Salan ligands assembled around chiral bipyrrolidine: predetermination of chirality around octahedral Ti and Zr centres†‡

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The first synthesis of Salan ligands assembled around the chiral 2,2′-bipyrrolidine backbone is described; as chelation to a metal can only occur *via* specific faces of the two pyrrolidine nitrogens, these ligands lead to predetermined chirality at metal centres of octahedral titanium and zirconium complexes.

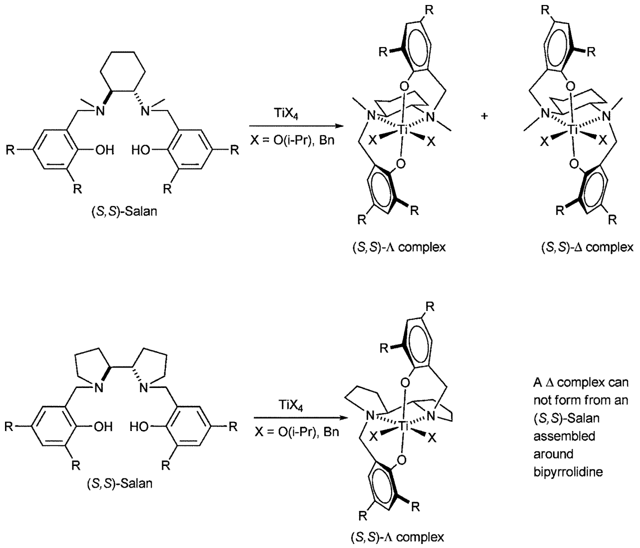
Salans are tetradentate dianionic sequential diamine-diphenolate ligands. They tend to wrap around octahedral centres of group 4 metals in a *fac–fac* mode thus creating chiral-at-metal complexes, designated by a Δ or Λ screw sense, in which the two labile groups are of *cis*-geometry. Non-chiral Salan ligands that feature identical phenolate arms lead to racemic mixtures of C_2-symmetric complexes, that have proven useful in isospecific olefin polymerization catalysis[1,2] and other transformations.[3] Chiral Salan ligands lead either to formation of *fac–fac* diastereomer mixtures[4] or to a single *fac–fac* diastereomer,[5] as a function of the efficiency of chiral induction from the ligand backbone to the ligand wrapping screw-sense. Single diastereomers of such complexes derived from enantiomerically pure ligands have emerged as highly promising catalysts for transformations such as chiral cyclopolymerization[6] and various oxidations.[7,8] The chiral Salan ligands introduced to date have been based on the *trans*-1,2-diaminocyclohexane backbone.[9,10] We have previously shown that while such chiral Salans yielded single diastereomers of zirconium complexes,[11] mixtures of diastereomers of titanium complexes were obtained unless a strict set of structural parameters was employed (*i.e.*, the nitrogens should be secondary, and the phenolate substituents should be non-bulky).[5] In an attempt to construct chiral Salan ligands that will wrap in a more defined fashion around metals, we sought different diamine skeletons. Herein we report that by constructing chiral Salan ligands around the 2,2′-bipyrrolidine backbone, predetermination of chirality[12] around octahedral titanium and zirconium centres is efficiently achieved.[13]

Chiral 2,2′-bipyrrolidine was previously synthesized by various routes.[14] 2,2′-Bipyrrolidine and its *N*-alkylated derivatives had been employed as chiral auxiliaries for metals[15] and as organocatalysts.[16] It was also employed as the backbone of chiral tetradentate neutral ligands (bearing pyridine-type arms).[17] However, to our knowledge, it has never been employed as the backbone of tetradentate dianionic ligands, such as Salans and related ligands. We anticipated that metal chelation by the endocyclic nitrogen donors would have to take place through specific faces of the bipyrrolidine system, leading to specific orientation of the methylene unit bound to the phenolate donor, and eventual determination of chirality at the metal. For example, chelation by an (*S*,*S*)-2,2′-bipyrrolidine requires binding *via* the *re*-face of the two nitrogen donors and an overall Λ-wrapping of the corresponding Salan around an octahedral metal centre, as shown in Scheme 1.

Two chiral Salan ligand precursors featuring the 2,2′-bipyrrolidine backbone, and either bulky di-*tert*-butyl phenolates (L^1H_2) or electron-withdrawing dichlorophenolates (L^2H_2) were synthesized by reactions between the chiral diamine and the bromomethyl derivatives of the corresponding phenols, as outlined in Scheme 2.

Upon reaction of the two ligand precursors with $Ti(O^iPr)_4$, the complexes $L^{1,2}Ti(O^iPr)_2$ were obtained as single diastereomers of C_2-symmetry according to ^1H NMR data (see ESI†).

This stands in sharp contrast to the reaction of the diaminocyclohexane-based Salan ligands (having tertiary *N*-donors)



Scheme 1 Octahedral titanium complexes derived from chiral Salan ligands based on diaminocyclohexane and bipyrrolidine skeletons, that may form as either two *fac–fac* diastereomers or as a single *fac–fac* diastereomer, respectively.

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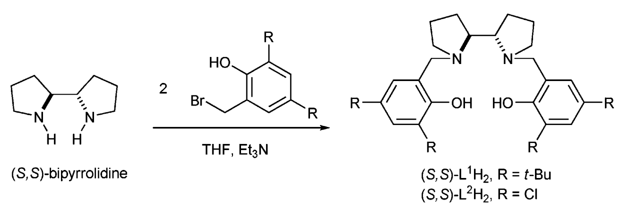
‡ *Crystal data* for $L^1Zr(O^tBu)_2$: $C_{46}H_{76}N_2O_4Zr$; M = 812.31; hexagonal; space group $P6_5$; a = 23.4652(5), b = 23.4652(5), c = 15.7143(2) Å; V = 7493.3(2) Å^3; T = 110(2) K; Z = 6; D_c = 1.080 g cm^{-3}; μ(Mo-Kα) = 0.257 mm^{-1}; No. of data collected 43878; R_{int} = 0.0747; R_1 = 0.0613 and wR_2 = 0.1376 for 7834 reflections with $I > 2\sigma(I)$; R_1 = 0.1039 and wR_2 = 0.1549 for all 11342 unique reflections.



Scheme 2

that gave diastereomer mixtures in this reaction. According to the ligand chirality and the arguments portrayed above, we propose that mononuclear octahedral complexes had formed in which the (*S*,*S*)-Salan ligands wrap in a *fac–fac* manner around the titanium centre to give Λ-chiral-at-metal diastereomers, as drawn in Scheme 1. The same high diastereoselectivity was found for zirconium. Reacting L^1H_2 and L^2H_2 with $Zr(O^tBu)_4$ and with $ZrBn_4$ (Bn = benzyl) led to the complexes $L^{1,2}Zr(O^tBu)_2$ and $L^{1,2}ZrBn_2$, respectively, obtained as single isomers of C_2-symmetry according to ^{1}H NMR.[18]

Single crystals of $L^1Zr(O^tBu)_2$ suitable for X-ray analysis were grown from cold pentane, and the structure was solved. The structure is very similar to that of a zirconium complex of the non-chiral Salan ligand, particularly apparent in the ligand *fac–fac* wrapping and *cis* geometry between the two O^tBu groups as may be appreciated in Fig. 1. Similar bond lengths and bond angles around the zirconium, and N–C–C–N dihedral angles in the two structures of 55.2 and 59.1°, respectively, reveal that the binding of the bipyrrolidine-Salan to the metal is not strained. The wide angles of *ca.* 166° of the labile alkoxo groups indicate a significant π-donation to the zirconium. The (*S*,*S*)-chirality of the ligand backbone was established in this chiral space group. Most importantly, the predicted Λ-wrapping of this enantiomer of the Salan ligand is clearly observed in the structure. We presume that the Salan ligands in the other zirconium and titanium complexes wrap analogously.

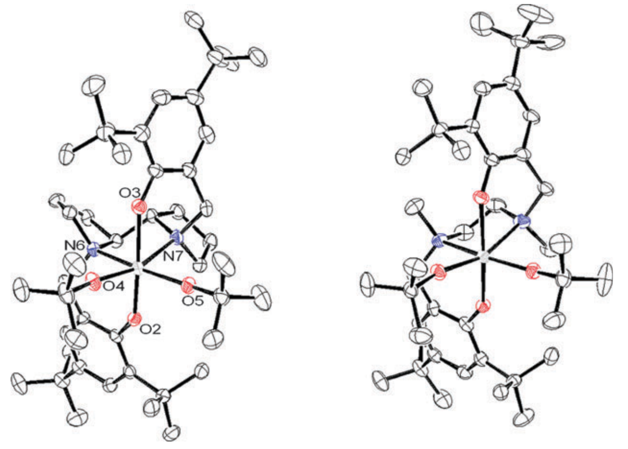


Fig. 1 ORTEP representation of (*S*,*S*)-$L^1Zr(O^tBu)_2$ (left) and a related complex prepared from non-chiral Salan ligand[3a] with 50% probability ellipsoids, and hydrogen atoms omitted for clarity. Selected bond lengths (Å) and angles (°): Zr–O2 2.050(3), Zr–O3 2.063(3), Zr–O4 1.940(3), Zr–O5 1.944(3), Zr–N6 2.464(4), Zr–N7 2.450(4); O2–Zr–O3 162.1(1), N6–Zr–N7 70.6(1), O4–Zr–O5 106.0(1), C46–O4–Zr 167.5(3), C50–O5–Zr 166.2(3).

To gain insight on the activity and stereoregulating ability of these systems we investigated the polymerization of neat 1-hexene by the two dibenzylzirconium complexes following activation with tris(pentafluorophenyl)borane. L^1ZrBn_2 featuring the bulky *tert*-butylphenolate substituents led to a polymerization catalyst of low activity of *ca.* 1 g mmol^{-1} h^{-1}, and to a polymer of relatively high isospecificity ([*mmmm*] = 87%). The pentad distribution supports an enantiomorphic site control mechanism for this polymerization. L^2ZrBn_2 featuring the electron-withdrawing chlorophenolate substituents led to a catalyst of considerably higher activity of *ca.* 150 g mmol^{-1} h^{-1}, and, as expected for the non-directing nature of the non-bulky groups, to a stereo-irregular polymer. The lower activity of the bipyrrolidine-based Salan complexes relative to those of the diaminoethane-based Salan complexes may result from the enhanced rigidity of the former. A related structure–activity trend was observed for the polymerization catalysis of 1-hexene by the dibenzylzirconium complexes of the Salan ligands based on the 1,2-*trans*-diaminocyclohexane bridge.[11]

In conclusion, we have synthesized the first Salan ligands assembled around chiral 2,2′-bipyrrolidine. These ligands were shown to lead to single diastereomers around octahedral metal centres, unlike the diaminocyclohexane based Salan ligands that gave diastereomer mixtures around titanium. The relatively high isospecificity in 1-hexene polymerization reflects on the potential applications of these chiral complexes in asymmetric catalysis. We are investigating the construction of related ligands around this strongly directing structural motif, which are expected to wrap in a predictable and diastereoselective manner in cases where ligands constructed around the *trans*-1,2-diaminocyclohexane lead to mixtures.

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Notes and references

1 E. Y. Tshuva, I. Goldberg and M. Kol, *J. Am. Chem. Soc.*, 2000, **122**, 10706; S. Segal, I. Goldberg and M. Kol, *Organometallics*, 2005, **24**, 200; S. Segal, A. Yeori, M. Shuster, Y. Rosenberg and M. Kol, *Macromolecules*, 2008, **41**, 1612.

2 V. Busico, R. Cipullo, R. Pellecchia, S. Ronca, G. Roviello and G. Talarico, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 15321; P. Corradini, G. Guerra and L. Cavallo, *Acc. Chem. Res.*, 2004, **37**, 231.

3 (*a*) For lactide polymerization by group 4 complexes of Salan ligands, see: S. Gendler, S. Segal, I. Goldberg, Z. Goldschmidt and M. Kol, *Inorg. Chem.*, 2006, **45**, 4783; (*b*) P. Hormnirun, E. L. Marshall, V. C. Gibson, A. J. P. White and D. J. Williams, *J. Am. Chem. Soc.*, 2004, **126**, 2688; A. J. Chmura, M. G. Davidson, M. D. Jones, M. D. Lunn, M. F. Mahon, A. F. Johnson, P. Khunkamchoo, S. L. Roberts and S. S. F. Wong, *Macromolecules*, 2006, **39**, 7250. For related transformations by related complexes, see: M. G. Davidson, C. T. O'Hara, M. D. Jones, C. G. Keir, M. F. Mahon and G. Kociok-Köhn, *Inorg. Chem.*, 2007, **46**, 7686.

4 J. Balsells, P. J. Carroll and P. J. Walsh, *Inorg. Chem.*, 2001, **40**, 5568.

5 A. Yeori, S. Groysman, I. Goldberg and M. Kol, *Inorg. Chem.*, 2005, **44**, 4466.

6 A. Yeori, I. Goldberg and M. Kol, *Macromolecules*, 2007, **40**, 8521.

7 Y. Sawada, K. Matsumoto, S. Kondo, H. Watanabe, T. Ozawa, K. Suzuki, B. Saito and T. Katsuki, *Angew. Chem., Int. Ed.*, 2006,

45, 3478; K. P. Bryliakov and E. P. Talsi, *Eur. J. Org. Chem.*, 2008, 3369.

8 For complexes of chiral Salan ligands with other metals, see: H. Egami and T. Katsuki, *J. Am. Chem. Soc.*, 2007, **129**, 8940; H. Egami and T. Katsuki, *Angew. Chem., Int. Ed.*, 2008, **47**, 5171.

9 Complexes of Salan ligands based on the 1,2-diphenyldiaminoethane were also explored but to a lesser extent.

10 K. Matsumoto, B. Saito and T. Katsuki, *Chem. Commun.*, 2007, 3619.

11 A. Yeori, I. Goldberg, M. Shuster and M. Kol, *J. Am. Chem. Soc.*, 2006, **128**, 13062.

12 U. Knof and A. von Zelewsky, *Angew. Chem., Int. Ed.*, 1999, **38**, 302.

13 For group 4 complexes of related biaryl-bridged ligands, see: P. D. Night, A. J. Clarke, B. S. Kimberley, R. A. Jackson and P. Scott, *Chem. Commun.*, 2002, 352; M. Strianese, M. Lamberti, M. Mazzeo and C. Pellecchia, *Macromol. Chem. Phys.*, 2008, **209**, 585.

14 See, for example: H. Kotsuki, H. Kuzume, T. Gohda, M. Fukuhara, M. Ochi, T. Oishi, M. Hirama and M. Shiro, *Tetrahedron: Asymmetry*, 1995, **6**, 2227; A. Alexakis, A. Tomassini, C. Chouillet, S. Roland, P. Mangeney and G. Bernardinelli, *Angew. Chem., Int. Ed.*, 2000, **39**, 4093; S. E. Denmark, J. Fu and M. J. Lawler, *Org. Synth.*, 2006, **83**, 121.

15 T. Oishi and M. Hirama, *J. Org. Chem.*, 1989, **54**, 5834.

16 S. Sulzer-Mossé and A. Alexakis, *Chem. Commun.*, 2007, 3123.

17 M. S. Chen and C. White, *Science*, 2007, **318**, 783; K. Suzuki, P. D. Oldenburg and L. Que Jr, *Angew. Chem., Int. Ed.*, 2008, **47**, 1887.

18 The similarity in the CD spectra of (R,R)-$L^{1,2}Ti(O^iPr)_2$ and (R,R)-$L^{1,2}Zr(O^tBu)_2$ support their identical absolute Δ-configuration (ESI†).