S. Afr. J. Chem., 2009, **62**, 60–66,
<http://journals.sabinet.co.za/sajchem/>.

Application of (*S,S*)-Pentacycloundecane bis(4-Phenyloxazoline) as a Novel Chiral Ligand for Catalysis of the Asymmetric Diels-Alder Reaction of Cyclopentadiene with 3-Acryloyl-2-oxazolidinone

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Received 7 October 2008, revised 25 November 2008, accepted 18 December 2008.

ABSTRACT

The synthesis of the novel C_1 symmetric (*S,S*)-pentacycloundecane bis(4-phenyloxazoline) ligand 5 and its evaluation as a chiral Lewis acid catalyst in the benchmark asymmetric Diels-Alder reaction between 3-acryloyloxazolidin-2-one (6) and cyclopentadiene (7) is reported. From the various metal salts screened the anhydrous magnesium perchlorate complex emerged as the best catalyst. The endo-cycloadduct product 8 was afforded in 81% enantiomeric excess with an endo:exo ratio of 98:2. An extensive screening of various metal ions as complexing agents was performed and is also reported.

KEY WORDS

Pentacycloundecane, oxazolines, chiral catalysis, Diels-Alder reaction.

1. Introduction

There is enormous interest in the design and development of efficient chiral ligands for asymmetric catalysis.[1–3] In particular, C_2-symmetric bis(oxazoline) **1** ligand-metal complexes have received attention because of their broad applicability in asymmetric reactions.[4,5] These ligands are derived from readily available chiral amino alcohols. The enantiocontrolling stereocentre lies adjacent to the coordinating nitrogen of the oxazoline ring, bringing the active metal in close proximity to the chiral centre. These ligands therefore have a marked influence on the stereochemical outcome of the reaction products.[6] As a result, various oxazoline-based ligands **1–4** incorporating a range of heteroatoms, additional chiral elements and other structural features have been employed in asymmetric catalysis.[7] Our research interests lie with the chemistry of pentacycloundecane (PCU) cage compounds and attachment of the rigid cage to chiral ligands.

The PCU cage renders the 'faces' of the ligand inherently diastereotropically non-equivalent.[8] We have employed the cage previously as the central unit in our chiral ligands.[9,10] Here we have chosen the same design strategy by appending an oxazoline moiety to each 'arm'. The synthetic elucidation of ligand **5** was recently reported.[11] This PCU-oxazoline bidentate ligand is one of a very few reported with C_1 symmetry.[10,12,13] It also offers a central ether oxygen which could potentially participate in the binding of the metal, thus leading to a tridentate ligand complex. Bis(oxazoline) catalyst complexes with this arrangement have not been pursued to any large extent.[7,14–17]

Bis(oxazoline)-derived ligands are well known to function as asymmetric Diels-Alder catalysts with alkenoyl imide dienophiles. 3-Acryloyl and 3-crotonoyl cyclopentadiene are used as the benchmark reactions to compare the efficiencies of different catalysts in asymmetric Diels-Alder reactions.[4] Herein we report a novel bis(oxazoline)-derived chiral ligand having a PCU framework. This new ligand was synthesized, complexed to various metal salts and the resulting complex was applied as an asymmetric Diels-Alder catalyst in the reaction of 3-acryloyl-2-oxazolidinone (**6**) and cyclopentadiene (**7**) to yield the chiral cycloadduct **8** (Scheme 1).

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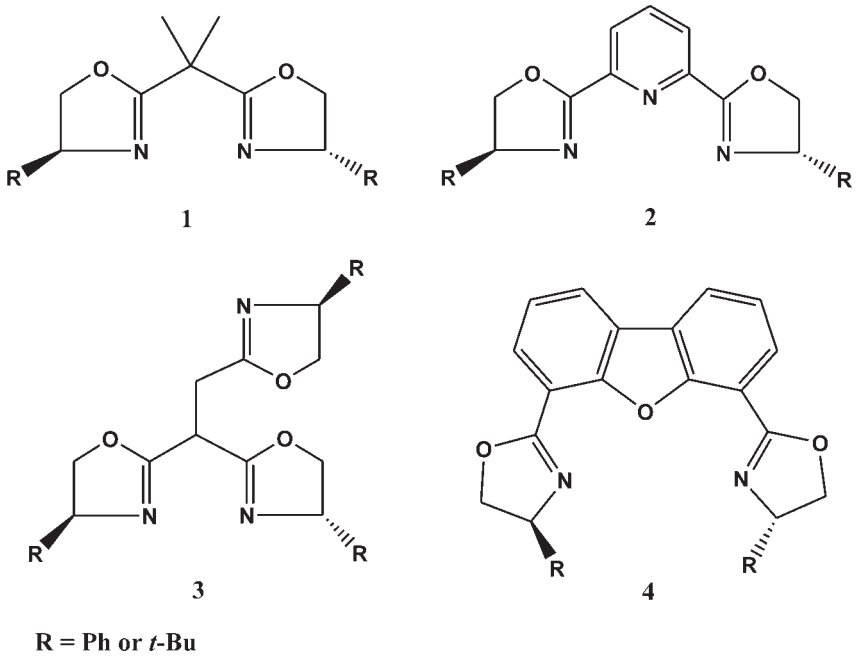
2. Results and Discussion

Synthesis of the novel PCU (*S,S*) bis(4-phenyloxazoline) ligand **5** follows the classical route involving the reaction of a diacid derivative (in this case the PCU diacid) with an amino alcohol to give the bis-amide intermediate; the latter is converted to the bis-(oxazoline) in two steps.[4,7] The PCU dione **9** was converted to the 3,5-diallyl-4-oxahexacyclo[5.4.1.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$.$0^{8,11}$]dodecane **10** as described previously.[18,19] Ozonolysis of **10** followed by an oxidative workup using formic acid and hydrogen peroxide afforded the PCU diacid **11**.[18] To avoid competing reactions due to the hydroxyl group on the amino alcohol it was decided to protect the alcohol by using tertiary butyl dimethyl silyl chloride (TBDMSiCl) to give (*S*)-N-(1-phenyl-2-tert-butyl-dimethylsilyl-ethoxy) amine (**12**).[20] This protecting group selectively protects hydroxyl groups in the presence of primary amines. *N,N*-Dicyclohexylcarbodiimide (DDC)-promoted condensation of the PCU diacid **11** with **12** afforded the protected PCU bis-amide **13** which was purified using column chromatography.[21] The PCU bis-amino alcohol **14** was obtained by deprotection of **13** with tetra-*N*-butylammonium fluoride (TBAF) and purification was again achieved using column chromatography.[20] Cyclization was obtained by the chlorination of **14** using thionyl chloride to give the PCU bis-chloride **15**, followed by treatment with

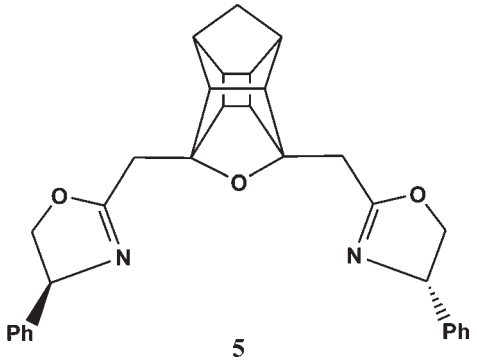


aqueous sodium hydroxide[4,15] to yield the PCU bis(4-phenyloxazoline) derivative **5**. The final product was isolated by column chromatography in 80% yield from the PCU bis-amino alcohol **14** as shown in Scheme 2. The full NMR elucidation of the novel compounds **13, 14** and **5** was recently published.[11]

Various alkaline earth and transition metals are known to complex to bis(oxazoline)-derived ligands. A series of metals was screened for the *in situ* formation of the catalyst complex from ligand **5** (Table 1). The complexation procedure involved the addition of an equimolar amount of the metal salt to a solution of the ligand in dichloromethane.[22] The resultant catalyst complex was used to promote the described asymmetric Diels-Alder reaction (Scheme 1).

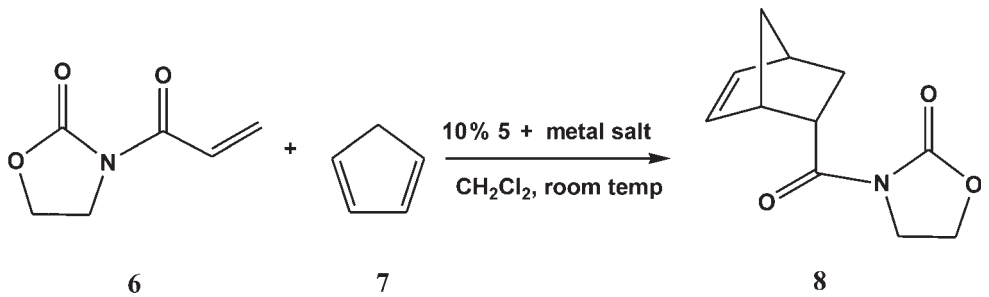
From a range of metal salts evaluated, anhydrous $Mg(ClO_4)_2$ emerged as the best Lewis acid complex in terms of enantioselectivity (Table 1, entry 6). Magnesium bis(oxazoline) complexes have been reported to display varying catalytic activity in Diels-Alder reactions.[15,23–26] Since anhydrous magnesium perchlorate gave the highest enantiomeric excess it was decided to optimize the solvent for this reaction. Substitution of the solvent CH_2Cl_2 with THF or CH_3CN led to lower yields and enantioselectivities (Table 2).

Once it was established that dichloromethane was the best solvent, we next optimized the counterion on the metal-ligand complex. Different magnesium salts were investigated to determine the effect of the counterion on the catalyst in the reaction (Table 3). These results indicated that the enantiomeric excess increased with increasing Lewis acidity of the metal in the order $Mg(OTf)_2 < Mg(SbF_6)_2 < Mg(ClO_4)_2$.

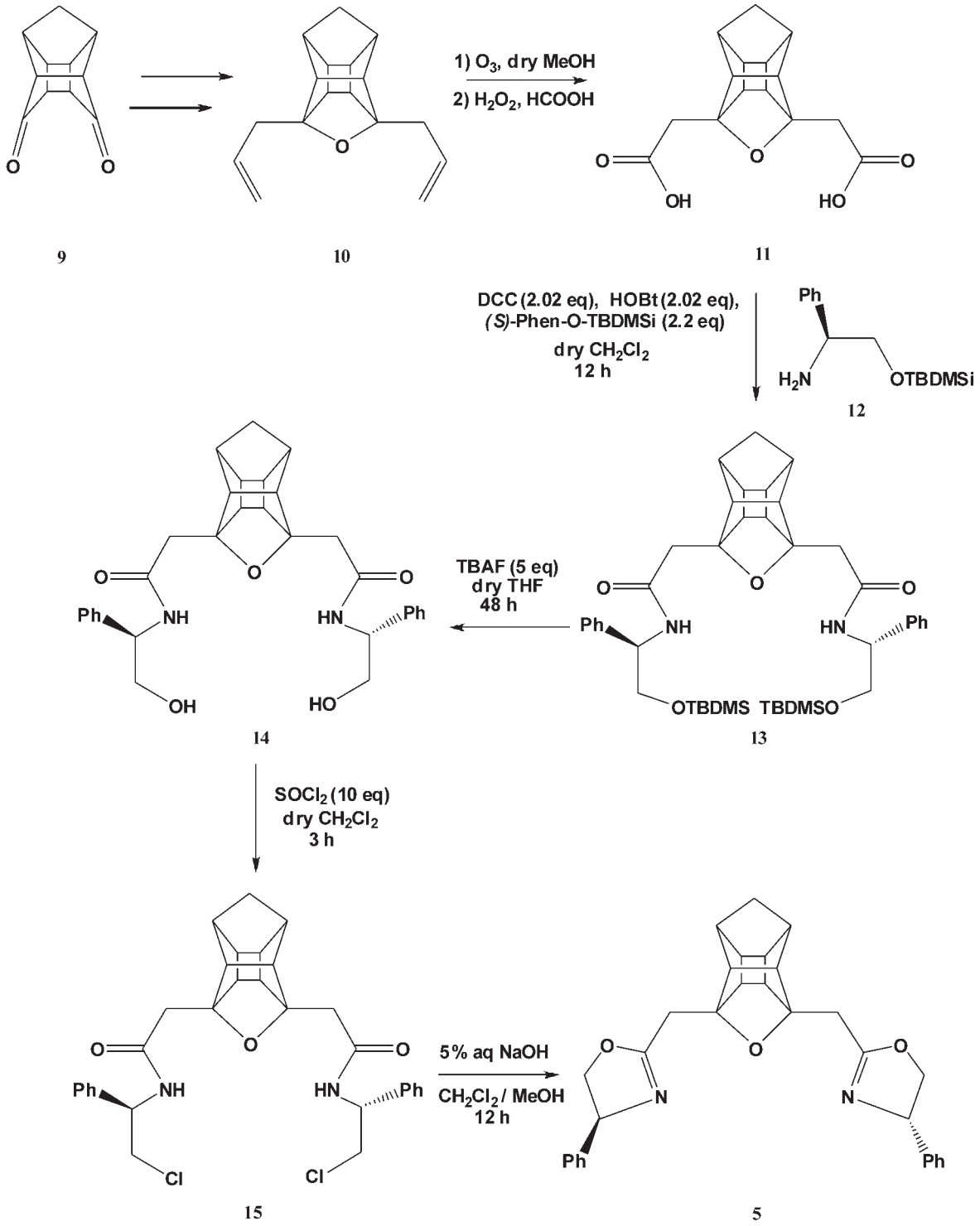


Once the optimum solvent and counterion were determined, different loadings of the catalyst were investigated and 10 mol % proved to be the best option (Table 4, entries 1, 2 and 4). The addition of molecular sieves to ensure strictly anhydrous conditions did not affect the enantiomeric excess or yield of the reaction (Table 4, entry 3). In order to evaluate the reaction temperature-enantioselectivity profile, experiments at room temperature, 0 °C and –40 °C were carried out (Table 4, entries 6 and 7). As expected for this reaction, the enantiomeric excess increased with decreasing temperature. Experiments at temperatures lower than –40 °C were impossible due to extremely low reaction rates, therefore the reaction at –40 °C proved to yield the best result with an enantiomeric excess of 81% (Table 4, entry 7).

It is important to note that the blank reaction (Table 1, entry 1) takes place without any catalyst, albeit much slower. In order to investigate to what extent the enantioselectivity is influenced by



Scheme 1
Diels-Alder reaction of 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**).



Scheme 2
Synthesis of ligand **5** from PCU dione **9**.

the non-catalyzed reaction (racemic products form), the experiment was performed with slow addition of cyclopentadiene (Table 4, entry 5). From the data, it is clear that the enantioselectivity is not influenced by a concurrent non-catalyzed racemic reaction.

From the metals screened (Table 1, entries 2 to 4), namely calcium, zinc and copper, the corresponding products resulted in excess of the (*R*)-enantiomer while the other metals gave rise to excess of the (*S*)-enantiomer. According to the literature bis(oxazoline) ligands are known sometimes to reverse the chirality of **8** when zinc or copper are used.[25,27–30] There are no other reports on bis(oxazoline)-calcium complexes tested on Diels-Alder type reactions, therefore a comparison with our calcium result could not be made from the literature. The inversion of chirality on the products when zinc or copper are used was attributed to the different transition states experienced by the complex as a result of changing the metal cation or substituents on the ligand.[31] Corey *et al.*[32] observed when magnesium complexes of (*R*)-**1** (*R* = Ph) were tested for this reaction that the predominant product was the (*S*)-configuration. A tetrahedral magnesium-bis(oxazoline) dienophile complex was proposed to account for the observed asymmetric induction. Evans *et al.*[29]

Table 1 The reaction of 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**) catalyzed by ligand (*S,S*)-**5** complexed to various metal salts in CH_2Cl_2 at room temperature.

Entry	Metal salt	Time/min	Yield/%	Endo:exo[a]	Endo ee/%[b]	Configuration (**8**)
1	Blank	240	80	96:4	0	–
2	$Ca(ClO_4)_2$	45	77	84:16	33	*R*
3	$Zn(ClO_4)_2$	15	75	88:12	40	*R*
4	$Cu(ClO_4)_2$	30	71	86:14	25	*R*
5	$Ni(ClO_4)_2$	120	60	83:17	25	*S*
6	$Mg(ClO_4)_2$	10	85	90:10	72	*S*
7	$Ba(ClO_4)_2$	150	17	80:20	0	–
8	$Al(ClO_4)_3$	20	86	83:17	0	–
9	$Co(ClO_4)_2$	45	86	86:14	28	*S*
10	$Fe(ClO_4)_2$	15	62	86:14	30	*S*
11	$Mn(ClO_4)_2$	60	78	89:11	36	*S*
12	$Cu(OTf)_2$	75	55	81:19	7	*S*
13	$Sc(OTf)_2$	15	62	85:15	5	*S*

[a] Determined by ^{1}H NMR.
[b] Determined by HPLC (Chiralpak IB).

Table 2 Solvent effect on the reaction of 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**) catalyzed by ligand (*S,S*)-**5** complexed to $Mg(ClO_4)_2$ at room temperature.

Solvent	Time/min	Yield/%	Endo:exo	Endo ee/%	Configuration (**8**)
DCM	10	85	90:10	72	*S*
THF	150	87	89:11	2	*S*
CH_3CN	240	80	92:8	14	*S*

Table 3 Effect of different counterions on reaction of 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**) catalyzed by ligand (*S,S*)-**5** and Mg salts in CH_2Cl_2 at room temperature.

Metal salt	Time/min	Yield/%	Endo:exo	Endo ee/%	Configuration (**8**)
$Mg(ClO_4)_2$	10	85	90:10	72	*S*
$MgBr_2$	240	60	90:10	2	*S*
$MgCl_2$	150	48	92:8	8	*S*
$Mg(OTf)_2$	120	73	91:9	17	*S*
$Mg(SbF_6)_2$	30	95	92:8	23	*S*

proposed a square planar coordination for the copper complex of (*R*)-**1** (R = *t*-Bu), in which the product was the (*R*)-configuration for the same Diels-Alder reaction. An interesting observation occurred when both Evans' and Corey's ligands with the (*R*)-configuration were complexed to magnesium. When the counterion is perchlorate the product of the reaction is (*S*)-**8**, but if two equivalents of water are added to the reaction the product obtained is (*R*)-**8**.[23] This stereochemical outcome was explained by Desimoni *et al.* by establishing that water acts as an auxiliary ligand which will expand the coordination number from four (tetrahedral) to six (octahedral) when the counterion is perchlorate.[4,33,34] Since our best result was from $Mg(ClO_4)_2$ it was decided to do a theoretical investigation to determine if the tetrahedral complex form proposed in the literature is applicable in the reaction investigated by us. Optimizations of the two possible conformations of the magnesium complex of ligand **5** with the substrate **6** were performed using density functional theory (DFT) calculations. The first complex A has the unsaturated bond of the dienophile **6** facing upwards while the second structure (complex B) has it facing downwards.

The geometry of both complexes is pentacoordinate. The calculations revealed the distance between the magnesium ion and imine nitrogens to be 2.18 Å and 2.11 Å. The distance between the magnesium ion and carbonyl oxygen of the dienophile is 2.01 Å. The ether oxygen on the PCU moiety also participated in binding to the magnesium ion since the calculated metal to oxygen distance is 2.21 Å. It is therefore proposed that the pentacoordinate system (Fig. 1) behaves similarly to the octahedral complex suggested by Desimoni *et al.* This could possibly explain the observation of no inversion occurring on

Table 4 Effect of different catalytic loadings, additives and temperatures on the reaction of 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**) catalyzed by ligand (*S,S*)-**5** complexed to $Mg(ClO_4)_2$ in CH_2Cl_2.

Entry	Mol % ligand	Temperature/°C	Time/min	Yield/%	Endo:exo[a]	Endo ee/%[b]
1	1	r.t.	60	80	87:13	25 (*S*)
2	5	r.t.	45	79	89:11	30 (*S*)
3	10[c]	r.t.	15	86	90:10	71 (*S*)
4	10	r.t.	[d]	87	90:10	72 (*S*)
5	10[d]	r.t.	10	86	90:10	72 (*S*)
6	10	0	30	84	90:10	74 (*S*)
7	10	–40	[e]	–	98:2	81 (*S*)

[a] Determined by ^{1}H NMR.
[b] Determined by HPLC (Chiralpak IB).
[c] 4 Å Molecular sieves added.
[d] Slow addition of cyclopentadiene over 1 h.
[e] Reaction was too slow and stopped after 24 h , without going to completion (<10% yield).

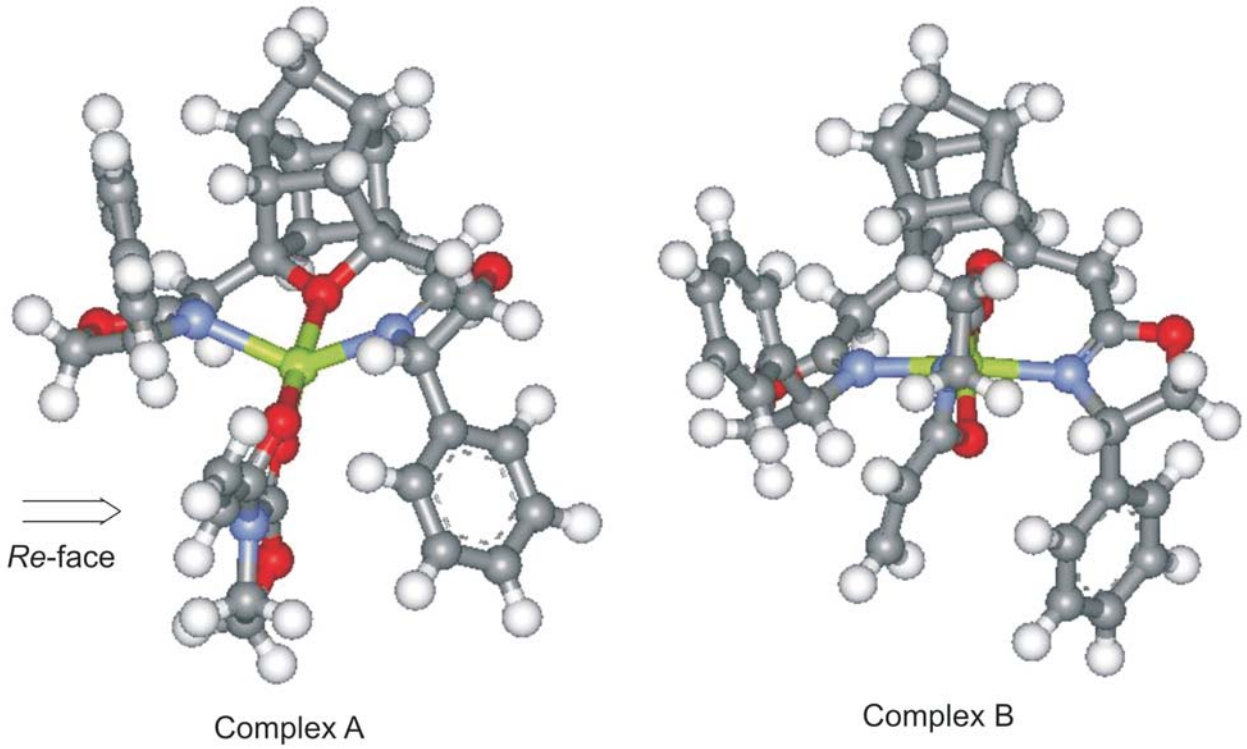


Figure 1 Optimized structures of the ligand-Mg-dienophile complexes [B3LYP/6-31+G(d)].

the chirality of the reaction product.

It appears that ligand **5** is one of very few tridentate *N,O,N*-bis(oxazoline)-type ligands reported before.[15,35,36]

In addition, the calculated energies of these possible complex structures show that complex A is more energetically favoured than complex B by 20 kJ mol^{-1}. Upon inspection of the low energy complex structure it was quite clear that the *Re*-face of the unsaturated bond of the dienophile **6** is much less hindered than the *Si*-face (see Fig. 1). This will lead to the (*S*)-*endo* product **8**. This theoretical result is consistent with the experimentally observed absolute configuration and enantiomeric purity of the (*S*)-*endo* product **8** determined by chiral HPLC analysis.

Furthermore, inspection of the HOMO of the computed complex structure also revealed that the dienophile (oxazolidinone **6**) experienced a high level of delocalization (the cube file of the calculated complex HOMO is available from kruger@ukzn.ac.za).

A significant level of delocalization would explain the rigidity of the dienophile, which prevents rotation around the C-1′-C-2′ bond, as indicated above. Oxazolidinone in form **6a** will yield the correct product for pro-*S* attack while **6b** will give the opposite product. Note that cyclopentadiene attacks the alkene **6a** with the CH_2 group farthest away from the carbonyl oxygen.

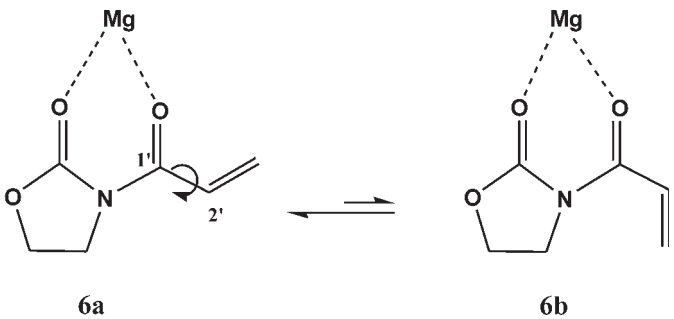


Figure 2 Simplified scheme of dienophile (**6**) complexed to Mg(II).

Conclusions

A novel C_1 symmetric PCU bis(4-phenyloxazoline) ligand **5** was synthesized and tested on the asymmetric Diels-Alder reaction between 3-acryloyloxazolidin-2-one (**6**) and cyclopentadiene (**7**). The anhydrous magnesium perchlorate complex emerged as the best catalyst providing the *endo*-cycloadduct product **8** of the reaction in 81% enantiomeric excess with an *endo:exo* ratio of 98:2. From the molecular modelling of this magnesium complex with substrate **6**, the more energetically favoured conformation was established which had the *Re*-face of the dienophile in a less hindered position. Diels-Alder cycloaddition of cyclopentadiene to the *Re*-face leads to a product consistent with the experimentally observed *endo* product **8**. A pentacoordinate complex system is observed in the computed complex structure. The calculated bond length revealed that the ether oxygen of the PCU moiety acts as a donor atom to the magnesium ion in the complex. The computational model also suggests that further modifications on the PCU skeleton will not affect any asymmetric induction and therefore further study will focus on the derivatization on the R-group of the oxazoline moiety and testing of ligand **5** analogues on additional asymmetric catalytic reactions.

4. Experimental

4.1. General

All solvents were distilled from the appropriate desiccant. NMR spectra were recorded on a Bruker (Karlsruhe, Germany) AVANCE III 400 MHz instrument. Infrared spectra were obtained on a Perkin-Elmer (Waltham, MA, USA) Spectrum 100 instrument with an attenuated total reflectance (ATR) attachment. Optical rotations were carried out on a Perkin-Elmer 341 polarimeter. All melting points are uncorrected. Column chromatography was carried out using silica gel 60. Mass spectra were measured on a Waters (Milford, MA, USA) LCT Premier time of flight (TOF) mass spectrometer. HPLC analysis was carried out with a Shimadzu (Tokyo, Japan) Prominence fitted

with a LC-2AD pump, SIL-20A autosampler and SPD-M2OA diode array detector. The type of column and conditions are described in the appropriate experimental section below.

4.2. 5,5-Dicarboxymethyl-4-oxahexacyclo[5.4.1.0^{2,6}.0^{5,10}.0^{5,9}.0^{8,11}] dodecane (11)[9,10]

A solution of the diene **10** (5.0 g, 20.3 mmol) in dry methanol (150 mL) was cooled to –78 °C *via* application of an external dry ice–acetone bath and was then purged with nitrogen for 20 min. Ozone was bubbled into the mixture until a blue-purple colour persisted, thereby indicating the presence of excess ozone and completion of the reaction. Excess ozone was flushed from the reaction vessel with a stream of nitrogen, and the reaction mixture was concentrated *in vacuo* to yield the ozonide. Hydrogen peroxide (50 mL, 30%) was added dropwise to a stirred, ice bath-cooled mixture of the ozonide and formic acid (50 mL, 80%). The resulting mixture was stirred at ambient temperature for 1 h and then refluxed for 12 h. The reaction mixture was allowed to cool gradually to ambient temperature, during which time the product precipitated out of solution. Pure **11** (4.7 g, 82%) was thereby obtained as a colourless microcrystalline solid: Melting point = 175–175.5 °C. ^{1}H NMR (DMSO) δ = 1.45 (AB, J_{AB} = 10 Hz, 1H), 1.83 (AB, J_{AB} = 10 Hz, 1H), 2.36–2.80 (m, 12H) and 12.15 ppm (br s, 2H); ^{13}C NMR (DMSO) δ = 37.94 (t), 41.27 (d), 42.81 (t), 44.04 (d), 47.91(d), 58.55 (d), 92.56 (s) and 171.40 ppm (s).

4.3. (*S*)-N-(1-phenyl-2-tert-butyl-dimethylsilylethoxy) amine (12)[20,37]

(*S*) Phenylglycine methyl ester (1.0 g, 4.9 mmol) was added to a stirred solution of lithium aluminum hydride (0.4 g, 9.8 mmol) in dry THF (150 mL) at ambient temperature. Thereafter the solution was refluxed for 1.5 h. The reaction mixture was then removed from the heat source and allowed to cool, after which an equal volume of diethyl ether was added. The reaction was quenched with saturated aqueous Na_2SO_4 solution. It was filtered and the solvent removed *in vacuo* to yield pure amino alcohol as yellow crystals (0.6 g, 88%). To a solution of the amino alcohol (3.0 g, 21.7 mmol) in dry CH_2Cl_2 (150 mL) were added Et_3N (6.3 mL, 44.5 mmol) and DMAP (0.5 g, 4.09 mmol) at room temperature. The solution was cooled to 0–1 °C and TBDMSiCl (3.4 g, 27.7 mmol) in CH_2Cl_2 (20 mL) was added. The solution was stirred for a further 48 h at room temperature and then H_2O (30 mL) was added. The layers were separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic phases were dried over anhydrous Na_2SO_4 and the solvent was removed *in vacuo.* The resulting residue was purified by column chromatography (CH_2Cl_2/MeOH = 95:5) to afford product **12** (4.5 g, 83%) as a yellow oil. ^{1}H NMR ($CDCl_3$) δ = 0.04 (6H, s), 0.91 (9H, s), 1.85 (NH, br s), 3.50 (1H, dd CH_2O), 3.72 (1H, dd, CH_2O), 4.07 (1H,dd, C*H*Ph) and 7.40–7.23 ppm (5H, m); ^{13}C NMR ($CDCl_3$) δ = –5.41 (CH_3), 18.3 (CH_3), 25.9 (*C*(CH_3)$_3$), 57.6 (*C*HPh), 69.5 (CH_2O), 126.9, 127.2, 128.2 and 142.6 ppm (aromatic).

4.4. PCU bis-amide 13[11]

To a stirred solution of **11** (2.0 g, 7.25 mmol) in dry CH_2Cl_2 (150 mL), HOBt (2.0 g, 14.6 mmol) and DCC (3.0 g, 14.6 mmol) were added respectively. This mixture was allowed to stir for 15 min until a clear homogenous solution was obtained. Thereafter a mixture of **12** (4.5 g, 18.0 mmol) and Et_3N (4.0 mL, 28.9 mmol) in 50 mL dry CH_2Cl_2 was added and the resulting mixture was stirred at ambient temperature for a further 12 h. The reaction mixture was then filtered and H_2O added to the filtrate. The layers were separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic phases were dried over anhydrous Na_2SO_4 and the solvent was removed *in vacuo.* The resulting residue was purified by column chromatography (hexane/EtOAc = 50:50) to afford compound **13** (4.8 g, 90%) as a yellow solid. $[\alpha]^{20}_D$ –11.35 ° (c = 1 g (100 mL)$^{-1}$, CH_2Cl_2). IR ν_{max}: 3312 cm^{-1} (s), 1646 cm^{-1} (vs), 1112 cm^{-1} (vs) and 776 cm^{-1} (vs). Melting point = 126–130 °C. HRMS calculated for $C_{43}H_{62}N_2O_5Si_2$ (M + H$^+$) 743.4231, found 743.4146. ^{1}H NMR ($CDCl_3$) δ = 0.00 (s), 0.98 (s), 1.65 (d) (AB, J_{AB} = 10.5 Hz), 1.98 (d) (AB, J_{AB} = 10.5 Hz), 2.87 (m), 3.06 (m), 4.05 (m), 5.21 (s) and 7.36–7.52 ppm (aromatic); ^{13}C NMR ($CDCl_3$) δ = –5.60 (t), 18.26 (s), 25.83 (q), 39.91 (t), 41.50 (d), 43.35 (t), 44.28 (d), 48.83 (d), 54.64 (d), 59.11 (d), 66.60 (t), 94.21 (d), 126.92 (d), 127.24 (d), 128.52 (d), 140.36 (s) and 169.2 ppm (s).

4.5. PCU bis-amino alcohol 14[11]

The PCU bis-amide **13** (5.5 g, 7.41 mmol) was dissolved in dry THF (200 mL) and TBAF (29.6 mL, 1 mol L^{-1} in THF) was added. The mixture was stirred for 48 h at ambient temperature. Brine was added and the layers were separated. The aqueous layer was extracted with EtOAc. The combined organic layers were dried over anhydrous Na_2SO_4 and the solvents were removed *in vacuo.* The resulting residue was purified by column chromatography (EtOAc/MeOH = 95:5) to afford the deprotected alcohol **14** (3.0 g, 76%) as a pale yellow solid. $[\alpha]^{20}_D$ +32.45 ° (c = 1 g (100 mL)$^{-1}$, CH_2Cl_2). IR ν_{max}: 3288 cm^{-1} (br), 1641 cm^{-1} (vs), 1039 cm^{-1} (s) and 706 cm^{-1} (vs). Melting point 50–60 °C. HRMS calculated for $C_{31}H_{34}N_2O_5$ (M + H$^+$) 515.2501, found 515.2418. ^{1}H NMR ($CDCl_3$) δ = 1.55 (d) (AB, J_{AB} = 10.5 Hz), 1.90 (d) (AB, J_{AB} = 10.5 Hz), 2.45 (s), 2.73 (m), 2.82 (m), 3.73 (m), 5.02 (s) and 7.23–7.43 ppm (aromatic); ^{13}C NMR ($CDCl_3$) δ = 39.49 (t), 41.54 (d), 43.48 (t), 44.12 (d), 48.63 (d), 55.23 (d), 59.05 (d), 65.90 (t), 94.14 (d), 126.6 (d), 127.6 (d), 128.6 (d), 139.3 (s) and 170.1 ppm (s).

4.6. PCU bis(4-phenyloxazoline) 5[11]

To a stirred solution of **14** (1.0 g, 1.88 mmol) in dry CH_2Cl_2 (100 mL), $SOCl_2$ (2.7 mL, 37.5 mmol) was added. The solution was stirred at ambient temperature for 3 h. The resulting mixture was poured into H_2O and extracted with CH_2Cl_2. The combined organic extracts were dried over Na_2SO_4 and the solvent removed *in vacuo* to yield a brown residue of the PCU bis-chloride **15**, which was used without further purification. The residue was treated with NaOH (1 g in 20 mL H_2O) in a MeOH (50 mL)/CH_2Cl_2 (30 mL) solution at ambient temperature for 12 h. The organic solvents were evaporated *in vacuo* and the residue was extracted with CH_2Cl_2. The combined organic extracts were dried over anhydrous Na_2SO_4 and the solvents were removed *in vacuo.* The resulting residue was purified by column chromatography (100% EtOAc) to afford the PCU bis(4-phenyloxazoline) ligand **5** (0.72 g, 80%) as a yellow oil. $[\alpha]^{20}_D$ –57.24 ° (c = 0.85 g (100 mL)$^{-1}$, $(CH_3)_2CHOH$). IR ν_{max}: 2964 cm^{-1} (w), 1663 cm^{-1} (s), 984 cm^{-1} (s) and 700 cm^{-1} (vs). HRMS calculated for $C_{31}H_{30}N_2O_3$ (M + H$^+$) 479.2290, found 479.2350. ^{1}H NMR ($CDCl_3$) δ = 1.55 (d) (AB, J_{AB} = 10.5 Hz), 1.90 (d) (AB, J_{AB} = 10.5 Hz), 2.45 (s), 2.73 (m), 2.82 (m), 3.73 (m), 5.02 (s) and 7.23–7.43 ppm (aromatic); ^{13}C NMR ($CDCl_3$) δ = 32.11 (t), 41.86 (d), 43.55 (t), 44.64 (d), 48.67 (d), 59.26 (d), 69.66 (d), 74.76 (t), 93.71 (d), 126.5 (d), 127.6 (d), 128.8 (d), 142.3 (s) and 165.9 ppm (s).

4.7. General Procedure for the Diels-Alder Reactions Catalyzed by the PCU bis (4-phenyloxazoline) Complexes

4.7.1. *Preparation of the Anhydrous Magnesium (II) Complex*

A mixture of PCU bis (4-phenyloxazoline) **5** ligand (17 mg, 0.04 mmol), anhydrous $MgBr_2$ (6.5 mg, 0.04 mmol), and anhydrous $AgClO_4$ (14.7 mg, 0.08 mmol) in dry CH_2Cl_2 (5 mL) was stirred under dry nitrogen at ambient temperature for 6 h,

during which time a gray precipitate of silver bromide appeared. The resulting suspension was used without filtration for the Diels-Alder reactions as follows: 3-acryloyl-2-oxazolidinone **6** (50 mg, 0.4 mmol) and freshly distilled cyclopentadiene **7** (0.3 mL, 4.0 mmol) were added to this suspension. The reaction was performed at room temperature and monitored by TLC. After the completion of reaction, saturated aqueous ammonium chloride was added and the mixture was extracted with CH_2Cl_2. The combined organic extracts were dried over Na_2SO_4 and the solvents were removed *in vacuo*. The resulting residue was purified by flash column chromatography (hexane/EtOAc = 70:30) to give a mixture of *endo* and *exo* isomers of cycloadduct **8** (60 mg, 85%). The *endo:exo* ratio was evaluated on the basis of the ^{1}H NMR spectrum and the enantiomeric excess determined by HPLC with a Daicel Chiralpak IB column (hexane/*i*-PrOH = 95:5), flow rate = 1 L min^{-1}, *t*(*R*) 24.0 min, *t*(*S*) 22.6 min. Other anhydrous PCU bis (4-phenyloxazoline) complexes were prepared according to a similar procedure by using anhydrous metal halides such as $NiBr_2$, $CaBr_2$, $MnBr_2$, $FeCl_2$, $CoBr_2$, $CuCl_2$ and ZnI_2.

4.8. 3-(Bicyclo[2.2.1]hept-5-en-2-carbonyl)oxazolidin-2-one (8)[15,38]

Colourless solid; enantiomeric purity was estimated on the basis of HPLC using a chiral column as described above and the *endo*:*exo* ratio was evaluated on the basis of the ^{1}H NMR spectrum; ^{1}H NMR ($CDCl_3$) δ = 1.3–1.7 (3H, m, H-3 and one of H-7), 1.9–2.1 (1H, m, the other of H-7), 2.94 (1H, m, H-1 or H-4), 3.31 (1H, m, H-4 or H-1), 3.8–4.1 (3H, m, H-2 and H-4′), 4.40 (2H, t, H-5′), 5.88 (1H, dd, H-5) and 6.25 ppm (1H, dd, H-6); ^{13}C NMR ($CDCl_3$) δ = 29.56 (C-3), 42.89, 42.95, 43.21, 46.39 (C-1, C-2, C-4, and C-4′), 50.18 (C-7), 61.97 (C-5′), 131.63, 138.11 (C-5 and C-6), 153.41 (C-2′), and 174.75 ppm (CO).

4.9. Computational Details

Complexes A and B were optimized using GAUSSIAN 03,[39] utilizing density functional theory (DFT) in the gas phase with the B3LYP functional and with the 6-31+(G)d basis set. Diffuse functions are typically used for a more accurate description where lone pair electrons are involved, while polarization functions remove some limitations of the basis set by expansion of the virtual space. Solvation effects were not considered in order to simplify the model. Cartesian coordinates of the optimized structures are available as Supplementary Material online. A number of variations of the starting geometry were explored, but it was quite clear that the rigid nature of the complexes revert to the same low energy structures.

Acknowledgements

This work was supported by Grants from the National Research Foundation Gun 2073251 (South Africa), the South African/Swedish Research Links Programme (Gun 2072799) and the University of KwaZulu-Natal.

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Supplementary material to:

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Complex A (See Figure 1 in the Research Article)

HF = -2247.9843573 a.u.

C,-0.8756594364,4.1301826061,2.3090924325
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Complex B (See Figure 1 in the Research Article)

HF = -2247.9763431 a.u.

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C,-5.6487908452,-0.5859286534,-3.1737930233
C,-5.0398352591,0.5672320835,-2.6715239004
H,3.1454559346,-1.4343542115,-2.5730850936
H,1.5244325755,-1.7467156163,-3.1527632022
H,-1.4192863501,-4.223977396,0.2896096403
H,-0.8683494547,-3.856493754,1.9068935645
H,0.9416420492,2.2578078596,-3.9131145326
H,2.52629632,2.9315358068,-3.4019963511
H,0.2497753718,2.7403607112,-1.6695049486
H,-3.3581589634,0.3421976006,0.9220686117
H,-4.0112759785,-1.1488220746,2.6758452005
H,-5.0577752489,-1.9820744384,1.4896658963
H,1.0872838087,4.7943154119,-0.8913082929
H,3.5257634261,1.281240133,-0.4619205154
H,2.7142292585,6.0855663627,0.4739439862
H,5.1338693198,2.5503220497,0.911886767
H,4.7494834454,4.964726291,1.3843691996
H,-4.7985138177,-2.7657585658,-0.7054404528
H,-3.8311955963,1.4123320082,-1.0861319665
H,-6.0232479196,-2.6885173637,-2.8449157639
H,-6.1916110998,-0.5530153828,-4.1154051716
H,-5.1013756804,1.5029030234,-3.2215225397
Mg,-0.4837761204,0.0570832323,-0.1423624541