Benzoquinones and Related Compounds. Part 2.[1] Preferred Conformations of Some Acyl-1,4-benzoquinones in Solution

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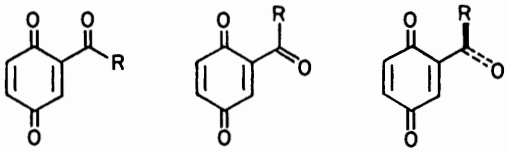
Studies based on polarographic reduction potentials, electronic absorption spectra, and ^1H and ^{13}C nuclear magnetic relaxation data show that in solution the preferred conformation of formyl-1,4-benzoquinone is that with the formyl and quinonoid groups coplanar, and the formyl carbonyl group *anti* to the 1-carbonyl, whereas that of acetyl- and pivaloyl-1,4-benzoquinone has the acyl groups approximately perpendicular to the quinonoid ring.

ACYL-1,4-BENZOQUINONES readily undergo Diels–Alder [2,3] and nucleophilic addition [2-4] reactions which are controlled by the acyl groups, and their orientations with respect to the quinonoid nucleus are clearly important. Formyl-, acetyl-, and pivaloyl-1,4-benzoquinone (1; R = H, Me, and Bu^t respectively) have acyl groups of progressively increasing bulk, and were chosen for the present study. Three extreme conformations must be considered, *syn*-planar (1), *anti*-planar (2), and orthogonal (3). The preferred conformation for a given acyl group will be governed by steric and electronic effects and solute–solvent interactions.



(1) (2) (3)

Measurements of polarographic reduction potentials, u.v.–visible absorption spectra, and ^1H and ^{13}C nuclear magnetic relaxation times have provided complementary evidence for the preferred conformation in solution.

Preparation of Acylquinones.[2]—Oxidation of 2,5-dihydroxybenzaldehyde with silver(I) oxide [5] was not reproducible, but oxidation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone consistently gave formyl-1,4-benzoquinone in yields of 80—85%. Oxidation of 2′,5′-dihydroxyacetophenone with silver(I) oxide readily gave acetyl-1,4-benzoquinone.[6] The best yields of pivaloyl-1,4-benzoquinone were obtained by oxidation of the corresponding hydroquinone with silver(II) oxide; [7] 2′,5′-dihydroxypivalophenone was prepared from 1,4-dimethoxybenzene *via* acylation with isobutyric acid in polyphosphoric acid, *C*-methylation of the potassium enolate [8] of the resulting 2′,5′-dimethoxyisobutyrophenone,[9] and *O*-demethylation using hydrogen bromide in acetic acid.

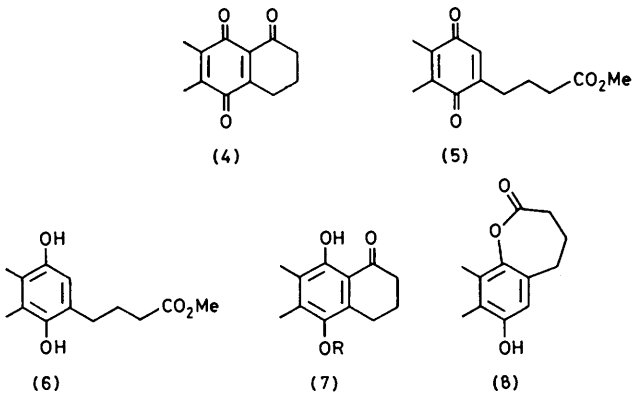
6,7-Dimethyltetralin-1,5,8-trione (4) was used as a model for the *syn*-planar system (1): Dreiding molecular models show that with the alicyclic ring in the preferred half-chair conformation, deviation of the 1- and 8-carbonyl groups from coplanarity is unlikely to exceed *ca.* 10°. It was prepared from 2,3-dimethyl-1,4-benzoquinone, which on treatment with methyl hydrogen glutarate in the presence of silver(II) ion [generated *in situ* from silver(I) nitrate and ammonium persulphate in aqueous acetonitrile [10]] gave 21% of the monoalkylated quinone (5), which was quantitatively reduced and hydrolysed to the hydroquinone (6) by treatment with titanium(IV) chloride in hydrochloric acid.[11] Cyclisation with boron(III) fluoride–ether at 50—55 °C gave the tetralone (7; R = H) in 97% yield, probably *via* the lactone (8) which could be isolated under milder conditions; the monoethyl ether (7; R = Et) was a by-product at 75—80 °C. Oxidation of the hydroquinone (7; R = H) with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone in benzene gave 95% of the tetralonequinone (4) as rose-red crystals which slowly decomposed even at 0 °C.

Polarographic Studies.—Addition of one electron to a benzoquinone gives the corresponding anion radical (semiquinone), and there is a linear relationship [12] between the energy of the lowest unoccupied molecular orbital, into which the electron enters, and the first half-wave reduction potential. Electron-accepting substituents facilitate the addition,[12-14] and for acyl substituents a prerequisite for maximum delocalisation, *e.g.* (9) ⟷ (10) ⟷ *etc.*, is coplanarity of the acyl group and the semiquinone ring. Steric and electronic (dipole–dipole) inhibition of such coplanarity will be present to a roughly equal extent in both the quinone and the semiquinone, and therefore the first half-wave reduction potentials of a series of acylquinones should provide, at least qualitatively, information about the conformation of the acyl group.

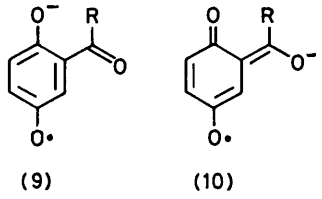
First half-wave potentials ($E_{\frac{1}{2}}$), *versus* the standard calomel electrode, were determined at 20 °C for solutions in acetonitrile containing tetraethylammonium perchlorate as supporting electrolyte, using a differential pulse polarograph, and are given in Table 1.

The $E_{\frac{1}{2}}$ values obtained for 1,4-benzoquinone and some of its derivatives are 0.06—0.08 V higher than those determined [12] at 25 °C. Since the temperature coefficient of $E_{\frac{1}{2}}$ is less than −0.001 V K^{-1}, this discrepancy is attributed to the use of a different aqueous–non-aqueous bridge.[15] There is a linear relationship between $E_{\frac{1}{2}}$ and the number of methyl groups present for the series 1,4-benzoquinone, methyl-, 2,3-dimethyl-, and trimethyl-1,4-benzoquinone, and the increment for each methyl group added is −0.09 V.

The tetralonequinone (4) had $E_{\frac{1}{2}}$ −0.45 V. Assuming that the effects of the 4-methylene and the 5- and 6-methyl groups are identical, and the same as those in the parent 1,4-benzoquinone series, subtraction of the total increment for three methyl groups (−0.27 V) gives an $E_{\frac{1}{2}}$ of −0.18 V for a hypothetical acyl-1,4-benzoquinone (1; R = CH_2^-) in an essentially planar conformation.



The $E_{\frac{1}{2}}$ value for formyl-1,4-benzoquinone is −0.13 V, 0.05 V higher than that of the above hypothetical quinone. This difference is to be expected because of the greater electron-accepting power of the formyl group, and is consistent with a *syn*- (1; R = H) or *anti*- (2; R = H) planar conformation. The lower values, −0.24 and −0.33 V, for acetyl- and pivaloyl-1,4-benzoquinone, respectively, suggest an aplanar arrangement, with the pivaloyl system most closely approaching the orthogonal conformation (3; R = Bu^t). The inductive contribution remains, and is likely to be responsible for



the fact that pivaloyl-1,4-benzoquinone has a first half-wave reduction potential 0.09 V higher than that of 1,4-benzoquinone itself.

Electronic Absorption Spectra.—The absorption maxima of 1,4-benzoquinone in hexane occur at 240 (ε 19 500), 276 (340), 456 (20), and 539 nm (0.5), attributed [16] respectively to allowed and 'forbidden' π–π*, and 'forbidden' and 'strongly forbidden' *n*–π* transitions. Those due to π–π* transitions are likely to provide most information regarding the conformation of acyl substituents, and were measured for the present quinones. The results are given in Table 1.

Progressive introduction of methyl groups into 1,4-benzoquinone moves both π–π* bands to longer wavelength,[17] the shifts in dichloromethane for three methyl groups being respectively 13 and 55 nm; the effect on the extinction coefficients is less regular, but for three methyl groups there is a decrease of *ca.* 2 000 for the allowed transition, and an increase of *ca.* 50 for the 'forbidden' one. Data are not available for the integrated intensities of the bands, which would provide a more significant guide. Application of these figures to the observed values for the tetralonequinone (4) gives maxima of 251 (ε 17 400) and 309 nm (850) for the hypothetical *syn*-planar acyl-1,4-benzoquinone (1; R = CH_2^-). The observed values for formyl-1,4-benzoquinone are 288 (ε 3 900) and 355 nm (1 120), which are appreciably different from those of the hypothetical system, and from those of 1,4-benzoquinone. This suggests that formyl-1,4-benzoquinone prefers neither the *syn*-planar (1; R = H) nor the orthogonal (3; R = H) conformations; an orthogonal formyl group would not be expected to have a big effect on π–π* transitions of the quinonoid moiety (see below). The *anti*-planar conformation (2; R = H), for which a model is not available, may account for the observed spectrum.

TABLE 1

First half-wave reduction potentials and electronic absorption spectra of 1,4-benzoquinones

1,4-Benzoquinone	$E_{\frac{1}{2}}$/V [a]	$\lambda_{max.}$/nm [b]	$\varepsilon_{max.}$	$\lambda_{max.}$ (CT)/nm [d]
Parent	−0.42	246 [c]	22 000	450 [e]
		289 [c]	350	
Methyl	−0.51	249 [c]	20 900	
		316 [c]	610	
2,3-Dimethyl	−0.59			
Trimethyl	−0.69	259 [c]	20 160	
		344 [c]	410	
Tetralone (4)	−0.45	264	15 350	
		364	900	
Formyl	−0.13	288	3 900	524
		355	1 120	
Acetyl	−0.24	250	18 300	476
Pivaloyl	−0.33	248	20 700	460
		291 (infl.)	560	
Tetrachloro				602 [f]

[a] In MeCN at 25°; values ±0.01 V. [b] In CH_2Cl_2. [c] Ref. 17. [d] In CH_2Cl_2; pyrene 0.5M; formyl- and pivaloyl-1,4-benzoquinone 4mM, acetyl-1,4-benzoquinone 5mM. [e] Ref. 19. [f] Ref. 20.

The allowed π–π* transitions of acetyl- and pivaloyl-1,4-benzoquinone are similar to that of 1,4-benzoquinone, indicating minimal conjugative interaction with the acyl group, thus suggesting a preferred orthogonal conformation (3; R = Me or Bu^t), and supporting the above argument for the *anti*-planar conformation of formyl-1,4-benzoquinone.

The wavelengths of the lowest energy intermolecular charge-transfer transitions with appropriate donors also provide relevant information.[13,18] Values for complexes with pyrene are given in Table 1. The maxima for acetyl- and pivaloyl-1,4-benzoquinone are similar to that for 1,4-benzoquinone,[19] whereas that for formyl-1,4-benzoquinone lies at an appreciably longer wavelength, roughly midway between those for 1,4-benzo-

quinone and its tetrachloro derivative.[20] Acetyl- and pivaloyl-1,4-benzoquinone gave bright orange solutions, whilst formyl-1,4-benzoquinone gave a purple one, consistent with a higher electron affinity, and, presumably, a more planar conformation.

Nuclear Magnetic Relaxation Results.—These provide more definitive information about conformation.

TABLE 2

^1H and ^{13}C chemical shifts of acyl-1,4-benzoquinones. Shifts are in p.p.m. downfield from Me_4Si. For conditions, see Experimental section

	Formyl	Acetyl	Pivaloyl
C_A, C_B, C_X	137.0 135.7 134.6	136.6 136.3 135.1	136.2 135.8 130.4
C_S [a]	189.3	30.3	25.9
H_A, H_B	(6.93, 6.86)	(6.84, 6.79)	6.75
H_X	7.13	6.96	6.48
H_S [a]	10.34	2.53	1.15

[a] C_S and H_S are the aldehyde nuclei in the formyl compound and the methyl nuclei in the acetyl and pivaloyl compounds.

Spin–lattice relaxation times (T_1) of all proton-bearing carbon atoms and all distinct protons were measured for formyl-, acetyl-, and pivaloyl-1,4-benzoquinone. The nuclear Overhauser enhancement factor, η_X^S, of the X quinonoid proton on saturation of the acyl protons (S) was also measured. Chemical shifts are listed in Table 2, and relaxation data in Table 3. The nuclear labelling scheme is shown in the Figure.

The A, B, and X ^{13}C resonances were not assigned. The A, B, and X protons form an ABX spin system with J_{AX} *ca.* 0, $|J_{BX}|$ 1.3, and $|J_{AB}|$ 5 Hz. Chemical shift assignments are therefore easily made from the characteristic form of this spectrum. The A and B resonances were coincident in the pivaloyl compound.

Geometrical data were required for analysis of the magnetic resonance results, and since crystallographic information for acyl-1,4-benzoquinones is not available, bond lengths and bond angles were estimated from

TABLE 3

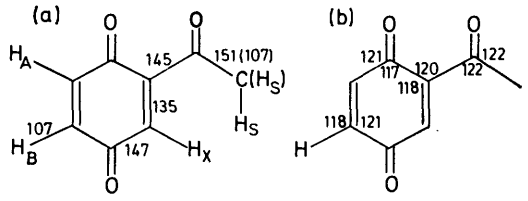
^{13}C and ^1H spin-lattice relaxation times (T_1), and X–[S] nuclear Overhauser enhancement factors (NOEF) (η_X^S) for acyl-1,4-benzoquinones. For conditions, see Experimental section

		Formyl	Acetyl	Pivaloyl
^{13}C T_1/s	C_A,C_B,C_X,	6.9 ± 0.5 7.7 ± 0.5 8.6 ± 0.5	6.8 ± 0.4	3.7 ± 0.3
	C_C [a]	9.0 ± 0.5	23 ± 1	2.7 ± 0.1
^1H T_1/s	H_X	50 ± 1	69 ± 2	27 ± 1
	H_A,H_B	28 ± 1	28 ± 1	18 ± 1
	H_S [a]	53 ± 1	11.3 ± 0.3	2.8 ± 0.1
NOEF	η_X^S	0.04 ± 0.02	0.12 ± 0.02	0.42 ± 0.03

[a] C_S and H_S are the aldehyde nuclei in the formyl compound and the methyl nuclei in the acetyl and pivaloyl compounds.

crystallographic data for 1,4-benzoquinone,[21] 2,5-dimethyl-1,4-benzoquinone,[22] chloro-1,4-benzoquinone,[23] cordeauxione [24] (an acetylnaphthazarin), phenacyl bromide,[25] 4-*p*-bromophenylbut-3-enone,[26] and related compounds.[27] The values used are shown in the Figure.

The ^{13}C T_1 values of C_A, C_B, and C_X in the acetyl and pivaloyl compounds are identical within experimental error, indicating isotropic re-orientation. There is some variation in the values for the formyl compound, presumably due to an anisotropic tumbling. Without an assignment of C_A, C_B, and C_X, it is not possible to determine the principal rotational diffusion constants. However, the spread of T_1 values is small, and molecular tumbling has been treated as isotropic, giving an effective mean relaxation time of 8 ± 1 s. It has been shown [28] that relaxation of proton-bearing ^{13}C nuclei in a



(a) Bond lengths (pm) and (b) angles (°). For the methyl and t-butyl groups, C–C and C–H bond lengths were assumed to be 154 and 109 pm, respectively, and bond angles to be tetrahedral

rigid framework is determined by dipolar interaction with the attached proton. Under ^1H decoupled conditions, the ^{13}C T_1 is related to the isotropic tumbling correlation time τ_c by equation (1) where μ_0 is the

$$\frac{1}{T_{1C}} = \left(\frac{\mu_0}{4\pi}\right)^2 \frac{N\gamma_H^2\gamma_C^2\hbar^2\tau_c}{r_{CH}^6} \qquad (1)$$

magnetic permeability of free space ($4\pi \times 10^{-7}$ H m^{-1}), N is the number of attached protons, γ_H and γ_C are the magnetogyric ratios of ^1H and ^{13}C nuclei respectively, and r_{CH} is the C–H bond length. The correlation times calculated from equation (1) are given in Table 4.

The T_1 values (Table 3) of acyl group carbon atoms show evidence of varying degrees of internal acyl group mobility. The T_1 of the formyl carbon is comparable

TABLE 4

Correlation times, intermolecular relaxation times, and effective X–S interaction parameters for acyl-1,4-benzoquinones

	Parameter	Formyl	Acetyl	Pivaloyl
	τ_c/ps	5.2 ± 0.8	6.1 ± 0.4	11.9 ± 0.7
	T_1*/s	100 ± 30	150 ± 50	>150
$10^{-2}y$ [a]/nm^{-6}	Observed	4.0 ± 2.5	7 ± 4	>7, <90
	syn-planar	42	64	2 400
	anti-planar	3.8	2.7	6.3
	Orthogonal	10	9.2	37.3

[a] $y = \tau_c^{-1} \langle \tau_{XS}/r_{XS}^6 \rangle$ (see text).

with those of the ring carbons, indicating a conformation which is rigid on the timescale of molecular tumbling. The methyl ^{13}C T_1 in the acetyl compound is a factor of 3.4 ± 0.3 greater than that of the corresponding ring carbons, indicating high internal freedom. According to the Woessner theory of the effect of internal rotation on dipolar relaxation,[29] the effective correlation time

replacing τ_c in equation (1) for an internuclear vector inclined at an angle α to the internal rotation axis is given by equation (2). This equation applies to random

$$\tau_c^{eff} = \tfrac{1}{4}(3\cos^2\alpha - 1)^2\tau_c + \tfrac{3}{4}(\sin^2 2\alpha + \sin^4\alpha)(\tau_c^{-1} + \tau_j^{-1})^{-1} \quad (2)$$

jumps between wells of a threefold potential with jump correlation time τ_j. The internuclear distance must remain constant during jumps. Assuming tetrahedral geometry and rapid internal rotation compared to overall tumbling ($\tau_c \ll \tau_c$), then for the C–H interactions in a CH_3 group, $\tau_c^{eff} = \tau_c/9$. Taking into account the different numbers of attached protons, the methyl ^{13}C T_1 should be a factor of 3 greater than that of the ring carbons, for equal C–H bond lengths. The observed ratio is 3.4. An aliphatic bond length of 109 pm, 2% greater than the quinonoid C–H bond, would account for the difference, as would a C–C–H bond angle of 111°. Alternatively, the difference could arise from a small degree of internal rotation about the ring–acetyl bond. Whatever the explanation, the experimental data indicate a sterically unhindered methyl group.

For the pivaloyl compound, T_1 for the methyl groups is approximately two-thirds that of the quinonoid methine T_1. If the molecule were completely rigid it would be expected to be one-third, whereas if the methyl groups were rotating rapidly it would be three times the value. Thus there is some internal motion, but it is not as rapid as in the acetyl compound. If rotation about the ring–acyl bond is disregarded, then rotation of either the methyl groups or the t-butyl group, or both, could account for the observed increase by a factor of 2.2 over the value for a rigid molecule. Assuming that only methyl rotation occurs by 120° jumps, equations (1) and (2) yield a value for τ_j of 8.6 ps, assuming tetrahedral bond angles and r_{CH} 109 pm in the methyl group.

Proton relaxation in these compounds is more complicated than ^{13}C relaxation for two reasons. First, there are several types of proton constituting a coupled relaxation system, and second, intermolecular as well as intramolecular interactions must be taken into account. Fortunately, several simplifying moves can be made. Estimates of internuclear distances using a reasonable molecular geometry (see Figure) indicate that the only important contributions to the relaxation of H_A and H_B are their mutual interaction and intermolecular effects, the latter predominantly with solvent. Knowing τ_c from ^{13}C T_1 data and the H_A–H_B internuclear distance r_{AB}, the former contribution can be calculated from equation (3). The intermolecular contribution,

$$\frac{1}{T_{1A}^{intra}} = \frac{1}{T_{1B}^{intra}} = \frac{3}{2}\left(\frac{\mu_0}{4\pi}\right)^2 \frac{\gamma_H^4\hbar^2\tau_c}{r_{AB}^6} \quad (3)$$

T_1*, is then obtained from equation (4). The structural data in the Figure give r_{AB} 236 pm, from which the values of T_1* listed in Table 3 were obtained.

The conformation of the acyl group was determined by means of the nuclear Overhauser enhancement factor η_X^S. Estimates of internuclear distances indicate that the X relaxation may have significant contributions from intramolecular interactions with A, B, and S protons, together with the intermolecular contribution T_1* which

$$\frac{1}{T_{1A(B)}^{expt}} = \frac{1}{T_{1A(B)}^{intra}} + \frac{1}{T_1^*} \quad (4)$$

is assumed to be the same as that for the A and B protons. Relaxation of the X longitudinal magnetisation (denoted by X) is given [30] by equation (5), where A, B, and S are the A, B, and S proton magnetisations, and the superscript zero indicates values at thermal equilibrium. The relaxation coefficients ρ and σ are defined below. For the moment, equation (5) gives the nuclear Overhauser enhancement factor η_X^S as follows. The Overhauser enhancement of the A and B spins due to irradiation of the S spins is very small, so that at equilibrium under the influence of S decoupling dX/dt, $(A-A^0)$, $(B-B^0)$, and S may be set to zero in equation (5), giving equation (6) where ρ_X and σ_{XS} are given by $\rho_X =$

$$dX/dt = -\rho_X(X-X^0) - \sigma_{XA}(A-A^0) - \sigma_{XB}(B-B^0) - \sigma_{XS}(S-S^0) \quad (5)$$

$$\eta_X^S = \frac{X-X^0}{X^0} = N_S\frac{\sigma_{XS}}{\rho_X} \quad (6)$$

$Q\{\tau_c(r_{AX}^{-6} + r_{BX}^{-6}) + N_S\langle\tau_{XS}/r_{XS}^6\rangle\} + (T_1^*)^{-1}$ and $\sigma_{XS} = \frac{1}{2}Q\langle\tau_{XS}/r_{XS}^6\rangle$ with $Q = (\mu_0/4\pi)^2\gamma_H^4\hbar^2$. N_S is the number of protons in the acyl group. The expression $\langle\tau_{XS}/r_{XS}^6\rangle$ represents the averaging effect of internal rotation in S on the interaction between proton X and one of the S protons. The evaluation of this term was performed in different ways depending on the degree of internal mobility in the acyl group, as follows.

(i) *Formyl group*. This was considered rigidly attached to the ring, so that equation (7) applies.

$$\langle\tau_{XS}/r_{XS}^6\rangle = \tau_c/r_{XS}^6 \quad (7)$$

(ii) *Acetyl group*. The equilibrium conformation of the methyl group relative to the acyl carbonyl was taken to be that in which a methyl proton eclipses the carbonyl group, as has been found for acetaldehyde.[31] The effect of methyl rotation on the dipolar relaxation interaction between a methyl proton and a framework proton situated off the rotation axis has been considered previously [32] in the case where two methyl protons are equidistant from the framework proton and symmetrically placed on opposite sides of the plane containing the third methyl proton, the methyl carbon atom, and the framework proton. The acetyl methyl protons and H_X are related in this way exactly in the *syn*-planar and *anti*-planar acetyl group conformations, and approximately in the orthogonal conformation. For the case of rapid methyl internal rotation, it is then found [32] that equation (8) applies where r_2 is the distance between

$$\langle\tau_{XS}/r_{XS}^6\rangle = (\tau_c/9)[2r_2^{-6} + r_1^{-6} + 2(3\cos^2\beta_{12} - 1)r_1^{-3}r_2^{-3} + (3\cos^2\beta_{22} - 1)r_2^{-6}] \quad (8)$$

H_X and the two equidistant methyl protons, r_1 is the distance between H_X and the unique methyl proton, β_{12}

is the angle between r_1 and r_2, and β_{22} is the angle between the two directions of r_2.

(iii) *Pivaloyl group.* Here, methyl rotation is comparable to overall tumbling. Assuming that only CH_3 rotation occurs, then from equation (2), τ_c^{eff} for the methyl C–H interaction is 5 ps, and τ_c^{eff} for the methyl H–H interaction is 7 ps, compared with a value of τ_c of 12 ps. Because there is a total of nine S protons, the evaluation of the term $\langle \tau_{XS}/r_{XS}^6 \rangle$ is rather complicated if internal rotation is neither extremely slow nor extremely fast. It has therefore been assumed that the effective correlation time τ_{XS} is intermediate between the value τ_c applicable when an internuclear interaction is not affected by internal rotation, and the value τ_c^{eff} for the methyl H–H interaction applicable when an interaction experiences a large modulation from internal rotation. Because the internal rotation rate is large compared to T_1, the effective distance r_{XS} is an average over the nine individual X–S interactions, *i.e.* equation (9) applies, with $\tau_{XS} = 10$ ps.

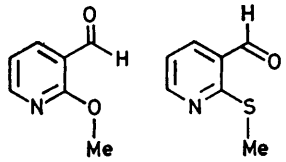
$$\langle \tau_{XS}/r_{XS}^6 \rangle = \frac{\tau_{XS}}{N_S} \sum_S \frac{1}{r_{XS}^6} \qquad (9)$$

The conformations were determined by comparing the experimental value of $y = \tau_c^{-1}\langle \tau_{XS}/r_{XS}^6 \rangle$ obtained from equation (6) with values calculated from equations (7)—(9), as appropriate, for the three extreme orientations of the acyl group relative to the ring, *viz.* *syn*-planar (1), *anti*-planar (2), and orthogonal (3). Results are listed in Table 4. The rather wide spread in the experimental values for the parameter y is due mainly to the unfortunate combination of experimental errors in the calculation of T_1*, since the difference between T_{1A}^{expt} and T_{1A}^{intra} is quite small. Relatively small absolute errors in η_X^S are also magnified when η_X^S approaches its limiting values of zero, as in the formyl compound, or 0.5 as in the pivaloyl compound. Nevertheless, a comparison of experimental and calculated values assigns the conformations reasonably well. The formyl side-group is clearly close to the *anti*-planar (2; R = H) conformation, whereas the acetyl and pivaloyl groups more closely approach the orthogonal (3; R = Me or Bu^t) conformation.

DISCUSSION

The above results show that whereas formyl-1,4-benzoquinone has the *anti*-planar conformation (2; R = H), the acetyl and pivaloyl analogues prefer the orthogonal conformation (3; R = Me or Bu^t).

The conformation of a molecule is determined by the balance of steric, electrostatic, and electron conjugational forces. The first of these is favoured by the orthogonal conformation, the last by the planar conformations. Electrostatic forces between the acyl carbonyl dipole and the nearest ring carbonyl dipole favour the *anti*-planar conformation. In the formyl case, the electrostatic and conjugational forces appear to be dominant, as they are in the formylpyridines (11) and (12) where the formyl group is probably very nearly coplanar with the ring;[33] electrostatic repulsion between the oxygen atoms is responsible for conformation (11), and attraction between oxygen and sulphur for conformation (12).



(11) (12)

In the acetyl and pivaloyl cases the conjugational forces are subdued by steric and electrostatic ones. It is interesting that, in a liquid crystal solution, acetophenone adopts a planar conformation.[34] Thus in acetyl-1,4-benzoquinone the steric interactions between H_X and either the methyl group in the *syn*-planar conformation or the acetyl oxygen in the *anti*-planar conformation are not likely to be great. It is therefore probable that the destabilisation of both planar conformations of acetyl-1,4-benzoquinone results from steric and/or electrostatic interactions between the acetyl group and the adjacent ring carbonyl group. (It must be noted, however, that the C=C bond length in the quinone is 135 pm compared to a ring C–C bond length of 140 pm in benzene. Steric interactions between H_X and the acetyl group may be increased by this bond shortening.) In the pivaloylquinone it is probable that the bulky t-butyl group creates steric conflicts which reinforce the preference for the orthogonal conformation.

EXPERIMENTAL

General.—Solvents were removed under reduced pressure. Sublimation and distillation (bulb-to-bulb) temperatures are those of the heating bath. Mass spectra were recorded on A.E.I. MS 12 and MS 30 instruments, ^{1}H n.m.r. spectra on Perkin-Elmer R 32 (90 MHz), and R 12A and R 12B (60 MHz) instruments, and i.r. spectra on Perkin-Elmer 237 and 257 instruments. N.m.r. signals due to hydroxy protons were removed on addition of D_2O.

Formyl-1,4-benzoquinone.— 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (319 mg) in dry benzene (10 ml) was added to 2,5-dihydroxybenzaldehyde (200 mg) and the mixture was stirred in the dark at room temperature for 16 h, and then filtered through Woelm polyamide to remove dichlorodicyanohydroquinone. Removal of the solvent from the filtrate gave formyl-1,4-benzoquinone as a bright yellow solid (167 mg, 85%) which on being sublimed at 70—75 °C and 0.1 mmHg gave orange needles, m.p. 89—94 °C (lit.,[5] 90—94 °C), δ (5%, CD_2Cl_2) 10.35 (s, CHO), 7.17 (m, H-3), and 6.94 (m, H-5 + -6), $\nu_{max.}$ (CH_2Cl_2) 2 875w, 1 712vs, and 1 667vs cm^{-1}.

2′,5′-Dimethoxyisobutyrophenone.—A mixture of 1,4-dimethoxybenzene (10 g), isobutyric acid (20 ml), and polyphosphoric acid (80 ml) was stirred at 60—70 °C for 4.5 h, and then dispersed in warm water (500 ml). After being cooled, the suspension was extracted with ether, and the extract was washed with saturated aqueous sodium hydrogencarbonate, then with water, and dried ($MgSO_4$). Removal of the solvent and distillation of the residue at

102—106 °C and 0.1 mmHg gave the ketone (12 g, 80%) as a pale yellow oil (lit.,[9] b.p. 160—165 °C at 17 mmHg), *m/e* 206 ($M^{\cdot+}$), δ (9%, CCl_4; 60 MHz) 7.10—7.00 (m, H-6′), 6.92—6.82 (m, H-3′ + -4′), 3.81 (s, OMe), 3.74 (s, OMe), 3.44 (septet, *J* 6.7 Hz, H-2), and 1.07 (d, *J* 6.7 Hz, Me_2), $\nu_{max.}$ (film) 1 682s cm^{-1}.

2′,5′-Dimethoxypivalophenone.— 2′,5′-Dimethoxyisobutyrophenone (6.35 g) in dry tetrahydrofuran (50 ml) was added to potassium hydride (1.84 g) under dry nitrogen, and the mixture was stirred at room temperature until evolution of hydrogen had ceased. The solution was then cooled in ice, and methyl iodide (3.87 ml) in dry tetrahydrofuran (20 ml) was added. The mixture was stirred for 10 min under nitrogen, then for 30 min under air, and added to water (300 ml). The solution was extracted with ether, and the extracts were washed with water, dried ($MgSO_4$), and evaporated, leaving a pale yellow solid, which on being crystallised from light petroleum (b.p. 60—80 °C) gave the pivalophenone (5.43 g, 80%), m.p. 47—48 °C, identical (m.p., mixed m.p., i.r. spectrum) with authentic [35] material prepared by oxidation of 1-(2,5-dimethoxyphenyl)-2-methylpropan-1-ol with manganese dioxide. It had δ (4%, CCl_4; 60 MHz) 6.79—6.72 (m, H-3′ + -4′), 6.50—6.44 (m, H-6′), 3.70 (s, 2 × OMe), and 1.13 (s, Bu^t), $\nu_{max.}$ (Nujol) 1 693vs cm^{-1}.

2′,5′-Dihydroxypivalophenone.— 2′,5′-Dimethoxypivalophenone (2 g) was dissolved in hydrogen bromide in glacial acetic acid (40 ml; 45% w/v), and the solution was refluxed for 1.5 h, cooled, and added to water (250 ml). The solution was neutralised with solid sodium hydrogencarbonate, and the resulting suspension was extracted with ether. The extracts were washed with saturated aqueous sodium hydrogencarbonate, then with water, and dried ($MgSO_4$). Removal of the solvent, distillation of the residue at 145—150 °C and 0.1 mmHg, and crystallisation of the distillate from light petroleum (b.p. 60—80 °C) gave the hydroquinone as bright yellow crystals (0.94 g, 54%), m.p. 93—95 °C, identical (m.p., mixed m.p., i.r. spectrum) with authentic [36] material. It had *m/e* 194 ($M^{\cdot+}$), δ (3%, $CDCl_3$; 60 MHz) 12.30 (s, 2′-OH), 7.57—7.47 (m, H-6′), 7.03—6.94 (m, H-3′ + -4′), 5.37br (5′-OH), and 1.41 (s, Bu^t), $\nu_{max.}$ (Nujol) 3 360s, 1 645m, and 1 616m cm^{-1}.

Pivaloyl-1,4-benzoquinone.—Anhydrous magnesium sulphate (0.6 g) and silver(II) oxide [7] (0.2 g) were added to a solution of 2′,5′-dihydroxypivalophenone (0.2 g) in dry ether (10 ml), and the suspension was stirred in the dark for 15 min, then filtered (Celite), and the solvent removed. Crystallisation of the residue from light petroleum (b.p. 60—80 °C) gave the quinone (0.13 g, 68%) as bright yellow crystals, m.p. 75—75.5 °C (lit.,[35] 72—73 °C), *m/e* 194 [10%, $(M + 2)^{\cdot+}$], 192 (8, $M^{\cdot+}$), 136 (100, $M - C_4H_8$), 108 (25, $M - C_5H_8O$), δ (3%, $CDCl_3$; 60 MHz) 6.90—6.79 (m, H-5 + -6), 6.60—6.53 (m, H-3), and 1.20 (s, Bu^t), $\nu_{max.}$ (Nujol) 1 700s, 1 669vs, and 1 658vs cm^{-1}.

2-(3-Methoxycarbonylpropyl)-5,6-dimethyl-1,4-benzoquinone.—A solution of 2,3-dimethyl-1,4-benzoquinone (1.36 g), methyl hydrogen glutarate [37] (1.46 g), and silver nitrate (1.7 g) in 50% aqueous acetonitrile (40 ml) was heated to 70 °C, treated with ammonium persulphate (4.56 g) in water (10 ml), and maintained at 65—75 °C for 1.25 h. It was then cooled, added to water, and the solution was extracted with ether. The extracts were washed with water, dried ($MgSO_4$), and the solvent was removed. Chromatography on silica gel (450 × 25 mm, 3 : 1 pentane–ether) gave (i) 2,3-dimethyl-1,4-benzoquinone (72 mg), (ii) the required *quinone* (493 mg, 21%) as a viscous yellow oil which distilled at 98—102 °C and 0.18 mmHg (Found: $M^{\cdot+}$, 236.1048. $C_{13}H_{16}O_4$ requires *M*, 236.1049), and had δ (3%, $CDCl_3$; 90 MHz) 6.50 (t, *J* 1.8 Hz, collapsed to s on irradiation at 7.53, H-3), 3.66 (s, OMe), 2.47 (tt, J_1 8, J_2 1.8 Hz, H-1′), 2.39 (t, *J* 8 Hz, H-3′), 2.02 (s, 5- + 6-Me), 1.84 (quintet, *J* 8 Hz, H-2′), $\nu_{max.}$ (CCl_4) 1 744 vs and 1 651vs cm^{-1}, and (iii) 2,3-bis-(3-methoxycarbonylpropyl)-5,6-dimethyl-1,4-benzoquinone (152 mg, 5%) as a viscous yellow oil which distilled at 160 °C and 0.1 mmHg (Found: $M^{\cdot+}$, 336.1572. $C_{18}H_{24}O_6$ requires *M*, 336.1573), and had δ (3%, $CDCl_3$; 90 MHz) 3.66 (s, 2 × OMe), 2.56 (t, *J* 8 Hz, H-1′ + -1″), 2.42 (t, *J* 8 Hz, H-3′ + 3″), 2.02 (s, 5- + 6-Me), 1.76 quintet, *J* 8 Hz, H-2′ + -2″), $\nu_{max.}$ (CCl_4) 1 740vs and 1 645vs cm^{-1}.

4-(2,5-Dihydroxy-3,4-dimethylphenyl)butanoic Acid.—Titanium(III) chloride (15 ml, 30% w/v in hydrochloric acid) was added to a solution of 2-(3-methoxycarbonylpropyl)-5,6-dimethyl-1,4-benzoquinone (339 mg) in acetone (15 ml), the mixture was stirred at room temperature for 3 days, and then diluted with water (30 ml). The solution was repeatedly extracted with ethyl acetate, and the combined extracts were dried (Na_2SO_4). Removal of the solvent left an off-white solid (320 mg, 100%), which on being crystallised from ethyl acetate gave the *butanoic acid* as needles, m.p. 177—179 °C (Found: C, 64.3; H, 7.1%; $M^{\cdot+}$, 224.1050. $C_{12}H_{16}O_4$ requires C, 64.3; H, 7.1%; *M*, 224.1049), δ [5%, $(CD_3)_2CO$; 90 MHz] 7.60—6.80 (3 × OH, partially exchanged with D from solvent), 6.50 (s, H-6′), 2.64 (t, *J* 8 Hz, 2 × H-4), 2.38 (t, *J* 8 Hz, 2 × H-2), 2.19 (s, Me), 2.14 (s, Me), and 1.88 (quintet, *J* 8 Hz, 2 × H-3), $\nu_{max.}$ (Nujol) 3 320br, s and 1 730—1 705s cm^{-1}.

5,8-Dihydroxy-6,7-dimethyl-1-tetralone.—A solution of 4-(2,5-dihydroxy-3,4-dimethylphenyl)butanoic acid (250 mg) in boron(III) fluoride–ether (30 ml) was heated at 50—55 °C for 3 days, cooled, and diluted with ether (150 ml). The solution was washed with water (7 × 30 ml), dried (Na_2SO_4), and the solvent was removed leaving a yellow solid (224 mg, 97%) which on being crystallised from carbon tetrachloride gave the *tetralone* as yellow platelets, m.p. 171.5—172.5 °C (Found: C, 70.3; H, 6.8%; $M^{\cdot+}$, 206.0941. $C_{12}H_{14}O_3$ requires C, 69.9; H, 6.8%; *M*, 206.0943), δ (3%, $CDCl_3$; 90 MHz) 12.48 (s, 8-OH), 4.27 (s, 5-OH), 2.84 (t, *J* 6 Hz, 2 × H-4), 2.66 (t, *J* 6 Hz, 2 × H-2), 2.27 (s, Me), 2.19 (s, Me), and 2.10 (quintet, *J* 6 Hz, 2 × H-3), $\nu_{max.}$ (CH_2Cl_2) 3 600m and 1 634s cm^{-1}.

8,9-Dimethyl-7-hydroxy-4,5-dihydro-1-benzoxepin-2(3H)-one.—A solution of 4-(2,5-dihydroxy-3,4-dimethylphenyl)-butanoic acid (7.4 mg) and boron(III) fluoride–ether (0.03 ml) in dry ether (2 ml) was kept at room temperature for 2 days, and then washed with water (2 × 1 ml) and dried ($MgSO_4$). Removal of the solvent and p.l.c. [silica gel, 4 : 6 light petroleum (b.p. 40—60 °C)–ether] of the residue gave the *benzoxepinone* (3 mg, 44%) as a solid, m.p. 144—145 °C (Found: $M^{\cdot+}$, 206.0943. $C_{12}H_{14}O_3$ requires *M*, 206.0943), δ (2%, $CDCl_3$; 90 MHz) 6.51 (s, H-6), 4.80br (OH), 2.76 (t, *J* 7.8 Hz, 2 × H-3), 2.49 (t, *J* 7.8 Hz, 2 × H-5), 2.35—2.05 (m, 2 × H-4), 2.24 (s, Me), 2.22 (s, Me), $\nu_{max.}$ (CH_2Cl_2) 3 580m and 1 765s cm^{-1}. Starting material and the foregoing tetralone were also present in the crude product.

5-Ethoxy-8-hydroxy-6,7-dimethyl-1-tetralone.—A solution of 4-(2,5-dihydroxy-3,4-dimethylphenyl)butanoic acid (160 mg) in boron(III) fluoride–ether (8 ml) was heated at 75—80 °C for 35 h, cooled, and diluted with ether (80 ml). The

solution was washed with water, dried ($MgSO_4$), and the solvent was removed. Distillation of the residue at 90—95 °C and 0.15 mmHg gave an orange oil which was subjected to p.l.c. [silica gel, 1 : 1 light petroleum (b.p. 40—60 °C)–ether]: the band with highest R_F afforded the *tetralone* (10 mg, 6%), m.p. 55—56.5 °C, which crystallised from hexane in pale yellow needles (Found: $M^{\cdot+}$, 234.1252. $C_{14}H_{18}O_3$ requires M, 234.1256). It had δ (2%, $CDCl_3$; 90 MHz) 12.69 (s, OH), 3.77 (q, J 7.2 Hz, OCH_2), 2.97 (t, J 6.7 Hz, 2 × H-4), 2.69 (t, J 6.7 Hz, 2 × H-2), 2.30 (s, 6- or 7-Me), 2.28—1.94 (m, 2 × H-3), 2.20 (s, 7- or 6-Me), and 1.44 (t, J 7.2 Hz, ethyl Me), $\nu_{max.}$ (CCl_4) 1 636s cm^{-1}. The major product was the corresponding 5-hydroxytetralone.

6,7-Dimethyltetralin-1,5,8-trione.— 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (33.2 mg) in dry benzene (5 ml) was added to 5,8-dihydroxy-6,7-dimethyl-1-tetralone (31.7 mg), and the mixture was stirred at room temperature for 2 h and then filtered through Woelm polyamide. Removal of the solvent gave the *trione* as a deep red solid (30 mg, 95%), m.p. 89—98 °C (decomp.) which crystallised from benzene–light petroleum (b.p. 40—60 °C) as a mixture of rose-red needles and plates (Found: C, 70.1; H, 5.8%; $M^{\cdot+}$, 204.0783. $C_{12}H_{12}O_3$ requires C, 70.6; H, 5.9%; M, 204.0786), *m/e* 206 [61%, $(M + 2)^{\cdot+}$], 205 (15), 204 (100, $M^{\cdot+}$), 176 [56, $(M - 28)^{\cdot+}$], δ (5%, $CDCl_3$; 90 MHz) 2.78 (t, J 6 Hz, 2 × H-4), 2.52 (t, J 6 Hz, 2 × H-2), 2.35—2.00 (m, 2 × H-3), 2.09 (s, 6- + 7-Me), $\nu_{max.}$ (CCl_4) 1 713s, 1 659s cm^{-1}.

Physical Measurements.—Quinones were purified by sublimation, or as described above, immediately before use.

First half-wave reduction potentials, at 20 ± 1° against a saturated calomel electrode separated from the polarographic cell by a sintered glass disc and agar plug, were determined by differential pulse polarography with a PAR 174 analyser. Quinones were 1.0 and 0.5mM in spectroscopic grade acetonitrile containing 0.1M-tetraethylammonium perchlorate; the quinone concentration did not affect the results. Solutions were purged with nitrogen for 15 min before analysis.

U.v.–visible spectra were recorded for dichloromethane solutions using a Perkin-Elmer 402 spectrometer. Pyrene was 99+% grade from Aldrich Chemical Co.

^1H Relaxation measurements were performed on a Varian Associates SC-300 spectrometer operating at 300 MHz. ^{13}C Relaxation measurements were made with a Varian Associates SC-300 spectrometer at 75.5 MHz for the formyl compound, and on a Varian Associates XL-100 spectrometer at 25.14 MHz for the acetyl and pivaloyl compounds. The formyl and acetyl compounds were in CD_2Cl_2, the pivaloyl in $CDCl_3$. Approximately 7% w/v solutions were used for the ^{13}C data, and 2% solutions for the ^1H data. The formyl compound was measured at 22 °C, the others at 30 °C. T_1 Values were obtained using the inversion recovery pulse sequence.

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