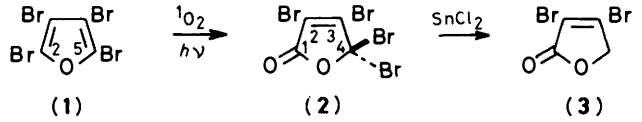
Photochemical Transformation of Tetrabromofuran by Oxygen into 2,3,4,4-Tetrabromobut-2-en-4-olide in the Solid State

Charles W. Shoppee
Department of Organic Chemistry, La Trobe University, Bundoora, Victoria, 3083, Australia.

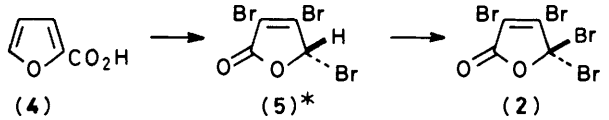
The solid-state photo-oxidation (**1**)→(**2**) recorded by Torrey in 1897 has been verified and structure (**2**) confirmed; a possible mechanism for the transformation involving free radicals is suggested. In contrast, the bromination (**5**)→(**2**) reported by Hill and Cornelison in 1894 could not be repeated despite many attempts. An ionic mechanism for the preparation (**4**)→(**6**) is proposed; the semi-aldehyde (**6**) in solution exists solely in the lactol form (**7**).

In 1897, Torrey[1] reported the solid-state conversion of tetrabromofuran (**1**) by sunlight in dry oxygen into the γ-lactone 2,3,4,4-tetrabromobut-2-en-4-olide (**2**), m.p. 58 °C, reduced by stannous chloride and hydrochloric acid to 2,3-dibromobut-2-en-4-olide (**3**), m.p. 90—91 °C. The γ-lactone (**2**) was partially and directly converted, especially by over-irradiation, into dibromomaleic anhydride and free bromine, and was hydrolysed by hot water to dibromomaleic acid.



(**1**) (**2**) (**3**)

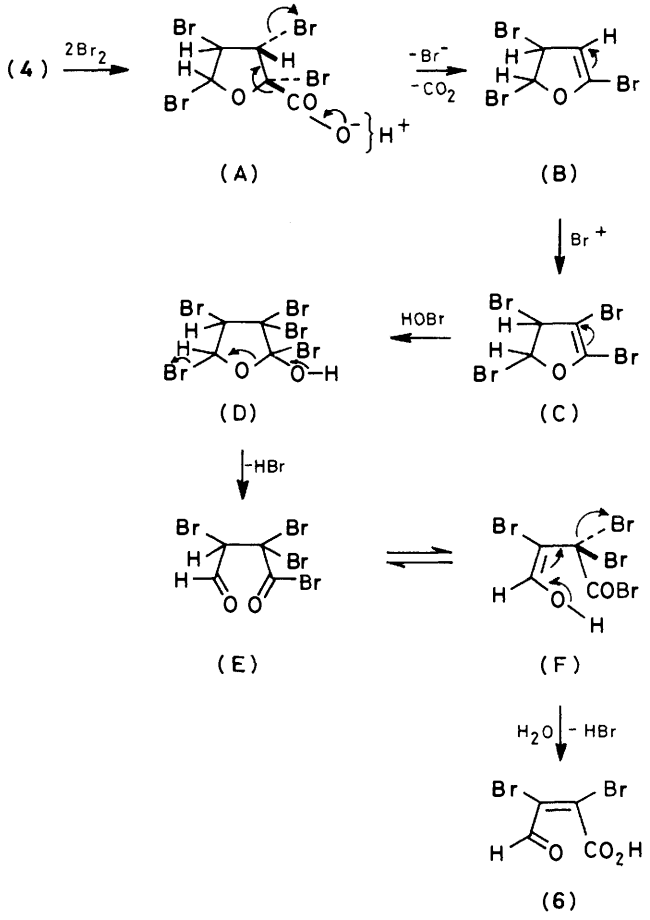
The tetrabromolactone ('dibromomaleyl bromide') (**2**) was stated to be identical with a compound, m.p. 58—59 °C, obtained by Hill and Cornelison[2] from 2-furoic acid ('pyromucic acid') (**4**) by decarboxylation and various stages of bromination to afford 2,3,4-tribromobut-2-en-4-olide ('muco-bromyl bromide') (**5**), m.p. 56—57 °C (giving a transient deep blue colour with an aqueous ethanolic solution of sodium carbonate), and bromination of the latter in a sealed tube for an unspecified time at 125—130 °C or more slowly at 100 °C.



(**4**) (**5**)* (**2**)

* One epimer

It seemed desirable to confirm the structure of the tetrabromolactone (**2**) by modern physicochemical methods, and its preparation from 2-furoic acid (**4**) by the method of Hill and Cornelison[2] was attempted. The initial step is the conversion of 2-furoic acid at 0 °C into the semi-aldehyde (**6**) of dibromomaleic acid ('mucobromic acid'); this is an ancient reaction[3-5] first performed in 1864, and its stoicheiometry is simple: $C_5H_4O_3 + 4Br_2 + 2H_2O \rightarrow C_4H_2Br_2O_3 + 6HBr + CO_2$ but its mechanism is complex. The only reagents available are bromine, water, hydrobromic acid, and hypobromous acid and the following mechanism is suggested (Scheme 1). 2-Furoic acid (**4**) gives a tetrabromide (A),[6] which as the anion of a β-bromoacid readily undergoes dehydrobromination and decarboxylation to yield the vinyl ether (B); this by bromination with hypobromous acid affords the tetrabromodihydrofuran (C), which by electrophilic addition of hypobromous acid furnishes the bromohydrin (D). This suffers ring-fission (*cf.* ref. 7) to give the aldehyde-acid bromide (E), which as the enol (F) by β-elimination of hydrogen bromide and hydrolysis of the acid bromide group, yields the semi-aldehyde (**6**) of dibromomaleic acid.

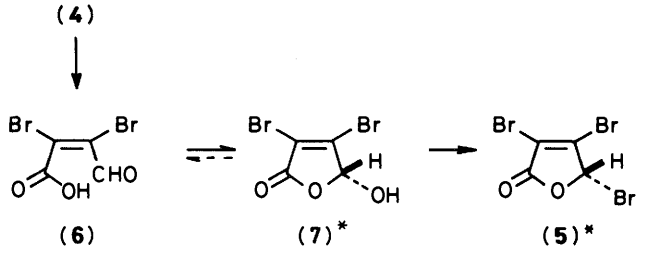


(A) (B) (C) (D) (E) (F) (**6**)

Scheme 1.

In the present work, the conversion (**4**) into (**6**) was effected by the procedure of Allen and Spangler[8] with some improvements. The ^{13}C n.m.r. spectrum of the semi-aldehyde (**6**) could not be recorded in deuteriochloroform because of insolubility, but a solution in dimethyl sulphoxide showed four resonances at δ 164.6 (s, CO), 147.3 (s, C-3), 116.4 (s, C-2), and 99.6 p.p.m. (s, C-4). Since the semi-aldehyde formula (**6**) requires the presence of two carbonyl resonances (for CO_2H and CHO), these observations prove that the compound in solution exists solely

in the lactol form (7). This conclusion, suggested by Anschutz in 1887,[9] is confirmed by the ^{1}H n.m.r. spectra, which in dimethyl sulphoxide show signals at δ 6.50 (s, 4-H) and 4.30 (4-OH, very small owing to exchange with HOD present in the solvent), whilst in deuteriochloroform, signals appear at δ 6.05 (1 H, s, 4-H) and at 4.70, 4.69 p.p.m. (1 H, d, 4-OH); there was no trace of a signal for an aldehydic proton at δ 9—10 p.p.m.



* One epimer

The lactol (7) with phosphorus tribromide at 100 °C[2] readily gave (4*R*,4*S*)-2,3,4-tribromobut-2-en-4-olide (**5**), m.p. 57 °C, which yielded a transient deep blue colour with an aqueous ethanolic solution of sodium carbonate. The structure of (**5**) was assigned on the basis of its ^{13}C n.m.r. spectrum in deuteriochloroform which showed resonances at δ 162.96 (s, CO), 147.14 [s, C(3)-Br], 116.80 [s, C(2)-Br], and 77.79 [s, C(4)-HBr], the last named signal becoming a doublet in the SFORD spectrum (for the u.v. and i.r. spectra see the Experimental section). The $\Delta^{\alpha\beta}$-carbonyl moiety of the tribromolactone (**5**) activates the vinylogous C(4)-hydrogen atom to afford the blue C(4)-anion (or the related enolate anion), and prevents replacement of the C(4)-hydrogen atom with bromine by use of *N*-bromosuccinimide.

Contrary to the statement of Hill and Cornelison,[2] the tribromolactone (**5**) does not react with bromine in a sealed tube at 100 °C; no hydrogen bromide is formed during 5 h. Again, contrary to the statement of Hill and Cornelison, when equal molecular amounts of the tribromolactone (**5**) and bromine are heated in a sealed tube at 125—130 °C, the product gives a transient deep blue colour with sodium carbonate in aqueous ethanolic solution, which is characteristic of the tribromolactone (**5**), whereas their product, described as a *colourless* oil, gave no blue colour in ethanolic solution with sodium carbonate, and gradually solidified to afford the tetrabromolactone (**2**) (which is *yellow*, see later), m.p. 58—59 °C. Many repetitions failed to yield the tetrabromolactone (**2**), and the product consisted of a trace of the dibromolactone (**3**) and the unchanged tribromolactone (**5**), as was proved by its ^{13}C SFORD n.m.r. spectrum which showed a doublet at δ 77.79 p.p.m. for >C(4)HBr. Fractional crystallisation of the total product from light petroleum (b.p. 40—60 °C), failed to yield any of the tetrabromolactone (**2**), whilst t.l.c. on silica in a variety of solvent systems gave only a single spot corresponding to the tribromolactone (**5**). Since Hill and Cornelison[2] (*cf.* ref. 1) found that their tetrabromolactone (**2**) was very slowly attacked by cold water, an attempt was made to remove the tribromolactone (**5**) from the total product by extraction of an ethereal solution with ice-cold 0.5M-Na_2CO_3; this gave a yellow extract, characteristic of the dibromolactone (**3**),[2] but failed to yield the tetrabromolactone (**2**). Hill and Cornelison[2] purified their solid product by recrystallisation from light petroleum, gave the correct m.p., correct duplicate analyses for bromine, described their compound as possessing 'a strong suffocating odour like that of the acid bromanhydrides', and reduced it with stannous chloride and hydrochloric acid to the dibromolactone (**3**), m.p. 90—91 °C. There appears to be some essential detail missing from the description of their experimental work since it cannot be repeated.

Hydrogen bromide should be formed in the reaction (**5**)→(**2**); it appears to act as a reducing agent setting up a double equilibrium of type (i). An attempt was therefore made

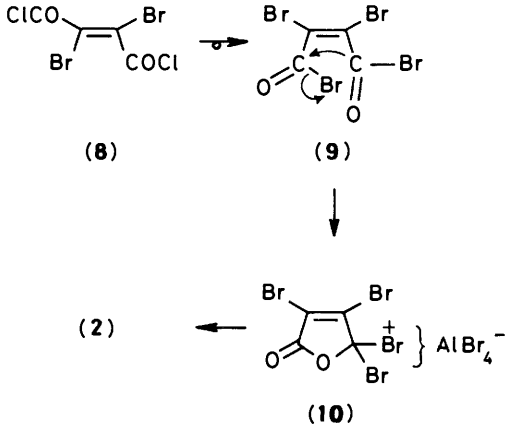
$$(3) \underset{Br_2}{\overset{HBr}{\rightleftharpoons}} (5) \underset{HBr}{\overset{Br_2}{\rightleftharpoons}} (2) \qquad \text{(i)}$$

favourably to influence the equilibrium (**5**)⇌(**2**) by use of 10 molar equivalents of bromine in a sealed tube at 125—130 °C for 2 h, but without production of any of the tetrabromolactone (**2**); likewise, heating the tribromolactone (**5**) with an excess of bromine in an unsealed vessel in a slow current of dry nitrogen, with constant replenishment of bromine and provision for escape of hydrogen bromide at 130 °C, failed. Use of pyridinium hydrobromide perbromide in pyridine to remove any formed hydrogen bromide was prevented by the discovery that the weak base pyridine (K_B *ca.* 10^{-9}), although giving an apparently stable red-purple colour with the tribromolactone (**5**) at 20 °C on a small scale, underwent, after a brief induction period, a sudden exothermic reaction, perhaps involving 1,1-dehydrobromination to a carbene, to furnish black insoluble (polymeric?) material. Finally, equal molecular equivalents of the tribromolactone (**5**) and bromine were heated with 3 molar equivalents of anhydrous aluminium bromide in a sealed tube at 100 °C for 2 h, so that the concentration of electrophilic bromonium ion might be increased: $Br_2 + AlBr_3 \rightarrow Br^+ + AlBr_4^-$, the concentration of hydrogen bromide decreased: $HBr + AlBr_3 \rightleftharpoons HAlBr_4$, and any formed tetrabromolactone captured: $R\text{-}Br_2 + AlBr_3 \rightarrow RBr\text{-}Br^+\text{-}AlBr_4^-$, since it is known (see later) that the tetrabromolactone (**2**) affords a complex, stable at 100 °C, with aluminium bromide. None of the tetrabromolactone could be isolated, and the sole product was unchanged tribromolactone (**5**).

Attempts to form the lithium enolate of the tribromolactone (**5**) with lithium di-isopropylamine in tetrahydrofuran under argon at −70 °C, or the derived trimethylsilyl ether, with a view to bromination to yield the tetrabromolactone (**2**), were thwarted by the concomitant production of the strong base di-isopropylamine, and led to formation of red-purple solutions which on contact with air gave black insoluble (polymeric?) material.

The apparent ready reduction of the tetrabromolactone (**2**) by hydrogen bromide to regenerate the prototropic three-carbon system of the tribromolactone (**5**) bears a striking similarity to the reduction by ethanol of blocked three-carbon tautomeric systems, with formation of the unusual product diethyl carbonate, listed by Ingold and Thorpe[10] [see (ii)].

$$RR^1C{=}CR^2\text{–}CR^3(CO_2Et)_2 + HOEt \rightarrow RR^1C{=}CR^2\text{–}CHR^3CO_2Et + CO(OEt)_2 \qquad \text{(ii)}$$



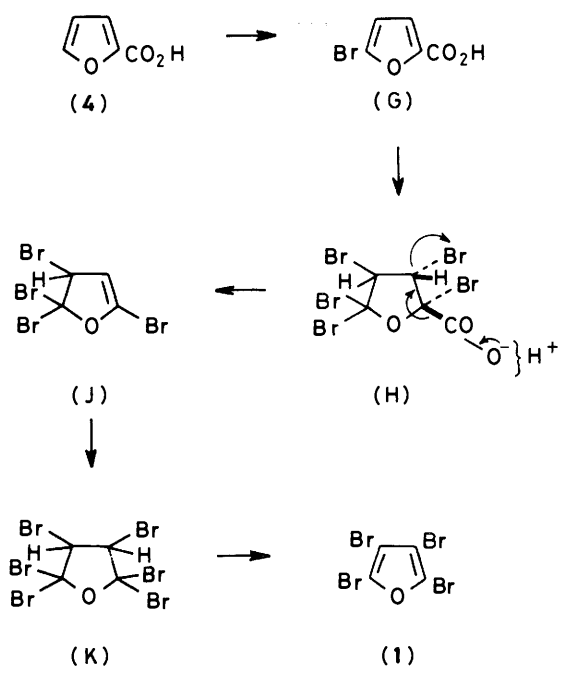
These phenomena can be attributed to the resonance energy generated by formation of mesomeric anions possessing enhanced thermodynamic stability.

The tetrabromolactone (**2**) has been prepared as sulphur-yellow leaflets, m.p. 55—57 °C by Ott;[11] dibromofumaric acid was converted with phosphorus pentachloride into dibromofumaroyl dichloride (**8**), which with aluminium bromide at 100 °C, underwent substitution of chlorine by bromine [probably by exchange: $(R > COCl)_2 + AlBr_3 \rightleftharpoons (R > CO\text{-}Br)_2 + AlCl_3$, and scrambling of Cl and Br] and geometrical inversion to yield dibromomaleoyl dibromide (**9**), rearranged by aluminium bromide at 100 °C to a dark brown-black complex (**10**),* converted by water at 0 °C and subsequent extraction with carbon tetrachloride into the tetrabromolactone ('dibromomaleic acid bromide') (**2**). The experimental observations of Ott [11] are as reliable as those of Hill and Cornelison[2] are unreliable. Compound (**2**) gives no colour with ethanolic sodium carbonate solution; it possesses a characteristic suffocating odour. The structure of the tetrabromolactone (**2**) is established by its ^{13}C n.m.r. spectrum, which in deuteriochloroform solution exhibits four signals at δ 159.18 (s, CO), 152.93 (s, C-3), 115.38 (s, C-2), and 73.77 p.p.m. (s, C-4), since in the SFORD spectrum, the singlet signal for $>C(4)Br_2$ remains a singlet (for the u.v. and i.r. spectrum see Experimental section).

Since dichloromaleoyl dichloride (*cf.* ref. 11) exists in equilibrium with the tetrachloro-analogue of the tetrabromolactone (**2**),[12] a short-cut to the latter was attempted; dibromomaleic acid was treated with thionyl bromide in the hope that it would provide dibromomaleoyl dibromide (**9**) for subsequent rearrangement with aluminium bromide to the tetrabromolactone (**2**). The sole product was, however, dibromomaleic anhydride.[13,14]

Tetrabromofuran, m.p. 64 °C, is colourless and completely stable in air and laboratory light at room temperature; it was prepared as follows (Scheme 2). 2-Furoic acid (**4**) by monobromination in acetic acid[15] gave 5-bromofuroic acid (G), which by further bromination in alkaline solution by Hill's improved method,[16] afforded the pentabromofuroic acid (H), a β-bromo acid which by loss of the β-bromine atom and carbon dioxide, yielded the tetrabromodihydrofuran (J). This, by addition of one molecular equivalent of bromine, gave the hexabromotetrahydrofuran (K),[17] which underwent dehydrobromination with hot ethanolic potassium hydroxide to give the tetrabromofuran (**1**).

In his irradiation of tetrabromofuran (**1**) with sunlight in dry oxygen, Torrey[1] used a glass flask presumably made of ordinary soda glass and more or less opaque to u.v. light (crown soda glass has a single 'window' with 94.7% transmission at 375 nm[18]); to increase illumination, Torrey employed a concave mirror, but made no attempt to control the temperature of the tetrabromofuran, which soon became bright yellow, although he states 'that the transformation [(**1**)→(**2**)] appeared to be more neatly affected at ordinary temperature'. The stoicheiometry of the photo-oxidation: $C_4Br_4O + O = C_4Br_4O_2$, was established gravimetrically. Torrey says 'although there could be little doubt that the original oxidation product contained dibromomaleoyl bromide' [tetrabromolactone (**2**)], his attempts to isolate and identify this compound leave much to be desired. In one experiment, the crude irradiation product was distilled at 140 °C/25 mmHg and the distillate partially solidified in a freezing mixture; filtration and recrystallisation of the solid from light petroleum gave dibromomaleic anhydride.



Scheme 2.

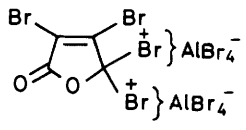
The filtrate was dissolved in light petroleum, and the solution by spontaneous evaporation and long standing yielded 'a few tabular crystals, which after careful pressing, melted at 58—59 °C'; no identification, *e.g.* by a mixed m.p. with the preparation of Hill and Cornelison,[2] was made. In another experiment, the crude irradiation product was finely powdered and shaken with successive portions of cold water; the aqueous solution contained dibromomaleic acid, whilst the insoluble material, repeatedly recrystallised from light petroleum had m.p. 51—52 °C, and consisted of an inseparable mixture of tetrabromofuran (**1**) and the tetrabromolactone (**2**), which by reduction with stannous chloride and hydrochloric acid gave the dibromolactone (**3**) in unspecified yield.

The photoconversion of tetrabromofuran (**1**) into the tetrabromolactone (**2**), reported by Torrey[1] using sunlight, has been confirmed, using u.v. light (366 nm), by t.l.c. on silica gel at 23—27 °C in air. The compounds (**1**) and (**2**) were applied separately to the plate; after irradiation for 2 h, the plate was loaded with reference samples of (**1**) (R_F 0.83) and (**2**) (R_F 0.53), and developed in methanol–chloroform (2:1) to give, after drying in air at 25 °C, a spot (R_F 0.53) corresponding to (**2**). This proves the phototransformation (**1**)→(**2**). Using the same procedure as described above, a plate was loaded with compounds (**1**) and (**2**) and kept in the dark in air at 25 °C for 2 h; reference samples of compounds (**1**) and (**2**) were applied separately to the plate, and the plate developed in methanol–chloroform (2:1) to give, after drying in air at 25 °C a pattern showing that both compounds (**1**) and (**2**) were unchanged.

Preparative t.l.c. in oxygen with irradiation at 366 nm at 23—27 °C gave the tetrabromolactone (**2**), but in quantity insufficient for direct comparison with the authentic sample. Possibly, extraction of the plate with hot methanol and evaporation of the extract led to methanolysis of the tetrabromo-γ-lactone (**2**).

Finally, solid tetrabromofuran (**1**) (m.p. 64 °C), in a silica flask in dry oxygen at atmospheric pressure and 25 °C, was flurried by rapid magnetic stirring and irradiated at 366 mm. The colourless crystals became bright yellow, and clumped together to give a viscous yellow liquid. The progress of the

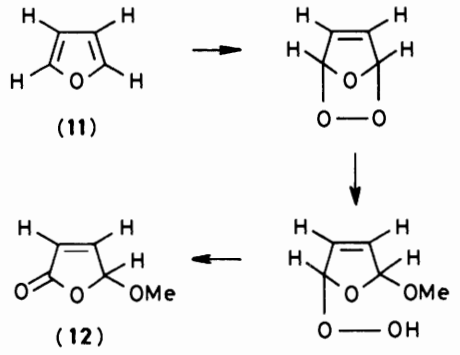
* Possibly



transformation (1)→(2) was monitored by t.l.c. After 2 h, the product was isolated and crystallised from hexane to give sulphur-yellow leaflets of the tetrabromolactone (2) (yield 27%), m.p. 59—60 °C, mixed m.p. with an authentic sample 59—60 °C, R_F value identical with that of the reference sample, and possessing the characteristic suffocating odour; ^{13}C n.m.r. spectrum: δ 159.20 (s, CO), 152.93 (s, C-3), 115.38 (s, C-2), and 73.79 p.p.m. [s, >C(4)Br_2].

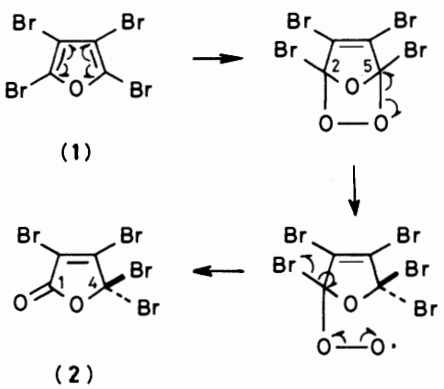
The question of immediate interest concerns the mechanism of the solid-state photochemical transformation (1)→(2), whereby a bromine atom is apparently transported from C-2 in tetrabromofuran (1) to C-4 in the tetrabromolactone (2) with acquisition of one atom of oxygen: $C_4Br_4O + O_2 \rightarrow C_4Br_4O_2 + O$.

The Diels–Alder reactions of molecular oxygen in the singlet first excited state ($^1\Delta_g$), lying 22.4 kcal mol^{-1} above the triplet ground state ($^3\Sigma_g^-$), with 1,3-dienes to form 1,4-endoperoxides have been reviewed recently.[19] In particular, photochemical oxygenation of furan (11) in methanol at 20 °C has been investigated by Schenck,[20] who gives the following mechanism (Scheme 3), without any discussion, to account for the production of the 4-methoxybut-2-en-4-olide (12), recently also obtained from furaldehyde by photochemical oxygenation in 92% yield by Machado-Araujo and Gore.[21]



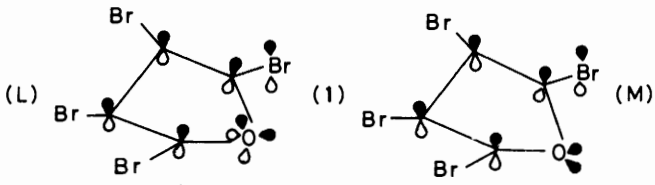
Scheme 3.

The resonance energy of furan (11) is 17 kcal mol^{-1},[22] and that of tetrabromofuran (1) is probably less because of the assistance of the four carbon-bromine dipoles to the π-electron delocalisation. Strained olefins, *e.g.* tetrabromofuran, are known to be highly reactive to oxidation by singlet molecular oxygen.[23] An overall mechanism (Scheme 4), similar to that of Schenck *et al.* (Scheme 3), can be written for the transformation (1)→(2) described by Torrey,[1] but is unsatisfactory in regard to detail because that transformation was performed in the solid state and not in solution. Torrey states that the initial product is the tetrabromolactone (2) and records the production of free bromine. Thus, it appears that the only available addendum to the 2,5-endoperoxide (which is also an ozonide) is a bromine atom.



Scheme 4.

It is well known that bonds adjacent to carbon–carbon double bonds show a high propensity to undergo homolytic fission, which is consistent with thermodynamic considerations because the product radicals are stabilised by conjugative interaction of the odd electron with the adjacent π-system. It is generally believed that homolytic fission of a bond is favoured when it can assume coplanarity with an adjacent filled orbital. Since the ring in tetrabromofuran (1) contains five sp^2 hybridised atoms—four sp^2 carbon atoms and one sp^2 oxygen atom—it must be statistically planar with the orbital arrangement (L)[24] or (M):[25] It therefore seems probable



that the initial step in the transformation (1)→(2) is the homolysis of an α C–Br bond,* and possible to write the following radical chain mechanism (Scheme 5); there seems to be no value available for the dissociation energy of the furan–bromine bond, but it should not be greater than that of the phenyl–bromine bond (*ca.* 72 kcal per mol) or the methyl–bromine bond (68 kcal per mol), and may well be somewhat less: The expulsion of a neutral oxygen atom, pairing to give molecular triplet oxygen, may be the only escape route available in a solid state reaction.

Alternatively, and more attractively, dimerisation of the radical (N) may occur to give transient *Z*- and/or *E*-tetraoxides (P. D. Bartlett and T. G. Traylor[26]), which then eliminate and so regenerate a molecule of triplet oxygen.

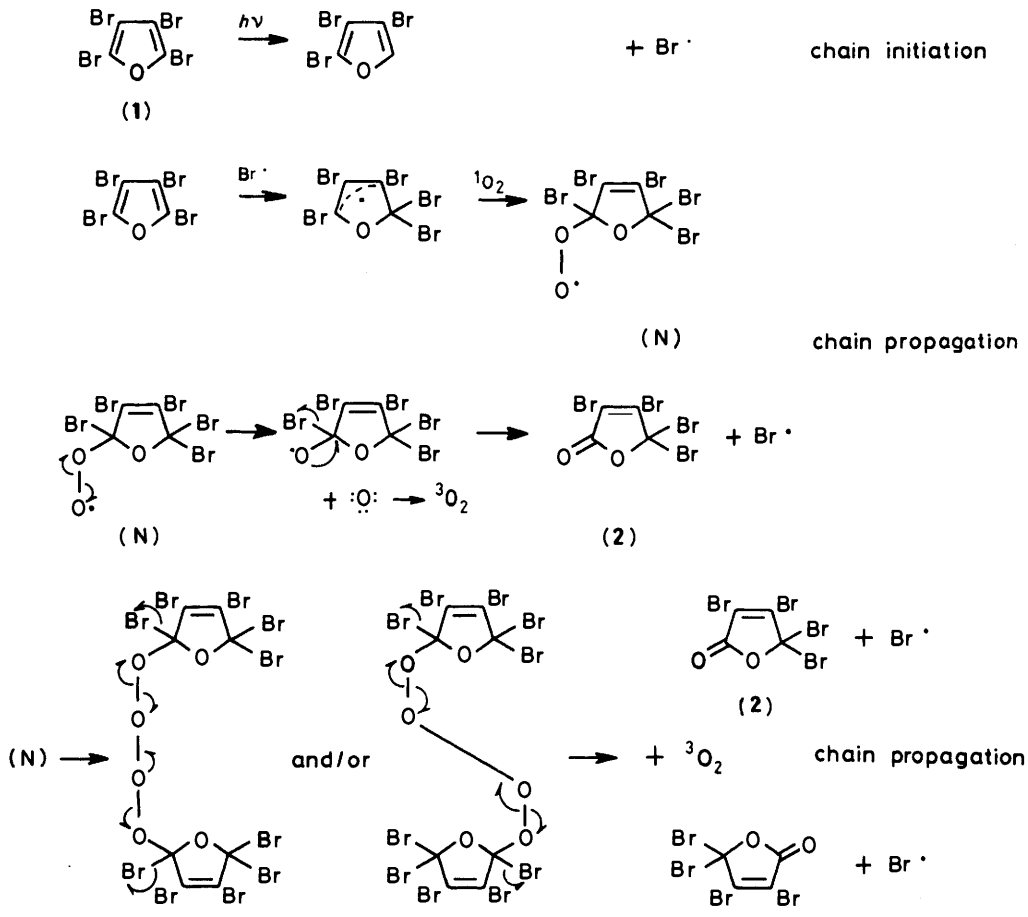
Experimental

M.p.s were determined thermoelectrically on a Reichert hot-stage. U.v. spectra were measured in ethanol using a Varian Techtron 635 spectrotophometer, i.r.-spectra were taken in KBr discs or CS_2 using a Perkin-Elmer 225 grating instrument, whilst ^{13}C and ^1H n.m.r. spectra were obtained with a Jeol FX 200 machine in deuteriochloroform, with this as internal standard (δ 77.000) in the ^{13}C spectra and tetramethylsilane in the ^1H spectra.

αβ-Dibromo-β-formylacrylic Acid (6).—Furan-2-carboxylic acid (m.p. 130–131 °C, B.D.H.; lit.,[8] m.p. 131—132 °C) was converted by treatment with bromine and water at *ca* 0 °C into the acid (6), m.p. 123 °C (lit.,[8] m.p. 123—124 °C) by the procedure of Allen and Spangler;[8] efficient mechanical stirring is essential (magnetic stirring is useless owing to the pasty consistency of the reaction mixture), and the initial filtration of the crystalline product from a cold concentrated solution of hydrobromic acid (47.5% hydrogen bromide) requires a hardened filter paper, or, better, a sintered glass plate.

2,3,4-*Tribromobut-2-en-4-olide* (5).—The acid (6) (7.5 g; dried *in vacuo* over calcium chloride) was dissolved in diethyl ether

* Polarisation of the C–O bond, due to the greater nuclear charge on oxygen, would stabilse an α-furyl radical relative to a β-furyl radical.



Scheme 5.

(15 ml) and treated with a solution of phosphorus tribromide[2] (2.85 g, 1 ml) in diethyl ether (5 ml) at 20 °C. The solvent was removed under reduced pressure at 35 °C, and the reaction mixture heated with exclusion of moisture at 100 °C for 1.5 h. After cooling of the mixture, ice–water (100 ml) was added to it and the whole well shaken. After 24 h at 20 °C the crystalline product was filtered off, well washed with cold water, and dried ($CaCl_2$), m.p. 55—56 °C (6.1 g); recrystallisation from ethanol gave the tribromolactone (**5**), m.p. 57 °C (lit.,[5] m.p. 55 °C,[2] m.p. 56–57 °C), as stout hexagonal prisms giving a transient deep blue colour with aqueous ethanolic sodium carbonate solution (but not with lithium hydride in dry ether or dry THF at 35 and 64 °C), $\lambda_{max.}$ 253 and 205 nm; $\nu_{max.}$(KBr) 1 770 (O=C–C=C in γ-lactones), 1 590 (C=C in-plane vibration in furan derivatives), 1 290 (heterocyclic C–H in-plane deformation), 1 200, 1 190 (O=C–C=C–*O*– stretching vibration), 1 005, 970, 875 (C=C ring-breathing vibrations in furan derivatives), 730 and 698 [>C(4)H-Br, C-Br vibrations in-phase and out-of-phase, intense with slightly stronger peak at higher frequency[27]), 590 [=C(2)-Br, with $(\delta^-)O{=}C(\delta^+)$ and $(\delta^+)C{-}Br(\delta^-)$ dipoles ~ coplanar), and 491 cm^{-1} [=C(3)-Br, with $(\delta^-)C{=}C(\delta^+)$ and $(\delta^+)C{-}Br(\delta^-)$ dipoles ~ anticoplanar); ^{13}C n.m.r. spectrum: δ 162.96 (s, C=O), 147.14 [s, =C(3)-Br], 116.80 [s, =C(2)-Br], and 77.79 p.p.m. [s, >C(4)HBr], the last named signal becoming a doublet in the SFORD spectrum.

2,3,4,4-*Tetrabromobut-2-en-4-olide* (**2**).—(*a*). The tribromolactone (**5**) (0.5 g), and bromine (0.08 ml, 1 mol equiv., from a microsyringe) in a sealed tube, was heated at 100 °C for 5 h. No hydrogen bromide was formed, and the product consisted of the starting material, giving a transient blue colour with aqueous ethanolic sodium carbonate solution, m.p. and mixed m.p. 56—57 °C from ethanol.

(*b*) The tribromolactone (**5**) (1 g) and bromine (0.16 ml, 1 mol equiv.) in nitrogen in a sealed tube were heated at 130 °C for 3 h. Unsealing the cold tube gave visible emission of a little hydrogen bromide; the contents of the tube were taken up in ether, the pale yellow ethereal solution washed rapidly with ice-cold M-$NaHCO_3$, with ice-cold 0.5M-Na_2SO_3, and with cold water, and was then dried quickly with sodium sulphate, and evaporated. The product (0.85 g), m.p. 40—41 °C, gave a blue colour with aqueous ethanolic sodium carbonate solution. The slightly yellow crystals were dissolved in ether, and the ethereal solution shaken with ice-cold 0.5M-Na_2CO_3 (×4) to give a *yellow* aqueous extract and with ice-cold water; it was then dried rapidly with sodium sulphate and evaporated. The residual oil crystallised on standing overnight (0.65 g); this product recrystallised from hexane as long shining colourless needles (0.40 g), m.p. 47 °C, giving a blue colour with aqueous ethanolic sodium carbonate solution. Concentration of the hexane mother liquor, cooling, and seeding with the tribromolactone, gave crystals (6 mg), which by draining on porous porcelain and washing with ice-cold hexane, had m.p. 57 °C; the compound gave a blue colour with aqueous ethanolic sodium carbonate, and was identified as the tribromolactone from the presence of a doublet signal in its ^{13}C n.m.r. SFORD spectrum at 77.9 p.p.m. T.l.c. on silica (Merck, 60F 254) or on neutral aluminium oxide (Merck, 60F 254 type E) gave only a single spot, giving a blue colour with sodium carbonate solution, and corresponding to the tribromolactone, in all solvent systems

tried [$CHCl_3$–hexane (1:1); C_6H_6–hexane (1:1); EtOH–hexane (1:19; 1:4; 1:1); C_6H_6; C_6H_6–Et_2O, (1:19; 1:4); Me_2CO–hexane (1:1). The crystals, m.p. 47 °C (100 mg) were dissolved in ethanol (1 ml; warm, then cooled) and the solution shaken with ice-cold 0.5M-Na_2CO_3 (0.6 ml, 33 mg Na_2CO_3, 2 mol equiv.) to give an instant blue colour. The blue solution was extracted thrice with ether. The colourless ethereal extracts, after washing with water and drying by evaporation gave a small residue, which was extracted with boiling hexane; evaporation, cooling, and inoculation with the tribromolactone, failed to give crystals. The blue alkaline aqueous solution was acidified with ice-cold 2M-HCl and became colourless; extraction with ether, drying of the extract with sodium sulphate (which became buff in colour), and evaporation yielded only a little dark residue. The original yellow alkaline aqueous extract was acidified with ice-cold 2M-HCl, and became colourless; the mixture was extracted with ether and the extract washed with water, dried, and evaporated to give a gum, which crystallised on rubbing with ethanol (1 drop); the crystals, drained on a porous tile, were colourless plates, m.p. 113 °C, mixed m.p. with dibromomaleic anhydride, 113–115 °C. The residual crystals (0.3 g), m.p. 47 °C, were extracted with boiling hexane (×4); concentration and cooling of the extract gave the tribromolactone as long needles, m.p. 58 °C, ^{13}C n.m.r. spectrum: δ 162.93 [s, C(1)=O], 147.11 [s, =C(3)-Br], 116.77 [s, =C(2)-Br], and 77.79 [s, >C(4)HBr], which latter signal became a doublet in the SFORD spectrum; the compound gave a transient blue colour with aqueous ethanolic sodium carbonate solution.

(*c*) The tribromolactone (1 g) and bromine (1.6 ml, 10 mol equiv.) were heated under nitrogen in a sealed tube at 125–130 °C for 2 h. Excess of bromine was removed from the opened tube in a vacuum. The residual oil which crystallised with time, was taken up in ether, and the ethereal solution washed with ice-cold M-$NaHCO_3$, with water, and was then dried with sodium sulphate, and evaporated. The residual yellow oil gave a blue colour with aqueous ethanolic sodium carbonate solution. To remove unchanged tribromolactone, the oil was dissolved in the minimum of warm methanol, cooled, seeded with the tribromolactone, and left at 20 °C. The crystals were filtered off and washed with ice-cold methanol; they gave the characteristic transient blue colour of the tribromolactone with aqueous ethanolic sodium carbonate solution. The filtrate was evaporated under reduced pressure, and the residue fractionally crystallised from hexane; fraction 1, a pale yellow oil, crystallised at once on seeding with the tribromolactone; fraction 2 was very small but failed to crystallise on inoculation with the tribromolactone during 2 h; fraction 3 contained no material.

(*d*) The tribromolactone (0.5 g) was heated in an open tube in a glycerol bath at 132 °C with an excess of bromine in a slow current of nitrogen with constant replenishment of bromine and provision for escape of hydrogen bromide formed for 4 h. No tetrabromolactone (**2**) could be isolated by the usual procedure, and unchanged tribromolactone was recovered.

(*e*) The tribromolactone (0.4 g), bromine (0.065 ml from a microsyringe), and anhydrous aluminium bromide (0.7 g), were heated in a sealed tube at 100 °C for 2 h. On cooling the tube some bromine was visible, and on opening the tube some hydrogen bromide fumes became visible. After cautious addition of ice, the solid product was removed from the tube with warm carbon tetrachloride. The orange-red solution was washed twice with ice-cold water, dried with sodium sulphate, and evaporated when the colour (due to bromine) disappeared. The residual yellow oil was dissolved in hot hexane, and left at 20 °C. The solid remaining after evaporation of hexane gave a blue colour with aqueous ethanolic sodium carbonate; recrystallisation from ethanol gave the tribromolactone, m.p. 56—57 °C.

(*f*) Dibromofumaric acid was prepared as follows. Acetylenedicarboxylic acid [m.p. 187 °C (decomp.), 11.4 g (Aldrich)], dissolved in ice-cold water (24 ml), was stirred magnetically in a dark cold-room (*t* 3.5 °C), and bromine vapour (from bromine, 7 ml) introduced by a slow stream of nitrogen during 4 days. After 7 days in the dark at 20 °C, the colourless solution, by rotary evaporation in the absence of light at 35 °C, gave pure dibromofumaric acid (27 g), m.p. (after a crystal transition at *ca.* 170 °C to long thin prisms) 237—238 °C (lit.,[28] m.p. 229 °C;[11] m.p. 220—225 °C;[29] m.p. 229 °C;[30] m.p. 225 °C).

Dibromofumaric acid (7 g, dried over P_2O_5), suspended in hexane (10 ml), was treated with phosphorus pentachloride[11] (10.6 g); a steady reaction occurred at 40—50 °C and no free bromine was produced (*cf.* ref. 11). Refluxing of the hexane gave a clear yellow solution, which was poured onto ice; after swirling, and being allowed to stand for 15 min with repeated shaking to decompose phosphorus oxychloride, the mixture was extracted with ether. The extract was dried with sodium sulphate, evaporated, and dibromofumaroyl dichloride (**8**) distilled as a colourless liquid, b.p. 105—110 °C/12 mmHg (lit.,[11] b.p. 92.5 °C/9.5 mmHg). The diacid chloride (7 g) was heated with anhydrous aluminium bromide (7 g; m.p. 97 °C) at 100 °C for 1 h. The cold, black solid was triturated with ice, and the solution extracted thrice with carbon tetrachloride, the extract dried with sodium sulphate, and evaporated. The residual brown oil, dissolved in hexane, on cooling in ice afforded sulphur-yellow plates, m.p. 59—60 °C. Recrystallisation from hexane gave 2,3,4,4-tetrabromobut-2-en-4-olide (**2**) as pale yellow leaflets, m.p. 59—60 °C (lit.,[11] m.p. 55—57 °C), $\lambda_{max.}$ 256 and 205 nm; $\lambda_{max.}$(KBr) 1 785 (O=C–C=C in γ-lactones), 1 585 (C=C in-plane vibration in furan derivatives) [no peak at 1 290 cm^{-1} as in (**5**)], 1 195, 1 160 (O=C–C=C–O-stretching vibration), 1 000, 980, 885 (C=C ring-breathing vibrations in furan derivatives), 760, 740, and 720 (>C_4Br_2 {C-Br vibrations in phase and out of phase [two modes]}, intense and occurring with two bromine atoms on the same carbon atom at higher frequencies than in compounds [*e.g.* (**5**)] with one bromine on the corresponding carbon atom[31]), 620 (=C(2)-Br, weak), and 610 (=C(3)-Br, weak) cm^{-1}; δ_C 159.18 (s, C=O), 152.93 (s, C-3), 115.38 (s, C-2), and 73.77 (s, C-4), the last named signal remaining a singlet in the SFORD spectrum.

Attempted Preparation of 2,3,4,4-*Tetrabromobut*-2-*en*-4-*olide* (**2**) *from Dibromomaleic Acid.*—Dibromomaleic acid [2.75 g; m.p. 150 °C—the polymorph, m.p. 142 °C, described by Diels and Reinbeck[14]—Aldrich (m.p. 126 °C)] was added to thionyl bromide (5.4 g, 2 ml; Alpha Chemicals) and heated at 100 °C under reflux for 0.5 h; neither sulphur dioxide nor hydrogen bromide were evolved, and dibromomaleic acid remained as a solid. Ether (4 ml) was added, and the mixture allowed to stand at 25 °C for 4 days. Ether and excess thionyl bromide were removed at 40—50 °C/20 mm; distillation of the residue at 120—130 °C/20 mmHg gave a colourless liquid, which soon crystallised. The crystals were filtered off, and washed with ether–hexane (2 g); recrystallisation from ether–hexane gave dibromomaleic anhydride (1.4 g) as needles, m.p. 117 °C (lit.,[1] m.p. 115 °C,[14] m.p. 118—119 °C).

5-Bromo-2-furoic Acid.—2-Furoic acid (25 g; m.p. 130—131 °C; B.D.H.), was dissolved in warm acetic acid (750 ml), and the cooled solution treated dropwise, with magnetic stirring, with bromine [14 ml, 1.2 mol, dissolved in acetic acid (5 ml)] during 1 h. No hydrogen bromide was evolved; the mixture was gently heated for 0.5 h with copious evolution of hydrogen bromide and some carbon dioxide. The clear brown solution became a magma of crystals whilst still warm; after cooling, the crystals were filtered off, washed with acetic acid, and kept in a

desiccator over potassium hydroxide to remove acetic acid. The product (24 g) was recrystallised from boiling water (650 ml) containing sodium sulphite (0.5 g) and charcoal (Darco) to give 5-bromo-2-furoic acid (15.2 g), m.p. 192 °C (lit.,[17] m.p. 183—184 °C).

2,2,3,4,5,5-Hexabromotetrahydrofuran.—5-Bromo-2-furoic acid (14.2 g) was dissolved in 2M-KOH (40 ml) under nitrogen, and the alkaline solution treated with bromine (11.5 ml, 3.3 mol) added dropwise with magnetic stirring at 30 °C during 1.25 h whilst the temperature of the reaction mixture rose to 60 °C. After 24 h under nitrogen the mixture was filtered and the crystalline product washed with ice–water, 0.15M-Na_2SO_3 (5 ml) to remove any traces of bromine, again with ice–water, and was then dried *in vacuo* over calcium chloride. This material (12 g), recrystallised from ethanol gave the hexabromo compound (3.6 g), m.p. 114—115 °C (lit.,[16] m.p. 110—111 °C). The mother-liquor by concentration gave no crystalline material, and by evaporation an oil (8 g).

Tetrabromofuran (**1**).—Hexabromotetrahydrofuran (3.6 g) reacted rapidly when refluxed with methanolic M-KOH; after 1 h, the solution was cooled to 20 °C, solid carbon dioxide slowly added, followed by cold water (50 ml). The precipitate was filtered off, washed with water, dried over calcium chloride in a desiccator, to give colourless needles of tetrabromofuran (2.15 g) which was recrystallised from hot ethanol, m.p. 64—65 °C, δ_C 123.26 (s, C-2, C-5) and 107.14 (s, C-3, C-4) p.p.m. (lit.,[17] m.p. 64—65 °C). The above oil (8 g), similarly dehydrobrominated, gave a further quantity (0.6 g) of product. Tetrabromofuran appears to possess a considerable vapour pressure when kept in a closed vessel with exclusion of light at 20 °C and a characteristic but not unpleasant odour; it decomposes in benzene solution after a few days in laboratory light at 20 °C as shown by t.l.c.

Photochemical Transformation of Tetrabromofuran (**1**) *into 2,3,4,4-Tetrabromobut-2-en-4-olide* (**2**).—(*a*) Solutions of tetrabromofuran (**1**) and 2,3,4,4-tetrabromobut-2-en-4-olide (**2**) (<0.1 mg in 0.05 ml of $CHCl_3$) were applied separately to a silica-gel plate (Merck $60F_{254}$, size 3 × 10 cm, layer depth 0.2 mm), which was irradiated with a CAMAG u.v. lamp (Type 29230) at λ 366 nm in air at 23—27 °C for 2 h. Thereafter, the plate was loaded with reference samples of compounds (**1**) and (**2**), developed in methanol–chloroform (2:1), and dried in a current of air at 25 °C. Tetrabromofuran (**1**) (R_F 0.83) was converted into 2,3,4,4-tetrabromobut-2-en-4-olide (**2**) (R_F 0.53) having the same R_F value (0.53) as the reference sample of (**2**). Using the same procedure, a plate was kept in the dark in air at 25 C for 2 h; development of the plate in methanol–chloroform (2:1) proved that both compounds (**1**) and (**2**) were unchanged.

(*b*) For preparative t.l.c., tetrabromofuran (**1**) (150 mg) in chloroform was added with an applicator to a silica-gel plate (Merck $60F_{254}$, size 20 × 20 cm, layer depth 2 mm) and irradiated at 366 nm in oxygen at 23—27 °C for 2 h. The plate was developed in methanol–chloroform (2:1) and dried in a current of air at 25 °C. The product, which could be recovered, was largely unchanged starting material, possibly because the u.v. radiation failed to penetrate into the thick layer of silica gel. The same procedure was repeated several times using tetrabromofuran (30 mg) applied to a silica-gel plate (size 20 × 20 cm, but layer depth 0.2 mm). After irradiation, the plate was developed as before, dried, reversed (180 °C), and redeveloped. For concentration, the strip (20 × 5 cm) containing 2,3,4,4-tetrabromobut-2-en-4-olide (R_F 0.53) was cut out and redeveloped lengthwise, to yield a visible, pale yellow area, extraction of which with methanol failed to give sufficient material for direct comparison with the authentic specimen.

Solid State Photochemical Conversion of Tetrabromofuran (**1**) *into 2,3,4,4-Tetrabromobut-2-en-4-olide* (**2**).—Tetrabromofuran (**1**) (0.5 g; m.p. 64 °C), in a 3-necked silica flask (250 ml) filled with dry oxygen, was flurried by rapid magnetic stirring, and irradiated with the u.v. element, extracted from a 100W 'artificial sun lamp', suitably shielded, in a slow stream of dry oxygen at atmospheric pressure at an ambient temperature of 23 °C rising gradually to 26 °C. The colourless crystals became yellow (*cf.* ref. 1), and soon collapsed to a viscous pale yellow fluid. Progress of the reaction (**1**)→(**2**) was monitored each 0.5 h by withdrawal of a small sample and t.l.c. on silica gel (Merck $60F_{264}$, plate size 3 × 10 cm, layer depth 0.2 mm), development with methanol–chloroform (2:1), drying in a current of air at 25 °C, and inspection of the plate under u.v. irradiation at 366 nm. A spot at R_F 0.53 [corresponding to formation of 2,3,4,4-tetrabromobut-2-en-4-olide (**2**)], appeared and increased in intensity with time, whilst the spot at R_F 0.83 [corresponding to tetrabromofuran (**1**)], decreased in intensity with time; a third spot (R_F *ca.* 0.75), possibly corresponding to dibromomaleic anhydride, gradually became visible. After irradiation for 2 h, during which no visible amount of bromine (*cf.* ref. 1) was formed, the reaction was stopped. The product was dissolved in carbon tetrachloride (*cf.* ref. 11), the solution shaken thrice with successive portions of cold water (25 ml) to convert any dibromomaleic anhydride into dibromomaleic acid (*cf.* ref. 1), dried with sodium sulphate, and evaporated. The residual yellow oil was dissolved in boiling hexane, and the solution concentrated and cooled to 0 °C to give sulphur-yellow leaflets (140 mg) of 2,3,4,4-tetrabromobut-2-en-4-olide (**2**), m.p. 59—60 °C, mixed m.p. with an authentic specimen, 59—60 °C; identical R_F value with that of the reference sample; δ_C 159.20 (s, C=O), 152.93 (s, C-3), 115.38 (s, C-2), and 73.79 p.p.m. [s, >C(4)Br_2].

Acknowledgements

The author thanks Dr. L. W. Deady for a bench in his research laboratory, Professor Sir Derek Barton, F.R.S., for helpful correspondence concerning the mechanism of the conversion of furoic acid into the semialdehyde of dibromomaleic acid [(**4**)→(**6**); Scheme 1], Professor A. L. J. Beckwith, F.A.A., for thermochemical data, Dr. R. T. C. Brownlee for recording the ^1H and ^{13}C n.m.r. spectra, Mr. Graeme Butt for recording the u.v. and i.r. spectra, Mr. Wen Yang Wu, of the Antibiotic Institute, Shanghai Pharmaceutical Co., Shanghai, China, temporarily a member of this Department, for exceedingly skilful assistance with t.l.c., Professor Lord Tedder, F.R.S.E., for photocopies of references 1 and 2, and Dr. M. Gill, Melbourne University, for gifts of methyl-lithium and of di-isopropylamine.

References

1 H. A. Torrey, *Am. Chem. J.*, 1897, **19**, 668.
2 H. B. Hill and R. W. Cornelison, *Am. Chem. J.*, 1894, **16**, 188 esp. 207.
3 J. Schmeltz and F. F. Beilstein, *Annalen Suppl.*, 1864, **3**, 276.
4 H. Limpricht, *Annalen*, 1873, **166**, 293.
5 O. R. Jackson and H. B. Hill, *Ber.*, 1878, **11**, 1671; *Am. Chem. J.*, 1881, **3**, 41; *Proc. Am. Acad.*, 1881, **16**, 168–203.
6 P. Tonnies, *Ber.*, 1878, **11**, 1086.
7 A. Pelter, R. S. Ward, D. C. James, and C. Kemakshi, *Tet. Lett.*, 1983, **24**, 3133.
8 C. H. F. Allen and F. W. Spangler, *Org. Synth.*, Coll. Vol. III, 1955, 621.
9 R. Anschutz, *Annalen*, 1887, **239**, 16.
10 C. K. Ingold and J. F. Thorpe, *J. Chem. Soc.*, 1919, **115**, 143.
11 E. Ott, *Annalen*, 1912, **392**, 245 esp. 267, 271; E. Ott and K. Packendorff, *Ber.*, 1931, **64**, 1327; cf. H. Kaufmann and H. Voss, *ibid.*, 1923, **56**, 2514.

12 L. Leder, *J. pr. Chem.*, 1931, [2], **130**, 255.
13 H. B. Hill, *Ber.*, 1880, **13**, 734.
14 O. Diels and M. Reinbeck, *Ber.*, 1910, **43**, 1271.
15 H. B. Hill, *Ber.*, 1886, **19**, 1130.
16 H. B. Hill and G. T. Hartshorn, *Ber.*, 1885, **18**, 448.
17 H. B. Hill, *Ber.*, 1883, **16**, 1130.
18 'Handbook of Chemistry and Physics', 63rd edn., 1982–83, E 402, C.R.C. Press Inc., Boca Raton, Florida, U.S.A.
19 H. H. Wasserman and J. L. Ives, *Tetrahedron*, 1981, **37**, 1825.
20 G. O. Schenck, *Annalen*, 1953, **584**, 156; S. H. Schroeter, R. Appel, R. Brammer, and G. O. Schenck, *ibid.*, 1966, **697**, 42; *cf.* M. L. Graziano, M. R. Iesce, and R. Scarpati, *J. Chem. Soc., Perkin Trans. 1*, 1982, 2007.
21 F. W. Machado-Araujo and J. Gore, *Tetrahedron. Lett.*, 1981, **22**, 969.
22 G. W. Wheland, 'The Theory of Resonance', Wiley, New York, 1944.
23 V. V. Voronenkov, *Russ. Chem. Rev.*, 1975, **44**, 333.
24 S. David, O. Eisenstein, W. J. Henre, L. Salem, and R. Hoffmann, *J. Am. Chem. Soc.*, 1973, **95**, 3806.
25 K. Hayday, *J. Org. Chem.*, 1976, **41**, 2222; D. G. Gorenstein, B. A. Luxon, J. B. Findlay, and R. Momii, *J. Am. Chem. Soc.*, 1977, **99**, 4170.
26 P. D. Bartlett and T. G. Traylor, *J. Am. Chem. Soc.*, 1963, **85**, 2407.
27 D. H. R. Barton, J. E. Page, and C. W. Shoppee, *J. Chem. Soc.*, 1956, 331.
28 W. Lossen and A. Treibich, *Annalen*, 1906, **348**, 324.
29 P. Ruggli, *Helv. Chim. Acta*, 1920, **3**, 569.
30 J. F. Grove, *Ann. appl. Biol.*, 1948, **35**, 38.
31 L. J. Bellamy, 'Infra-red Spectra of Complex Molecules', 2nd edn., Methuen, London, 1969, pp. 331 and 332.

Received 20*th February* 1984; *Paper* 4/297