Chiral arene ruthenium complexes as asymmetric Diels–Alder catalysts

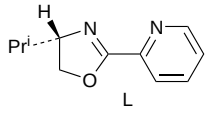
David L. Davies,* John Fawcett, Shaun A. Garratt and David R. Russell

Department of Chemistry, University of Leicester, Leicester, UK LE1 7RH

The cation [RuCl(L)(η⁶-mes)]⁺ [L = 4-isopropyl-2-(2-pyridyl)-1,3-oxazoline] is synthesised diastereoselectively; treatment with $AgSbF_6$ gives a dication which is an enantioselective catalyst for the asymmetric Diels–Alder reaction between methacrolein and cyclopentadiene.

Recently, much attention has focussed on the development of chiral Lewis-acid catalysts for a variety of carbon–carbon bond-forming reactions.[1] Impressive results have been reported for Diels–Alder reactions mostly with titanium, aluminium or boron based catalysts.[2] Such catalysts have a number of drawbacks *viz*. they are often extremely sensitive to water, hence are generally employed at high catalytic loadings (often *ca*. 20%); also, attempts to understand the mechanisms of catalysis and selectivity are hampered by the complexity of the chemical behaviour of the catalyst, *e.g.* formation of oligomers, ligand-exchange reactions. Recently some transition-metal and lanthanide complexes have been described as promising catalysts for these reactions.[3] Half-sandwich complexes have been extensively used in stoichiometric and catalytic organic transformations often with impressive asymmetric induction. Indeed, half-sandwich complexes of Rh and Fe with chiral phosphorus ligands have recently been shown to be asymmetric catalysts for Diels–Alder reactions.[4]

Bisoxazolines have given high enantioselectivity in a number of asymmetric catalytic processes, for example copper catalysed cyclopropanation and aziridination[5] and more recently Diels–Alder reactions;[3b,c,f] whilst phosphino-oxazolines work well in palladium-catalysed allylic substitution.[5c,6] However, the use of these types of ligands with half-sandwich complexes is less well studied, the first arene ruthenium complexes with bisoxazoline ligands having been reported recently.[7]



L

Refluxing L with $[RuCl_2(\eta^6\text{-mes})]_2$ (mes = 1,3,5-trimethylbenzene) in methanol in the presence of $NaSbF_6$ or KPF_6 gives [RuClL(η⁶-mes)]X (X = SbF_6, PF_6) in good yield.† The complexation of the ligand is highly diastereostereoselective, only one of two possible diastereomers being observed by ^1H NMR spectroscopy. The X-ray structure was carried out to determine which diastereomer was formed. The structure of the cation with selected bond distances and angles is shown in Fig. 1.‡ The ruthenium has a pseudo-octahedral geometry with L coordinated such that the isopropyl substituent is on the same side as the chloride rather than the arene to miminise unfavourable steric interactions. The Ru–N(1) oxazoline and Ru–N(2) pyridine bond lengths are the same, as found previously for other 2-iminopyridine complexes.[8] The use of L-valine in the ligand preparation means that the configuration at the chiral carbon is (*S*) and the structure shows that the ruthenium is also (*S*) (based on the priority arene > Cl > N_{ox} > N_{py}).[9] There is no evidence for formation of the other diastereomer in the NMR spectrum and thus it is assumed that this geometry is retained in solution and the configuration at ruthenium is stable in CD_2Cl_2 solution as found for related iminopyridine complexes.[8b]

In order for the complex to be used as a Lewis-acid catalyst the chloride must be removed, this is easily done by treating with $AgSbF_6$ in acetone–water to give $[Ru(H_2O)L(\eta^6\text{-mes})][SbF_6]_2$ **2**.† The ^1H NMR spectrum of **2** in $[CD_2Cl_2$–$(CD_3)_2CO$ 10 : 1] shows a broad singlet at δ 5.40 due to coordinated water with free water from the NMR solvent at δ 1.81. The observation of separate signals for free and co-ordinated water indicates that water exchange is relatively slow on the NMR timescale.

Complex **2** catalyses the Diels–Alder reaction between methacrolein and cyclopentadiene (Table 1).§ The reaction proceeds rapidly at room temp. (essentially quantitative conversion in < 45 min monitored by ^1H NMR) at low catalyst loading (as little as 0.5 mol%) and with good *exo* : *endo* selectivity (⩾95 : 5) and good enantioselectivity (ee 70%) (entry 1). As can be seen from entries 2, 5 and 7 increasing the catalyst ratio to 5 mol% has very little effect on the *exo* : *endo* ratio or on the enantioselectivity. However, reducing the temperature of the reaction to 0 °C (entries 3, 6 and 8) or −20 °C (4 and 9) leads to small improvements in the enantioselectivity. The major product is identified as (1*R*,2*S*,4*R*)-2-methylbicyclo[2.2.1]hept-5-ene-2-carbaldehyde by comparison of the sign of the optical rotation [α], and the GC behaviour of the acetal formed from (2*R*,4*R*)-pentanediol with literature values.[3b] The absolute configuration of the major *exo* product can be rationalised by assuming that the methacrolein coordinates in the preferred *S–trans* conformation with the aldehyde H pointing towards the

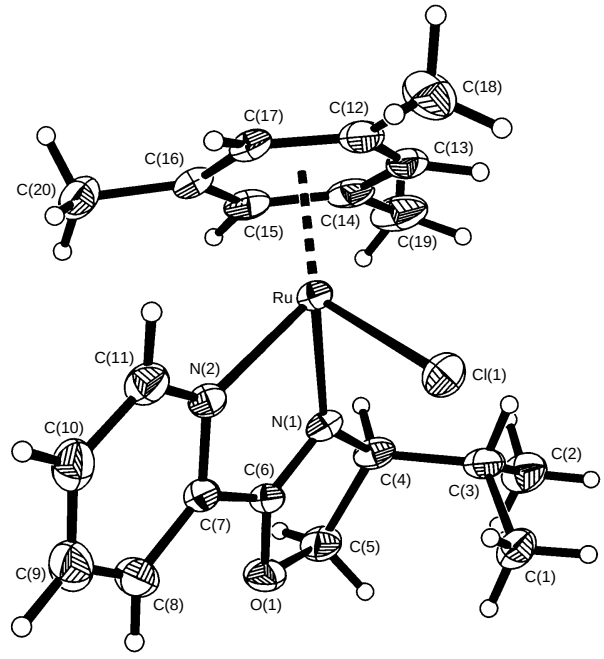
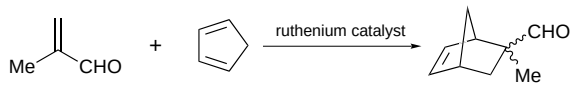


Fig. 1 Molecular structure and atom numbering scheme for the cation of **1**. Selected bond distances (Å) and angles (°): Ru–N(1) 2.118(4), Ru–N(2) 2.117(4), Ru–Cl(1) 2.402(2), N(2)–C(7) 1.351(7), C(7)–C(6) 1.449(8), C(6)–N(1) 1.280(7), N(2)–Ru–N(1) 76.4(2).

Table 1 Enantioselective Diels–Alder reaction of methacrolein with cyclopentadiene catalysed by complex **2** in dichloromethane



Entry	Catalyst (mol%)	*T*/°C	*t*/h	Yield[a] (%)	Isomer ratio (*exo : endo*)	Ee (%)
1	0.5	r.t.[b]	0.25	> 95	95 : 5	70
2	1	r.t.	0.2	> 95	95 : 5	70
3	1	0	3	72[c]	96 : 4	76
4	1	−20	24	30[c]	96 : 4	78
5	2	r.t.	0.33	> 95	95 : 5	71
6	2	0	24	92[c]	95 : 5	75
7	5	r.t.	1	> 95	94 : 6	72
8	5	0	6	53[c]	95 : 5	75
9	5	−20	72	90[c]	96 : 4	81

[a] NMR tube reaction, yield from integration. [b] r.t. = Room temperature. [c] Isolated yield.

arene ring; the alternative orientation formally obtained by a 180° rotation about the Ru–O bond would be disfavoured due to steric interactions between the vinyl substituent and the arene. Attack of the cyclopentadiene is expected to occur at the *Re* face of the methacrolein, the *Si* face being shielded by the isopropyl of L which is consistent with the observed major product. Further studies to try and identify the actual catalyst, *i.e.* with methacrolein coordinated, to extend the range of substrates and to optimise the enantioselectivity are currently underway.

We thank the University of Leicester for a studentship (S. A. G.) and Johnson Matthey for a loan of $RuCl_3$.

Footnotes

* E-mail: dld3@le.ac.uk

† *Selected spectroscopic data*: for **1**: ^{1}H NMR (300 MHz, CD_2Cl_2, 20 °C, $SiMe_4$); δ 0.77 (d, 3 H, *J* 7 Hz, CH*Me*′Me′), 1.02 (d, 3 H, *J* 7 Hz, CHMe*Me*′), 2.25 (s, 9 H, C_6Me_3), 4.82 (m, 2 H, OCH + NCH), 5.00 (t, 1 H, *J* 11 Hz, OCH), 5.33 (s, 3 H, C_6H_3), 7.75 (m, 1 H, pyr), 7.88 (d, 1 H, *J* 7 Hz, pyr), 8.10 (dt, 1 H, *J* 1.5, 7.5 Hz, pyr), 9.05 (d, 1 H, *J* 5 Hz, pyr). Satisfactory elemental analysis (C, H, N). For **2**: ^{1}H NMR [300 MHz, CD_2Cl_2–$(CD_3)_2CO$ (10 : 1), 20 °C, $SiMe_4$], δ 0.57 (d, 3 H, *J* 7 Hz, CH*Me*′Me′), 1.01 (d, 3 H, *J* 7 Hz, CHMe*Me*′), 2.22 (s, 9 H, C_6Me_3), 4.78 (dd, 1 H, *J* 5, 8.5 Hz, OCH), 4.92 (m, 1 H, NCH), 5.03 (t, 1 H, *J* 10 Hz, OCH), 5.40 (s, 2 H, H_2O), 5.55 (s, 3 H, C_6H_3), 7.87 (m, 2 H, pyr), 8.15 (t, 1 H, *J* 8 Hz, pyr), 9.40 (d, 1 H, *J* 5 Hz, pyr). Satisfactory elemental analysis (C, H, N).

‡ *Crystal data* for **1**: $C_{20}H_{26}ClF_6N_2OPRu$, M = 591.92, orthorhombic, space group $P2_12_12_1$, a = 8.461(1), b = 9.330(1), c = 29.347(4) Å, U = 2316.5 Å^3, Z = 4, D_c = 1.697 g cm^{-3}, μ = 0.925 mm^{-1}, F(000) = 1192, graphite-monochromated Mo-Kα radiation (λ = 0.710 73 Å). Data collected on a Siemens P4 diffractometer at 190 K. 3080 reflections collected with 5 < θ < 25°, 2881 unique (R_{int} = 0.027). A ψ-scan absorption correction was applied. The structure was solved by Patterson methods and refined using full-matrix least squares on F^2 (SHELXL-96). Anisotropic displacement parameters used for all atoms, hydrogens included in calculated positions (C–H 0.96 Å), with isotropic displacement parameters set to 1.2 U_{eq}(C). Final R_1 = 0.0406, wR_2 = 0.0838 for all data). CCDC 182/521.

§ NMR tube experiments (in air): methacrolein (*ca.* 0.25 mmol) was added to a suspension of **2** (1.25, 2.5, 5, or 12.5 μmol) in CD_2Cl_2 (0.5 cm^3) which lead to rapid dissolution of **2** to give a yellow solution. The solution was transferred to an NMR tube and 2,6-di-*tert*-butylpyridine (1 equiv./mol catalyst) and cyclopentadiene (0.5 mmol) were added. The ^{1}H NMR spectrum was run immediately and then repeated after suitable time intervals. Schlenk reactions (under N_2). Methacrolein (1 mmol) and 2,6-di-*tert*-butylpyridine (1 equiv./mol catalyst) were added to a suspension of **2** (0.01, 0.02, or 0.05 mmol) in CH_2Cl_2 (2 cm^3). The resulting yellow solution was cooled to the appropriate temperature before addition of cyclopentadiene (2 mmol). At the end of the reactions, the mixture was passed through a silica plug, the solvent was removed and the product was obtained as a colourless oil. The *exo : endo* ratio was determined by NMR spectroscopy and the enantiomeric excess was determined by GC after conversion to the acetal with (2*R*,4*R*)-pentanediol.[3b] The catalyst could also be prepared *in situ* from complex **1** and 1 equiv. of $AgSbF_6$ in CH_2Cl_2, filtration through Celite into a Schlenk tube to remove AgCl and then addition of the reagents as described above.

References

1 *Catalytic Asymmetric Synthesis*, ed. I. Ojima, VCH, Weinheim, 1993; R. Noyori, *Asymmetric Catalysis in Organic Synthesis*, Wiley, New York, 1994.
2 H. B. Kagan and O. Riant, *Chem. Rev.*, 1992, **92**, 1007; K. Narasaka, *Synthesis*, 1991, 1.
3 (*a*) S. Kobayashi and H. Ishitani, *J. Am. Chem. Soc.*, 1994, **116**, 4083; (*b*) D. A. Evans, J. A. Murry, P. von Matt, R. D. Norcross and S. J. Miller, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 798; (*c*) D. A. Evans, S. J. Miller and T. Lectka, *J. Am. Chem. Soc.*, 1993, **115**, 6460; (*d*) J. Jaquith, J. Guan, S. Wang and S. Collins, *Organometallics*, 1995, **14**, 1079; (*e*) S. Kobayashi, H. Ishitani, I. Hachiya and M. Araki, *Tetrahedron*, 1994, **50**, 11623; (*f*) E. J. Corey, N. Imai and H.-Y. Zhang, *J. Am. Chem. Soc.*, 1991, **113**, 728.
4 D. Carmona, C. Cativiela, R. Garcia-Correas, F. J. Lahoz, M. P. Lamata, J. A. Lopez, M. P. Lopez-Ram de Viu, L. A. Oro, E. San Jose and F. Viguri, *Chem. Commun.*, 1996, 1247; E. P. Kundig, B. Bourdin and G. Bernardinelli, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 1856.
5 (*a*) A. Pfaltz, *Acc. Chem. Res.*, 1993, **26**, 339; (*b*) D. A. Evans, K. A. Woerpel, M. M. Hinman and M. M. Faul, *J. Am. Chem. Soc.*, 1991, **113**, 726; (*c*) A. Pfaltz, *Acta Chem. Scand.*, 1996, **50**, 189.
6 G. J. Dawson, J. M. J. Williams and S. J. Coote, *Tetrahedron. Lett.*, 1995, **36**, 461 and references therein.
7 H. Asano, K. Katayama and H. Kurosawa, *Inorg. Chem.*, 1996, **35**, 5760.
8 (*a*) S. K. Mandal and A. R. Chakravarty, *Polyhedron*, 1992, **11**, 823; (*b*) D. L. Davies, J. Fawcett, R.Krafczyk and D. R. Russell, submitted for publication.
9 T. E. Sloan, *Top. Stereochem.*, 1981, **12**, 1; K. Stanley and M. C. Baird, *J. Am. Chem. Soc.*, 1975, **97**, 6598.

Received in Cambridge, UK, 16th May 1997; 7/03386I