.

[b] For the CD and UV measurements.

[c] "i" = inflection; "!" indicates that maximum was not reached; "?" indicates inaccurate data.

[d] Optical purity is about 20%.

[e] Measured in benzene solution.

[f] Optical purity is about 53%.

Though in theory of the Cotton effect polarizabilities also play an important rôle,[29,30] a similar simple treatment is not possible for the CD, as has already been stated by Brewster himself.[24] One reason for this failure is the fact that polarizability values are tabulated only for a few wavelengths far away from the region of absorption. In looking for any new rule for the prediction of the CD one has to find out which is the nearest chiral sphere to the chromophore;[31] in our case it is the third (first sphere = chromophore is achiral, second sphere does not exist). Therefore we have to follow first Ruch's general treatment[32] to know which type of rule can be applied. If it is of sector-type, then and only then Schellman's paper[33] determines for each chromophore, which is the simplest rule. Furthermore it would be necessary to know the type of excitation for each absorption band. However, only few such data are available. For arsenates e.g. the $n \rightarrow \pi^*$ transition is allowed,[34] whereas for phosphates the absorption band at the longest wavelength (265 nm) is very weak.[35] The origin of the band about 200 nm, whose CD we are investigating in the phosphonothioic acid derivatives, is still unknown and therefore we can refer only to Schellman's pseudoscalar functions.[33]

Treating a compound of type $R(R'O)P(=X)Y$ as derived from an asymmetric P atom leads to symmetry class $T_d$ for the achiral skeleton $A$. (Fig 2), and the corresponding complete chirality function (second approximation of Ruch[32]) is

$$\tilde{\chi} = \omega(1, 2, 3) - \omega(2, 3, 4) + \omega(3, 4, 1) - \omega(4, 1, 2).$$

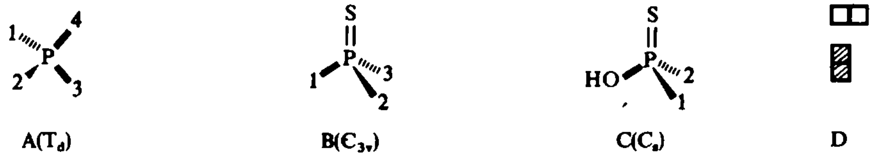


Fig 2. Skeleton symmetry of three different tetravalent phosphorus compounds *A*, *B* and *C*. The Young partition diagrams corresponding to *C* are given under *D* (*cf* ref.[32]), for this case $n = 2$, the chiraltity order $o = 1$.

This means that we cannot describe this system by a simple sector-type rule, but we have to take into account the interactions between each possible trio of the four ligands. Even if we refer only to the compounds of e.g. type R(R′O)P(═S)Y, we do not get a sector rule, because in this case of $C_{3v}$-symmetry for the skeleton *B* (Fig 2) pairwise ligand interactions should still be taken into account, the corresponding chirality function being[32]

$$\bar{\chi} = \omega(1, 2) + \omega(2, 3) + \omega(3, 1).$$

Only if we specify both X and Y explicitly, can we build up a sector rule, because e.g. in the case of the *R*-compounds **1**–**10** of the general formula R(R′O)P(═S)OH the chromophore is now of $C_S$-symmetry (*C* in Fig 2). From the Young partition diagram[32] (*D* in Fig 2) follows the chirality order[32] $o = 1 = n\text{-}1$, and, therefore, here indeed a sector type rule exists with the corresponding chirality function

$$\bar{\chi} = \omega(1) - \omega(2).$$

According to Schellman[33] the simplest rule describing the chiroptical properties of these molecules is a "planar rule".

One cannot, therefore, expect that a single type of simple rule will cover all Cotton effects described in this paper. Nevertheless, as a simple mnemotechnical means the following correlation can be derived from our measurements and applied to those compounds where no ambiguity exists in band assignment. The molecule is projected along the double bond from S or O towards P and the alkyl group is arranged in a horizontal plane to the left (Fig 3). If of the two remaining bonds that with the higher polarizability points upwards, the CD within the first intense absorption band is positive. This simple rule explains e.g. correctly the sign inversion of the 200 nm CD band by going from the free acid **7** to its S-methyl ester **13**.

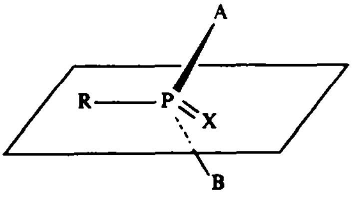


Fig 3. Projection of the alkylphosphonothioic acid derivatives for prediction of the sign of the Cotton effect at about 200 nm. X = O or S, R = alkyl, A and B = other groups (see text). The horizontal plane shown contains R, P and X.

The acids **1–10** follow this rule. In case of compound **14** the Δε-values are very inaccurate because of the aforementioned "quasi-achirality" of the molecule. Nevertheless, at least the sign of the CD was found to be positive in agreement with this rule. For **19** the $g'$-factor was too small to determine even the sign of the Cotton effect. The polarizability of the P—N(C, C) bond is 1·30,[25] that of the P—O(C) bond is 1·35;[25] thus compound **17** is also "quasi-achiral" as regards bond polarizabilities and also here the CD data are very inaccurate because of a small signal/noise ratio. The simple rule predicts a negative sign for **17**, while for found CD is positive. It may well be, however, that the polarizability values change with wavelength in such a manner that at about 200 nm indeed that of the P—N(C, C) bond is larger than that of the P—O(C) bond.

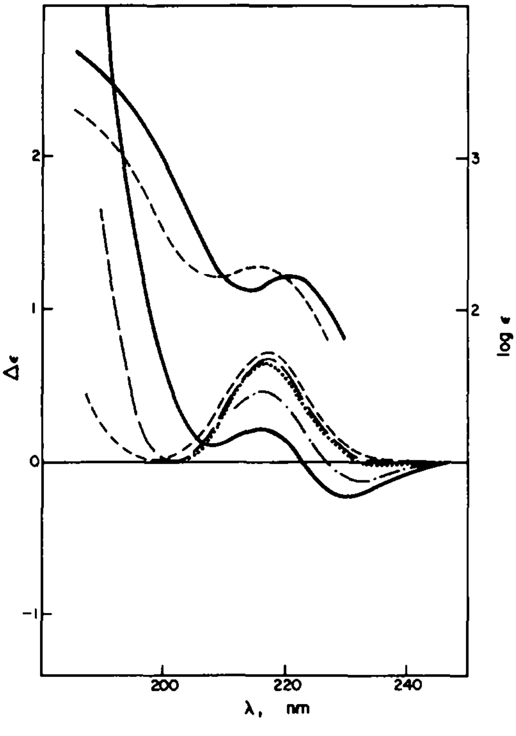
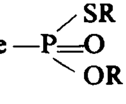


Fig 4. CD of *R*-**13** in isooctane (———), dioxane (–·–·–), acetonitrile (·······), ethanol (— — —) and water (-----); and UV (at the top) in isooctane (———) and water (-----).

Compounds lacking a free OH group show a second CD band around 215 nm which corresponds to a weak UV absorption ($\varepsilon < 300$) at about 216–221 nm. For the diester **13** in nonpolar solvents we even observed two CD bands in this region (Fig 4) and ascribe this to a conformational equilibrium caused by the presence of at least two rotamers (restricted rotation around P—S, P—O or P—C bonds). Most probably this band belongs to an n→π* transition of the  $—\overset{SR}{\underset{OR}{P}}{=}O$ grouping because of its solvent dependence. The CD band below 200 nm of compound **13** follows the rule and the same is true for the isomer **18**.

In the CD spectrum of the acid chloride **15** (Fig 5) two bands are found at about 192 and 225 nm, the asymmetry of the latter band suggests, however, the presence of one more smaller CD band at about 240 nm of the same sign as at 225 nm. As, furthermore, the absorption at 225 nm is more than 10 times stronger, as in the case of the other compounds, we ascribe this latter band to the same transition as for the 200 nm band of the acids **1–10**, and indeed it follows the abovementioned rule. The shorter wavelength band of opposite sign of **15** corresponds very probably to that band of the acids which could not be observed in their CD spectra, but has to be postulated on the basis of the sign of their rotations at the NaD line (cf p. 4364). The bathochromic shift for these bands has an analogy in the carboxylic acid series.[36]

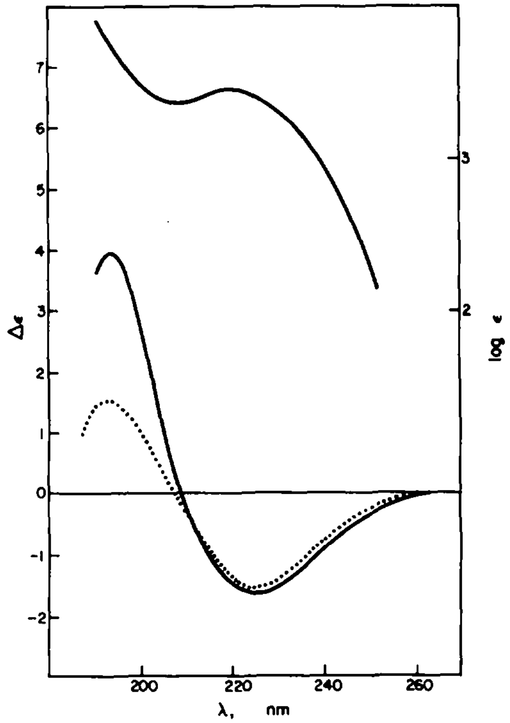


Fig 5. CD of *R*-**15** in isooctane (———) and acetonitrile (······); and UV (at the top) in isooctane (———).

In the case of **16** and **20** which both contain two S-atoms in the chromophore three CD bands and the beginning of a fourth one are present (Fig 6). The one at the longest wavelength is most probably of n → π* type, as it shows a bathochromic shift by going from ethanol to isooctane. The UV band at 220 nm has an ε of the same order of magnitude as the 200 nm band in the acids **1–10**, thus, as in the case of **15**, it is this band to which the rule should be applied. A positive CD is predicted and this agrees with that found by experiment.

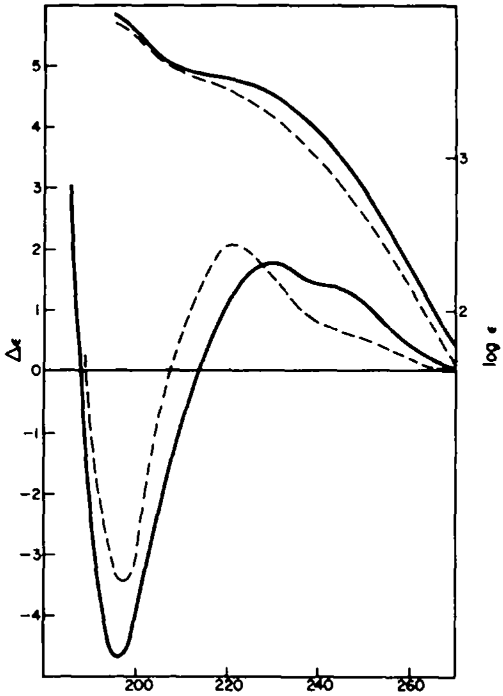


Fig 6. CD and UV (at the top) of *S*-**20** in isooctane (———) and ethanol (-----).

As for the rule of Fig 3 our reference groups are the P═X and the P—alkyl ligands and only two substituents are changed, it is, therefore, in agreement with Ruch's general treatment. The fact that it does not influence the sign whether a P═O or a P═S moiety is present, may be merely fortuitous and cannot necessarily be taken as a proof that we are dealing with identical transitions, though this is very probable.

*Chiroptical properties of alkylphenylphosphinothioic acids and derivatives*

The rotations at the NaD line of the aromatic compounds **11**, **12** and **21**–**24** can again be rationalized by applying Brewster's treatment.[23,24] Since the torsion angle around the P—Ph bond has not been considered, in case of **11** and **12** only the simple polarizability rule[23,24] can be used. It leads to a positive sign for the *R*-compounds in agreement with experiment (*cf* ref 6). The conformational asymmetry rule, applied to **21** and **22** in a similar way as to the phosphonothioic acid derivatives leads to $[M]_D = k(C - E)(O_d - C) > 0$, agreeing with the measurements. The same is true for the esters **23** and **24**, for which $[M]_D = k(C - E)(S_d - C) > 0$ is obtained.

The CD spectra of these compounds show at least four bands in the accessible range (Table 1; Figs 7 and 8). The one at the longest wavelength (around 270 nm) exhibits a pronounced fine structure and without any doubt can be assigned to the $^1L_b$-transition of the benzene ring. The band at around 230 nm is at a wavelength too long to be due to the $^1L_a$-transition. Its bathochromic shift found by going from water to isooctane solution cannot be taken as an indication that it is of $n \rightarrow \pi^*$ parentage, as the 220 nm CD band is strongly increased and thus simple band overlap can cause the same shift. But as this band has not been found in the CD spectrum of compounds with the $>$P(=X)YR chromophore if both X and Y are oxygen,[37] we believe that it indeed belongs to an $n \rightarrow \pi^*$ transition. The band at 215–220 nm has the right position and magnitude for a $^1L_a$-transition of the benzene ring; it is found in the same wavelength range for menthyl phenylphosphinate and menthyl methylphenylphosphinate.[37] In the S-methyl ester **21** it occurs at somewhat longer wavelength than in the O-methyl ester **23**. A similar CD and/or UV band can be detected in the spectra of other compounds with the Ph—P(=X) grouping[37–39] and even for aromatic phosphines and phosphonium salts.[40] At least in the last two classes of compounds this band must be of $^1L_a$ origin. The fourth band below 200 nm may correspond to the transition of the $>$P(=X)YR chromophore found also in the aliphatic analogues. As both CD bands, (a) at 220 nm and (b) below 200 nm have the same sign, it does not matter if these two assignments have to be reversed.

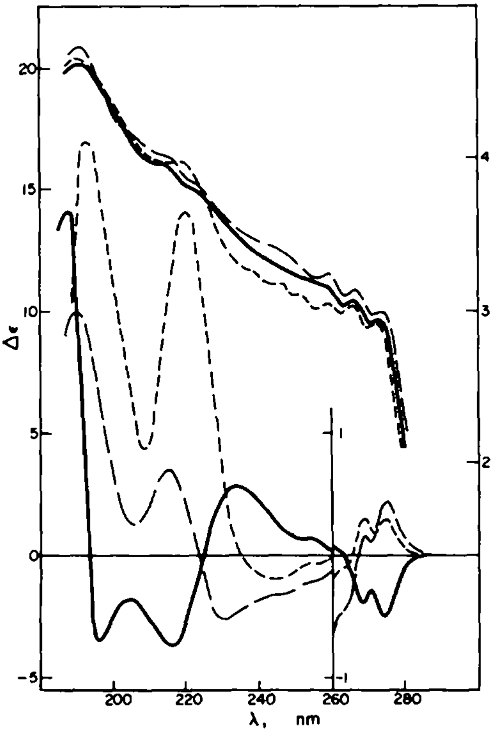


Fig 7. CD and UV (at the top) of *R*-**11** (———), *R*-**21** (-----) and *S*-**23** (— — —) in isooctane. (The CD between 260 and 300 nm is drawn on a larger scale.)

With this assignment of the 220 nm CD band the formal rule discussed above (Fig 3) gives the right prediction for the free acids **11** and **12** and for the O-methyl esters **23** and **24**, but not for **21** and **22**. One of the reasons for its failure may be the fact that the preferred torsion angle of the benzene ring will also be of pronounced influence upon the Cotton effects. Thus one should not rely unduly on this simple rule in cases where its application obviously is hazardous.

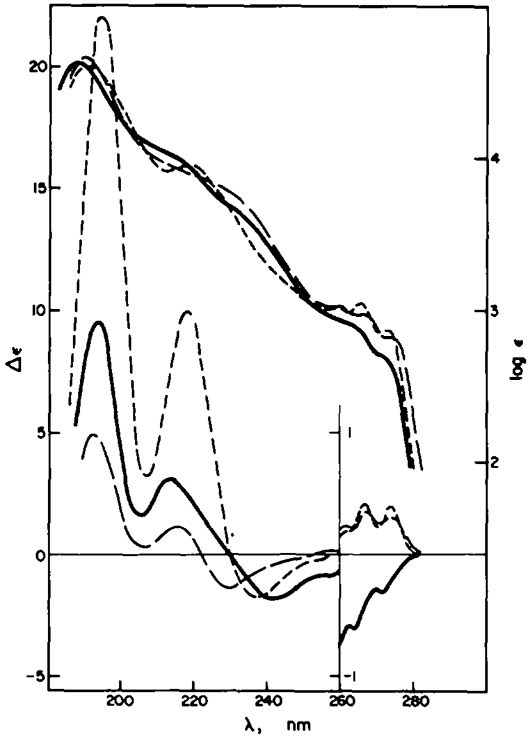


Fig 8. CD and UV (at the top) of *R*-**11** (———), *R*-**21** (- - - - -) and *S*-**23** (— — —) in water. (The CD between 260 and 300 nm is drawn on a larger scale.)

In isooctane solution the CD curves of **11** and **23** above 200 nm are not only of enantiomorphous type, but the absolute values of the rotational strengths are also practically identical. Indeed, these two compounds belong to heterochiral classes[15] if the free acid **11** is mainly or even exclusively present in the undissociated $>$P(=S)OH form. This is again in agreement with the results of other investigations.[6, 41] The signs of the CD bands of the S-methyl ester **21** are the same as those for the O-methyl ester **23**, though the magnitudes are different. The two compounds **21** and **23** must, therefore, be homochiral analogs[15] to each other. As in the formal rule for the CD band given above (p. 4367), it is thus only of importance, where there is (a) the P=X double bond and (b) the P—YR single bond. This renders very improbable any strong conjugation between the aromatic ring and the P atom as well as a great importance of canonical structures like $P(=\overset{\oplus}{Y}R)\overset{\ominus}{X}$. Mislow *et al.*[39] used an analogous argumentation to explain the similar CD curves of sulfoxides and phosphinoxides. In these compounds it is of no importance, whether the chiral atom is S or P (*i.e.* $>S{=}O$ *vs* $>P{=}O$).

In water solution the two esters **21** and **23** give Cotton effects which are of the same sign as in isooctane solution. This is not the case for the free acid **11** whose CD spectrum deviates appreciably from that in the nonpolar solvent. Obviously this acid is already extensively dissociated in water, thus forming a new chromophore. In agreement with this assumption, the CD does not change by going from water to alkaline solution. In methanol or ethanol solution the CD resembles that for isooctane, addition of water or aqueous KOH to ethanol gives rise to similar CD spectra as are found in water. This explanation is supported by the fact that an aqueous solution of the acid **11** reacts acidic.

For the free acid **11** in isooctane solution a fifth strongly positive Cotton effect is found at 188 nm. It may perhaps have the same parentage as the CD band that could not be seen in case of the phosphonothioic acids.

## EXPERIMENTAL

The CD spectra were measured with a Roussel–Jouan type 185 dichrograph at 20°, using cells of path lengths of 0·01 to 1·0 cm, in concentrations of about 0·5 to 2 mg/ml.

The UV measurements were made using a Cary–14 spectrophotometer at room temp in cells of path lengths of 0·01 and 0·1 cm, in concentrations of about 0·5 to 2 mg/ml.

### S-(+)-O-*Methyl methylphenylphosphinothionate* (**23**)

To a suspension of the dicyclohexylammonium salt of (+)-**11** [5 g, $[\alpha]_D$ + 7·83 (MeOH)] in benzene (50 ml) diethyl phosphorochloridate (2·5 g) was added. The mixture was stirred for 2 days, then the dicyclohexylammonium chloride was filtered off and the stoichiometric amount of NaOMe in MeOH was added. After the reaction was complete (5 hr) the solvent was removed and benzene (50 ml) was added. The benzene soln was washed with water, dried and chromatographed on an $Al_2O_3$ column. After the removal of the solvent the residue was distilled to give 1 g of (+)-**23**; b.p. 80–85°/0·4 mm, $n_D^{19}$ 1·5770, $[\alpha]_D$ +24·55 (neat). (Found: P, 16·21. Calc. for $C_8H_{11}OPS$: P, 16·63%).

### S-(+)-O-*Methyl ethylphenylphosphinothionate* (**24**)

According to the procedure described above (+)-**24** [b.p. 70°/0·05 mm, $n_D^{28}$ 1·5405, $[\alpha]_D$ +25·1 (neat)] was obtained from the dicyclohexylammonium salt of (+)-**12** ($[\alpha]_D$ +11·44 [MeOH]). (Found: P, 15·63. Calc. for $C_9H_{13}OPS$: P, 15·46%).

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