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Ligand tuning in the chromium–salen-mediated asymmetric epoxidation of alkenes

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Abstract—A series of Cr(salen) complexes have been synthesised from 5-substituted-3-bromosalicylaldehydes and *trans*-1,2-cyclohexanediamine. These have been used to probe the Cr(salen)-mediated asymmetric epoxidation of alkenes. No simple correlation was found between the electronic character of the salen-substituents and the enantioselectivity—multiple oxidation pathways are proposed as a possible explanation. Enantioselectivities of up to 90% have been achieved using a novel, synthetically accessible Cr(salen) complex.

1. Introduction

The synthetic value of enantiopure epoxides is well established and a very substantial amount of research on synthetic methods for their production has been carried out.[1–3] Synthetic methods based on metal(salen) complexes have been developed for both asymmetric epoxidation (AE) of alkenes[2–4] and the asymmetric ring-opening of epoxides.[5–13] We have specifically investigated Cr(salen)-mediated AE,[14–23] as have others.[24–28] We found it intriguing that the Cr-system shows high enantioselectivity for the conversion of *trans*-1,2-disubstituted alkenes (*trans*-alkenes henceforth) in contrast to almost all known Mn(salen) systems.[29,30] Also in contrast to the Mn(salen) system, with Cr(salen) it is possible to isolate the metal–oxo complex proposed as the active oxidant in both systems.[31–33] This has allowed us to study the reaction of the alkene with the (salen)Cr^{V}=O species in isolation from other aspects of the catalytic cycle.

We have concentrated much of our efforts on variation of the substituents on the aromatic rings of the salen ligand. Our first investigations showed that it is necessary to have a substituent on the 3,3′-positions of the salen ligand in order to obtain high enantioselectivity[17,20,23] although this does not have to be bulky, again in contrast to the Mn(salen) systems. More recently, we detailed results from a comprehensive survey of all positions of the aromatic ring of the salen ligand.[22] Although this yielded new information with respect to the trajectories of approach of the substrate to the alkene, it did not directly suggest further improvements that might be made to the catalyst structure. We noted that once the 3,3′-position was substituted, addition of another group at any other position was detrimental to the ee obtained. However, all of the complexes surveyed were derived from salicylaldehydes with only one type of substituent, for example, dimethyl, tetrachloro etc. In light of the studies by Jacobsen et al.[34,35] we felt it would be prudent to examine some cases where the substituents at the 3,3′-positions were different from those at the other positions on the ring. Specifically, the decrease in ee observed on going from, for example, 3,3′-dichloro-substituted complex to 3,3′,5,5′-tetrachlorosubstituted complex, could be due to an increase in the reactivity of the complex and an earlier transition state and therefore less selectivity. Consistent with this, we note that Rajagopal and co-workers have reported that reduction potentials and reactivity of O=Cr(salen) complexes towards sulfoxides correlate with Hammett constants of the salen-ring substituents.[36] We report here our efforts to synthesise a series of 3,3′-dibromosubstituted complexes **1**–**3a**–**f**, and the results from their subsequent use in the asymmetric epoxidation of *trans*-β-methylstyrene.

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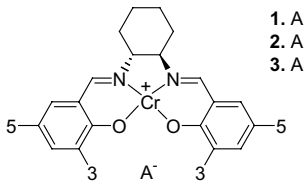


2. Results

Scheme 1 shows the synthesis of the requisite salicylaldehydes **4** and **5**, which were not commercially available. **4b**,**d**–**f** were synthesised using the method of Levin et al.[37] Although the unoptimised isolated yield of 21% for **4b** is low, it compares favourably with yields reported in the literature using traditional methods such as the Duff reaction (14%)[38] or the Reimer–Tiemann reaction (17%).[39] Indeed it is actually better than expected because just 5% was reported by Levin and co-workers for 3-fluorosalicylaldehyde. These poor yields obtained can be partially attributed to the ability of the fluoro group to chelate magnesium along with phenoxide thereby preventing formation of the correctly orientated complex between the magnesium phenolate and the paraformaldehyde. This may be less of a problem with the softer halogens. **4d**–**f** were isolated in good yield as expected. The bromination of salicylaldehydes, using a slight excess of elemental bromine in acetic acid, proceeded in good yield using literature procedures.[40–42]

The salicylaldehydes were converted to salen ligands by standard methods in good yield and fully characterised by normal methods (see experimental section). The ligands were reacted with $CrCl_2$ and oxidized to form chromium(III) salen chloride complexes **1** using our standard procedure.[20] After synthesis of the chloride complexes it is necessary to change to a noncoordinating counterion to get an active epoxidation complex.[31] The Cr(salen) complexes were precipitated from the reaction mixture and after washing with solvent were not purified further. The paramagnetic complexes were characterised by IR and ES-MS. Elemental analyses were not satisfactory, however, this is not unusual for these complexes[43] and epoxidation results were reproducible from batch to batch.

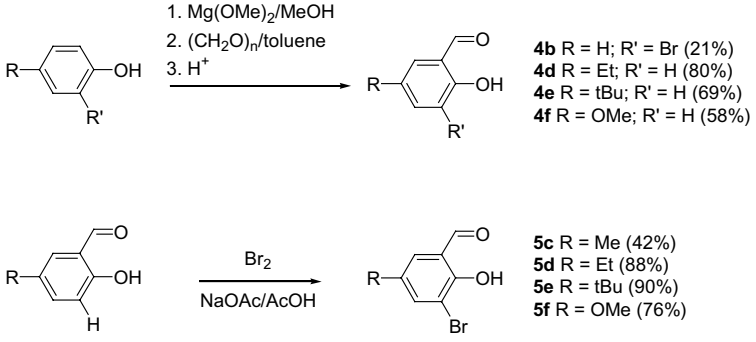
The results obtained in the epoxidation of *trans*-β-methylstyrene are shown in Table 1. The Cr(III)salen complexes were reacted with PhIO to form the green-black O=Cr(V) species in situ. Excess PhIO was removed by filtration and the substrate was added to the solution of O=Cr(V)salen at 0 °C. The epoxidations were carried out in the absence and presence of Ph_3PO since this has been shown to improve the ee.[21] Preliminary results with **2** and **3a**,**b** have been previously communicated.[22]

3. Discussion

The unusual behaviour of the methoxy-substituted catalyst **3f** makes it difficult to determine whether its performance can be compared with the other catalysts. It would appear from the colour changes that a O=Cr(salen) complex is formed initially but rapidly decomposes. Therefore, a different species may be responsible for the AE reaction. As such it would be unwise to place any significance on the result obtained with **3f**. Aside from that, all the ees were moderate to excellent as would be expected due to the presence of the 3,3′-bromo group.[23] The addition of Ph_3PO increased the ee obtained in all cases, confirming itself as the most reliable additive we have studied.[21,22] In line with previous results,[17,22] the effect of additive was most noticeable when the ee in its absence was relatively low. The optimum choice of counterion varied with catalyst structure.

Yields were below 30% in all cases. This is not unexpected in the stoichiometric mode as the Cr(III)salen generated can react with the O=Cr(V)salen to form a sink for the active complex.[20,26] The recovered mass is also low and this is due to the fact that Cr(salen) complexes can also act as polymerisation catalysts.[31,44]

An attempt was made to correlate Hammett substituent constants σ and the ratio of enantiomers (ln(*R*/*S*)). Assuming only one active oxidant, the latter should be directly proportional to $\Delta\Delta G^{\ddagger}$, the free energy difference between two diastereomeric transition states as a result of two facial approaches of *trans*-β-methylstyrene towards the Cr–oxo species.[34,35] Figures 1 and 2 show



Scheme 1. Synthesis of salicylaldehydes (unoptimised isolated yields in parentheses).

Table 1. Results for the stoichiometric AE of *trans*-β-methylstyrene with oxo–Cr^{V}(salen) complexes generated in situ from Cr^{III}(salen) complexes **2**, **3a–f**[a]

#	Complex	5,5′	Time (h)	Additive L	*trans*-epoxide		Unreacted alkene (%)	Recovered mass[c]
					Ee (%)	Yield (%)[b]		
1	**3a** (PF_6^-)	Br	3	None	71	2	10	—
2	**3a**	Br	3	Ph_3PO	79	14	22	—
3	**2a** (NO_3^-)	Br	3	None	63	2	3	—
4	**2a**	Br	3	Ph_3PO	77	3	4	—
5	**3b** (PF_6^-)	H	5.5	None	79	4	2	6
6[d]	**3b**	H	4.5	Ph_3PO	84	27	21	52
7	**2b** (NO_3^-)	H	5	None	81	7	8	17
8	**2b**	H	5	Ph_3PO	86	13	28	42
9	**3c** (PF_6^-)	Me	7.7	None	73	13	23	38
10	**3c**	Me	8.3	Ph_3PO	79	16	15	32
11	**2c** (NO_3^-)	Me	9	None	77	14	9	24
12	**2c**	Me	9	Ph_3PO	82	9	5	15
13[e]	**3d** (PF_6^-)	Et	5	None	77	2	28	30
14[e]	**3d**	Et	3.25	Ph_3PO	79	4	25	30
15[f]	**2d** (NO_3^-)	Et	2.5	None	Nd	Nd	—	—
16[f]	**2d**	Et	2.5	Ph_3PO	Nd	Nd	—	—
17[g]	**3e** (PF_6^-)	*t*-Bu	9	None	87	15	5	22
18	**3e**	*t*-Bu	9	Ph_3PO	90	15	18	34
19	**2e** (NO_3^-)	*t*-Bu	10	None	82	23	16	40
20	**2e**	*t*-Bu	10	Ph_3PO	88	26	18	45
21[h]	**3f** (PF_6^-)	OMe	9	None	41	0.3	15	15
22[i]	**2f** (NO_3^-)	OMe	N/A	None	—	—	—	—

[a] Alkene (1 equiv) was used w.r.t. Cr^{III}(salen). Solvent = acetonitrile. Temperature = 0 °C. Time = time for green-black Cr(V) colour to discharge to orange-brown Cr(III) colour. Benzaldehyde and phenylacetone were detected as side-products $\leqslant 1\%$, unless otherwise stated. (*R*,*R*)-*trans*-β-Methlystyrene oxide was the major enantiomer when (*R*,*R*)-catalyst was used. Ees (±2%) were determined by chiral GC (see Section 5 for full details).

[b] Using *n*-decane as internal standard.

[c] Sum of all organic material (%), excluding PhI.

[d] Phenylacetone (4%) as side-product.

[e] Cr^{III}(salen) complex had low solubility in acetonitrile but addition of PhIO gave a black solution.

[f] Cr^{III}(salen) complex was sparingly soluble in acetonitrile. Addition of PhIO did not give a colour change. The standard protocol was followed but only alkene was recovered. No PhI was detected.

[g] Phenylacetone (2%) as side-product.

[h] The black colour due to the O=Cr^{V}(salen) complex disappeared within 10 min of adding PhIO. The reaction was carried out with the resulting brown solution and worked up after 9 h.

[i] Cr^{III}(salen) complex was insoluble in acetonitrile, CH_2Cl_2, $CHCl_3$ and toluene. No reaction was carried out.

Hammett plots of the enantioselectivity versus the substituent effect. The enantioselectivities of catalysts do not show the expected linear correlation with the substituent electronics. In our previous communication we had observed that addition of more halo substituents to a 3,3′-halo complex results in a decrease in ee. However, on addition of an electron-donating groups (EDGs) such as methyl or ethyl the ee also decreases, contrary to what might have been predicted from work on O=Cr(salen) by Rajagopal et al.[36] and the Mn(salen) systems of Jacobsen et al.[34,35] On a more positive note, we discovered that placement of *tert*-butyl groups on the 5,5′-positions leads to ees of up to 90%. Prior to considering the enantioselectivity obtained in the Cr(salen)-mediated AE of alkenes in terms of possible substituent-electronic effects, **2e** and **3e** would not have been considered good candidates for enantioselective complexes because the chromium analogue of Jacobsen's catalyst was a mediocre epoxidation catalyst and EWGs were best for the 3,3′-positions. Thus, we have found that the choice of optimum substituent for the 3,3′-positions and the 5,5′-positions is quite different. The effect of the bulky *tert*-butyl group would appear to be, at least partly, of a steric nature since **2** and **3e** give quite different results from the electronically similar **2** and **3c**,**d**. This may take the form of more effective blocking of the alkene trajectory of approach over the 5,5′-positions of the arene ring which otherwise would allow the formation of the disfavoured enantiomer of the epoxide. This is not wholly unexpected since a similar role has been proposed for the *tert*-butyl group in the 5,5′-positions in Jacobsen's manganese(salen) catalyst while the effect of methyl groups in the same positions could be fully rationalised in terms of electronic considerations.[35,45] It is noteworthy that this complex is less expensive and requires less synthetic operations than the only other Cr(salen) complex shown to be capable of epoxidising an alkene in greater than 90% ee.[20]

As regards the Hammett plots, one might speculate that as EDGs are added to the ligand a different oxidation pathway or alkene approach trajectory may become competitive since EDGs are expected to reduce the reaction rate. Imanishi and Katsuki found the sense of the enantioselectivity in the AE by a given catalyst could change depending on the solvent used, which led them to suggest that two different oxidation pathways were competing.[24] Recently, we have also found evidence

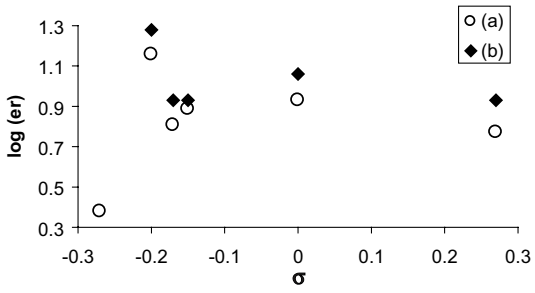


Figure 1. Hammett plot of σ vs log(er). Er = enantiomeric ratio obtained in the O=Cr(salen)-mediated AE of *trans*-β-methylstyrene using **3a**–**f**; (a) No additive; ee range: 41–87%. (b) Additive = Ph_3PO; ee range: 79–90%.

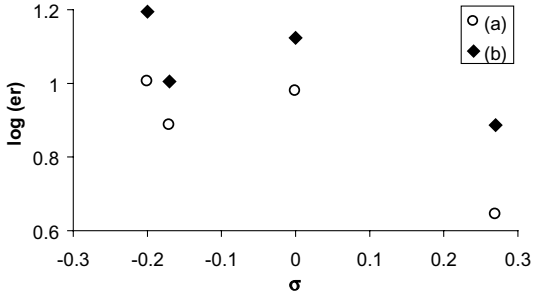


Figure 2. Hammett plot of σ vs log(er). Er = enantiomeric ratio obtained in the O=Cr(salen)-mediated AE of *trans*-β-methylstyrene using **2a**–**c**, **2e**. (a) No additive; ee range: 63–82%. (b) Additive = Ph_3PO; ee range: 77–88%.

suggestive of competing oxidation cycles in the catalytic mode of Cr(salen)-mediated AE.[20] Daly et al. found that using bleach as oxidant instead of PhIO favoured epoxide of the opposite configuration and in catalytic mode the level of enantioselectivity is less than that in the stoichiometric mode. Last year, Bryliakov and Talsi[26] reported evidence that there were two semi-stable oxygen-bearing Cr(salen) species present in solution under catalytic conditions although they proposed that only one of these was involved in transfer of oxygen to the alkene. Interestingly, Linde et al. and Adam et al. have recently published evidence to support the existence of multiple oxidation pathways in Mn(salen) AE reactions.[46,47] Ultimately, more experimental results are needed to establish the details of this reaction.

4. Conclusions

Investigations into salen-substituent effects in Cr(salen)-mediated epoxidation have yielded nonlinear Hammett plots and the involvement of multiple oxidation pathways has been suggested to explain this. These ligand-tuning studies have also led to the development of a synthetically accessible chromium–salen complex capable of mediating the asymmetric epoxidation of *trans*-β-methylstyrene with high enantioselectivity. Further studies are underway to use the knowledge gained to further improve the design of Cr(salen) complexes.

5. Experimental

5.1. General

Melting points were determined using a Gallenkamp melting point block, a Griffin melting point apparatus or a Reichert Thermovar hot stage microscope and are uncorrected. Elemental analyses were carried out by the Microanalytical Laboratory, University College Dublin. Infrared spectra were obtained on either a Mattson Galaxy Series FTIR 3000 spectrometer or a Nicolet Impact 410 FTIR Spectrometer and processed using Omnic 4.1. Mass spectra were obtained by the Mass Spectrometry Service, University College Dublin. Optical rotation values were obtained using a Perkin-Elmer 241 polarimeter or a Bellingham and Stanley Polarimeter ADP 220. $[\alpha]_D$ values are reported without units, which are understood to be 10^{-1} deg cm^2 g^{-1} at 589 nm. ^{1}H NMR spectra were recorded at 300 MHz on a Varian INOVA 300 spectrometer or, where stated, at 270 MHz on a Jeol JNM-GX270 FT spectrometer. ^{13}C NMR spectra were recorded at 75 MHz (Varian). Chemical shifts are reported as δ-values in ppm relative to tetramethylsilane (TMS). Either TMS or a residual solvent signal was used as an internal standard for ^{1}H and ^{13}C. Chiral gas–liquid chromatography (GC) was performed on either a Shimadzu GC-8A gas chromatograph, coupled to a Shimadzu C-R3A integrator or a Perkin-Elmer Autosystem Gas Chromatograph. Details of the chiral column used are described in the relevant section.

All solvents were commercially available and used as supplied, unless otherwise stated. All chemicals, were obtained from the Aldrich Chemical Company and used as received unless otherwise stated. The resolution and liberation of (±)-*trans*-cyclohexane-1,2-diamine were carried out according to literature procedures.[48–50]

5.2. Synthesis of salicylaldehydes

5.2.1. Use of the method of Levin et al.[51] for *o*-formylation. General method: The phenol (1 equiv) was added to a methanolic solution of magnesium methoxide (0.6 equiv) under a N_2 atmosphere in a three-neck RB flask equipped for reduced pressure distillation. The solutions were made in situ by reaction of magnesium turnings with freshly distilled dry MeOH (15–20 mL per g of magnesium). Approximately half the MeOH was removed by distillation. Dry toluene was added to replace the distilled MeOH. Distillation continued until the reaction mixture reached a specified temperature (see below). A slurry of paraformaldehyde (3 equiv) in dry toluene (1.8 mL per g of paraformaldehyde) was added in small portions with washings over 1 h. Removal of the azeotrope of toluene/MeOH by distillation was maintained between additions and for a further 1–3 h (see below) at constant temperature. Extra toluene was added if the heterogeneous mixture became viscous. Sometimes the mixture developed a bright yellow colour. After a number of hours (see below), heating was discontinued and the reaction left to cool down (sometimes this was done overnight for convenience). Sulfuric

acid (10%, ~75 mL per 50 mmol of Mg) was added and the reaction was stirred at 50 °C for 2 h. The reaction was allowed to cool and the layers were separated. The aqueous layer was extracted with toluene (2 × 50 mL per 200 mL of aqueous solution). The combined organic layers were washed with water (2 × 25 mL per 100 mL of toluene). The solvent was removed in vacuo to give the crude product.

Two basic variations of the method of Levin et al. were used. The procedures used are typified by the *o*-formylation of alkylphenols (Method A) and 2-bromophenol (Method B).

Method A: The reaction was carried out at 95 °C and normal pressure. Two hours of further heating followed the paraformaldehyde addition period.

Method B: The reaction was carried out at 75 °C under sufficient reduced pressure (using a water pump) to allow removal of the azeotrope by distillation. Three hours of further heating followed the paraformaldehyde addition period. Pressure was decreased gradually so as to maintain slow distillation and typically varied over a range of 160–360 mmHg.

5.2.2. 3-Bromosalicylaldehyde 4b. Method B: 2-Bromophenol (6.2 mL, 10 g, 58 mmol) gave an orange oil (9.65 g, 83% crude yield). ^{1}H NMR indicated that the ratio of product to starting material was 1.9:1 and that there were only small amounts of unidentified material. The yield was estimated at 40–50%. The oil mostly solidified on standing. It was filtered and the residue washed with hexane to give pale yellow crystals (1.61 g, 14% yield). An additional crop of crystals was obtained (0.83 g, 7% yield). The combined isolated yield was 21%. Mp 49–52 °C (lit.[52] 49 °C); ^{1}H NMR (300 MHz) δ (ppm): 11.60 (d, ArOH, $J = 0.6$ Hz, 1H), 9.86 (s, ArCHO, 1H), 7.77–7.80 (m, ArH_4, 1H), 7.55 (dd, ArH_6, $J = 7.6$, 1.5 Hz, 1H), 6.95 (apparent t, ArH_5, $J = 7.9$ Hz, 1H); ^{13}C NMR (75 MHz) δ (ppm): 196.2 (ArCHO), 158.4, 140.2 (ArCH), 133.2 (ArCH), 121.6, 121.0 (ArCH), 111.5; IR (cm^{-1}): 2855, 1654 (s, C=O), 1440, 1365, 1292, 1218, 1172, 1129, 1073, 900, 819, 760, 732, 668, 601, 488; MS (EI) m/z (% relative intensity): 203 (4, **M + 3**), 202 (27, **M + 2**), 201 (23, **M$^+$ − 1 + 2**), 200 (30, **M$^+$**), 199 (26, **M$^+$ − 1**), 184 (6), 182 (6), 174 (3), 172 (4), 156 (5), 154 (5), 145 (14), 143 (16), 132 (2), 131 (2), 120 (7), 119 (9), 117 (6), 103 (7), 92 (50), 86 (3), 81 (6, **Br**), 79 (7, **Br**), 75 (29), 74 (16), 63 (100), 53 (44), 46 (10). Anal. Calcd for $C_7H_5BrO_2$: C, 41.82; H, 2.51; Br, 39.75. Found: C, 41.74; H, 2.43; Br, 39.71.

5.2.3. 5-Ethylsalicylaldehyde 4d. Method A with Dean–Stark apparatus: 4-Ethylphenol (20.0 g, 164 mmol) was reacted as per the described procedure with the internal temperature in the range 95–105 °C. A Dean–Stark apparatus was used to ensure efficient solvent removal. A red oil (25.5 g, 104% crude yield) was obtained. ^{1}H NMR indicated that the desired product was the major component (estimated at 80% by mass using ^{1}H NMR spectroscopy with 1,4-dimethoxybenzene as internal standard). Vacuum distillation of some of this oil (19.7 g) gave the desired product as a clear liquid [15.23 g, 80% yield (correcting for the amount distilled)]. Bp 50–52 °C (0.3 Torr); lit.[53] 236 °C @ 760 mmHg; ^{1}H NMR (300 MHz) δ (ppm): 10.84 (s, ArOH, 1H), 9.86 (d, ArCHO, $J = 0.6$ Hz, 1H), 7.38–7.34 (m, ArH, 2H), 6.91 (m, ArH, 1H), 2.64 (q, $ArCH_2$, $J = 7.6$, 2H), 1.24 (t, CH_3, $J = 7.6$ Hz, 3H); lit.[53] (CCl_4, 60 MHz) 10.90 (s), 9.90 (s), 6.80–7.50 (m), 2.5 (q), 0.80 (t); ^{13}C NMR (75 MHz) (ppm): 196.8 (ArCHO), 160.0, 137.2 (ArCH), 135.9, 132.4 (ArCH), 120.7, 117.7 (ArCH), 27.9 (CH_2), 15.7 (CH_3).

5.2.4. 5-*tert*-Butylsalicylaldehyde 4e. Method A: 4-*tert*-Butylphenol (10.0 g, 66.6 mmol) gave a bright canary yellow coloured reaction mixture. Work-up yielded an orange oil (12.2 g, 103% crude yield). ^{1}H NMR indicated that the desired product accounted for ~83% of *tert*-butyl signals. Distillation (82–84 °C @ 1 mmHg) gave a yellow liquid (8.68 g). ^{1}H NMR indicated that this was >95% pure with just traces of 4-*tert*-butylphenol remaining. The isolated yield was, therefore, >69%. This was used without further purification.

Yellow liquid, bp 82–84 °C @ 1 mmHg, lit.[54] 60–65 °C @ 0.1 Torr; ^{1}H NMR (300 MHz) δ (ppm): 10.87 (s, ArOH, 1H), 9.90 (d, ArCHO, $J = 0.5$ Hz, 1H), 7.59 (dd, ArH_4, $J = 8.8$, 2.5 Hz, 1H), 7.53 (d, ArH_6, $J = 2.5$ Hz, 1H), 6.95 (dd, ArH_3, $J = 0.5$, 8.8 Hz, 1H), 1.35 (s, C_4H_9, 9H); lit.[55]; ^{13}C NMR (75 MHz) δ (ppm): 196.7 (ArCHO), 159.4, 142.7, 134.6 (ArCH), 129.7 (ArCH), 120.0, 117.2 (ArCH), 34.0 (CMe_3), 31.2 ($(CH_3)_3$); lit.[56]

5.2.5. 5-Methoxysalicylaldehyde 4f. Method A at lower temperature: 4-Methoxyphenol (10.0 g, 80.6 mmol) was subjected to the standard reaction conditions except that the internal temperature did not rise above 80 °C. A red oil (11.5 g, 93% crude yield) was obtained. In addition to unreacted starting material and the desired product, there was a small amount (<10% relative to the desired product) of an unidentified impurity characterised by peaks @ 9.8 and 11.5 ppm in the ^{1}H NMR. The starting material to product ratio was 3:10. The yield of the desired product is ~69%. The oil darkened on standing. Distillation yielded a nonviscous yellow liquid (7.88 g, bp 88–90 °C @ 1.5 mmHg), which contained 5-methoxysalicylaldehyde (>90% pure by ^{1}H NMR, >58% yield) and a trace of unreacted substrate. Yellow liquid, bp 88–90 °C @ 1.5 mmHg (lit.[57] 80 °C @ 0.5 Torr); ^{1}H NMR (270 MHz) δ (ppm): 10.67 (s, ArOH, 1H), 9.87 (d, ArCHO, $J = 0.6$ Hz, 1H), 7.15 (dd, ArH_4, $J = 9.1$, 3.1 Hz, 1H), 7.01 (d, ArH_6, $J = 3.1$ Hz, 1H), 6.94 (m, ArH_3, 1H), 3.82 (s, $ArCH_3$, 3H); lit.[58,59]

5.3. Bromination of salicylaldehydes

5.3.1. 3-Bromo-5-methoxysalicylaldehyde 5f. The procedure of Rubenstein[60] was followed with the modifications to the work-up as described by Swenton and

Raynolds.[61] Thus, **4f** (1.50 g, 9.86 mmol) was dissolved in glacial acetic acid (10 mL). Sodium acetate (0.90 g, 11 mmol) was added. The mixture was cooled on ice/water. To this stirring slurry was added a solution of bromine (0.5 mL, 9.8 mmol), in glacial acetic acid (3 mL), via syringe over 10 min. The deep red homogeneous solution that resulted was stirred for a further 3 h. The mixture was then poured into a saturated solution of $SnCl_2$ (45 mL, ~5 mol%). This was then filtered to give a pale yellow solid (2.91 g, 128% crude yield). This was recrystallised immediately (this is recommended by Swenton and Raynolds) with EtOH. After leaving the recrystallisation to stand overnight, filtration yielded pale yellow fluffy crystals, 1.76 g, 76% yield. Mp 110–112 °C (lit. 109–110.5 °C (Swenton and Raynolds) or 107 °C (Rubenstein)). ^{1}H NMR (300 MHz) δ (ppm): 11.11 (s, ArOH, 1H); 9.82 (s, ArCHO, 1H); 7.40 (d, ArH, $J = 2.9$ Hz, 1H); 7.03 (d, ArH, $J = 2.9$ Hz, 1H); 3.82 (s, OCH_3, 3H) (lit.[61]); ^{13}C NMR (75 MHz) δ (ppm): 195.6 (CHO), 152.8, 152.4, 127.3 (CH), 120.4, 115.7 (CH), 111.4, 56.1 (OCH_3).

5.3.2. 3-Bromo-2-hydroxy-5-methylbenzaldehyde 5c. The method of Rubenstein (see above) was used.[60] Thus, sodium acetate (0.72 g, 8.78 mmol) was added to a solution of 2-hydroxy-5-methylbenzaldehyde (1.04 g, 7.64 mmol) in glacial acetic acid (5 mL). The resulting suspension was cooled on ice and then removed from the ice before dropwise addition of a solution of bromine (1.32 g, 8.26 mmol) in glacial acetic acid (2.6 mL). The yellow mixture was stirred for 3 h at room temperature and then poured onto water (8 mL + 16 mL washings). The pale yellow solid was filtered and washed with water (5 mL). This was dissolved in CH_2Cl_2 (20 mL) and washed with sodium metabisulfite solution (10% w/v, 10 mL) and saturated sodium bicarbonate solution (10 mL). After drying over magnesium sulfate the solvent was removed in vacuo to yield a yellow solid (1.46 g, 89% crude yield). A small amount of starting material was still present (as detected by ^{1}H NMR). Recrystallisation with EtOH yielded fluffy yellow crystals (0.69 g, 42%). Mp 63–64 °C (lit.[62] 65–66 (aq EtOH)); ^{1}H NMR (300 MHz) δ (ppm): 11.36 (s, ArOH, 1H), 9.80 (s, ArCHO, 1H), 7.61 (dd, ArH, $J = 2.1$ Hz, 1H), 7.32 (dd, ArH, $J = 2.1$ Hz, 1H), 2.34 (s, CH_3, 3H); ^{13}C NMR (75 MHz) δ (ppm): 195.9 (CHO), 155.9, 140.6 (CH), 132.8 (CH), 130.4, 120.9, 110.7, 19.9 (CH_3).

5.3.3. 3-Bromo-5-*tert*-butyl-2-hydroxybenzaldehyde 5e. The procedure of Lam et al. was followed.[63] A solution of **4e** (1.58 g, 8.86 mmol) and sodium acetate (1.34 g, 16.3 mmol) in glacial acetic acid (40 mL) was made up. A solution of bromine (1.44 g, 9.01 mmol) in glacial acetic acid (15 mL) was added via a dropping funnel over 30 min. The yellow solution was stirred at 50 °C for 12 h. After cooling this resulted in a colourless liquid with a whitish precipitate. The solvent was removed in vacuo and water (50 mL) and CH_2Cl_2 (40 mL) were added. After separation of the layers the aqueous layer was extracted with a further 2×30 mL CH_2Cl_2. The combined organic layers were washed with sodium metabisulfite solution (50 mL, 10% w/v) and saturated sodium bicarbonate solution (50 mL). After drying over magnesium sulfate the solvent was removed in vacuo to give a yellow solid (2.89 g, 127% crude yield). Recrystallisation with light petroleum spirits (bp 40–60 °C) yielded pale yellow crystals (1.90 g, 83% yield). A second crop of crystals was obtained (0.15 g, 7% yield). Overall yield = 90%. Mp 89–90 °C (Light pet. spirits, 40–60 °C) lit.[63] 81–83 °C (CH_2Cl_2/hexane); ^{1}H NMR (300 MHz) δ (ppm): 11.39 (d, ArOH, $J = 0.6$ Hz, 1H), 9.85 (s, ArCHO, 1H), 7.81 (dd, ArH_4, $J = 2.3$, 0.6 Hz, 1H), 7.51 (d, ArH, $J = 2.3$ Hz, 1H), 1.33 (s, C_4H_9, 9H); lit.[63] 11.39 (s), 9.82 (s), 7.79 (d, $J = 2.2$ Hz), 7.48 (d, $J = 2.2$ Hz), 1.30 (s); ^{13}C NMR (75 MHz) δ (ppm): 196.1 (CHO), 155.8, 143.8, 137.6 (CH), 129.3 (CH), 120.7, 110.8, 34.2 (CMe_3), 31.1 (CH_3).

5.3.4. 3-Bromo-5-ethylsalicylaldehyde 5d. The procedure of Lam et al., as described above, was followed.[63] **4d** (5.00 g, 33.3 mmol) gave a yellow liquid and a whitish precipitate after heating for 12 h @ 50 °C. Work-up as before gave a yellow liquid (7.18 g, 94% crude yield), which was distilled to give 3-bromo-5-ethylsalicylaldehyde as a yellow liquid (6.68 g, 88% yield). Bp 116–118 °C (0.9 Torr); ^{1}H NMR (300 MHz) δ (ppm): 11.38 (s, ArOH, 1H), 9.82 (d, ArCHO, $J = 0.6$ Hz, 1H), 7.63 (dt, ArH, $J = 2.2$, 0.6 Hz, 1H), 7.34 (m, ArH, 1H), 2.64 (qt, CH_2, $J = 7.6$, 0.6 Hz, 2H), 1.25 (t, CH_3, $J = 7.6$ Hz, 3H); ^{13}C NMR (75 MHz) δ (ppm): 195.9 (ArCHO), 156.0, 139.6 (ArCH), 136.9, 131.6 (ArCH), 121.0, 110.8, 27.4 (CH_2), 15.3 (CH_3); IR (cm^{-1}): 3097 (br, OH), 2967, 2933, 2872, 1660 (s, C=O), 1455, 1378, 1342, 1301, 1275, 1190, 1140, 935, 881, 779, 736, 696; GC–MS m/z (% relative intensity): 230 (53, $\mathbf{M}+\mathbf{2}$), 229 (11, $\mathbf{M}+\mathbf{1}$), 228 (55, **M**), 215 (80, $\mathbf{M}+\mathbf{2}-\mathbf{CH_3}$), 214 (8, $\mathbf{M}+\mathbf{1}-\mathbf{CH_3}$), 213 (100, $\mathbf{M}-\mathbf{CH_3}$), 201 (5), 199 (5), 149 (6), 120 (17), 105 (11), 103 (7), 92 (8), 91 (27), 89 (7), 78 (16), 77 (31), 65 (17), 63 (16). Anal. Calcd for $C_9H_9BrO_2$: C, 47.19; H, 3.96; Br, 34.88. Found: C, 46.89; H, 3.84; Br, 35.06.

5.4. Synthesis of salen ligands

(*R*,*R*)-(−)-*trans*-Cyclohexane-1,2-diamine (0.5 equiv, as a frozen white solid) was weighed into an appropriately sized RB flask, immediately followed by EtOH (GR, approximately 25 mL per 2 g of salicylaldehyde). This solution was brought to reflux and salicylaldehyde (1 equiv) was added portionwise down the condenser with washings of EtOH (~25 mL per 2 g of salicylaldehyde) resulting in an immediate development of a bright yellow colour. After refluxing for 2 h the solution was allowed to cool which, if it had not happened already, usually led to precipitation of bright yellow crystals. The crystals were then filtered and washed with ice-cold EtOH (~5 mL) before air-drying at the pump. If insufficient product precipitated the filtrate or reaction solution could be concentrated by removal of some solvent in vacuo to obtain more. The bright yellow powders/crystals were recrystallised from EtOH. These were then powdered and dried under vacuum at 60 °C to remove any residual solvent.

5.4.1. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromosalicylidene)-*trans*-cyclohexane-1,2-diamine 6b. Compound **4b** (2.01 g, 1.00 mmol) gave yellow crystals (EtOH, 1.81 g, 75%). Mp 150–153 °C; ^{1}H NMR (300 MHz) δ (ppm): 14.4 (s, br, ArOH, 2H), 8.20 (s, ArCH=NR, 2H), 7.50 (dd, ArH, $J = 1.5$, 7.9 Hz, 2H), 7.10 (dd, ArH, $J = 1.5$, 7.6 Hz, 2H), 6.70–6.64 (m, ArH, 2H), 3.35–3.32 (m, C=N–CH, 2H), 1.97–1.41 (m, cyclohexyl–CH_2's, 8H); ^{13}C NMR (75 MHz) δ (ppm): 164.3 (C=N), 158.5, 135.6 (ArCH), 130.8 (ArCH), 119.1 (ArCH), 118.9, 111.0, 71.9 (cyclohexyl–CH), 32.9 (CH_2), 23.9 (CH_2); IR (cm^{-1}): 2937, 2857, 1627 (s, C=N), 1568, 1490, 1445, 1271, 1181, 1146, 855, 771, 736; MS (EI) m/z (% relative intensity): 482 ($\mathbf{M}^+ + \mathbf{4}$, 4), 481 (3), 480 ($\mathbf{M}^+ + \mathbf{2}$, 16), 479 (3), 478 ($\mathbf{M}^+$, 9), 283 (6), 282 (22), 281 (**279** + **2**, 90), 280 (55), 279 ($\mathbf{M}^+ - \mathbf{C_7H_6BrNO}$, 100), 278 (42), 264 (9), 252 (8), 238 (8), 226 (5), 212 (9), 202 (47), 200 (69), 198 (23), 185 (14), 172 (4), 146 (6), 132 (7), 120 (14), 105 (27), 91 (16), 81 (39), 77 (29), 67 (24), 54 (24), 41 (47). Anal. Calcd for $C_{20}H_{20}N_2O_2Br_2$: C, 50.02; H, 4.20; N, 5.83; Br, 33.28. Found: C, 50.28; H, 4.18; N, 5.70; Br, 33.41; $[\alpha]_D^{25} = -578$ ($c = 0.601$, CH_2Cl_2).

5.4.2. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methylsalicylidene)-*trans*-cyclohexane-1,2-diamine 6c. Compound **5c** (0.64 g, 3.0 mmol) gave yellow crystals (EtOH, 0.63 g, 83%). Mp 167–168 °C; ^{1}H NMR (300 MHz) (δ ppm): 14.1 (s, br, ArOH, 2H), 8.14 (s, ArCHNR, 2H), 7.33 (d, ArH, $J = 1.8$ Hz, 2H), 6.89 (d, ArH, $J = 1.8$ Hz, 2H), 3.32–3.29 (m, C=NCH, 2H), 2.20 (s, $ArCH_3$, 6H), 1.96–1.45 (m, cyclohexyl–CH_2's, 8H); ^{13}C NMR (75 MHz) (δ ppm): 164.1 (C=N), 155.9, 136.1 (ArCH), 130.9 (ArCH), 128.6, 118.6, 110.3, 72.2 (cyclohexyl–CH), 32.9 (cyclohexyl–CH_2), 24.3 (cyclohexyl–CH_2), 19.9 ($ArCH_3$); IR (cm^{-1}): 2945, 2924, 2847, 1633 (s, C=N), 1575, 1445, 1367, 1274, 1245, 1203, 1152, 1098, 1065, 1045, 975, 942, 862, 787, 741, 703, 571; MS (ES) m/z (% relative intensity) (0.1 mg/mL in MeOH): 533 ($\mathbf{M} + \mathbf{Na}^+ + \mathbf{4}$, 10), 531 ($\mathbf{M} + \mathbf{Na}^+ + \mathbf{2}$, 11), 529 ($\mathbf{M} + \mathbf{Na}^+$, 5), 511 ($\mathbf{MH}^+ + \mathbf{4}$, 32), 510 (13), 509 ($\mathbf{MH}^+ + \mathbf{2}$, 100), 508 (3), 507 ($\mathbf{MH}^+$, 36), 256 ($(\mathbf{M} + \mathbf{4})\mathbf{H}_2^{2+}$, 5), 255 ($(\mathbf{M} + 2)\mathbf{H}_2^{2+}$, 8), 254 ($\mathbf{MH}_2^{2+}$, 5). Anal. Calcd for $C_{22}H_{24}Br_2N_2O_2$: C, 51.99; H, 4.76; N, 5.51. Found: C, 51.99; H, 4.73; N, 5.44; $[\alpha]_D^{31} = -498$ ($c = 1.03$, CH_2Cl_2).

5.4.3. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-ethylsalicylidene)-*trans*-cyclohexane-1,2-diamine 6d. Compound **5d** (6.00 g, 26.2 mmol) gave yellow crystals (EtOH, 4.65 g, 66%). Mp 71–74 °C; ^{1}H NMR (300 MHz) δ (ppm): 14.1 (s, broad, ArOH, 2H), 8.17 (s, ArCH=NR, 2H), 7.36 (dd, ArH, $J = 2.1$, 0.5 Hz, 2H), 6.92 (d, ArH, $J = 2.1$ Hz, 2H), 3.33–3.30 (m, C=NCH, 2H), 2.51 (q, CH_2, $J = 7.6$ Hz, 4H), 1.96–1.43 (m, cyclohexyl-CH_2's, 8H), 1.15 (t, CH_3, $J = 7.6$ Hz, 6H); ^{13}C NMR (75 MHz) δ (ppm): 164.3 (C=N), 156.1, 135.2, 135.1 (ArCH), 129.8 (ArCH), 118.7, 110.4, 72.2 (cyclohexyl–CH), 32.9 (CH_2), 27.4 (CH_2), 24.0 (CH_2), 15.4 (CH_3); IR (cm^{-1}): 2930, 2858, 1629 (s, C=N), 1573, 1462, 1371, 1278, 1151, 877, 772, 741, 702; MS (ES) m/z (% relative intensity) (0.1 mg/mL in MeOH): 561 ($\mathbf{M} + \mathbf{4} + \mathbf{Na}^+$, 10), 559 ($\mathbf{M} + 2 + \mathbf{Na}^+$, 16), 557 ($\mathbf{M} + \mathrm{Na}^+$, 10), 539 ($\mathbf{MH}^+ + \mathbf{4}$, 62), 538 (15), 537 ($\mathbf{MH}^+ + \mathbf{2}$, 100), 536 (4), 535 ($\mathbf{MH}^+$, 55), 270 ($(\mathbf{M} + \mathbf{4})\mathbf{H}_2^{2+}$, 4), 269 ($(\mathbf{M} + \mathbf{2})\mathbf{H}_2^{2+}$, 11), 268 ($\mathbf{MH}_2^{2+}$, 4); Anal. Calcd for $C_{24}H_{28}Br_2N_2O_2$: C, 53.75; H, 5.26; Br, 29.80; N, 5.22. Found: C, 53.72; H, 5.14; Br, 30.00; N, 5.15; $[\alpha]_D^{34} = -450$ ($c = 1.06$, CH_2Cl_2).

5.4.4. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-*tert*-butylsalicylidene)-*trans*-cyclohexane-1,2-diamine 6e. Compound **5e** (1.81 g, 7.04 mmol) gave yellow crystals (EtOH, 1.61 g, 77%). Mp 202–203 °C; ^{1}H NMR (300 MHz) δ (ppm): 14.2 (s, br, ArOH, 2H), 8.21 (s, ArCH=NR, 2H), 7.53 (d, ArH, $J = 2.3$ Hz, 2H), 7.10 (d, ArH, $J = 2.3$ Hz, 2H), 3.34–3.31 (m, C=N–CH, 2H), 1.96–1.43 (m, cyclohexyl–CH_2's, 8H), 1.23 (s, ArC_4H_9, 18H); ^{13}C NMR (75 MHz) δ (ppm): 164.6 (C=N), 155.9, 142.4, 132.9 (ArCH), 127.4 (ArCH), 118.4, 110.4, 72.2 (cyclohexyl–CH), 34.0 (CMe_3), 33.0 (CH_2), 31.2 (CH_3), 24.0 (CH_2); IR (cm^{-1}): 2960 (s), 2931 (s), 2861, 1630 (s, C=N), 1574, 1466, 1447, 1378, 1362, 1281, 1263, 1170, 701; MS (EI) m/z (% relative intensity): 594 ($\mathbf{M}^+ + \mathbf{4}$, 6), 593 (4), 592 ($\mathbf{M}^+ + \mathbf{2}$, 17), 590 ($\mathbf{M}^+$, 7), 338 (27), 337 (**335** + **2**, 98), 336 (40), 335 ($\mathbf{M}^+ - \mathbf{C_{11}H_{14}BrNO}$, 100), 322 (27), 320 (40), 308 (3), 294 (6), 282 (18), 281 (26), 280 (16), 258 (21), 257 (15), 256 (30), 255 (14), 242 (32), 241 (15), 240 (38), 225 (8), 212 (6), 200 (4), 161 (9), 146 (8), 133 (7), 117 (12), 105 (6), 96 (12), 91 (9), 82 (13), 81 (33), 80 (14), 79 (19), 57 (63), 56 (15), 55 (12), 41 (32). Anal. Calcd for $C_{28}H_{36}Br_2N_2O_2$: C, 56.77; H, 6.13; N, 4.73. Found: C, 56.67; H, 6.00; N, 4.63; $[\alpha]_D^{32} = -396$ ($c = 1.19$, CH_2Cl_2).

5.4.5. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methoxysalicylidene)-*trans*-cyclohexane-1,2-diamine 6f. Compound **5f** (1.00 g, 4.33 mmol) gave orange crystals (EtOH, 0.88 g, 75%). Mp 183–185 °C; ^{1}H NMR (300 MHz) δ (ppm): 13.8 (s, br, ArOH, 2H), 8.16 (s, ArCH=NR, 2H), 7.15 (d, ArH, $J = 2.9$ Hz, 2H), 6.67 (d, ArH, $J = 2.9$ Hz, 2H), 3.71 (s, OCH_3, 6H), 3.34–3.31 (m, C=N–CH, 2H), 1.97–1.43 (m, cyclohexyl–CH_2's, 8H); ^{13}C NMR (75 MHz) δ (ppm): 164.0 (C=N), 152.2, 151.9, 122.5 (ArCH), 118.4, 114.9 (ArCH), 110.7, 72.4 (cyclohexyl–CH), 56.0 (CH_3), 32.9 (CH_2), 24.0 (CH_2); IR (cm^{-1}): 2941, 2859, 1632 (s, C=N), 1574, 1471, 1434, 1369, 1286, 1253, 1177, 1142, 1096, 1052, 964, 852, 778, 716; MS (EI) m/z (% relative intensity): 542 ($\mathbf{M}^+ + \mathbf{4}$, 10), 541 (5), 540 ($\mathbf{M}^+ + \mathbf{2}$, 28), 538 ($\mathbf{M}^+$, 6), 312 (14), 311 (**309** + **2**, 100), 309 ($\mathbf{M}^+ - \mathbf{C_8H_8BrNO_2}$, 85), 294 (22), 268 (10), 232 (17), 231 (42), 230 (30), 229 (50), 214 (36), 186 (8), 161 (5), 135 (9), 94 (12), 82 (15), 81 (38, **Br**), 80 (17), 79 (35, **Br**), 77 (21), 67 (17), 56 (16), 55 (16), 54 (17), 53 (26), 41 (32). Anal. Calcd for $C_{22}H_{24}Br_2N_2O_4$: C, 48.91; H, 4.48; N, 5.19; Br, 29.58. Found: C, 48.99; H, 4.59; N, 4.89; Br, 29.61; $[\alpha]_D^{23} = -432$ ($c = 0.41$, CH_2Cl_2).

5.5. Synthesis of chromium(III) salen complexes

5.5.1. General procedure. The complexes were prepared following the method described by Mabbs et al.[64] Chromium(salen) chloride complexes were synthesised

by reacting chromium(II) chloride with the appropriate salen ligand. The chromium(II) chloride was made by reducing chromium(III) with zinc amalgam and used immediately. The general procedure is described below, along with procedures for exchanging the chloride counter-ion for either nitrate or hexafluorophosphate. **CAUTION**: There is evidence that Cr(III)salen complexes are genotoxic and carcinogenic and thus due care should be taken to avoid contact.[65]

5.5.2. Preparation of zinc amalgam. This preparation was adapted from the method of Caesar.[66] Granular zinc was stored under N_2 when not in use. Exposure to air led to deactivation of the zinc due to oxidation of the surface. Concd HCl (3.3 mL) was added to a suspension of mercury(II) chloride (4.38 g, 16.1 mmol) in distilled water (42 mL) in a 100 mL conical flask resulting in a homogeneous solution. Granular zinc (20 mesh, 99.8%, 21.93 g, 0.335 mol) was then added and stirring continued for 30 min. Stirring was sufficiently slow that air did not come into contact with the solid amalgam. The zinc amalgam was then filtered and washed with water, EtOH and Et_2O (10 mL each). It was immediately placed under an atmosphere of N_2 in a three-necked RB flask equipped as described in the next section. It is important to minimise any contact with air during this procedure.

5.5.3. Reduction of chromium(III) chloride to chromium(II) chloride. The zinc amalgam and stirring bar were transferred into a waiting three-necked RB flask equipped with a pressure equalizing dropping funnel and nitrogen inlet/outlet, under a positive flow of N_2. The dropping funnel contained a green solution of chromium(III) chloride in water (1.83 g, 6.87 mmol, in 12 mL), which was added slowly to the stirring amalgam. Within 30 min of commencing stirring, a sky blue colour characteristic of chromium(II) chloride persisted. The mixture was stirred for a further hour before use. After removal of the chromium(II) solution the amalgam was transferred to a plastic vessel for safe disposal.

5.5.4. Complex generation. A solution of **6b** (2.20 g, 4.58 mmol) was prepared in acetone/MeOH (5:1 ratio, 90 mL) in a three-necked RB flask under a nitrogen atmosphere. The chromium(II) chloride solution prepared as described above was added dropwise with stirring, via syringe through a septum, under a positive flow of N_2. The solution immediately changed to a brown colour. The reaction was stirred for 1 h and then the N_2 flow was stopped. After leaving to stir overnight under a N_2 blanket, the reaction was exposed to air and left to stir for 4 h. At this point, any brown precipitate present was removed by filtration and worked-up separately from the later precipitate. The solution was then concentrated in vacuo to yield a brown precipitate, which was removed by filtration. The precipitate(s) were washed with water and Et_2O (10 mL each) and dried at the pump before being placed in an oven overnight. For analysis, the samples were further dried under vacuum at 60 °C for ~12 h. Samples were analysed by IR, MS (ES, 0.1 mg/mL in HPLC grade MeOH unless stated), elemental analysis and mp.

5.6. Counterion exchange protocols

5.6.1. Exchange of chloride to nitrate 2b. Compound **1b** (0.657 g, 1.16 mmol) was dissolved in MeOH (116 mL). A 0.01 M solution of complex is typically used. In some cases it was necessary to use more MeOH or a 1:5 acetone/MeOH solution to obtain dissolution. If any solid was still insoluble, after doubling the volume of MeOH or adding acetone, the mixture was filtered and the residue discarded. An aqueous solution of silver nitrate (398 mg, 2.34 mmol in 8.5 mL, ~0.3 M, 2 equiv) was added dropwise to the stirring homogeneous solution of complex. A white precipitate of silver chloride could be observed immediately. The reaction was stirred for a further hour before gravity filtration was performed to remove the silver chloride. The filtrate was concentrated in vacuo to ~10 mL to yield a brown precipitate, which was collected by filtration, washed with water (2×10 mL) and Et_2O (10 mL), and dried in the same manner as the chloride complex.

5.6.2. Exchange of chloride to hexafluorophosphate 3b. In the same manner as for the synthesis of nitrate complexes a ~0.01 M solution of **1c** (0.605 g, 1.07 mmol in 107 mL) was prepared in a 250 mL RB flask. To this solution was added an aqueous solution of potassium hexafluorophosphate (0.394 g, 2.14 mmol in 7.1 mL, ~0.3 M, 2 equiv). The resulting solution was stirred overnight before concentration in vacuo to just over 10 mL to yield a brown precipitate, which was collected by filtration. The complex was washed with water (50 mL) and Et_2O (10 mL) before drying in the same manner as for the chloride and nitrate complexes.

5.6.3. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromosalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] chloride 1b. 1st precipitate, 26% yield; 2nd precipitate, 51% yield. Total yield = 77%. Mp dec >320 °C; IR (cm^{-1}): 3253 (br), 2932, 2856, 1631 (s, C=N), 1589, 1530, 1435, 1394, 1346, 1332, 1227, 1182, 1135, 1084, 1021, 932, 845, 738, 703, 643, 625, 567, 472, 446; MS (ES) m/z (% relative intensity) (all peaks >2%): 526 (2), 528 (53), 529 (16), 530 (100, $\mathbf{M - Cl^-}$), 531 (31), 532 (50), 533 (15), 546 (5), 547 (5), 548 (9, $\mathbf{M - Cl^- + H_2O}$), 549 (2), 550 (4), 559 (11), 561 (21, $\mathbf{M - Cl^- + OMe}$), 562 (6), 563 (7), 564 (2), 582 (2), 584 (4, $\mathbf{M - Cl^- + OMe + Na}$), 586 (2), 606 (10), 607 (3), 608 (20, $\mathbf{M - Cl^- + MeOH + 2Na}$), 609 (6), 610 (10), 611 (3), 626 (3, $\mathbf{M - Cl^- + MeOH + 2Na + H_2O}$), 639 (2, $\mathbf{M - Cl^- + MeOH + 2Na + OMe}$), 686 (2, $\mathbf{M - Cl^- + 2(MeOH + 2Na)}$). Anal. Calcd for $C_{20}H_{18}Br_2ClCrN_2O_2$: C, 42.47; H, 3.21; N, 4.95; Br, 28.25; Cl, 6.27; Cr, 9.19. Found: C, 41.03; H, 3.51; N, 4.55; Br, 27.91; Cl, 5.79; Cr, 8.33.

5.6.4. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromosalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] nitrate 2b. Compound **1b** (657 mg, 1.16 mmol) yielded a brown

powder (476 mg, 69%). Mp dec >280 °C; IR (cm^{-1}): 3150 (br), 2928, 2857, 1626 (s, C=N), 1589, 1532, 1434 (s), 1394, 1345, 1315, 1286, 1225, 1184, 1136, 1064, 1021, 933, 846, 777, 741, 707, 649, 568; MS (ES) m/z (% relative intensity) (all peaks >2%): 526 (3), 527 (2), 528 (56), 529 (22), 530 (100, $\mathbf{M-NO_3^-}$), 531 (36), 532 (49), 533 (17), 534 (4), 545 (4), 546 (6), 547 (3), 548 (11, $\mathbf{M-NO_3^- + H_2O}$), 549 (4), 550 (5), 559 (13), 560 (7), 561 (30, $\mathbf{M-NO_3^- + OMe}$), 563 (17), 564 (4), 569 (3), 571 (4, $\mathbf{M-NO_3^- + H_2O + Na}$), 572 (2), 573 (3), 582 (5), 583 (2), 584 (10, $\mathbf{M-NO_3^- + OMe + Na}$), 585 (3), 586 (4), 587 (2), 612 (3, $\mathbf{M-NO_3^- + H_2O + 2MeOH}$). Anal. Calcd for $C_{20}H_{18}Br_2CrN_3O_5$: C, 40.56; H, 3.06; N, 7.10; Br, 26.99; Cr, 8.78. Found: C, 38.04; H, 3.40; N, 6.34; Br, 25.22; Cr, 7.91.

5.6.5. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromosalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] hexafluorophosphate 3b. Compound **1b** (323 mg, 0.571 mmol) gave a brown powder (251, 65%). Mp dec >300 °C; IR (cm^{-1}): 2936, 2862, 1629 (s, C=N), 1589, 1535, 1434 (s), 1394, 1349, 1313, 1282, 1227, 1187, 1138, 1083, 1016, 934, 916, 845 (s), 774, 738, 709, 646, 616, 556, 491, 443; MS (ES) m/z (% relative intensity) (all peaks >2%): 526 (2), 528 (52), 529 (19), 530 (100, $\mathbf{M^+ - PF_6^-}$), 531 (34), 532 (48), 533 (3), 534 (3), 545 (3), 546 (6), 547 (3), 548 (11, $\mathbf{M^+ - PF_6^- + H_2O}$), 549 (3), 550 (5), 559 (8), 560 (5), 561 (17, $\mathbf{M^+ - PF_6^- + OMe}$), 562 (11), 563 (10), 564 (2), 582 (7), 584 (11, $\mathbf{M^+ - PF_6^- + MeO + Na}$), 585 (3), 586 (6), 612 (5, $\mathbf{M^+ - PF_6^- + H_2O + 2MeOH}$), 614 (2). Anal. Calcd for $C_{20}H_{18}Br_2CrF_6N_2O_2P$: C, 35.58; H, 2.69; Br, 23.67; Cr, 7.70; F, 16.88; N, 4.15; P, 4.59. Found: C, 35.22; H, 3.15; Br, 23.86; Cr, 7.05; F, 11.39; N, 3.90; P, 4.38.

5.6.6. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] chloride ($C_{22}H_{22}Br_2ClCrN_2O_2$) 1c. Compound **6c** (0.58 g, 1.1 mmol) gave brown solids in two precipitates (198 mg, 29% and 315 mg, 47%). Total yield = 75%. Mp dec >270 °C; IR (cm^{-1}): 3427 (br), 2925, 2857, 1630 (s, C=N), 1528, 1452, 1389, 1341, 1307, 1229, 1151, 1032, 856, 812, 746, 542; MS (ES) m/z (% relative intensity) (all peaks >3%): 296 (6), 326 (3), 328 (3), 378 (3), 554 (4), 555 (3), 556 (54), 557 (26), 558 (100, $\mathbf{M-Cl^-}$), 559 (42), 560 (53), 561 (19), 562 (5), 574 (3), 575 (4, $\mathbf{M-Cl^- + OH}$), 576 (3), 587 (12), 588 (4), 589 (21, $\mathbf{M-Cl^- + OMe}$), 590 (5), 591 (8), 612 (3, $\mathbf{M-Cl^- + OMe + Na}$), 614 (3). Anal. Calcd for $C_{22}H_{22}Br_2ClCrN_2O_2$: C, 44.51; H, 3.74; N, 4.72. Found: C, 41.64; H, 3.75; N, 4.25.

5.6.7. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] nitrate 2c. Compound **1c** (178 mg, 0.300 mmol) gave a brown solid (157 mg, 84%). Mp dec >240 °C; IR (cm^{-1}): 3421 (br), 2932, 2859, 1626 (s, C=N), 1530, 1494, 1449, 1384, 1306, 1284, 1234, 1153, 1031, 851, 813, 746, 717, 547; MS (ES) m/z (% relative intensity) (all peaks >3%): 296 (8), 300 (3), 302 (3), 310 (4), 326 (5), 328 (5), 377 (3), 378 (3), 554 (4), 555 (4), 556 (53), 557 (26), 558 (100, $\mathbf{M-NO_3^-}$), 559 (41), 560 (50), 561 (20), 562 (4), 572 (3), 573 (4), 574 (6, $\mathbf{M-NO_3^- + O}$), 575 (5), 576 (3), 587 (9), 588 (6), 589 (24, $\mathbf{M-NO_3^- + OMe}$), 590 (6), 591 (11), 610 (4), 612 (7, $\mathbf{M-NO_3^- + OMe + Na}$), 614 (4). Anal. Calcd for $C_{22}H_{22}Br_2CrN_3O_5$: C, 42.60; H, 3.58; N, 6.77. Found: C, 37.03; H, 3.35; N, 6.07.

5.6.8. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] hexafluorophosphate 3c. Compound **1c** (113 mg, 0.190 mmol) gave a brown solid (117 mg, 87%). Mp dec >280 °C; IR (cm^{-1}): 3228 (br), 2939, 2861, 1629 (s, C=N), 1533, 1450, 1387, 1306, 1288, 1232, 1154, 1029, 855, 813, 747, 547; MS (ES) m/z (% relative intensity) (all peaks > 3%): 273 (4), 296 (4), 310 (3), 328 (3), 554 (3), 556 (55), 557 (27), 558 (100, $\mathbf{M-PF_6^-}$), 559 (43), 560 (55), 561 (21), 562 (6), 573 (3), 574 (4), 575 (4, $\mathbf{M-PF_6^- + OH}$), 587 (12), 588 (3), 589 (23, $\mathbf{M-PF_6^- + OMe}$), 590 (3), 591 (11). Anal. Calcd for $C_{22}H_{22}Br_2CrF_6N_2O_2P$: C, 37.58; H, 3.15; N, 3.98. Found: C, 35.57; H, 3.37; N, 3.58.

5.6.9. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-ethylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] chloride 1d. Compound **6d** (3.01 g, 5.61 mmol) gave brown powders (1.11 g, 32%) and (1.37 g, 39%). Total yield = 71%. Mp dec >325 °C; IR (cm^{-1}): 3201 (br), 2956, 2929, 2855, 1634 (s, C=N), 1534, 1449, 1391, 1347, 1307, 1224, 1147, 854, 795, 746, 716, 541, 447; MS (ES) (% relative intensity) (all peaks >3%): 310 (5), 324 (3), 569 (10), 570 (4), 571 (21, $\mathbf{M-Cl^- - CH_3}$), 572 (7), 573 (10), 574 (3), 582 (3), 583 (3), 584 (52), 585 (30), 586 (100, $\mathbf{M-Cl^-}$), 587 (46), 588 (56), 589 (24), 590 (6), 602 (5, $\mathbf{M-Cl^- + O}$), 603 (3), 604 (3), 615 (20), 616 (6), 617 (28, $\mathbf{M-Cl^- + OMe}$), 618 (8), 619 (15), 620 (3), 638 (3), 640 (6, $\mathbf{M-Cl^- + OMe + Na}$), 642 (5), 644 (3); Anal. Calcd for $C_{24}H_{26}Br_2ClCrN_2O_2$: C, 46.36; H, 4.22; N, 4.51. Found: C, 44.84; H, 4.34; N, 4.21.

5.6.10. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-ethylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] nitrate 2d. Compound **1d** (596 mg, 0.959 mmol) gave a brown powder (522 mg, 84%). Mp dec >250 °C; IR (cm^{-1}): 2928, 2856, 1627 (s, C=N), 1593, 1519, 1449, 1385, 1315, 1259, 1224, 1146, 1058, 876, 852, 793, 751, 717, 548; MS (ES) (% relative intensity) (all peaks >5%): 310 (8), 328 (5), 340 (5), 342 (8), 391 (8), 392 (5), 506 (5), 508 (5), 569 (16), 570 (5), 571 (21, $\mathbf{M-NO_3^- - CH_3}$), 572 (8), 573 (12), 574 (7), 582 (8), 583 (7), 584 (63), 585 (36), 586 (100, $\mathbf{M-NO_3^-}$), 587 (40), 588 (57), 589 (19), 590 (7), 598 (10), 599 (7), 600 (16), 601 (9), 602 (15, $\mathbf{M-NO_3^- + O}$), 603 (8), 604 (5), 605 (5), 607 (5), 608 (7), 609 (9), 610 (5), 611 (8), 613 (6), 614 (5), 615 (22), 616 (10), 617 (30, $\mathbf{M-NO_3^- + OMe}$), 618 (11), 619 (10), 620 (5), 625 (5), 626 (5), 628 (6), 629 (5), 630 (5), 638 (12), 639 (9), 640 (28, $\mathbf{M-NO_3^- + OMe + Na}$), 641 (12), 642 (17), 643 (6), 646 (5), 652 (5), 654 (10, $\mathbf{M-NO_3^- + MeOH + 2H_2O}$), 655 (5), 656 (5). Anal. Calcd for $C_{24}H_{26}Br_2CrN_3O_5$: C, 44.46; H, 4.04; N, 6.48. Found: C, 41.92; H, 3.54; N, 4.83.

5.6.11. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-ethylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] hexafluorophosphate 3d . Compound **1d** (718 mg, 1.15 mmol), gave a brown powder (630 mg, 75%). Mp dec >275 °C; IR (cm^{-1}): 2961, 2933, 2861, 1630 (s, C=N), 1524, 1448, 1391, 1311, 1225, 1147, 872, 854, 796, 551; MS (ES) (% relative intensity) (all peaks >3%): 310 (7), 314 (5), 316 (4), 324 (3), 340 (5), 342 (5), 354 (3), 356 (3), 391 (4), 393 (3), 506 (4), 507 (3), 508 (4), 539 (7), 569 (15), 570 (7), 571 (28, $\mathbf{M-PF_6^- - CH_3}$), 572 (12), 573 (13), 574 (7), 582 (4), 583 (3), 584 (57), 585 (27), 586 (100, $\mathbf{M-PF_6^-}$), 587 (41), 588 (54), 589 (19), 590 (5), 600 (6), 601 (5), 602 (7, $\mathbf{M-PF_6^- + O}$), 603 (5), 604 (4), 605 (3), 615 (14), 616 (9), 617 (23, $\mathbf{M-PF_6^- + OMe}$), 618 (5), 619 (13), 620 (3). Anal. Calcd for $C_{24}H_{26}Br_2CrF_6N_2O_2P$: C, 39.42; H, 3.58; N, 3.83. Found: C, 41.47; H, 3.80; N, 3.91.

5.6.12. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-*tert* butylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] chloride 1e. No initial precipitate was obtained. Compound **6e** (1.53 g, 2.58 mmol) gave a brown solid (1.60 g, 91%) after concentration of the homogeneous reaction solution. Mp dec >300 °C; IR (cm^{-1}): 2952, 2861, 1628 (s, C=N) 1516, 1449, 1392, 1362, 1310, 1257, 1234, 1206, 1164, 1129, 1028, 876, 856, 837, 740, 718, 546; MS (ES)m/z (% relative intensity) (all peaks >3%): 638 (3), 640 (51), 641 (21), 642 (100, $M-Cl^-$), 643 (37), 644 (51), 645 (19), 646 (5), 671 (11), 672 (5), 673 (18, $\mathbf{M-Cl^- + MeO}$), 674 (8), 675 (7), 676 (3), 696 (3, $\mathbf{M-Cl^- + MeO + Na}$), 718 (17), 719 (7), 720 (33, $\mathbf{M-Cl^- + MeOH + 2Na}$), 721 (12), 722 (18), 723 (6), 724 (3), 749 (3), 750 (3), 751 (5, $\mathbf{M-Cl^- + MeOH + 2Na + MeO}$), 752 (3), 753 (3), 796 (3), 798 (7, $\mathbf{M-Cl^- + 2(MeOH + 2Na)}$), 799 (3), 800 (4). Anal. Calcd for $C_{28}H_{34}Br_2ClCrN_2O_2$: C, 49.61; H, 5.06; N, 4.13. Found: C, 44.28; H, 4.88; N, 3.46.

5.6.13. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-*tert*-butylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] nitrate 2e. Compound **1e** (739 mg, 1.09 mmol) gave a brown solid (643 mg, 84%). Mp dec >300 °C; IR (cm^{-1}): 2956, 2864, 1628 (s, C=N), 1518, 1449, 1385, 1362, 1310, 1258, 1235, 1207, 1165, 1129, 1028, 878, 856, 837, 740, 719, 549; MS (ES) m/z (% relative intensity) (all peaks >3%): 638 (4), 640 (56), 641 (22), 642 (100, $\mathbf{M-NO_3^-}$), 643 (40), 644 (52), 645 (20), 646 (5), 671 (10), 672 (4), 673 (11, $\mathbf{M-NO_3^- + MeO}$), 674 (6), 675 (8), 718 (18), 719 (7), 720 (32, $\mathbf{M-NO_3^- + MeOH + 2Na}$), 721 (13), 722 (20), 723 (5), 749 (3), 751 (6, $\mathbf{M-NO_3^- + MeOH + 2Na + MeO}$), 752 (3), 796 (3), 798 (5, $\mathbf{M-NO_3^- + 2(MeOH + 2Na)}$), 800 (3). Anal. Calcd for $C_{28}H_{34}Br_2CrN_3O_5$: C, 47.74; H, 4.87; N, 5.97. Found: C, 45.37; H, 4.59; N, 5.17.

5.6.14. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-*tert*-butylsalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] hexafluorophosphate 3e. Compound **1e** (792 mg, 1.17 mmol) gave a brown solid (751 mg, 82%). Mp dec >300 °C; IR (cm^{-1}): 2960 (s), 2866, 1631 (s, C=N), 1518, 1449 (s), 1393, 1362 (w), 1257, 1165, 837, 740, 548; MS (ES) m/z (% relative intensity) (all peaks >3%): 638 (4), 640 (58), 641 (23), 642 (100, $\mathbf{M-PF_6^-}$), 643 (42), 644 (55), 645 (19), 646 (5), 671 (12), 672 (5), 673 (21, $\mathbf{M-PF_6^- + MeO}$), 674 (7), 675 (7), 718 (19), 719 (8), 720 (33, $\mathbf{M-PF_6^- + MeOH + 2Na}$), 721 (15), 722 (20), 723 (6), 749 (3), 751 (6, $\mathbf{M-PF_6^- + MeOH + 2Na + MeO}$), 753 (3), 796 (3), 798 (6, $\mathbf{M-PF_6^- + 2(MeOH + 2Na)}$), 800 (3). Anal. Calcd for $C_{28}H_{34}Br_2CrF_6N_2O_2P$: C, 42.71; H, 4.35; N, 3.56. Found: C, 43.36; H, 4.75; N, 3.39.

5.6.15. (*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methoxysalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III) chloride 1f. Compound **6f** (0.500 g, 0.925 mmol) gave brown precipitates (205 mg, 35% and 136 mg, 23%). Total yield = 58%. Mp dec >340 °C; IR (cm^{-1}): 3442, 2934, 2854, 1629 (s, C=N), 1535, 1454, 1435, 1392, 1335, 1307, 1279, 1222, 1137, 1040, 854, 808, 737, 671, 550, 470; MS (ES) m/z (% relative intensity) (all peaks >3%): 286 (17), 312 (3), 394 (3), 422 (5), 424 (3), 450 (3), 465 (5), 467 (5), 468 (3), 532 (4), 545 (3), 547 (6), 549 (3), 560 (3), 573 (13), 574 (5), 575 (28, $\mathbf{M-Cl^- - CH_3}$), 576 (9), 577 (15), 578 (4), 586 (3), 587 (3), 588 (55), 589 (27), 590 (100, $\mathbf{M-Cl^-}$), 591 (39), 592 (55), 593 (20), 594 (5), 619 (11), 620 (6), 621 (20, $\mathbf{M-Cl^- + OMe}$), 622 (7), 623 (10), 624 (3), 644 (3, $\mathbf{M-Cl^- + OMe + Na}$), 646 (3). Anal. Calcd for $C_{22}H_{22}Br_2ClCrN_2O_4$: C, 42.23; H, 3.54; N, 4.48. Found: C, 41.65; H, 4.16; N, 3.39.

5.6.16. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methoxysalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] nitrate 2f. Compound **1f** (151 mg, 0.241 mmol) gave a brown solid (118 mg, 75%). Mp dec >210 °C; IR (cm^{-1}): 3448, 2933, 2854, 1628 (s, C=N), 1535, 1455, 1435, 1372, 1337, 1309, 1226, 1139, 1053, 854, 808, 634; (ES)m/z (% relative intensity) (all peaks >3%): 424 (3), 547 (3), 573 (12), 574 (4), 575 (22, $\mathbf{M-NO_3^- - CH_3}$), 576 (7), 577 (11), 578 (4), 586 (3), 587 (4), 588 (55), 589 (26), 590 (100, $\mathbf{M-NO_3^-}$), 591 (42), 592 (49), 593 (19), 594 (6), 606 (3), 607 (3, $\mathbf{M-NO_3^- + OH}$), 619 (11), 620 (3), 621 (19, $\mathbf{M-NO_3^- + OMe}$), 622 (6), 623 (7), 624 (3), 644 (8, $\mathbf{M-NO_3^- + OMe + Na}$), 646 (3), 653 (3), 666 (11), 668 (22, $\mathbf{M-NO_3^- + MeOH + 2Na}$), 670 (11), 744 (3), 746 (7, $\mathbf{M-NO_3^- + 2(MeOH + 2Na)}$), 747 (4), 748 (4). Anal. Calcd for $C_{22}H_{22}Br_2CrN_3O_7$: C, 40.51; H, 3.40; N, 6.44. Found: C, 38.87; H, 3.64; N, 5.51.

5.6.17. [(*R*,*R*)-(−)-*N*,*N*′-Bis(3-bromo-5-methoxysalicylidene)-*trans*-cyclohexane-1,2-diamine chromium(III)] hexafluorophosphate 3f. Compound **1f** (100 mg, 0.160 mmol) gave a brown solid (60 mg, 51%). Mp dec >270 °C; IR (cm^{-1}): 3447, 2940, 2860, 1631 (s, C=N), 1537, 1456, 1434, 1391, 1335, 1225, 1140, 1052, 844, 809, 558; MS (ES) m/z (% relative intensity) (all peaks >3%): 312 (3), 424 (3), 547 (4), 573 (13), 574 (4), 575 (21, $\mathbf{M-PF_6^- - CH_3}$), 576 (7), 577 (11), 578 (5), 586 (5), 588 (52), 589 (24), 590 (100, $\mathbf{M-PF_6^-}$), 591 (42), 592 (49), 593 (19), 594 (5), 619 (12), 620 (5), 621 (18,

$\mathbf{M-PF_6^- + OMe}$), 622 (7), 623 (8), 624 (3), 668 (6, $\mathbf{M-PF_6^- + MeOH + 2Na}$) 670 (3). Anal. Calcd for $C_{22}H_{22}Br_2CrF_6N_2O_4P$: C, 35.94; H, 3.02; N, 3.81. Found: C, 34.11; H, 3.40; N, 2.98.

5.7. Asymmetric epoxidation of alkenes

5.7.1. Preliminary notes. Iodosylbenzene was synthesised using the procedure of Saltzmann and Sharefkin.[67] (±)-(*E*)-methlystyrene oxide was synthesised by reacting *trans*-β-methylstyrene with *m*CPBA. **CAUTION**: There is evidence that chromium(III)(salen) and oxo-chromium(V)(salen) complexes are genotoxic and carcinogenic and thus due care should be taken to avoid contact.[65]

5.7.2. Procedure for stoichiometric epoxidations with OCr(salen)$^+$. Iodosylbenzene (1.5 equiv) was added to a solution of the chromium salen complex (30 mg, 1 equiv) in acetonitrile (4 mL) and the mixture stirred for 30 min. A deep green-black colour developed rapidly. The mixture was then filtered through a cotton wool-plugged Pasteur pipette, to remove excess iodosylbenzene, into a 10 mL RB, which contained the donor ligand (1 equiv), if required. An additional 2 mL of acetonitrile was used as washings. The solution was stirred for 30 min in an ice/water bath to cool it to 0 °C. The alkene substrate (typically 5–10 μL, 1 equiv unless stated) was then added by microlitre syringe. The reaction was stirred at 0 °C until the brown colour of the original complex was adjudged to have returned (reaction times varied from 1 h to overnight). The solvent was removed in vacuo and the residue washed onto a short alumina pad (sometimes in a Pasteur pipette) using Et_2O (50 mL) as eluent. This was then concentrated to less than 1 mL, 1 μL of *n*-decane was added as internal standard and the sample was analysed by GC as described below. Benzaldehyde, iodobenzene and phenylacetone were detected in addition to unreacted alkene and the epoxides. Benzaldehyde was present as an impurity in *trans*-β-methlystyrene (1%).

5.7.3. Procedures for analysis of asymmetric epoxidation reactions

5.7.3.1. Ee determination. The worked up reaction mixture (see above) was an Et_2O solution (<1 mL) containing 1 μL of *n*-decane as an internal standard. 1 μL of this solution was injected onto the GC column. The ee of *trans*-β-methlystyrene oxide was determined using a GC equipped with a Supelco cyclodextrin-α capillary column (alphadex 120), 30 m×0.25 mm internal diameter (i.d.), 0.25 μm film, operated at an injection temperature of 230 °C and a column temperature of 93 °C. The retention times of the components of the reaction mixture relative to that of *n*-decane were as follows: benzaldehyde (2.1), *trans*-β-methlystyrene (2.2), iodobenzene (2.8), *trans*-β-methlystyrene oxide (4.3 and 4.5) and phenylacetone (5.7). Phenylacetone eluted after approximately 24 min.

5.7.3.2. Yield determinations. The compositions of the reaction mixtures were determined by comparison of individual peak areas to the peak area due to *n*-decane, the internal standard. GC analysis of authentic samples of possible products and by-products confirmed that the components of a typical chromium-mediated epoxidation of *trans*-β-methlystyrene were: the alkene and epoxide, iodobenzene, benzaldehyde and phenylacetone. The relative burn ratios of each of these were calculated by injecting 1 μL samples of solutions of known composition. The values determined were *trans*-β-methlystyrene oxide (1.41), *trans*-β-methylstyrene (1.09), iodobenzene (1.54), benzaldehyde (1.30) and phenylacetone (1.12). All yields were calculated using these ratios.

5.7.3.3. Determination of absolute configurations. The absolute configuration of *trans*-β-methlystyrene oxide was assigned by comparison with the data of Witkop and Foltz[68] and of Shi et al.[69] On the cyclodextrin-α column the (*R,R*)-*trans*-β-methlystyrene oxide eluted after the (*S,S*)-isomer.

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