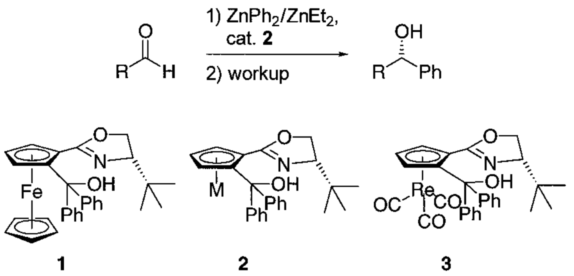
# Application of a Planar Chiral $\eta^5$-Cyclopentadienylrhenium(I)tricarbonyl Complex in Asymmetric Catalysis: Highly Enantioselective Phenyl Transfer to Aldehydes**

Carsten Bolm,* Martin Kesselgruber, Nina Hermanns, Jens P. Hildebrand, and Gerhard Raabe

*Dedicated to Professor Günter Helmchen
on the occasion of his 60th birthday*

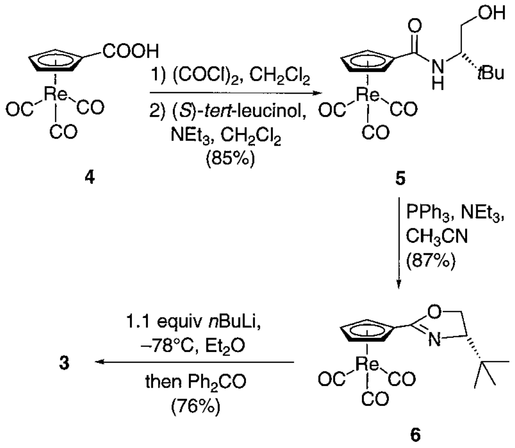
Asymmetric metal catalysis is one of the most active areas in modern organic chemistry, and the number of novel ligands for catalytic asymmetric transformations is growing rapidly.[1] Among these compounds, planar chiral ferrocenes[2] are of immense importance and some of them have already found application in industrial processes.[3] Often, ferrocenes are superior to other metal $\pi$ complexes,[4] although for some catalyses it was found that a variation of the $\pi$-bound metal fragment can be of benefit.[5]

Recently, we developed a system for the enantioselective, catalytic synthesis of diarylmethanol compounds from aldehydes by utilizing ferrocene **1**[6] and a zinc species generated in situ from ZnPh$_2$/ZnEt$_2$ (Scheme 1).[7] Further optimization of the process was expected to be possible by variation of the metal–$\pi$-fragment of **2**.[8, 9] Herein, we describe the synthesis and application of novel cyrhetrene **3**, which was found to be superior in terms of both enantioselectivity and catalyst loading in the phenyl transfer to a wide variety of aldehydes.[10]



Scheme 1. Enantioselective phenyl transfer onto aldehydes and catalytically active metal complexes.

Modifications of the metal–$\pi$-fragment of **2** were expected to have an impact on the steric and electronic properties of the catalyst. Assuming that decreased electron density on the ligand would result in increased Lewis acidity of the catalyst, we focussed our attention primarily on the synthesis of metal tricarbonyl complexes.[9] There, the electron-withdrawing properties of the carbonyl groups would lower the electron density on the metal center as well as on the remaining cyclopentadienyl fragment bearing the stereogenic elements. If these electronic changes are then efficiently transferred to the catalytically active site and if the simultaneously occurring steric modifications are not counterproductive, beneficial effects in the catalysis could result. Due to its expected chemical stability rhenium(I) complex **3** appeared to be the complex of choice. To the best of our knowledge, $\eta^5$-cyclopentadienylrhenium(I)tricarbonyl complexes have not been utilized in asymmetric catalysis, and only one nonracemic planar chiral derivative has been described.[11, 12] Our synthesis of **3** started from cyrhetrenyl carboxylic acid **4**, which was obtained in a straightforward manner from [Re$_2$(CO)$_{10}$] and cyclopentadienyl carboxylic acid following an excellent, high-yielding procedure published by Jaouen et al.[13] The cyrhetrenyl oxazoline **6**[14] was synthesized in an analogous manner to the corresponding ferrocene derivatives via amide **5**, which was cyclized using the Appel protocol (Scheme 2).[15] Directed *ortho*-metalation[16] of **6** using *n*BuLi in diethyl ether[17] and subsequent quenching of the resulting lithiated species with benzophenone led to diastereomeric products in a ratio of 9:1 in favor of the product with $S,R_p$ configuration.[18] All transformations give good to excellent yields, and the compounds are crystalline and stable to air, light, and moisture.[14]



Scheme 2. Synthesis of complex **3**.

To confirm the relative configuration of **3**, the solid-state structure of the cyrhetrenyl complex was determined by single-crystal X-ray structure analysis.[14, 19] As depicted in Figure 1 one phenyl group of **1** is equatorial, while the other occupies an axial position with regard to the cyclopentadienyl

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[**] We are grateful to the Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center (SFB) 380 “Asymmetric Synthesis by Chemical and Biological Methods” and the Fonds der Chemischen Industrie for financial support and to Dr. C. W. Lehmann, MPI für Kohlenforschung, Mülheim, for collecting the X-ray diffraction data. M.K. acknowledges the DFG for a predoctoral fellowship (Graduiertenkolleg). We thank Degussa and Witco for donations of chemicals and Professor Dr. A. Salzer as well as Dipl.-Ing. M. Treu for inspiring discussions. We also appreciate the stimulus of Dr. K. Muñiz for the investigation of the influence of the metal–$\pi$-fragment on catalyses of this type.

Supporting information for this article is available on the WWW under http://www.angewandte.com or from the author.

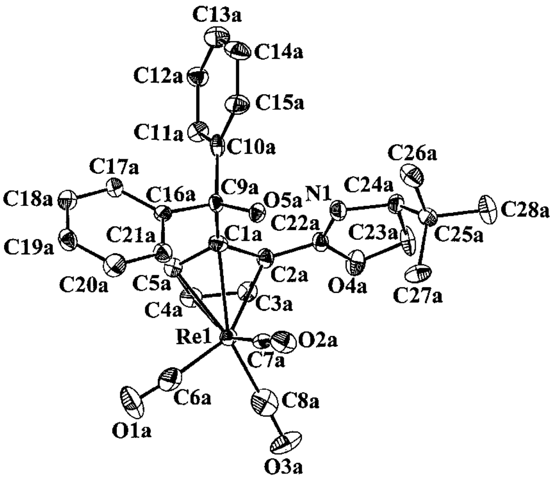


Figure 1. Structure of **3** (ORTEP plot; ellipsoids plotted with 50% probability).

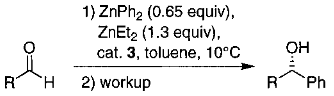
backbone. The relative location of the *tert*-butyl group at the oxazoline group is *trans* with respect to the axial phenyl group. Overall, the structural features of cyrhetrene **3** are very similar to those of ferrocene **1**, which suggested its potential use in catalysis.

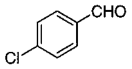
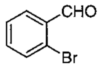
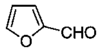
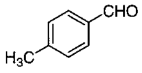
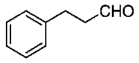
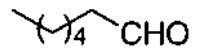
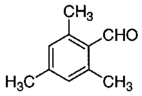
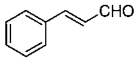
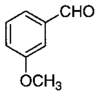
The catalytic properties of **3** were explored in the asymmetric phenyl transfer from organozinc compounds to aldehydes. Initial approaches by ourselves[7a] and others[10] using diphenylzinc as phenyl source, encountered the difficulty that the uncatalyzed background reaction with the substrate is comparatively rapid, leading to a diminished enantioselectivity.[20] The use of diethylzinc as an additive had been shown to be the key to significantly raise the enantiomeric excesses.[7b, 10b] The replacement of the CpFe moiety by the $Re(CO)_3$ fragment now led to a further improvement of this transformation (Table 1).

For most examples, complex **3** shows higher enantioselectivity than ferrocene **1**. A significant increase was observed in reactions with *ortho*-substituted aldehydes (Table 1, entries 2 and 7) which are now among the best substrates for this transformation. Especially noteworthy is the result obtained with 2,4,6-trimethylbenzaldehyde (Table 1, entry 7; 98% *ee*), which demonstrates that even *ortho*-disubstitution at the aromatic aldehyde is well tolerated. The reactions with other substrates follow trends that have previously been observed in catalyses with **1**: cinnamyl aldehyde displays lower levels of enantioselection (Table 1, entry 8), and aliphatic aldehydes are still somewhat problematic with respect to asymmetric induction (Table 1, entries 5 and 6). In several cases, even a catalyst loading of only 2 mol% of **3** was sufficient to achieve high *ee* values similar to the ones obtained with 10 mol% of **1** (Table 1, entries 1, 3, 5, 8).[21]

In summary, we have described the synthesis of the $\eta^5$-cyclopentadienylrhenium(I)tricarbonyl complex **3** and demonstrated its use in asymmetric catalysis. Compared to its analogous ferrocene derivative, cyrehetrene **3** shows significantly higher enantioselectivities in the catalyzed phenyl transfer from a phenylzinc species to aromatic and aliphatic aldehydes, leading to the currently most efficient approach for this reaction. Further studies are directed towards the use of other $\eta^5$-cyclopentadienylrhenium(I)tricarbonyl complexes in asymmetric catalysis.

Table 1. Asymmetric phenyl transfer to various aldehydes.



| Entry[a] | Substrate | *ee* of product [%][b,c]<br>2 mol%<br>of **3** | <br>10 mol%<br>of **3** | Absolute<br>config.<br>of alcohol[d] |
|---|---|---|---|---|
| 1 |  | 96 | 98 (97) | *R* |
| 2 |  | 83 | 96 (91) | *R* |
| 3 |  | 95 | 95 (95) | *R* |
| 4 |  | 85 | 99 (98) | *R* |
| 5 |  | 76 | 83 (75) | *S* |
| 6 |  | 74 | 78 (78) | *S* |
| 7 |  | 80 | 98 (92) | *R* |
| 8 |  | 88 | 92 (90) | *R* |
| 9 |  | 93 | 98 (96) | *R* |

[a] All reactions gave good to quantitative yields (>80% on a 0.25 mmol scale). [b] Determined by HPLC using a chiral stationary phase. For exact separation conditions see Supporting Information. [c] Values in parentheses represent *ee* values obtained with 10 mol% of ferrocene ligand **1**. [d] Determined by comparison of the order of peak elution during HPLC with literature values, or tentatively assigned by assumption of an identical reaction pathway (entries 4, 6, 7, 9).

Received: November 10, 2000
Revised: February 6, 2001 [Z16073]

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[8] Use of 1-[*o*-(diphenylhydroxymethyl)-phenyl]-3-*tert*-butyloxazoline in the addition of the phenylzinc species to 4-chlorobenzaldehyde resulted in an *ee* of 62 % compared with 97 % obtained with ferrocene **1**.

[9] A positive effect upon the introduction of a metal fragment on the enantioselectivity in the Pd-catalyzed asymmetric allylations was found by Helmchen et al. There, a P,N-chelating ligand with a cymantrene unit was used. a) G. Helmchen, S. Kudis, P. Sennhenn, H. Steinhagen, *Pure Appl. Chem.* **1997**, *69*, 513; b) S. Kudis, G. Helmchen, *Angew. Chem.* **1998**, *110*, 3210; *Angew. Chem. Int. Ed.* **1998**, *37*, 3047. Studies on the use of the manganese tricarbonyl complex of **2** ($M = [Mn(CO)_3]$) in the catalyzed phenyl transfer revealed a slightly lower enantioselectivity compared to that of **3** (97 % *ee* in the addition onto 4-chlorobenzaldehyde). The complete results of our screening study of metal complexes will be reported in due course.

[10] For other catalyzed diphenylzinc additions to aldehydes, see: a) P. I. Dosa, J. C. Ruble, G. C. Fu, *J. Org. Chem.* **1997**, *62*, 444; b) W.-S. Huang, Q.-S. Hu, L. Pu, *J. Org. Chem.* **1999**, *64*, 7940; c) W.-S. Huang, L. Pu, *Tetrahedron Lett.* **2000**, *41*, 145, and references therein.

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[12] Some compounds containing this moiety have been used for labeling of biologically active substances because of the importance of radioactive rhenium isotopes for medicinal diagnosis and treatment. For an example see: S. Top, H. El Hafa, A. Vessières, J. Quivy, J. Vaissermann, D. W. Hughes, M. J. McGlinchey, J.-P. Mornon, E. Thoreau, G. Jaouen, *J. Am. Chem. Soc.* **1995**, *117*, 8372.

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[14] New compounds have been fully characterized by spectroscopic methods and elemental composition established by combustion analysis or HR-MS (see Supporting Information). A concise comparison between complexes **1** and **3** will be discussed elsewhere.

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[16] a) V. Snieckus, *Chem. Rev.* **1990**, *90*, 879; concerning the analogous lithiation of ferrocenyl oxazolines, see: b) T. Sammakia, H. A. Latham, D. R. Schaad, *J. Org. Chem.* **1995**, *60*, 10; c) Y. Nishibayashi, S. Uemura, *Synlett* **1995**, 79; d) C. J. Richards, A. W. Mulvaney, *Tetrahedron: Asymmetry* **1996**, *7*, 1419.

[17] Attempted *ortho*-metalation of **6** with *s*BuLi resulted in the formation of products which presumably stem from nucleophilic addition. Those reactions are well-known from the chemistry of chromium(tricarbonyl) arene complexes. For examples, see: E. P. Kündig, D. Amurrio, R. Liu, A. Ripa, *Synlett* **1991**, 657.

[18] For the nomenclature, see: K. Schlögl, *Top. Stereochem.* **1967**, *1*, 39.

[19] Crystal data for **3**: trigonal, $a = 11.1669(3)$, $c = 35.5114(14)$ Å, $Z = 2 \times 3$ (two symmetrically independent molecules), $V = 3835.0(3)$ Å$^3$, space group $P3_2$, colorless crystals obtained by recrystallization from MTBE, measured on a SMART Bruker diffractometer at 100 K, $R = 0.046$, $R_w = 0.033$, GOF = 1.471. Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-147702. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

[20] In the analogous dialkylzinc additions to aldehydes this background reaction takes place only to a minor extent. For reviews on this reaction, see: a) R. Noyori, M. Kitamura, *Angew. Chem.* **1991**, *103*, 34; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 49; b) K. Soai, S. Niwa, *Chem. Rev.* **1992**, *92*, 833; c) see also: K. Soai, T. Shibata in *Comprehensive Asymmetric Catalysis, Vol. 2* (Eds.: E. N. Jacobsen, A. Pfaltz, H. Yamamoto), Springer, Berlin, **1999**, p. 911.

[21] In a separate study (ref. [6c]), we had shown that the use of diastereomeric mixtures of **1** can lead to high enantioselectivity. As a consequence we proposed that this phenomenon could be exploited in cases where the directed *ortho*-metalation was not completely diastereoselective. Here we have now found that using 10 mol % of a 7:1 mixture of ($S$,$R_p$)-**3** and diastereomeric ($S$,$S_p$)-**3**, the phenylation of *p*-chlorobenzaldehyde proceeded with 97 % *ee*. Thus, it appears that this mixture as such can be used in catalysis. The overall process applying **3** in the aryl transfer is thereby simplified even further.

## Individual Alumina Nanotubes**

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Avid attention has been given to the preparation, properties, and applications of nanotubes of different materials. Nanotubes composed of carbon,[1] tungsten disulfide ($WS_2$),[2] boron nitride (BN),[3] vanadium oxide [$VO_{2.40}(C_{16}H_{33}NH_2)$],[4] titanium dioxide ($TiO_2$),[5] and others, were studied during the last decade. However, the reproducible usage of nanotubes in electrical devices is complicated by the fact that the tubes exist in different chiralities and diameters.[6] Moreover, the raw materials consist of dense networks of closely connected nanotubes, and individual tubes are often obtained by ultrasonic agitation, which may introduce defects into the tubes.[7] Here we report on two easy and controlled electrochemical-anodizing routes for the synthesis of individual alumina nanotubes (ANTs) in a single fabricating step. The structure of ANTs provides clues to unraveling the mechanism of nanotube growth and gives valuable hints on solving the long-standing problem of the self-organization mechanism in the porous anodization of aluminum.[8–15]

Two different preparation methods (Figure 1), designated normal stepwise anodization (NSA) and lateral stepwise anodization (LSA), were used to make ANTs. The major difference between these two arrangements is the position on the sample (Al/Si) to which the potential difference $U$ is applied. For NSA, it is the bottom surface of the Si substrate, and for LSA, the top surface of the Al metal film. This results in completely different current paths for the two methods. Note, however, that the orientation of the sample is not important.

The transmission electron microscope (TEM) images in Figure 2 show a general view of the ANTs. They are attached to the anodic porous alumina (APA) mother film. In the TEM

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[**] This work was supported by the National Natural Science Foundation under the contract No. 59832100.