# Remote Oxidation of Carboxylic Acids by Peroxodisulphuryl Difluoride in Fluorosulphuric Acid : a General Synthesis of Lactones

By **Christopher J. Myall, Derek Pletcher,** * and **Carmen Z. Smith,** The Department of Chemistry, The University of Southampton, Southampton SO9 5NH

Peroxodisulphuryl difluoride, $(FSO_3)_2$, generated by constant-current electrolysis of fluorosulphuric acid–potassium fluorosulphate (1.0M), reacts rapidly and smoothly with a series of carboxylic acids $(C_3–C_{10})$ in fluorosulphuric acid at 273 K. Oxidation occurs at a site remote from the carboxy-group and, after work-up, lactones can be isolated in high yields.

IN an earlier publication [1] the direct anodic oxidation of some medium chain-length carboxylic acids in anhydrous fluorosulphuric acid containing potassium fluorosulphate was described. It was shown that in this medium the carboxylic acids are protonated [equation

$$RCO_2H + H^+ \rightleftharpoons RC{\overset{\textstyle OH}{\underset{\textstyle OH}{\lessgtr}}}^+ \qquad (i)$$
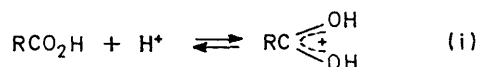
(i)]. Since the *i–E* curves for solutions of these acids at a smooth platinum electrode showed a well formed, diffusion-controlled oxidation wave prior to the solvent/electrolyte oxidation potential it was concluded that the initial step is removal of an electron from the protonated acid. The nature of the electrode process was essentially confirmed by the way in which the half-wave potentials for the carboxylic acids varied with their structure. The overall reaction involved the transfer of two electrons and cleavage of a C–H bond at a site remote from the carboxy-group, leading to the formation of lactones or cyclic αβ-unsaturated ketones, depending on whether the anolyte was quenched immediately after the electrolysis or left for 20—50 h prior to work-up. This direct anodic oxidation is, however, limited to carboxylic acids with six or more carbon atoms; those of lower molecular weight did not give oxidation waves before oxidation of the fluorosulphate ion.

Peroxodisulphuryl difluoride is a strong oxidising agent [2] in this strongly acidic solvent in which it is easily prepared [3,4] and is known to react with the small alkanes $(C_1–C_4)$ [4,5] which cannot be oxidised directly in an anodic reaction. In addition, a preliminary publication [4] has reported that peroxodisulphuryl difluoride reacts with propanoic acid to give acrylic acid. We have studied the reaction of peroxodisulphuryl difluoride with a series of carboxylic acids to see whether the lower molecular weight acids underwent remote oxidation and, in the case of the medium chain-length acids, to compare the direct and indirect oxidation routes. In a more general context, the reactions of peroxodisulphuryl difluoride are of interest since they are generally rapid and smooth and offer possibilities for the remote oxidation of other aliphatic series where the functional group is prone to undergo solvolysis slowly but significantly on the timescale of an electrolysis.

EXPERIMENTAL

The electrolyses were carried out with a Chemical Electronics Valve Potentiostat and a glass cell with two platinum gauze electrodes (6 cm²) separated by a No. 3 glass sinter.

N.m.r. spectra were recorded with a Perkin-Elmer R12 (60 MHz) or a Varian HA-100 (100 MHz) instrument, i.r. spectra with a Perkin-Elmer 157G spectrometer and mass spectra with a A.E.I. MS12 instrument. G.l.c. analyses were carried out with a Pye 104 chromatograph with a flame ionisation detector and a 3 m, 10% polyethylene glycol adipate +1% phosphoric acid on Celite column at a temperature in the range 410—440 K and a nitrogen carrier gas flow rate of 60 cm³ min⁻¹.

Fluorosulphuric acid (Fluorochem) was distilled at atmospheric pressure prior to use. The potassium salt was prepared by a standard procedure.[6] 3-Cyclohexylpropanoic acid and 4-cyclohexylbutanoic acid (Aldrich), 5-methylhexanoic acid (Pfaltz and Bauer), and the other carboxylic acids (B.D.H.) were used without purification.

Preparation of Peroxodisulphuryl Difluoride.—Solutions of peroxodisulphuryl difluoride in fluorosulphuric acid were prepared by constant-current electrolysis at a current density of 30 mA cm⁻² of solutions of potassium fluorosulphate (1M) in anhydrous fluorosulphuric acid. The electrolyses were terminated after the passage of 80 C per cm³ of anolyte and the anolyte was used directly for the chemical reactions.

The yield of dimer from these electrolyses was, however, determined by the following procedure. A cyclic voltammogram of a solution of the dimer in $HSO_3F–KSO_3F$ at a platinum electrode shows a reduction peak at E_p 0.2 V [*vs.* Pd(H_2) reference electrode] and the height of this peak was used to monitor the formation of $(FSO_3)_2$ during the electrolyses; plots of i_p *vs.* charge passed were linear. At the end of an electrolysis the anolyte was transferred to a vacuum line and the $(FSO_3)_2$ was distilled into a trap at 0.5 mmHg pressure. Following a further trap-to-trap distillation the dimer isolated was weighed; the fluorosulphuric acid was shown not to distil at the temperature employed. The pure dimer was then used to calibrate the analysis by cyclic voltammetry. The current yield based on both the cyclic voltammetry and the weight of isolated product was $85 \pm 5\%$ (3 experiments).

Chemical Reactions.—The anolyte (15 or 30 cm³) after electrolysis was added dropwise to a solution of the carboxylic acid (5—20 mmol) in fluorosulphuric acid (10 cm³). Both solutions had previously been cooled to 273 K. After 10 min the products were isolated by one of the following two routes. (1) The solution was quenched by adding slowly to crushed ice and the resulting solution was neutralised by adding solid sodium carbonate. This solution was then shaken several times with ether, made acid with

[1] D. Pletcher and C. Z. Smith, *J.C.S. Perkin I*, 1975, 948.
[2] R. L. Kirchmeier and J. M. Shreeve, *Inorg. Chem.*, 1973, **12**, 2886.
[3] F. B. Dudley, *J. Chem. Soc.*, 1963, 3407.
[4] J. P. Coleman and D. Pletcher, *Tetrahedron Letters*, 1974, 147.

[5] D. Pletcher and C. Z. Smith, *Chem. and Ind.*, 1976, 371.
[6] J. Bertram, J. P. Coleman, M. Fleischmann, and D. Pletcher, *J.C.S. Perkin II*, 1973, 374.

concentrated hydrochloric acid and extracted further with ether. Both ethereal extracts were separately dried and evaporated and the resulting oils were weighed and examined by spectroscopic methods. Finally the oils were separately dissolved in known volumes of ether and the products and recovered starting material were estimated by g.l.c. (2) The solution was poured onto methylene chloride (400 cm³) at 170 K. When the resulting solution had warmed to room temperature, it was partially neutralised by adding solid, anhydrous sodium carbonate. Water (300 cm³) was added and further sodium carbonate. The methylene chloride was evaporated off under reduced pressure and

mined by comparison of spectral data with literature data: products from pentanoic and hexanoic acids,[7] 3-cyclohexylpropanoic acid,[8] and 4-cyclohexylbutanoic acid.[9]

RESULTS AND DISCUSSION

All the acids investigated, including those of lower molecular weight (C_3–C_5), reacted rapidly and smoothly with peroxodisulphuryl difluoride despite the fact that the i–E curves for solutions of the lower molecular weight acids did not show an oxidation process prior to oxidation of fluorosulphate ion. The products and yields of these

TABLE 1

Products and yields from the reaction of carboxylic acids with electrolytically generated $(FSO_3)_2$ in anhydrous HSO_3F; yields are based (i) on current consumed in preparation of $(FSO_3)_2$ and (ii) on carboxylic acid consumed

Substrate (1)			Quantity (mmol)	Coulombs used to prepare $(FSO_3)_2$	Product (2)				Acid (1) recovered (mmol)	Yield (%)	
R^1	R^2	n			R^3	R^4	n	mmol		(i)ᶜ	(ii)
H	H	2ᵃ	16	2 420	H	H	2	0.82	5.5	7	8
Me	H	2ᵃ	14	2 400	Me	H	2	3.8	2.6	32	33
Et	H	2ᵃ	12	2 400	{Me	H	3	4.3	2.7	36	46
					{Et	H	2	0.76		6	8
Prⁿ	H	2ᵇ	7	1 230	Et	H	3	2.4	3.0	39	60
Buⁿ	H	2ᵇ	7.6	1 218	Et	Me	3	2.2	3.2	36	50
Prⁱ	H	2ᵇ	7	1 230	Me	Me	3	3.1	2.8	50	74
[CH₂]₅		2ᵇ	9	1 240	[CH₂]₅		2	3.3	4.6	54	75
[CH₂]₅		3ᵇ	8.3	1 250	[CH₂]₅		3	2.2	3.8	36	49

ᵃ Work-up procedure (2). ᵇ Work-up procedure (1). ᶜ Assuming two-electron oxidation.
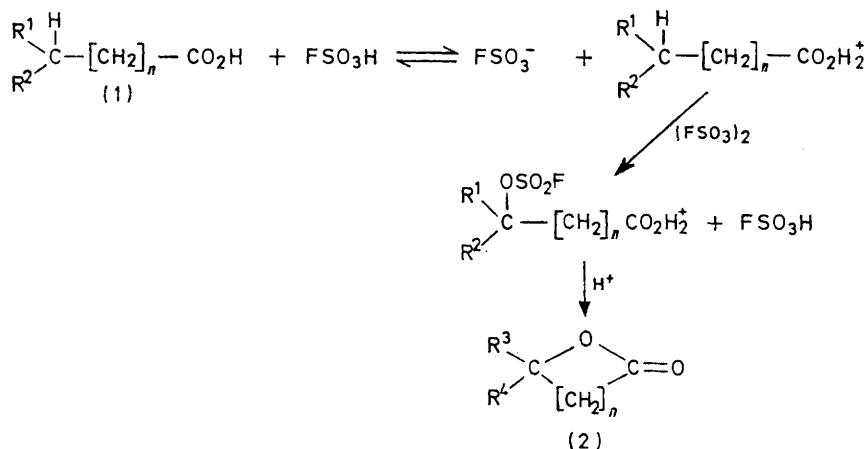
SCHEME

the remaining aqueous solution adjusted to pH 2 with hydrochloric acid and extracted three times with ether. The extract was dried and evaporated and the remaining oil was weighed and examined by n.m.r.; the starting material recovered was estimated by g.l.c. The oil was dissolved in ether and the carboxylic acid was removed by shaking with aqueous sodium carbonate. The ethereal solution was again dried and evaporated and the product estimated by g.l.c.

In the cases of butanoic, octanoic, and 5-methylhexanoic acids the products were identified by comparing the g.l.c. retention times with those of authentic samples. When authentic samples were not available structures were deter-

reactions, carried out by the procedure described in the Experimental section, are reported in Table 1.

The yields (conversion of carboxylic acid into lactone) are high for the acids C_5 and above; with most acids a single isomer is by far the major product. The efficiencies based on the consumption of electricity are less good; since the preparation of $(FSO_3)_2$ is 85% efficient this indicates that the yields with respect to $(FSO_3)_2$ are low. An experiment where the carboxylic acid was present in the anolyte during the electrolysis and the chemical reaction therefore occurred continuously during the generation of the peroxodisulphuryl difluoride, led to an almost identical yield of product.

[7] M. Oyama and M. Ohno, *Tetrahedron Letters*, 1966, 5201.
[8] T. K. Das Gupta, D. Felix, U. M. Kempe, and A. Eschenmaser, *Helv. Chim. Acta*, 1972, **55**, 2198.

[9] J. M. Surzur and P. Teissier, *Bull. Soc. chim. France*, 1970, 653.

During the experiments with propanoic acid and butanoic acid the solutions were examined by n.m.r. spectroscopy immediately after the chemical reactions. As reported previously,[4] the n.m.r. spectrum of the solution from the reaction of propanoic acid shows the presence of only the 3-fluorosulphate ester, and it may be concluded that the reaction takes place solely at the β-carbon atom. With butanoic acid the position is less clear-cut; the n.m.r. spectrum shows the presence of both 3- and 4-fluorosulphate esters in the ratio 3 : 4 [τ(external Me$_4$Si) 3-ester 4.62(t), 6.68(d), and 8.41(d); 4-ester 5.41(t), 7.08(t), and 7.75(m).] The amount of the 3-ester decreased more rapidly than that of the 4-ester, and no product was isolated from the 3-ester. The yields of products isolated from reactions with these acids were poor and not reproducible. In some experiments when the solution from the reaction of the dimer with propanoic acid was quenched with methylene chloride–methanol (10 : 1), methyl acrylate (25%) was isolated. In later attempts to reproduce these results the major product appeared to be propiolactone [τ(CH$_2$-Cl$_2$; external Me$_4$Si) 5.79(t) and 6.52(t)].
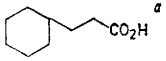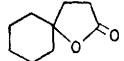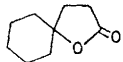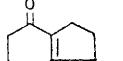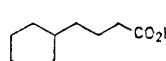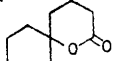
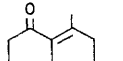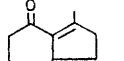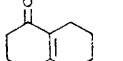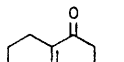In all other cases the products isolated were consistent with a mechanism where the initial step is the cleavage of a secondary C–H bond at a site remote from the carboxy-group. Hence it is apparent that the products are formed by a pathway of the type illustrated in the Scheme. The detailed mechanism is, however, less clear. First, it is currently a matter of speculation whether the initial step is electron transfer or hydrogen radical abstraction. We favour initial electron transfer because of the similarity of the products to those from the direct anodic oxidation and the apparent selectivity in the site of C–H cleavage away from the protonated carboxy-group. Certainly the major product from the oxidation of octanoic acid indicates a carbocation intermediate (note skeletal rearrangements). Secondly, the stage at which ring closure occurs is far from certain, although it is probably during the work-up since the n.m.r. spectra suggest that the fluorosulphate esters are stable in fluorosulphuric acid, and with the lower molecular weight acids (C$_3$–C$_6$) the yields are very dependent on the work-up procedure. For example, the yield of the δ-lactone from the oxidation of hexanoic acid was only 16% when the ice work-up was employed.

The products isolated from these reactions are similar to those formed by direct anodic oxidation of the carboxylic acids (see ref. 1 and Table 2); as in the case of the medium chain-length acyclic acids, the cyclohexyl-

propanoic and cyclohexylbutanoic acids show well formed, diffusion-controlled oxidation waves and electro-lyses may be carried out at potentials where no (FSO$_3$)$_2$ can be formed. The yields of lactones by the indirect route involving peroxodisulphuryl difluoride are consist-ently as good as or better than those obtained by the

TABLE 2

Products and current yields from the direct, controlled-potential, anodic oxidation of 3-cyclohexylpropanoic and 4-cyclohexylbutanoic acids in HSO$_3$F–KSO$_3$F (1.0M); platinum anode

^{a} Work-up procedure (1). ^{b} Two electron-oxidation process.

direct anodic oxidation. Moreover, the electrolysis can tolerate much less controlled conditions. On the other hand the current yields via the indirect route are poorer.

On standing after reaction the fluorosulphuric acid solutions from the longer chain carboxylic acids again afforded cyclic unsaturated ketones.[1] Typical was octanoic acid; the reaction gave 2-isopropylidenecyclo-pentanone (22%) and 2,3-dimethylcyclohex-2-enone (28%).