The Bridge Chemistry of Paracyclophanes. The Mono- and Dichloroformylation of [2.2]Paracyclophane (Di-*p*-xylylene) with Oxalyl Chloride

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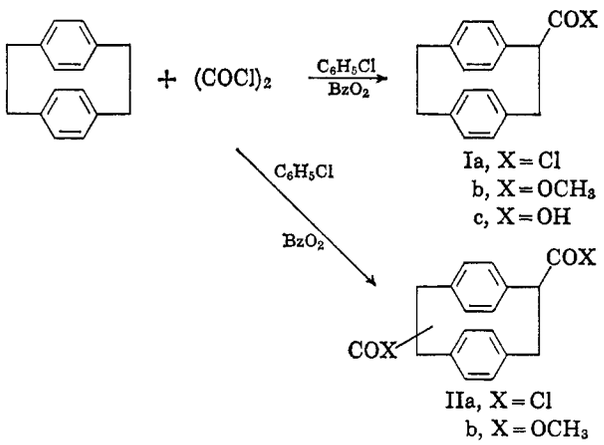
The preparation of 1-carbomethoxy[2.2]paracyclophane or an isomeric mixture of 1,9- and 1,10-dicarbomethoxy[2.2]paracyclophane by chloroformylation with oxalyl chloride is described, and a discussion of the reaction in terms of plausible intermediates is given. The ultraviolet spectra of the tetracyanoethylene complexes of these side-chain-substituted paracyclophane derivatives are compared with similar paracyclophane ring derivatives.

Very early in our research program on the bridge chemistry of [2.2]paracyclophane we required derivatives such as 1-chloroformyl[2.2]paracyclophane where a new carbon–carbon bond is formed. The obvious route involving the carboxylation of 1-lithio or 1-magnesium halide derivatives was unsuccessful because of the unreactivity of 1-bromo[2.2]paracyclophane with magnesium or apparent dimerization reactions when the 1-bromo compound was allowed to react with butyl lithium. Consequently another route was sought. The early work of Kharasch and Brown,[1] where hydrocarbons were chloroformylated by oxalyl chloride utilizing initiation by ultraviolet irradiation or benzoyl peroxide, motivated a similar attempt to chloroformylate [2.2]paracyclophane ([2.2]-PCP). Even though Kharasch and Brown reported[1b] that chloroformylation of aralkyl hydrocarbons gave low yields (5–10%) of acid chloride when benzoyl peroxide was used as an initiator and no chloroformylation product in the presence of ultraviolet irradiation, it was anticipated that the unique geometry[2] of the benzylic hydrogens of rigid [2.2]paracyclophane, which should result in a more reactive noncoplanar benzylic radical, could lead to higher yields of product. The successful bromination of [2.2]PCP with N-bromosuccinimide[3] furthermore indicated that free-radical substitution can occur at the bridge. In this paper we present and discuss the results of our investigation.

Results

Mono- and Dichloroformylation of [2.2]Paracyclophane.—In the initial experiment, a mixture of [2.2]-PCP (0.3 *M*), oxalyl chloride (0.6 *M*), and benzoyl peroxide (0.06 *M*) was stirred in chlorobenzene solvent at 90° for 24 hr. The initial concentration of [2.2]-PCP represents the approximate solubility under these conditions. A crude acid chloride was obtained which was converted into a methyl ester (over-all yield) was 10% based on consumed [2.2]PCP), having the correct composition for structure Ib and strong characteristic absorption in the infrared at 5.82 (C=O), 9.00 (C—O), 12.1, and 14.0 μ. The ultraviolet spectrum in 95% ethanol has λ_{max} 224 mμ (ϵ 1.87 × 10^4), which is very close to [2.2]paracyclophane itself. Furthermore, the acid derived from the methyl ester was clearly not 4-carboxy[2.2]paracyclophane[4] on the basis of a comparison with an authentic sample. The most definitive evidence was obtained, however, from nmr which displayed aromatic, benzylic, and methyl group protons in an area ratio of 8:7:3, respectively. The benzylic proton adjacent to the carbomethoxy group was easily distinguished by its low-field resonance at 4.18–3.80 ppm (multiplet).



The results of an attempt to maximize the yield of the monoester Ib are summarized in Table I. The first three experiments indicate that a molar ratio of [2.2]PCP to oxalyl chloride of 1:5 doubles the yield obtained in the initial experiment. Further increase of this ratio did not lead to increased yields. A better yield (35%) was achieved by the slow, dropwise addition of benzoyl peroxide in oxalyl chloride. Carrying out the reaction in a nitrogen atmosphere had no apparent effect. The use of ultraviolet irradiation

TABLE I

MONOCHLOROFORMYLATION OF [2.2]PARACYCLOPHANE WITH OXALYL CHLORIDE IN CHLOROBENZENE[a]

OxCl/[2.2]-PCP[b]	Condition[c]	[2.2]-PCP,[d] %	Yield,[e] %
2	...	42	11
5	...	46	20
10	...	26	8.6
5	Dropwise addn of BzO_2 in OxCl; N_2	33	34
5	Dropwise addn of BzO_2 in OxCl	25	36

[a] Concentration of [2.2]PCP was approximately 0.3 *M*. Reaction temperature was 80–90°. Initiator concentration was 0.05 *M* unless noted. [b] Molar ratio of oxalyl chloride to [2.2]PCP. [c] Conditions are those of footnote *a* unless noted. [d] Per cent recovered [2.2]PCP. [e] Yield of chloroformylation product after methanolysis based on consumed [2.2]PCP.

(1) (a) M. S. Kharasch and H. C. Brown, *J. Am. Chem. Soc.*, **64**, 329 (1942); (b) M. S. Kharasch, S. S. Kane, and H. C. Brown, *ibid.*, **64**, 1621 (1942).

(2) (a) C. J. Brown, *J. Chem. Soc.*, 3265 (1953); (b) K. Lonsdale, H. J. Milledge, and K. V. K. Rao, *Proc. Roy. Soc.* (London), **A225**, 82 (1960); (c) D. A. Bekoe and K. N. Trueblood, Meeting of American Crystallographic Association, Bozeman, Mont., 1964.

(3) K. C. Dewhirst and D. J. Cram, *J. Am. Chem. Soc.*, **80**, 3115 (1958).

(4) D. J. Cram and N. L. Allinger, *ibid.*, **77**, 6289 (1955).

(sunlamp through Pyrex) led to no product and nearly complete recovery of [2.2]PCP. Also, the use of azoisobutyrylnitrile (AIBN) as an initiator led to consumption of [2.2]PCP without generation of chloroformylation product. Finally, little or no consumption of [2.2]PCP was observed at initiator concentrations very much below the indicated level.

We initially attempted to obtain dichloroformylated products by adding three 0.05 *M* portions of benzoyl peroxide at 24-hr intervals with the concentration of [2.2]PCP and oxalyl chloride being held at the 0.3 and 1.5 *M* levels, respectively. Chromatography on Florisil of the crude product obtained after methanolysis gave a material (maximum yield, 15%), which after sublimation had the anticipated nmr and infrared spectra and C–H analysis for the diester IIb. It was clear that the carbomethoxy groups were on opposite bridges since the nmr absorption characteristic of the unsubstituted bridge was absent in the product. Indeed, the nmr spectrum of the diester corresponded closely to that of the monoester except for the absence of this absorption at 3.0 ppm.

Further attempts to maximize yields as in the monochloroformylation reaction were unsuccessful. For example, carrying out the reaction under nitrogen and/or slow dropwise addition of benzoyl peroxide in oxalyl chloride at 24-hr intervals led to close to quantitative consumption of [2.2]PCP but no diester product. Addition of the three portions of benzoyl peroxide in one batch led to a 1:1 mixture of mono- and diester in about 20% yield after chromatography, while addition of two portions of benzoyl peroxide at 24-hr intervals gave only monoester product.

Although the diester IIb is most certainly a mixture of four geometric isomers, no attempt was made to separate them and determine their distributions. Chromatography at our conditions (gas and thin layer) gave broad peaks or spots characteristic of an unresolved mixture. Also, the purified diester product has a melting point range of about 40°.

Discussion

Chloroformylation Reaction Mechanism and [2.2]-Paracyclophane Results.—The key steps generally considered in discussions of the mechanism of the oxalyl chloride[1,5] chloroformylation of saturated hydrocarbons initiated by benzoyl peroxide are given below.

$$R_1\cdot + ClCOCOCl \longrightarrow R_1COCl + \cdot COCl \quad (1)$$

$$\cdot COCl \longrightarrow CO + Cl\cdot \quad (2)$$

$$Cl\cdot + RH \longrightarrow R\cdot + HCl \quad (3)$$

$$R\cdot + ClCOCOCl \longrightarrow RCOCl + \cdot COCl \quad (4)$$

$$R\cdot + ClCOCOCl \longrightarrow RCl + \cdot COCOCl \quad (5)$$

$$R\cdot + ClCOCOCl \longrightarrow RCOCOCl + Cl\cdot \quad (6)$$

$$COCl\cdot + RH \longrightarrow R\cdot + HCl + CO \quad (7)$$

In the original discussion of Kharasch and Brown[1] of the mechanism, steps such as 5 and 6 were ruled out since RCl and RCOCOCl generally were absent in the products. In particular, decomposition of benzoyl peroxide in oxalyl chloride gave only benzoyl chloride and no benzoylformyl chloride or chlorobenzene. The former acid chloride was prepared independently and was reported to be stable under the reaction conditions.

The possibility that the chlorocarbonyl radical abstracts hydrogen and propagates the chain in competition with the chlorine radical has never been clearly eliminated. The dissociation of the chlorocarbonyl radical is reported[6] to be endothermic by only 6.3 kcal so that unless its hydrogen abstraction rate is high or it is especially stabilized in solution it does not appear to be stable enough to serve as an important propagating radical species.

The low yield of aralkyl chloroformylation product compared with that observed with cyclohexane was rationalized by Kharasch and Brown[1c] on the basis of a high activation energy for step 4 which can be written as a radical displacement on carbon or an addition–elimination-type process.[7] It was argued that cyclohexyl radicals are more reactive than benzyl radicals and consequently the chain length was higher for the former species. Alternatively, the low yield with aralkyl hydrocarbons might be ascribed to an unfavorable equilibrium position as shown below. The position of equilibrium will depend of course on the stability of the radical R·.

$$R\cdot + ClCOCOCl \rightleftharpoons R{-}\overset{\displaystyle O}{\overset{|}{C}}{-}COCl \rightleftharpoons RCOCl + \cdot COCl$$
$$\qquad\qquad\qquad\qquad\qquad\quad \underset{\displaystyle Cl}{|}$$

In our case, the low chain length implied by high levels of initiator required and moderate yields of chloroformylation product could be due to the low concentration of [2.2]PCP imposed by its insolubility and/or competing side reactions rather than an unfavorable propagation step compared with that for cyclohexane. However, chloroformylation of cyclohexane[8] at the same conditions used for the paracyclophane reaction resulted in a high yield of predominantly diester products and some monoester after methanolysis with the former being a mixture of four major isomers on the basis of vpc and nmr. In contrast, chloroformylation of toluene[3] at these same conditions resulted in yields of monoester close to those in the paracyclophane reaction. This suggests, but does not require, that abstraction of the benzylic hydrogens of [2.2]PCP leads to a radical which, despite its apparent lack of resonance stabilization, is similar to the resonance-stabilized benzyl radical in its reactivity with oxalyl chloride. Indeed, a more direct and less equivocal comparison of [2.2]paracyclopan-1-yl generated by decomposition of a *t*-butyl perester[9] with other similarly generated aralkyl radicals has revealed that the former species is apparently not destabilized by its unique structure.

Our observation of ineffective initiation by ultraviolet light is in accord with the results[1] of Kharasch and Brown with aralkyl hydrocarbons and saturated hydrocarbons in aromatic solvents. In both cases the

(5) (a) R. Runge, *Z. Electrochem.*, **56**, 779 (1952); (b) *ibid.*, **60**, 956 (1956).

(6) W. G. Burns and T. S. Dainton, *Trans. Faraday Soc.*, **48**, 39 (1952).

(7) Apparently there are no unequivocal examples of radical displacement at saturated carbon; see W. A. Pryor and H. Guard, *J. Am. Chem. Soc.*, **86**, 1150 (1964), for a recent discussion. E. Muller and H. Huber [*Chem. Ber.*, **96**, 670, 2319 (1963)] gave an example involving cyanogen chloride of apparent radical displacement at an unsaturated carbon site.

(8) E. Hedaya and L. M. Kyle, unpublished results.

(9) E. Hedaya and L. M. Kyle, in preparation.

ineffectiveness of ultraviolet light was ascribed to screening of irradiation by the aromatic.

An interesting feature of our reaction which has not been previously discussed is apparent complex formation between [2.2]PCP and oxalyl chloride. Oxalyl chloride is known to complex with aromatics[10] and in our case visual evidence for complex formation was afforded by the bright yellow color of the solution of [2.2]PCP and oxalyl chloride in chlorobenzene. Either component alone did not give a color in chlorobenzene. This is not unexpected since [2.2]PCP is one of the stronger π bases.[11]

Perhaps the most remarkable feature of the dichloroformylation reaction is that the only product isolated is the one with chloroformyl groups on opposite bridges. In contrast, vicinal and geminal disubstitution products were isolated in the reaction of N-bromosuccinimide with [2.2]PCP.[3] Furthermore, a number of monoacid chlorides give geminal diacid chlorides[5a,12] with oxalyl chloride alone. It is possible that the lack of vicinal or geminal diacid chloride product in our case results from subsequent degradation of these products under the reaction conditions and/or steric effects. A more interesting possibility would involve the isomerization of a vicinal diacid chloride to the 1,9-diacid chloride through a *p*-xylylene intermediate.

Ultraviolet Absorption Spectra of the Tetracyanoethylene Complexes of Ib and IIb.—As mentioned above, a characteristic property of paracyclophane is their high π basicity. In particular Singer and Cram[11b] have recently published ultraviolet data for a large number of ring-substituted [2.2]paracyclophane–TCNE π complexes. These data were interpreted on the basis that the stability of the complex increases with the position of the long wavelength absorption band. We have obtained the ultraviolet spectra of the TCNE π complexes of Ib and IIb and these are listed in Table II along with comparative data from Singer and Cram.

TABLE II

ULTRAVIOLET SPECTRA OF TETRACYANOETHYLENE COMPLEXES OF [2.2]PARACYCLOPHANES IN METHYLENE CHLORIDE

Paracyclophanes	λ_{max}, mμ
[2.2]PCP	521[a]
Ib	507
Ic	506
IIb	490
4-Acetyl[2.2]PCP	496[a]
4-Carboxy[2.2]PCP	497[a]

[a] Data from Singer and Cram.[11b]

From these data it is clear that electron-withdrawing carbomethoxy substituents on the side chain are almost as effective in reducing λ_{max} and the stability of the complex as analogous ring substitution. Furthermore, the effect of the side-chain carbomethoxy on λ_{max} appears to be additive. The effect of electron-withdrawing aromatic substituents was interpreted as evidence for transannular effects, on the basis of the assumption that TCNE complexes the unsubstituted ring. Our results with side-chain electron-withdrawing substituents may reflect unusual inductive effects or possibly destabilization of the complex due to steric effects. We are currently collecting data from other side-chain derivatives which will enable us to understand these effects more clearly.

(10) B. D. Saksena and R. E. Kaganir, *J. Chem. Phys.*, **19**, 994 (1951).

(11) (a) D. J. Cram and R. A. Bauer, *J. Am. Chem. Soc.*, **81**, 5971 (1959); (b) L. Singer and D. J. Cram, *ibid.*, **85**, 1080 (1963).

(12) M. S. Kharasch, K. Eberly, and M. Kleiman, *ibid.*, **64**, 2975 (1942).

Experimental Section

All infrared spectra were obtained on a Beckman IR-5A instrument in potassium bromide pellets. Ultraviolet spectra were recorded on a Beckman DK-2 spectrophotometer. Solvents were Spectrograde 95% ethanol or methylene chloride. Nmr spectra were obtained on a Varian A-60 instrument and data are expressed in parts per million relative to tetramethylsilane. All melting points are uncorrected.

1-Carbomethoxy[2.2]paracyclophane (Ib).—[2.2]Paracyclophane (50.0 g, 0.24 mole) and oxalyl chloride (75.0 g, 0.6 mole) were heated to 90° with stirring in 800 ml of chlorobenzene. Benzoyl peroxide (10.0 g, 0.04 mole) in oxalyl chloride (75.0 g, 0.6 mole) was added dropwise and the temperature was maintained at 90° for 24 hr. Upon cooling 15.0 g (30%) of starting material was filtered off. The filtrate was concentrated *in vacuo* and redissolved in methylene chloride. Methanol (350 ml) was added to the solution and stirred overnight. The mixture was concentrated *in vacuo* and chromatographed on Florisil (900 g, 60–100 mesh) with ether–pentane as eluent. Pure pentane eluted a small amount of [2.2]PCP along with substantial amounts of methyl benzoate. Ether–pentane (2–10%) eluted 11.0 g of product (25%). Recrystallization twice from hot hexane yielded the analytical sample, mp 96.5–97.5°.

Infrared bands characteristic of the [2.2]PCP system were observed at 12.2 and 14.0 μ along with ester absorption. The nmr spectrum in chloroform-*d* shows resonances at 7.3–6.9 (aromatic protons, multiplet), 4.18–3.80 (benzylic proton, multiplet), 3.57 (methyl protons, singlet), 3.45–3.22 (benzylic protons, multiplet), and 2.86 ppm (bridge protons, singlet) in and area ratio of 8:1:3:2:4.

Anal. Calcd for $C_{18}H_{18}O_2$: C, 81.17; H, 6.81. Found: C, 81.48; H, 6.82.

The experiments at varying reaction conditions (Table I) were carried out as above except on a much smaller scale.

1-Carboxy[2.2]paracyclophane (Ic).—The above ester (Ib) was saponified in 95% ethanol solvent giving 1-carboxy[2.2]paracyclophane with mp 187–188° after recrystallization from aqueous ethanol. The infrared and nmr spectra were in accord with the assigned structure, but a carbon analysis (0.52% low) indicated that the compound was not analytically pure. A direct comparison with authentic 4-carboxy[2.2]paracyclophane[4] (mp 221–223°) indicated that the two acids were different.

1,9-Dicarbomethoxy[2.2]paracyclophane and 1,10-Dicarbomethoxy[2.2]paracyclophane.—[2.2]Paracyclophane (50.0 g, 0.24 mole) and oxalyl chloride (150.0 g, 1.20 moles) were heated at 80–90° in 800 ml of chlorobenzene. Benzoyl peroxide (10.0 g) was added at three 24-hr intervals. After 96 hr the mixture was concentrated *in vacuo*. The residual brown gum was dissolved in methylene chloride and 250 ml of methanol was added. After 24 hr the mixture was concentrated *in vacuo* and the residue was chromatographed on Florisil (1100 g, 60–100 mesh) with ether–pentane as eluent. Pure pentane eluted methyl benzoate as above while ether–pentane (5–60%) eluted 15 g of crude product, which was sublimed at 0.1 mm and 155° to give 11.4 g (14.7%) of white solid, mp 90–130°.

The infrared spectrum shows strong carbonyl absorption at 5.8, the characteristic paracyclophane absorption at 14.0, and a broad absorption at 12.2–12.4 μ. The nmr spectrum in chloroform-*d* shows resonances at 6.75–6.37 (aromatic protons, multiplet), 4.17–3.81 (benzylic protons, multiplet), 3.60–3.23 (benzylic protons, multiplet), and 3.77 ppm (methyl protons, singlet) in an area ratio of 8:2:4:6.

Anal. Calcd for $C_{20}H_{20}O_4$: C, 74.07; H, 6.17. Found: C, 74.40; H, 6.30.

Ultraviolet Spectra of TCNE Complexes.—These measurements were carried out by the method of Singer and Cram.[11b]