[Ta(=CH*t*Bu)(CH_2*t*Bu)$_3$] which yields Cl–Ta(CH_2*t*Bu)$_4$: R. R. Schrock, J. D. Fellmann, *J. Am. Chem. Soc.* **1978**, *100*, 3359.

[6] a) For comprehensive information on the pK_a values of silicas, see: *The Surface Properties of Silicas* (Ed.: A. P. Legrand), Wiley, New York, **1998**, chapter 4B; b) for related comments on **4**, see ref. [1f].

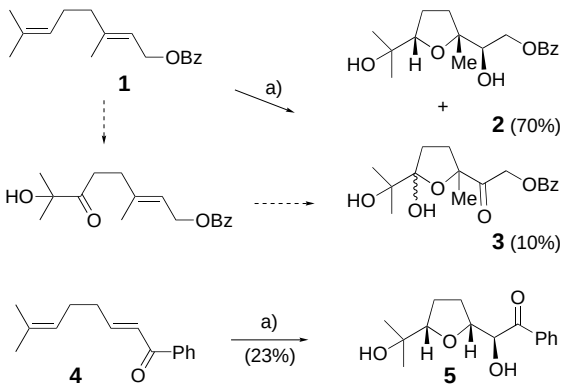
Asymmetric Permanganate-Promoted Oxidative Cyclization of 1,5-Dienes by Using Chiral Phase-Transfer Catalysis**

Richard C. D. Brown* and John F. Keily

2,5-Bis(hydroxymethyl)-substituted tetrahydrofurans (THF diols) are an important structural unit found in many natural and synthetic, biologically active molecules.[1] An elegant approach to the synthesis of THF diols is by the permanganate-promoted oxidative cyclization of 1,5-dienes, which leads to the stereospecific formation of up to four new stereocenters and the THF ring.[2–6] The same transformation has been carried out using other metal–oxo reagents and catalysts.[7, 8] In the permanganate-promoted oxidative cyclization reaction, control of absolute stereochemistry has been achieved with chiral auxiliaries;[4a,b] however, preparation of enantiomerically enriched THF diols by oxidative cyclizations of achiral 1,5-dienes has not been reported. Herein we report the novel high-yielding phase-transfer permanganate-promoted oxidation of geranyl benzoate (**1**) to the corresponding THF diol **2** (Scheme 1), and a procedure for the asymmetric oxidative cyclization of phenone dienes to produce enantiomerically enriched THF diols.

The use of phase-transfer conditions in permanganate-promoted oxidations is well known,[9] although we were not aware of application to the oxidative cyclization of 1,5-dienes. Therefore before attempting to develop an asymmetric process, we investigated the phase-transfer oxidative cyclization of a readily available substrate **1** using achiral tertiary ammonium salts (Scheme 1).[10]

Oxidation of diene **1** with potassium permanganate (2 equiv) in diethyl ether buffered with ethanoic acid gave the best yield of THF diol **2** (70%) when Adogen 464 (0.1–1 equiv) was employed (entry 4, Table 1). Oxidation of enone **4** under the same conditions gave the desired THF diol **5**,



Scheme 1. Oxidative cyclization of dienes **1** and **4**. a) 0.4 M $KMnO_4$ (2 equiv), AcOH (4 equiv), Adogen 464 (0.4 equiv)/Et_2O. Bz = benzoyl.

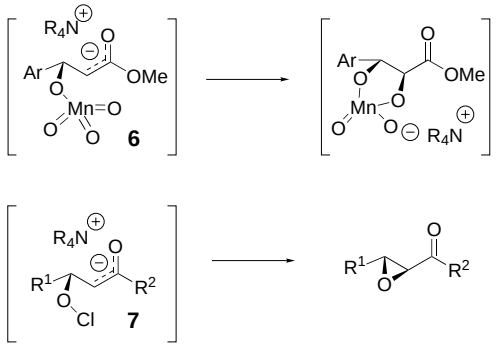
Table 1. Oxidative cyclization of geranyl benzoate (**1**) (see Scheme 1).[a]

Entry	Solvent	Phase-transfer agent	Yield of **2** [%]	Yield of **3** [%]
1	CH_2Cl_2[b]	TBAB	8[c]	not recorded
2	CH_2Cl_2	TBAB	44[d]	21[d]
3	Et_2O	TBAB	40[d]	7[d]
4	Et_2O	Adogen 464	70[d]	10[d]

[a] Reactions were conducted on a 0.19 mmol scale. TBAB = tetrabutylammonium bromide. [b] No AcOH added to the reaction mixture. [c] Yield estimated by HPLC. [d] Yields represent analytically pure isolated material.

albeit in lower yield (Scheme 1). We then returned to our primary goal of developing an asymmetric oxidative cyclization.

Studies on the oxidation of cinnamate esters by quaternary ammonium permanganates led Lee et al. to conclude that the transition state was electron-rich, and they proposed an enolate-like structure **6** with stabilization due to interaction with the ammonium ion (Scheme 2).[11] The similarity of **6** and the initial adduct **7** formed in the phase-transfer-catalyzed nucleophilic epoxidation of enones suggested that chiral catalysts developed for the epoxidation reaction might also be applied to the oxidative cyclization.[12]



Scheme 2. Possible reaction pathways for the permanganate-promoted oxidation of electron-poor olefins (top), and the nucleophilic epoxidation of α,β-enones with ClO^- (bottom).

Oxidative cyclization of geranyl benzoate (**1**) in the presence of **8** in dichloromethane/water/ethanoic acid at

[*] Dr. R. C. D. Brown, J. F. Keily
Department of Chemistry
University of Southampton
Highfield, Southampton SO17 4BJ (UK)
Fax: (+44) 23-80596805
E-mail: rcb1@soton.ac.uk

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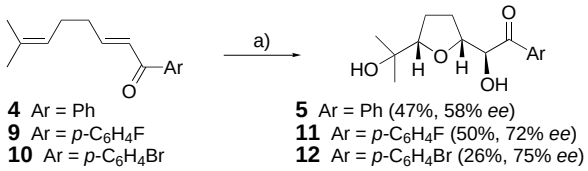
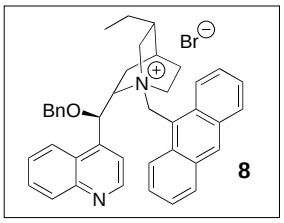
room temperature gave the THF diol **2** with <3% *ee*. Gratifyingly, oxidation of α,β-enone **4** under the same conditions afforded **5** with an encouraging enantiomeric excess (38% *ee*, 14% yield; Scheme 3). A range of solvents



4 Ar = Ph
9 Ar = *p*-C_6H_4F
10 Ar = *p*-C_6H_4Br

5 Ar = Ph (47%, 58% *ee*)
11 Ar = *p*-C_6H_4F (50%, 72% *ee*)
12 Ar = *p*-C_6H_4Br (26%, 75% *ee*)



Scheme 3. Asymmetric oxidative cyclization of 1,5-dienes **4**, **9**, and **10**. a) $KMnO_4$ (powder) (1.6 equiv), AcOH (6.5 equiv), **8** (0.1 equiv)/CH_2Cl_2, $-30\,^{\circ}C$.

were screened for the asymmetric liquid–liquid phase-transfer reaction, and two trends emerged, namely that the yield of **5** improved with solvent polarity, and its enantiomeric excess decreased. Repeating some of the reactions without the phase-transfer catalyst confirmed that a background oxidation was occurring in more polar solvents. The highest level of asymmetric induction observed for the liquid–liquid phase-transfer reaction (40% *ee*) occurred in toluene when **8** (30 mol%) was used as catalyst.

Additional improvements to the yield and enatiomeric excess of **5** (47%, 58% *ee*) were achieved in dichloromethane at $-30\,^{\circ}C$. Importantly, the amount of the tertiary ammonium salt **8** could be reduced to 5 mol% without lowering the enatiomeric excess of **5**, but further reduction to 1 mol% gave **5** with only 26% *ee*. The identities of the compounds that make up the remainder of the mass balance remain unclear; however, they are likely to be highly polar, water-soluble or volatile substances given the high purity of the crude product **5** after the usual work-up, as judged from the ^1H NMR spectrum prior to chromatography.

The asymmetric oxidative cyclization of *para*-substituted systems **9** and **10** afforded the THF diols **11** and **12**, respectively, with slightly higher enatiomeric excesses although oxidation of the *para*-bromo compound **10** was incomplete under the same conditions, explaining the lower yield. The level of asymmetric induction obtained here (58-75% *ee*) is already comparable with the diastereoselectivity obtained for the oxidative cyclization of dienes bearing the Oppolzer sultam chiral auxiliary (80% *de*).[4a]

The relative stereochemistry of the products **5**, **11**, and **12** was determined by X-ray crystallography, and the presence of a heavy atom in **12** allowed its absolute stereochemistry to be established from enantiomerically pure crystals.[13] The observed stereochemical outcome is accounted for by a model presented for the nucleophilic epoxidation of α,β-enones by hypochlorite.[12e] The lack of enantioselectivity observed for the oxidative cyclization of geranyl benzoate (**1**), which is oxidized more rapidly at the C6–C7 double bond, is also in accord with the model.

In conclusion, very promising levels of enantioinduction have been achieved in a novel phase-transfer-catalyzed oxidative cyclization of 1,5-dieneones by permanganate with as little as 5 mol% **8**. The reaction is unusual in that up to four new stereocenters are created with control of relative and absolute stereochemistry in a single synthetic step from an achiral starting material.

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[1] a) F. Q. Alali, X. X. Liu, J. L. McLaughlin, *J. Nat. Prod.* **1999**, *62*, 504–540; b) C. J. Dutton, B. J. Banks, C. B. Cooper, *Nat. Prod. Rep.* **1995**, *12*, 165–181; c) S. T. Jan, C. Mao, A. O. Vassilev, C. S. Navara, F. M. Uckun, *Bioorg. Med. Chem. Lett.* **2000**, *10*, 1193–1197; d) H. Wagner, K. Harms, U. Koert, S. Meder, G. Boheim, *Angew. Chem.* **1996**, *108*, 2836–2839; *Angew. Chem. Int. Ed.* **1996**, *35*, 2643–2646; e) J. J. Fernandez, M. L. Souto, M. Norte, *Nat. Prod. Rep.* **2000**, *17*, 235–246.

[2] For early papers describing the oxidative cyclization of 1,5-dienes: a) E. Klein, W. Rojahn, *Tetrahedron.* **1965**, *21*, 2353–2358; b) D. M. Walba, M. D. Wand, M. C. Wilkes, *J. Am. Chem. Soc.* **1979**, *101*, 4396–4397.

[3] For mechanistic discusions of the oxidative cyclization see ref. [2b] and: a) J. E. Baldwin, M. J. Crossley, E.-M. M. Lehtonen, *Chem. Commun.* **1979**, 918–920; b) S. Wolfe, C. F. Ingold, *J. Am. Chem. Soc.* **1981**, *103*, 940–941.

[4] For asymmetric oxidative cyclization of 1,5-dienes: a) D. M. Walba, C. A. Przybyla, C. B. Walker, *J. Am. Chem. Soc.* **1990**, *112*, 5624–5625; a) P. J. Kocienski, R. C. D. Brown, A. Pommier, M. Procter, B. Schmidt, *J. Chem. Soc. Perkin Trans. 1*. **1998**, 9–39.

[5] For application towards the synthesis of natural products see reference [4] and: a) D. M. Walba, P. D. Edwards, *Tetrahedron Lett.* **1980**, *21*, 3531–3534; b) C. Spino, L. Weiler, *Tetrahedron Lett.* **1987**, *28*, 731–734; c) R. C. D. Brown, R. M. Hughes, J. Keily, A. Kenney, *Chem. Commun.* **2000**, 1735–1736.

[6] For general reviews on the synthesis of tetrahydrofurans: a) T. L. B. Boivin, *Tetrahedron* **1987**, *43*, 3309–3362; b) J.-C. Harmange, B. Figadere, *Tetrahedron: Asymmetry* **1993**, *4*, 1711–1754; c) R. Hoppe, H. D. Scharf, *Synthesis* **1995**, 1447–1464; d) U. Koert, *Synthesis* **1995**, 115–132.

[7] a) P. H. J. Carlsen, T. Katsuki, V. S. Martin, K. B. Sharpless, *J. Org. Chem.* **1981**, *46*, 3936–3938; b) M. de Champdore, M. Lasalvia, V. Piccialli, *Tetrahedron Lett.* **1998**, *39*, 9781–9784; c) T. J. Donohoe, J. J. G. Winter, M. Helliwell, G. Stemp, *Tetrahedron Lett.* **2001**, *42*, 971–974; d) V. Piccialli, N. Cavallo, *Tetrahedron Lett.* **2001**, *42*, 4695–4699.

[8] a) For related cyclizations of hydroxyalkenes: a) D. M. Walba, G. S. Stoudt, *Tetrahedron Lett.* **1982**, *23*, 727–730; b) S. Tang, R. M. Kennedy, *Tetrahedron Lett.* **1992** *33*, 5299–5302; c) S. Tang, R. M. Kennedy, *Tetrahedron Lett.* **1992**, *33*, 5303–5306; d) F. E. McDonald, T. B. Towne, *J. Am. Chem. Soc.* **1994**, *116*, 7921–7922; e) F. E. McDonald, T. B. Towne, *J. Org. Chem.* **1995**, *60*, 5750–5751; f) L. J. D'Souza, S. C. Sinha, S. F. Lu, E. Keinan, S. C. Sinha, *Tetrahedron* **2001**, *57*, 5255–5262.

[9] D. G. Lee in *Oxidation in Organic Chemistry*, (Ed.: W. S. Trahanovsky), Academic Press, New York, **1982**, pp. 147–206.

[10] R. J. Armstrong, L. Weiler, *Can. J. Chem.* **1983**, 2530–2539.

[11] a) D. G. Lee, K. C. Brown, *J. Am. Chem. Soc.* **1982**, *104*, 5076–5081; b) D. G. Lee, K. C. Brown, H. Karaman, *Can. J. Chem.* **1986**, *64*, 1054–1059; c) J. F. Perez-Benito, D. G. Lee, *J. Org. Chem.* **1987**, *52*, 3239–3243.

[12] a) J. C. Hummelen, H. Wynberg, *Tetrahedron Lett.* **1978**, 1089–1092; b) R. Helder, J. C. Hummelen, R. W. P. M. Laane, J. S. Weiring, H. Wynberg, *Tetrahedron Lett.* **1976**, 1831–1834; c) B. Lygo, P. G. Wainwright, *Tetrahedron Lett.* **1998**, *39*, 1599–1602; d) B. Lygo, P. G. Wainwright, *Tetrahedron* **1999**, *55*, 6289–6300; e) E. J. Corey, F. Y.

Zhang, *Org. Lett.* **1999**, *1*, 1287–1290; f) B. Lygo, D. C. M. To, *Tetrahedron Lett.* **2001**, *42*, 1343–1346.

[13] M. B. Hursthouse, M. E. Light, S. J. Coles, Department of Chemistry, University of Southampton, personal communication.

Reactivity of Dimetallapentaboranes—*nido*-$[Cp^*_2M_2B_3H_7]$—with Alkynes: Insertion to Form a Ruthenacarborane (M = RuH) versus Catalytic Cyclotrimerization to Form Arenes (M = Rh)**

Hong Yan, Alicia M. Beatty, and Thomas P. Fehlner*

A significant fraction of modern chemistry incorporates the use of transition metals to modify and control the reactivity of main group moieties, for example, organometallic chemistry, and the use of ligands to modify and control the reactivity at metal sites, for example, supramolecular chemistry. Relative to the other p-block elements, the chemistry of carbon is dominant, however, in principle, a similar wealth of chemistry exists for the other p-block elements.[1] In fact, transition metal promoted main group chemistry[2] and main group element promoted transition metal chemistry[3] has generated more interest recently.

Since developing a practical synthetic route to a class of metallaboranes containing metals ranging from Group 5–9,[4] we have begun to examine the systematic reaction chemistry of these compounds. Thus, thermal elimination reactions as well as reactions with metal fragments, monoboranes, and Lewis bases have been described.[5–11] In these reactions, the distinctive electronic contributions of metal and borane fragments to the cluster structure are seen to be expressed in the overall reactivity. In one case, a new class of metallaborane was revealed, the hypoelectronic rhenaboranes.[12]

In the early days of organometallic chemistry, the reaction of metal species with alkynes yielded a wealth of compounds that helped define structural possibilities.[13] Likewise, the reaction of alkynes with boranes gave rise to carboranes[14] and a subsequent bountiful chemistry of these heteroboranes with metals[15] including catalytic applications.[16] Here we report the comparative reactivity of two isoelectronic *nido*-dimetallapentaboranes with alkynes and demonstrate that a change from Group 8 to Group 9 metal drives a change in the reaction from alkyne insertion to catalytic cyclotrimerization. The latter reaction shows that, with the proper choice of metal, metallaborane clusters provide access to a novel catalytic pathway.

[*] Prof. T. P. Fehlner, Dr. H. Yan, Dr. A. M. Beatty
Department of Chemistry and Biochemistry
University of Notre Dame
Notre Dame, IN 46556 (USA)
Fax: (+1) 219-631-6652
E-mail: fehlner.1@nd.edu

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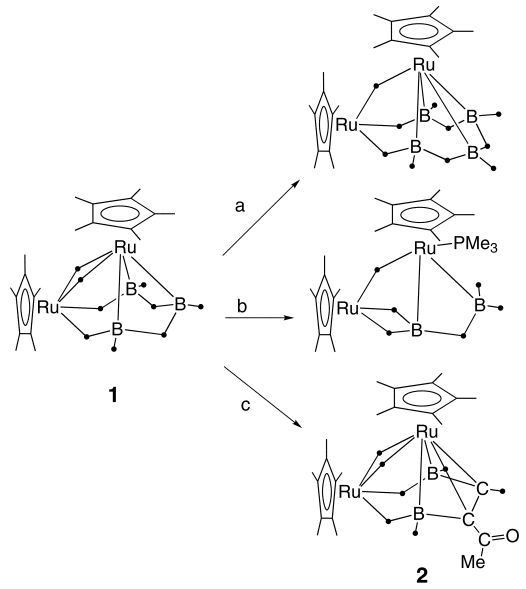
The chemistry of $[1,2\text{-}(Cp^*RuH)_2B_3H_7]$ (**1**; $Cp^* = C_5Me_5$), has been explored by our group[8] and that of Shimoi.[17–19] The results pertinent to this work are shown in Scheme 1 and illustrate a) cluster expansion and b) cluster degradation. Reaction of **1** with $HCCCO_2Me$ leads to $[1,2\text{-}(Cp^*RuH)_2\text{-}3,4\text{-}CHC(CO_2Me)B_2H_4]$ (**2**; Figure 1),[20] which results from combined cluster degradation and expansion (path c in Scheme 1). This reaction is analogous to the reaction of **1** with phosphanes except that ultimately the alkyne base is incorporated into the borane framework rather than coordinated to a metal site. Thermal reaction of metallaboranes with alkynes



Scheme 1. Reactions of **1** with a) monoborane to give cluster expansion, b) with PMe_3 to give cluster degradation, and c) with $HCCCO_2Me$ to yield **2**. The structures shown are schematic representations, for clarity only the H-bridge of the H-bridged bonds is shown, ● = H.

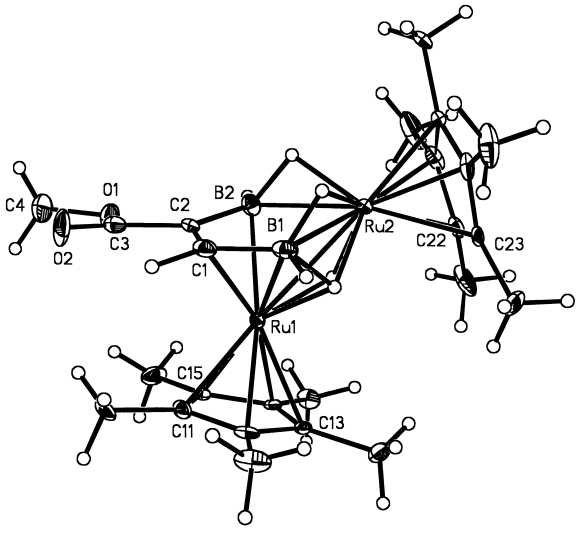


Figure 1. Molecular structure of **2**. Selected bond lengths [Å]: Ru1–Ru2 2.9424(10), Ru1–C1 2.170(8), Ru1–C2 2.180(8), Ru1–B1 2.358(10), Ru1–B2 2.360(10), Ru2–B2 2.385(10), Ru2–B1 2.399(10), B1–C1 1.508(14), B2–C2 1.557(13), C1–C2 1.391(12), C2–C3 1.493(12), O1–C3 1.352(11), O1–C4 1.448(11), O2–C3 1.208(11).

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