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The reactivity, as electrogenerated bases, of chiral and achiral phenazine radical-anions, including application in asymmetric deprotonation†

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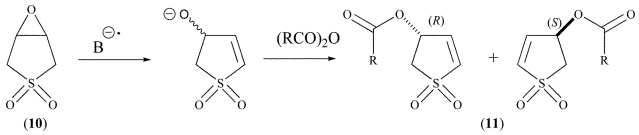
Radical-anions, electrochemically generated in aprotic solvent from C_2 symmetric homochiral phenazine derivatives, act as chiral electrogenerated bases (EGBs) in the desymmetrisation by selective deprotonation of a prochiral epoxide (3,4-epoxy-2,3,4,5-tetrahydrothiophene-1,1-dioxide); the anion produced is trapped by mesitoic anhydride. The phenazines may be recovered in high yield by air oxidation. Enantiomeric excesses are modest (8–34%) but this is to our knowledge the first demonstration of such stereoselective electrochemically-initiated deprotonation. The reactivity of phenazine radical-anions as EGBs has also been explored by measurements of the rates of proton transfer; the prochiral epoxide was found to have a kinetic acidity similar to that of the methyltriphenylphosphonium cation.

Introduction

Electrochemical reduction of neutral substrates ('probases') generates radical-anions and dianions that may be used as electrogenerated bases (EGBs) in synthetic transformations.[1] Previous studies have shown that the radical-anion of phenazine is able to deprotonate phosphonium ions such as $Ph_3PCH_3^+$ at conveniently measurable rates.[2] There have not hitherto been any descriptions of the use of electrogenerated bases in asymmetric deprotonation from prochiral acids, although *N*-acylation of chiral oxazolidin-2-ones has been achieved[3] through formation of the required nitrogen anion using achiral EGBs. We have reported[4,5] the synthesis of a good number of phenazine derivatives (**1**–**9**) including several C_2 symmetric homochiral phenazine derivatives and their resolution.

Most of these may be cathodically converted into radical-anions, and those pertinent to this study are displayed as (**4**, **8** and **9**). A preliminary account of their enantioselectivity in the rearrangement of a prochiral epoxide (**10**) (Scheme 1) has been given.[4] Conveniently, the spent electrogenerated base



Scheme 1 Desymmetrisation of epoxide **10**.

(the corresponding 5,10-dihydrophenazine) may be efficiently regenerated through simple air oxidation.

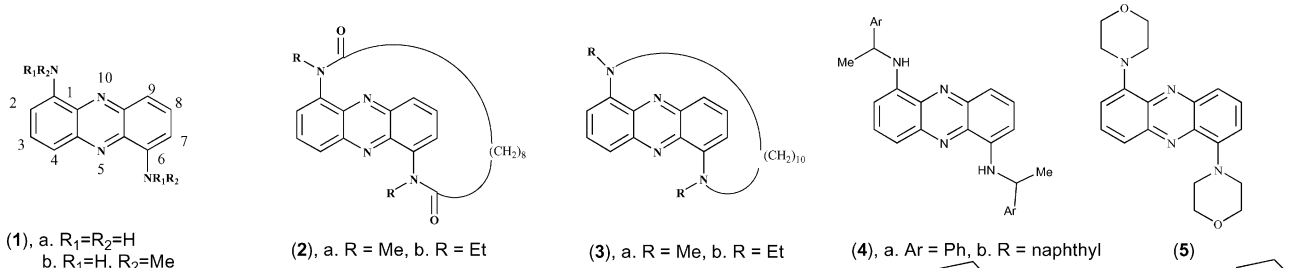
Herein, we fully report on the use of cathodically generated chiral phenazine radical-anions for asymmetric deprotonation and describe what we believe to be the first demonstration of enantioselective deprotonation using an electrogenerated base. Quantitative aspects of the kinetic basicity of chiral and achiral phenazine radical-anions have been determined with a view to identifying features that relate to the observed stereoselectivity.

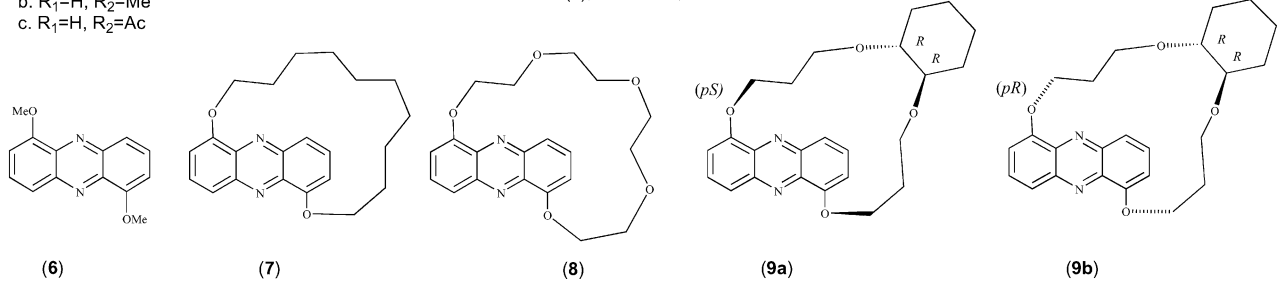
Results and discussion

Enantioselective proton transfer

Chiral bases are conventionally used to select between enantiotopic acidic hydrogens in compounds such as 4-*t*-butylcyclohexanone or *cis*-2,6-dimethylcyclohexanone; these

† Electro-organic reactions Part 59. Part 58 is ref. 11.





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and similar experiments have been well reviewed.[6,7] The cyclohexanones are insufficiently acidic to allow deprotonation by phenazine radical-anions; no reaction could be detected on the slowest cyclic voltammetric time scale. Therefore desymmetrisation of the epoxysulfone **10** (Scheme 1), that cyclic voltammetry shows to react with phenazine radical-anions (see below), was chosen as the test reaction and mesitoic anhydride was chosen as the trapping electrophile.

Having ascertained by cyclic voltammetry that chiral and achiral phenazine radical-anions reacted with **10**, preparative experiments were performed by controlled potential co-electrolysis of the phenazine (at close to its E^0 value) in the presence of **10** and an electrophilic trapping agent. We found that less-hindered candidates (acetic anhydride, benzoic anhydride) reacted with the phenazine radical anions to acylate at the nitrogen. Furthermore, trapping with mesitoic anhydride provided a chromophore in the product **11** for analysis of products by chiral HPLC. The structure of *rac*-**11** was confirmed by X-ray crystallography (Fig. 1).‡ The sulfone **10** is readily available through epoxidation of butadiene sulfone.[8,9]

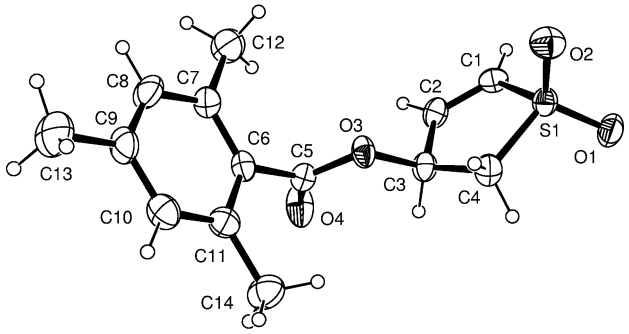


Fig. 1 X-Ray crystallographic structure of **11**.

The chiral probases used were (*R*,*R*)- and (*S*,*S*)-**4a**, (*R*,*R*)-**4b**, (−)-(*pS*)-**8**, (+)-(*pR*)-**8**, (*pS*,*R*,*R*)-**9a** and (*pR*,*R*,*R*)-**9b** with the product being isolated by short column chromatography and analysed by chiral HPLC. The probase was recovered by air oxidation and chromatography.

Results are summarised in Table 1, which includes an example of ring-opening using an achiral EGB. The unambiguous synthesis of the (*R*)-enantiomer of **11**, was carried out according to Scheme 2. The configuration was established by X-ray crystallography on the intermediate α-methoxyphenylacetate **13** (Fig. 2).

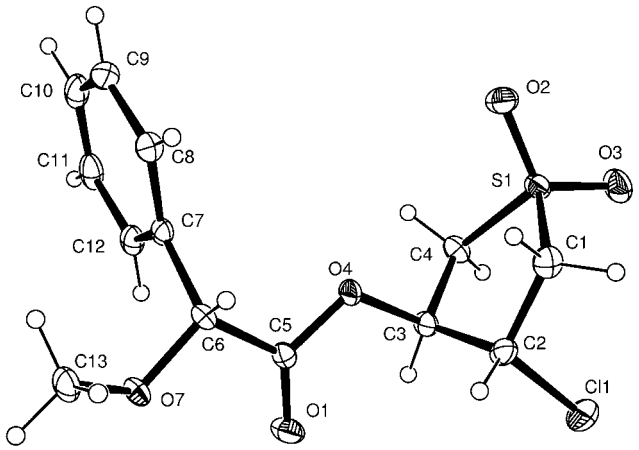


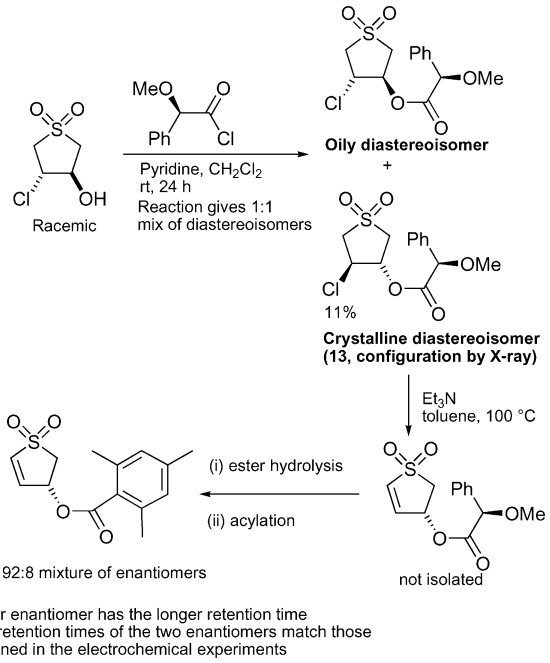
Fig. 2 X-Ray crystallographic structure of **13**.

‡ CCDC reference numbers CCDC 266539 and 269382. See http://dx.doi.org/10.1039/b506309d for crystallographic data in CIF or other electronic format.

Table 1 Conversion of epoxide **10** into ester **11** using chiral electrogenerated bases[a]

Probase	Additive[b]	Yield of **11**	ee[c] of **11**	Recovery of probase
6	—	53	—	100
(*R*,*R*)-**4a**	—	50[d]	+8	72
(*S*,*S*)-**4a**	—	50[d]	−8	—
(*R*,*R*)-**4b**	—	63	+18	74
(+)-(*pR*)-**8**	—	33	<10	71
(+)-(*pR*)-**8**	$LiClO_4$	53	+20	78
(−)-(*pS*)-**8**	—	38	<10	57
9a	—	43	+34	100
9a	$LiClO_4$	77	+28	100
9a	—	39	+32	100
9a	—	48[d]	+28	67
9a	$Yb(OTf)_3$	0	—	—
9b	—	63	+16	100
9b	$LiClO_4$	72	+24	80
9b	$Mg(OTf)_2$	19	<10	100

[a] Experiments were conducted in DMSO with Bu_4NPF_6 as supporting electrolyte unless indicated otherwise. [b] 3 equiv relative to probase. [c] Determined by chiral HPLC on Daicel Chiralpak OT-(+) eluted with 9 : 1 hexane : propan-2-ol; a positive ee value indicates an excess of the (*R*)-enantiomer, which we have synthesised independently (Scheme 2) and found to have a longer retention time than the (*S*)-form. [d] DMF was used as solvent.



Scheme 2 Unambiguous synthesis of *R*-**11**.

The first experiments with **4a** gave low stereoselectivity but the enantiomers of the probase reacted to give the product **11** in moderate yield and with the enantiomeric excess in equal amount and, according to chiral HPLC, in the opposite direction. The diastereoisomers of **9** give higher and significant ee values; changes in reaction conditions so far bring no significant improvement in results.

For the phenazines, an important feature is the easy regeneration of the starting phenazine by air oxidation of the 5,10-dihydrophenazine product (PBH_2 formed in step 4, Scheme 3).

1. $PB + e = PB^{\bullet -}$
2. $PB^{\bullet -} + HA = PBH^{\bullet} + A^-$
3. $PBH^{\bullet} + PB^{\bullet -} = PBH^- + PB$
4. $PBH^- + HA = PBH_2 + A^-$

reoxidises to PB

Scheme 3 DISP mechanism.

Table 2 Reduction potentials[a] of phenazine derivatives

Compound	Phenazine	1a	1b	1c	2a	3b	4a	5	6	7	8	9
$-E^0_1$	1.10	1.34	1.31	0.97	0.89	0.97	0.91	1.21	1.25			
	1.13[b]								1.16[b]	1.14[b]	1.36[b]	1.10[b]
$-E^0_2$	1.77	1.83	1.72	1.33	2.09	—	—	1.94	1.76			
	1.98[b]								2.04[b]	2.08[b]	2.22[b]	2.05[b]

[a] Hg/Pt, DMF–Bu_4NPF_6 (0.1 M), scan rates 1–100 V s^{-1}, V *vs.* SCE. [b] DMSO–Bu_4NPF_6 (0.1 M).

This means that investment in the synthesis of relatively complex phenazine derivatives is not wasted and they can be recovered from product mixtures. Most of the examples given in Table 1 indicate efficient recovery of the phenazine probase.

Phenazine **8** has been resolved on a small scale but it is not particularly effective as a probase. Its efficiency is improved in the presence of lithium cation, probably through chelation to the crown ether function. However, it seems that planar chirality on its own does not produce enantioselective behaviour and the proximity of the bulky *trans*-1,2-substituted cyclohexane unit, as in **9a** and **9b** and evident from X-ray crystallography (see previous preparative paper[5]), is needed to reinforce the effect of planar chirality.

Reactivity and mechanism

With a view to understanding better factors that may control the enantioselectivity described above the electrochemical behaviour of the phenazines was studied. In particular, the mechanism of proton transfer was determined and for several cases the rates of proton transfer in the slow step measured.

Cyclic voltammetry

Cyclic voltammetry in aprotic solvents (DMF or DMSO) shows the phenazine derivatives to give two reduction peaks each for 1e transfer, the first being chemically reversible at modest scan rates (< 1 V s^{-1}) and the second being reversible at relatively high scan rates (up to 100 V s^{-1}); E^0 values are given in Table 2.

Reaction between an added carbon acid and the radical-anion formed at the first reduction potential results in loss of reversibility of the first peak and a consequent doubling of peak height. This is characteristic of the well-established mechanism set out in Scheme 3, in which the second electron transfer (step 3) involves a second equivalent of the radical-anion (DISP).[10] Confirmation of this mechanism comes from the kinetic results.

Kinetics of proton transfer

Cyclic voltammetry (CV) and digital simulation (BAS DigiSim 3.03), assuming the mechanism in Scheme 3 and several experimentally determined parameters (diffusion coefficients, E^0 values), allows the measurement of rate constants (k_2) for the rate-limiting proton transfer (step 2). This provides an estimation of relative kinetic acidities of the carbon acids and of the kinetic basicities of the phenazine radical-anions. The same approach has been successful in a study of the kinetics of cleavage of oxalate radical-anions.[11]

For CV runs giving i_{pc}/i_{pa} between 0.2–0.4, allowing k_2 to float gave excellent fits between experimental and simulated CVs (see Fig. 3) except for the very slowest reactions. For each rate coefficient determination, the values were averaged from experiments conducted over a range of probase and acid concentrations and at several scan rates and excellent internal consistency was found. The successful application of digital simulation over such a variety of conditions is powerful support for the mechanism assumed and for the validity of the rate constants. Because digital simulation can mislead, especially by assumption of a false mechanism, justification of the approach is required. The DISP mechanism[10] (Scheme 3) is universally accepted for the cathodic hydrogenation of aromatic hydrocarbons, the first proton transfer is undoubtedly the slow step, and the results are consistent over a considerable range of scan rates and concentrations. An alternative mechanism, the ECE route, can be ruled out because on the voltammetric time scale used (see Fig. 3) some radical-anion survives, *i.e.*, the chemical step is relatively slow. The ECE route demands very rapid chemical reaction (the C step) so that the product of the chemical step is close to the cathode for subsequent direct reduction. This is only the case for very fast reactions, *e.g.*, the cathodic cleavage of alkyl or benzyl halides.

Further confirmation of the acceptability of the application of DigiSim comes from a comparison of the proton transfer rate coefficients obtained for reaction in DMSO between phenazine radical-anion and benzyltriphenylphosphonium ion obtained in

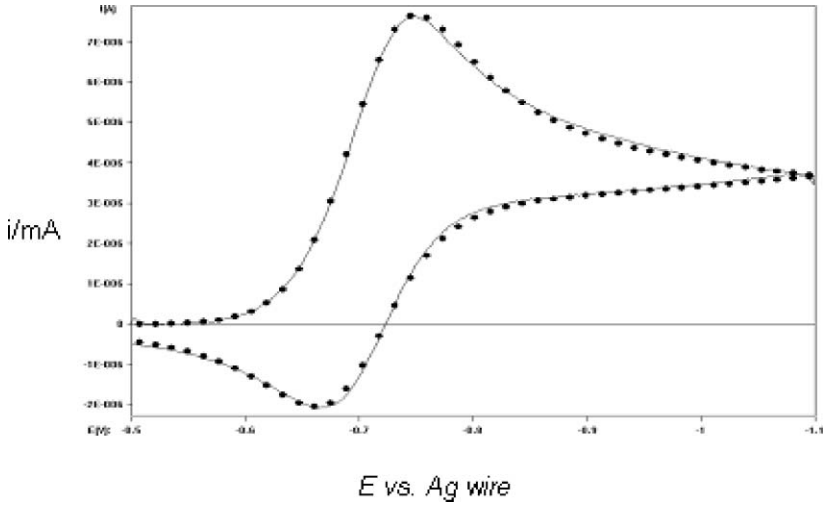


Fig. 3 Experimental (solid line) and simulated (solid circles) cyclic voltammograms for reaction between phenazine radical-anion and $Ph_3PCH_3^+$; DMF–Bu_4NPF_6 (0.1 M), EGB 1 mM, carbon acid 10 mM, 10 V s^{-1}.

our laboratory and in an earlier study using derivative cyclic voltammetry. Our experiments gave a value (per acidic H) of $(6.94 \pm 0.07) \times 10^2$ M^{-1} s^{-1} whereas the earlier study[2] gave 8×10^2. These results, from different laboratories using different methods, agree with a concordance of 14% and are well within acceptable limits. We therefore have high confidence in the kinetic results presented herein.

We have chosen to use true carbon acids, *i.e.*, those involving unambiguous proton transfer from carbon, where complications from tautomerism are avoided. For instance, it has been established that proton transfer from carbonyl-activated CH functions, using EGBs, often involves prior enolisation[12,13] with subsequent proton transfer from oxygen. Phosphonium salts and the epoxysulfone (**10**) are in this sense true carbon acids.

A selection of the rate constants is given in Table 3. Because the carbon acids used have differing numbers of acidic hydrogen atoms the rate constants are adjusted accordingly and expressed as rate per hydrogen atom. For the four potentially acidic hydrogens of the epoxysulfone (**10**) only two are in the favourable stereoelectronic arrangement with the epoxy group and hence the overall rate constant is divided by 2.

From the kinetic data we conclude: (i) that proton transfer is faster in DMF than in DMSO; (ii) that the kinetic acidity of the benzyltriphenylphosphonium ion is much greater than that of the methyltriphenylphosphonium ion, which is comparable to that of the epoxysulfone **10**; (iii) that comparison of the data involving the methyltriphenylphosphonium ion, which is presumably the least affected by steric hindrance, indicates that 1,6-diamino substitution is slightly rate-enhancing (**1b** *vs.* phenazine in DMSO) but that the radical anions of the macrocycle **3b** and probase **4a** are significantly less reactive. In the 1,6-dioxy series the radical-anion of **6** is more reactive than that of phenazine, suggesting that the electronic effect of dioxy substitution is rate enhancing. However, the relative reactivity in DMSO of the radical-anions of the macrocycles (**7**–**9**) is in the order **8** > phenazine ≈ **7** > **9**. We propose that this reflects relative steric hindrance to proton transfer.

The electrochemical results have an important bearing on the preparative results. The slow step of the overall process is undoubtedly proton transfer of prochiral protons to the chiral radical-anions. Furthermore the low reactivity of the radical-anion of **9** is significant as this was the most effective chiral base in the enantioselective proton transfer experiments (Table 1); this an example of the common situation whereby slow reactions (high free energies of activation) discriminate well between diastereoselective transition states.

Experimental

'Petrol' or 'petroleum spirit' refers to the fraction of bp 40–60 °C. DMF and DMSO were Fluka puriss. grade ($H_2O \leq$ 0.005%), supplied over molecular sieves. Bu_4NPF_6 was Fluka electrochemical grade. Cyclic voltammetry (cv) experiments were run using a Princeton Applied Research EG & G VersaStat II 263A potentiostat. The potentiostat was controlled and the voltammograms were saved using Model 270/250 Research Electrochemistry Software v4.00 or Condecom 2000CV v.2.00. A Hg-coated Pt electrode (diameter 1 mm) was used as the working electrode, platinum wire as the counter electrode and the reference electrode was a simple Ag wire in a glass tube. Because the potential of the Ag wire reference electrode can vary over a relatively short timescale, the E^0 value for anthracene was measured at the beginning and at the end of a series of measurements, against the Ag wire electrode, so that reduction potentials could be consistently referred to the SCE electrode (E^0 for anthracene = −1.92 V *vs.* SCE in DMF[14]). The cv measurements were obtained in an undivided cell using a 10 ml solution of 0.1 M Bu_4NPF_6 in DMSO. The concentration of the probase was 1 mM. Preparative electrolyses were performed using a Potentiostat Type DT 2101 (Hi-Tek Intruments) with an electronic integrator built in our department. Flash chromatography was performed on BDH silica gel (33–70 μm). All new compounds were homogeneous as assessed by TLC and high field NMR. Melting points were determined using a Reichert hot stage microscope. Specific rotations were determined on an Optical Activity Ltd AA-1000 polarimeter with a path length of 0.5 dm. IR spectra were recorded using a Shimadzu FTIR 8300; samples were prepared as films by evaporation of CH_2Cl_2 solutions on NaCl plates. NMR spectra were recorded on Jeol EX270 or Bruker AMX400 spectrometers. FAB mass spectra were recorded on a ZAB-SE4F machine at the School of Pharmacy, University of London; other mass spectra were obtained by the EPSRC National Service in Swansea using a Finnigan MAT 900. All HPLC experiments were performed using a Hewlett-Packard 1100 series liquid chromatography system equipped with Daicel Chiralpak OT(+) chiral columns (0.46 cm × 5 cm guard column and 0.46 cm × 25 cm main column) and a UV absorbance detector.

rac-3-(2,4,6-Trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (*rac*-11): example procedure using an electrochemically generated base

The electrochemical cell was equipped with a mercury pool cathode, a carbon rod as the anode and a silver wire reference electrode; the electrode compartments were separated by sintered glass partitions. 1,6-Dimethoxyphenazine (9 mg, 0.037 mmol), 3,4-epoxy-2,3,4,5-tetrahydrothiophene-1,1-dioxide[8,9] **10** (10 mg, 0.0745 mmol) and mesitoic anhydride (35 mg, 0.112 mmol) were dissolved in a 0.1 M solution of tetrabutylammonium hexafluorophosphate in DMSO (7 ml) and placed in the cathode

Table 3 Rate constants for proton transfer[a]

Carbon acid		$PhCH_2PPh_3^+$	$CH_3PPh_3^+$	Epoxysulfone (**10**)
Probase	Solvent	k_{HA} per H/M^{-1} s^{-1}	k_{HA} per H	k_{HA} per H
Phenazine	DMF	4800 ± 100	840 ± 60	770 ± 10
	DMSO	694 ± 7	2.8	—
1b	DMF	—	—	1370 ± 46
	DMSO	141 ± 1	5.6 ± 0.14	—
3b	DMF	—	560 ± 10	—
5	DMF	2500 ± 150	240 ± 3	—
4a	DMF	250 ± 15	28 ± 1	33
6	DMSO	979 ± 15	3.9 ± 0.3	2.6 ± 0.7
7	DMSO	—	2.1 ± 0.5	—
8	DMSO	1830 ± 49	16.4 ± 0.7	—
(*pS*,*R*,*R*)-**9a**	DMSO	—	0.35	—
(*pR*,*R*,*R*)-**9b**	DMSO	—	0.40	—

[a] By digital simulation of cyclic voltammetry using BAS DigiSim v 3.1.

compartment under nitrogen. The anode compartment was then filled with a 0.1 M solution of tetrabutylammonium hexafluorophosphate in DMSO (9 ml). A potential of −1.5 V was applied until the current fell to its background value and 2.2 F passed through the solution. The solutions in the cathode and the anode compartments were diluted with water and extracted twice with ether. The ether extracts were dried ($MgSO_4$) and concentrated under vacuum. The residue was subjected to flash chromatography (CH_2Cl_2) to yield *rac*-3-(2,4,6-trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (*rac*-**11**) (11 mg, 53%) as a white solid and 1,6-dimethoxyphenazine (9 mg, 100% recovery). A crystal of *rac*-**11** suitable for single crystal X-ray diffraction was obtained by slow evaporation of a propan-2-ol solution.

rac-3-(2,4,6-Trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (*rac*-**11**) had mp 111–113 °C, δ_H (270 MHz, $CDCl_3$) 6.87–6.83 (4H, m, Ar + CH=CH), 6.17–6.12 (1H, m, OCH), 3.83 (1H, dd, *J* 14.1, 7.7 Hz, CH_2), 3.31 (1H, dd, *J* 14.1, 3.3 Hz, CH_2), 2.30 (9H, s, CH_3); δ_C (68 MHz, $CDCl_3$) 169.7, 141.0, 136.4, 136.1 135.9, 129.0, 128.7, 69.6, 54.3, 21.4, 20.0; ν_{max}/cm^{-1} (film) 3090, 3080, 2922, 1728, 1311, 1072; *m*/*z* (FAB) 303.0650 (M+Na$^+$, $C_{14}H_{16}SNa$ requires 303.0677); HPLC, t_R/min [Daicel Chiralpak OT (+), hexane-propan-2-ol (9:1), 0.5 ml min^{-1}, 5 °C, 261 nm detector] 26.1 (*S*)-enantiomer (50%), 29.1 (*R*)-enantiomer (50%).

Non-racemic 3-(2,4,6-trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (11) using an electrochemically generated chiral base

This was performed similarly to the preceding experiment, using (*R*,*R*,*pS*)-(+)-7(1,2)-cyclohexana-1(1,6)phenazina-2,6,8,12-tetraoxacyclododecaphane (**9a**) (15 mg, 0.029 mmol), 3,4-epoxy-2,3,4,5-tetrahydrothiophene-1,1-dioxide (**10**) (10 mg, 0.0745 mmol), mesitoic anhydride (35 mg, 0.112 mmol) and lithium perchlorate (12 mg, 0.112 mmol) in a 0.1 M solution of tetrabutylammonium hexafluorophosphate in DMSO (14 ml). A potential of −1.5 V was applied until the current fell to its background value and 2 F passed through the solution. The solutions in the cathode and the anode compartments were diluted with water and extracted twice with ether. The ether extracts were dried ($MgSO_4$) and concentrated under vacuum. The residue was subjected to flash chromatography (CH_2Cl_2, then $CHCl_3$) to yield 3-(2,4,6-trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide **11** (16 mg, 77%) and then (*R*,*R*,*pS*)-(+)-7(1,2)-cyclohexana-1(1,6)phenazina-2,6,8,12-tetraoxacyclododecaphane (**9a**) (15 mg, 100% recovery). HPLC on **11** showed 28% ee in favour of the (*R*)-enantiomer.

(α*R*,3*S*,4*R*)-3-(α-Methoxyphenylacetoxy)-4-chlorotetrahydrothiophene-1,1-dioxide (13)

rac-3-Hydroxy-4-chlorotetrahydrothiophene-1,1-dioxide (**12**) (660 mg, 3.86 mmol) was dissolved in pyridine (30 ml) and treated with (*R*)-α-methoxyphenylacetyl chloride (1.5 g, 8.13 mmol) in CH_2Cl_2, which was added dropwise at room temperature over 10 min. The mixture was stirred at room temperature for 24 h, then diluted with Et_2O, and washed with 2 M hydrochloric acid, followed by water. The organic phase was dried ($MgSO_4$) and concentrated to leave a yellow solid residue which was recrystallised six times from methanol to give (α*R*,3*S*,4*R*)-3-(α-methoxyphenylacetoxy)-4-chlorotetrahydrothiophene-1,1-dioxide (**13**) (138 mg, 11%) as white crystals, mp 120–122 °C, $[\alpha]_D^{28}$ +43 (*c* 1, CH_2Cl_2). δ_H (270 MHz, $CDCl_3$) 7.5–7.3 (m, 5H, Ar), 5.53–5.49 (m, 1H, CHOCO), 4.83 (s, 1H, C*H*OMe), 4.61–4.57 (m, 1H, CHCl), 3.74–3.58 (m, 2H, CH_2SO_2), 3.42 (s, 3H, OMe), 3.42–3.39 (m, 1H, CH_2SO_2), 3.1–2.9 (m, 1H, CH_2SO_2); δ_C (68 MHz, $CDCl_3$, number of attached protons confirmed by DEPT) 169.3 (C=O), 135.0 (Ph, quaternary C), 129.4 (CH), 129.0 (CH), 127.1 (CH), 82.2 (CH), 74.8 (CH), 57.6 (CH_3), 57.5 (CH), 54.3 (CH_2), 53.9 (CH_3); ν_{max}/cm^{-1} (film) 3422, 1760, 1749, 1313, 1184, 1137, 1100; *m*/*z* (ESI) 336.0664 (M+NH_4^+, $C_{13}H_{19}ClNO_5S$ requires 336.0667).

Non-racemic 3-(2,4,6-trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (11) from (α*R*,3*S*,4*R*)-3-(α-methoxyphenylacetoxy)-4-chlorotetrahydrothiophene-1,1-dioxide (13)

(α*R*,3*S*,4*R*)-3-(α-Methoxyphenylacetoxy)-4-chlorotetrahydrothiophene-1,1-dioxide (**13**) (138 mg, 0.439 mmol) was heated in toluene (9.2 ml) at 100 °C in the presence of triethylamine (0.168 ml, 1.21 mmol) for 1 h. The solvent was then evaporated and the residue was dissolved in CH_2Cl_2; the solution was washed with 2 M HCl and then with water. The organic phase was dried ($MgSO_4$) and the solvent evaporated to leave a residue (45 mg), which was then stirred for 1 h at room temperature with a mixture of NaOH (8 mg, 0.19 mmol), water (1 ml), EtOH (2 ml) and MeOH (1 ml). The pH of the mixture was then adjusted to 7 using dilute hydrochloric acid and the solvent was evaporated. The residue was dissolved in CH_2Cl_2 (2 ml) and treated with pyridine (0.015 ml, 0.189 mmol) and mesitoyl chloride (0.035 ml, 0.189 mmol), then stirred at room temperature for 24 h. The solution was diluted with CH_2Cl_2 and washed with 2 M hydrochloric acid followed by water. The organic phase was dried ($MgSO_4$) and subjected to flash chromatography (CH_2Cl_2) to give 3-(2,4,6-trimethylbenzoyl)oxy-2,3-dihydrothiophene-1,1-dioxide (**11**) (5 mg), $[\alpha]_D^{28}$ −17 (*c* 0.2, CH_2Cl_2), identical by ^{1}H NMR (270 MHz, $CDCl_3$) with material prepared by the action of electrochemically generated bases on 3,4-epoxy-2,3,4,5-tetrahydrothiophene-1,1-dioxide in the presence of mesitoic anhydride; t_R/min [Daicel Chiralpak OT (+), hexane–propan-2-ol (9 : 1), 0.5 ml min^{-1}, 5 °C, 261 nm detector] 26.1 (*S*)-enantiomer (8%), 29.1 (*R*)-enantiomer (92%).

Crystal data for rac-11‡. $C_{14}H_{16}O_4S$, M = 280.33, monoclinic, a = 21.102(8), b = 10.963(6), c = 5.929(2) Å, α = 90.00, β = 92.57(5), γ = 90.00°, V = 1370.2(10) Å^3, space group $P2_1/c$, Z = 4, D_c = 1.359 Mg m^{-3}, μ = 0.243 mm^{-1}, reflections measured 2730, reflections unique 2394 with R_{int} = 0.0192, T = 160 (2) K, final R indices [$I > 2\sigma(I)$] $R1$ = 0.0521, $wR2$ = 0.1250 and for all data $R1$ = 0.1293, $wR2$ = 0.1498. CCDC reference number 269382.

Crystal data for 13‡. $C_{13}H_{15}ClO_5S$, M = 318.76, orthorhombic, a = 6.8530(2), b = 9.6726(3), c = 21.2802(7) Å, α = 90.00, β = 90.00, γ = 90.00°, V = 1410.59(8) Å^3, space group $P2_12_12_1$, Z = 4, D_c = 1.501 Mg m^{-3}, μ = 0.434 mm^{-1}, reflections measured 10821, reflections unique 3199 with R_{int} = 0.0472, T = 120 (2) K, final R indices [$I > 2\sigma(I)$] $R1$ = 0.0276, $wR2$ = 0.0666 and for all data $R1$ = 0.0309, $wR2$ = 0.0683, Flack parameter −0.05(5). CCDC reference number 266539.

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