

# Multisite Catalysis: A Mechanistic Study of $\beta$ -Lactone Synthesis from Epoxides and CO—Insights into a Difficult Case of Homogeneous Catalysis

Ferenc Molnar,<sup>\*[a]</sup> Gerrit A. Luinstra,<sup>\*[b]</sup> Markus Allmendinger,<sup>[c]</sup> and Bernhard Rieger<sup>\*[c]</sup>

**Abstract:** Carbonylation of epoxides with a combination of Lewis acids and cobalt carbonyls was studied by both theoretical and experimental methods. Only multisite catalysis opens a low-energy pathway for *trans* opening of oxirane rings. This ring-opening reaction is not easily achieved with a single-site metal catalyst due to structural and thermodynamic constraints. The overall reaction pathway includes epoxide ring opening, which requires both a Lewis acid and a tetracarbonylcobaltate nucleophile, yielding a cobalt alkyl—alkoxy—

Lewis acid moiety. After CO insertion into the Co—C<sub>alkyl</sub> bond, lactone formation results from a nucleophilic attack of the alkoxy Lewis acid entity on the acylium carbon atom. A theoretical study indicates a marked influence of the Lewis acid on both ring-opening and lactone-formation steps, but not on car-

bonylation. Strong Lewis acids induce fast ring opening, but slow lactone formation, and *visa versa*: a good balance of Lewis acidity would give the fastest catalytic cycle as all steps have low barriers. Experimentally, carbonylation of propylene oxide to  $\beta$ -butyrolactone was monitored by online ATR-IR techniques with a mixture of tetracarbonylcobaltate and Lewis acids, namely BF<sub>3</sub>, Me<sub>3</sub>Al, Et<sub>2</sub>Al<sup>+</sup>·diglyme, and a combination of Me<sub>3</sub>Al/dicobaltoctacarbonyl. We found that the last two mixtures are extremely active in lactone formation.

**Keywords:** carbonylation · homogeneous catalysis · multisite catalysis · polymerization · reaction mechanisms

## Introduction

Catalysis is the key to controlling chemical reactions in many cases. Recognizing and understanding the functionality of catalysts has without doubt been of tremendous importance for progress in chemistry. In this context, homogeneous catalysis has very much become a domain of organometallic chemistry.<sup>[1]</sup> Recently, combinatorial and parallel experimentation techniques have been introduced into the field. Encouraging results are emerging, but these do not necessarily represent a systematic extension to our understanding of catalysis.<sup>[2]</sup> Catalysts have been developed for a fair number of reactions. However, the scope of the so-called single-site

catalysts has its inherent limitations, that is, excellent catalysts are available for olefin and CO transformations such as metathesis,<sup>[3]</sup> polymerization,<sup>[4]</sup> hydrogenation,<sup>[5]</sup> (hydro)carbonylation,<sup>[6]</sup> epoxidation,<sup>[7]</sup> and other processes in which individual *elementary* reactions of a sequence of steps are thermodynamically accessible.<sup>[8]</sup> Other processes, however, like methane oxidation,<sup>[9]</sup> nitrogen fixation,<sup>[10]</sup> and also carbonylation of epoxides (*vide infra*) are not yet conveniently amenable.<sup>[11]</sup>

This might be the consequence of an oversimplified approach and too narrow a view of single-site catalysis for “non-simple reactions”: both in enzyme and heterogeneous catalysis, multiple sites and multiple interactions are of essential importance. One key element of the catalytic action of enzymes is the “favorable” orientation of the substrate in both space and time with respect to some catalytic entity. Minute structural and dynamic details of the multiple interactions of the active site with the substrate are very important for a highly selective and smooth transition from reactants to products. In heterogeneous catalysis, in a different and yet related way, several intermediates in metal catalysts for carbon monoxide hydrogenation, for example, are stabilized on the catalytic surface with its multiple binding sites and types.

Homogeneous hydrogenation of CO on the other hand is still a challenging reaction.<sup>[12]</sup> Although multisite catalysis has been around in homogeneous catalysis for some time, it has

[a] Dr. F. Molnar  
BASF Aktiengesellschaft, Polymer Research  
67056 Ludwigshafen (Germany)  
Fax: (+49) 621-60-92281  
E-mail: ferenc.molnar@basf-ag.de

[b] Dr. G. A. Luinstra  
BASF Aktiengesellschaft, Polymer Research  
67056 Ludwigshafen (Germany)  
Fax: (+49) 621-60-20313  
E-mail: gerrit.luinstra@basf-ag.de

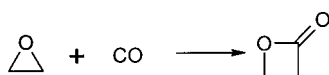
[c] Prof. B. Rieger, M. Allmendinger  
Department of Materials and Catalysis, University of Ulm  
89069 Ulm (Germany)  
Fax: (+49) 731-50-23039  
E-mail: bernhard.rieger@chemie.uni-ulm.de

perhaps received too little attention thus far.<sup>[13]</sup> It seems to play a role in reactions with relatively strong bonds: these cannot be broken without sufficient compensation. Such reactions that do not readily occur are, for example, the oxidative addition of strong C–H bonds in alkanes to (electron-rich) metals or dehydrogenation of alcohols. Opportunities for homogeneous catalysis become wider if, as in the case of enzymes, more than one center of a catalytic system directs the reaction. This is perspicuous when considering the smooth activation of methane at room temperature with a dinuclear rhodium complex,<sup>[14]</sup> the action of ruthenium–nitrogen complexes in the reduction of keto compounds,<sup>[15]</sup> or the hydroxylation of olefins.<sup>[16]</sup> In the first of these, a hydrogen atom and the corresponding methyl group end up at two different sites, and in the second case, two hydrogen atoms are delivered from a ruthenium center and a nitrogen functionality, respectively.

We became interested in the catalytic conversion of oxiranes,<sup>[17]</sup> and performed studies on metal-centered reactions involving single-site catalysts with these substrates, which clearly behave quite differently to simple olefins. To minimize time-consuming experiments, a broad theoretical study was initiated. The theoretical results and their experimental verification are reported herein. We demonstrate that multisite homogeneous catalysis is key to controlling the reactivity of epoxides. Recently, two publications appeared on the carbonylation of oxiranes with a mixture of Lewis acids and cobalt carbonyls.<sup>[18]</sup> Here also cooperation of two different catalytic centers is conjecturable. Older reports by Inoue and Aida on aluminum porphyrins show similar behavior.<sup>[19]</sup> The notion of multisite catalysis is therefore not new in this context, but it still has to establish its role in the field of homogeneous catalysis. We therefore want to offer “multisite thinking” as a general concept for the future development of tailor-made homogeneous catalytic systems.

## Results and Discussion

The formation of  $\beta$ -lactones through cobalt-catalyzed carbonylation of epoxides has been observed in a number of cases and as a side reaction in the synthesis of polyesters (vide supra).<sup>[17]</sup> It is this reaction (Scheme 1) that is in the focus of our efforts.



Scheme 1. Generalized formation of lactones starting from epoxides and CO.

We started our theoretical investigation by considering the interaction of ethylene oxide with single-site catalysts. However, in spite of numerous attempts, calculations (also involving Zn and Pd catalysts, data not shown) did not reveal a chemically attractive low-energy pathway for ethylene oxide ring opening at the metal center. Following these initial attempts, we turned to cobalt carbonyl complexes, with the cobaltate anion  $[\text{Co}(\text{CO})_4]^-$  as a model for the active species.

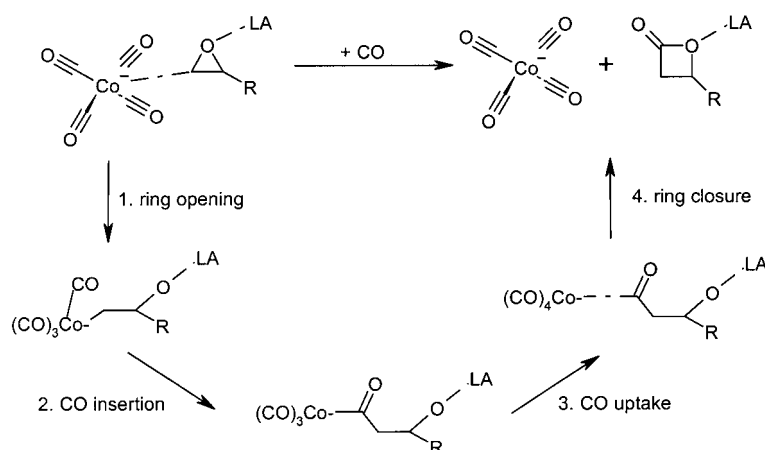
However, ring opening of ethylene oxide, which should be a step in forming the lactone with “naked”  $\text{Co}(\text{CO})_4^-$ , was not observed; slowly decreasing the distance between Co and a C atom of ethylene oxide, while at each point relaxing the rest of the molecular structure, eventually does lead to opening of the epoxide. However, the resulting structure is not stable and reverts to the cobaltate ion and ethylene oxide after the distance constraint is relaxed.

For reaction to occur, it seems that an initial activation (polarization) of ethylene oxide is required for two reasons: 1) the energetic barrier to ring opening must be lowered by stabilizing the transition state, and 2) the ring-opened structure needs to be stabilized. The latter can be achieved, for example, through interaction with the alkoxy oxygen atom generated. An elegant way to arrive at such a situation is the use of a two-site interaction. Polarization of ethylene oxide could in general be affected by interaction of electron-deficient species with the epoxide oxygen atom. On the one hand, the use of a proton for the purpose of polarizing ethylene oxide results in immediate ring opening of ethylene oxide without direct participation of the carbonylation catalyst, and the concomitant risk of side reactions taking place. A weaker electrostatic interaction on the other hand, such as with the tetramethylammonium ion, does not improve the situation compared to  $\text{Co}(\text{CO})_4^-$  alone: instead of polarizing ethylene oxide, the cation tends to associate with the cobaltate anion and to decrease the anion’s effective nucleophilicity. A whole variety of Lewis acids with “tunable” acid strength are available in between the tetramethylammonium ion and a proton. Lewis acids turn out to be ideal candidates for polarizing epoxides for ring opening in combination with cobalt carbonyl complexes and for eventually forming  $\beta$ -lactones by multisite catalysis.

The carbonylation reaction is thought to proceed through consecutive steps of epoxide activation, ring opening, CO insertion, and ring closure to eventually yield the lactone. Various mechanisms for activation, ring opening, and CO insertion have been put forward;<sup>[20]</sup> however, details about these reactions are still unknown. We set out to elucidate the characteristics of the reaction pathway with the help of quantum-chemical calculations. Density functional theory (DFT) was used to determine the potential energy surfaces and structures of the key intermediates in the proposed reaction scheme (Scheme 2). Details of the methodology used for the calculations can be found later.

An active catalytic system comprises the combination of the tetracarbonylcobaltate anion and a Lewis acid. The Lewis acid polarizes (activates) the epoxide, and the cobaltate ion facilitates ring opening through backside attack. The resulting alkoxy group is stabilized by a Lewis acid. Thereafter, CO insertion occurs into the  $\text{Co}-\text{C}_{\text{alkyl}}$  bond. After the coordination sphere of Co has again been completed by the addition of a CO ligand, lactone ring closure with subsequent dissociation of the lactone/Lewis acid complex and carbonylation unit takes place.

Each of the following subsections discusses one of the reaction steps of the proposed mechanism of Scheme 2. Calculations for each step were carried out for the following Lewis acids:  $\text{Al}(\text{iPrO})_3$ ,  $\text{AlMe}_3$ ,  $\text{AlMe}_2^+ \cdot \text{diglyme}$ ,  $\text{Bi}(\text{OMe})_3$ ,



Scheme 2. Reaction scheme for formation of lactones starting from epoxides and CO.

$\text{Bi}(\text{O}_2\text{CPh})_3$ ,  $\text{BF}_3$ ,  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ ,  $\text{BH}_3$ ,  $\text{B}(\text{OMe})_3$ ,  $\text{BMe}_3$ ,  $\text{SnMe}_3\text{Cl}$ , and  $\text{SO}_3$ . Ethylene oxide was used as the model epoxide. Structures and energies for each step were calculated as a function of Lewis acid strength. Figures are used to illustrate molecular structures at critical points on the potential energy surface for the  $\text{BF}_3$  case.

### Ring opening of epoxide and formation of Co-alkyl complexes:

Figure 1 displays the ring opening of ethylene oxide by backside attack of  $\text{Co}(\text{CO})_4^-$  with  $\text{BF}_3$  as the Lewis acid. From the geometrical parameters presented in Table 1 it can be inferred that a Co–C interaction is present in the reactants structure even before reaction; the Co–C distance shortens in the transition state (TS). In the product, a typical Co–C bond length of approximately 2.2 Å is achieved. Ring opening is also characterized by a growing C–O bond length, on going from reactant to product. The C–O bond is already weak in the TS structure. In addition, based on bond length considerations, the  $\text{B} \cdots \text{O}$  interaction is strongest in the product structure, thus stabilizing the (formation of the) alkoxy-type oxygen.

Table 2 gives an overview of the energetics of the ring-opening reaction with various Lewis acids. Assuming that Lewis acid strength correlates with bond length between the Lewis acid and the oxygen atom within a set of related Lewis

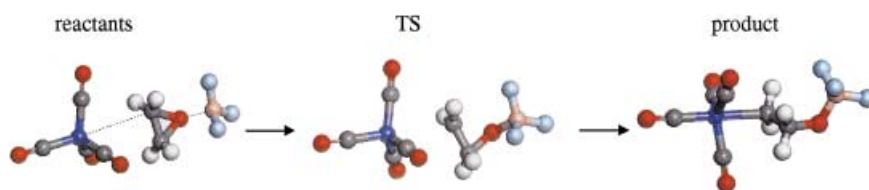


Figure 1. Schematic representation of the ring-opening event. From left to right: reactants, transition state (TS), and product structure. Color code: Co: dark blue; C: gray; O: red; H: white; B: pink; F: light blue.

Table 1. Geometry data: distances between atoms.<sup>[a,b]</sup>

	Initial	TS	Product
Co–C	3.659	3.003	2.199
C–O	1.484	1.769	2.337
B–O	1.683	1.602	1.499

[a] Bond lengths [Å]. [b] Data corresponds to structures in Figure 2.

Table 2. Energies for EO ring opening with Lewis acid assistance.<sup>[a]</sup>

	$E_a$ [kJ mol <sup>-1</sup> ] <sup>[b]</sup>	$E_r$ [kJ mol <sup>-1</sup> ] <sup>[c]</sup>	$d$ [Å] <sup>[d]</sup>
$\text{Al}(\text{O}i\text{Pr})_3$	14	–42	1.81
$\text{AlMe}_3$	23	–12	1.86
$\text{AlMe}_2^+ \cdot \text{diglyme}$	11	–116	1.77
$\text{Bi}(\text{OMe})_3$	82	35	2.17
$\text{Bi}(\text{O}_2\text{CPh})_3$	34	–34	2.33
$\text{BF}_3$	14	–38	1.50
$\text{BF}_3 \cdot \text{Et}_2\text{O}$	16	–44	1.49
$\text{BH}_3$	25	5	1.52
$\text{B}(\text{OMe})_3$	35	–3	1.52
$\text{B}(\text{Me})_3$	27	3	1.56
$\text{SnClMe}_3$	41	18	2.26
$\text{SO}_3$	13	–52	1.80

[a] All energies were determined at the B-P86/TZVP//B-P86/SV(P) level except for systems containing Bi, for which the B-P86/SV(P) level energies are given. [b]  $E_a$  = activation energy. [c]  $E_r$  = Reaction energy. [d] Bond length between the Lewis acid and the alkoxy oxygen atom.

**CO insertion:** Figure 2 shows the details of the CO insertion into the Co–C bond of the  $\beta$ -alkoxy species in the  $\text{CoCO}_4^-/\text{BF}_3$  system. A cobalt acyl species is formed in the process. The CO inserted originates from the ligand sphere. The geometrical data in Table 3 shows the changes in structure. The length of the C–CO bond formed in the reaction shortens from 2.70 Å to a typical C–C value of 1.51 Å. The B–O bond length remains virtually unaffected by this transformation. The Lewis acid is remote from the cobalt site, and therefore as expected the energetics of the CO insertion are more or less independent of the type of Lewis acid (Table 4). As in the case of ring opening,  $\text{AlMe}_2^+ \cdot \text{diglyme}$  represents a special case. The influence of the cation is even felt by the insertion of CO into the remote Co–C bond.

**CO uptake and lactone formation:** The formation of the free lactone does not occur before uptake of additional CO completes the coordination sphere of cobalt to  $[\text{Co}(\text{CO})_4^-]$

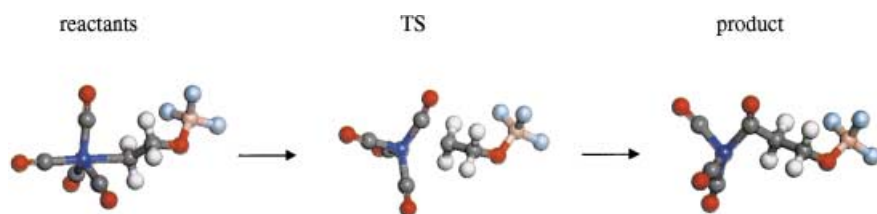


Figure 2. Schematic representation of CO insertion into the Co–C bond. Energetics of insertion is indifferent to the nature of the Lewis acid. From left to right: reactants, transition state (TS), and product structure. Color code: Co: dark blue; C: gray; O: red; H: white; B: pink; F: light blue.

Table 3. Geometry data: distances between atoms.<sup>[a,b]</sup>

	Initial	TS	Product
Co–C <sup>[c]</sup>	1.798	1.765	1.888
C–CO <sup>[d]</sup>	2.698	2.007	1.511
O–B	1.498	1.502	1.499

[a] Bond lengths [Å]. [b] Data corresponds to structures in Figure 3. [c] Distance between cobalt and carbonyl carbon atom. [d] Carbon–carbon bond created in reaction.

Table 4. Energies for CO insertion into Co–C bond.<sup>[a]</sup>

	$E_a$ [kJ mol <sup>-1</sup> ] <sup>[b]</sup>	$E_r$ [kJ mol <sup>-1</sup> ] <sup>[c]</sup>	$d$ [Å] <sup>[d]</sup>
Al(O <i>i</i> Pr) <sub>3</sub>	27	–16	1.81
Al(CH <sub>3</sub> ) <sub>3</sub>	24	–17	1.79
Al(CH <sub>3</sub> ) <sub>2</sub> <sup>+</sup> ·diglyme	35	4	1.79
Bi(OCH <sub>3</sub> ) <sub>3</sub>	19	–24	2.25
Bi(O <sub>2</sub> CPh) <sub>3</sub>	22	–24	2.14
BF <sub>3</sub>	25	–19	1.50
BF <sub>3</sub> ·Et <sub>2</sub> O	28	–16	1.49
BH <sub>3</sub>	22	–23	1.52
B(OCH <sub>3</sub> ) <sub>3</sub>	24	–21	1.52
B(CH <sub>3</sub> ) <sub>3</sub>	21	–19	1.56
CO <sub>2</sub>	26	–19	1.52
SnCl(CH <sub>3</sub> ) <sub>3</sub>	24	–13	2.28
SO <sub>3</sub>	28	–17	1.80

[a] All energies were determined at the B-P86/TZVP//B-P86/SV(P) level expect for systems containing Bi, for which the B-P86/SV(P) level energies are given. [b]  $E_a$  = activation energy. [c]  $E_r$  = Reaction energy. [d] Bond length between the Lewis acid and the alkoxy oxygen atom.

(acyl)]. This became clear after multiple attempts to locate transition state structures failed for a Co(CO)<sub>3</sub> species. A common feature of all these fruitless attempts was that the lactone resulting from a nucleophilic attack of the alkoxy moiety at the acyl carbon was bound too strongly to cobalt at the vacant coordination site. After prior CO uptake, modeled by a simple addition of CO to cobalt and relaxation of the structure, the resulting [Co(CO)<sub>4</sub>(acyl)] species readily converts to propiolactone as the BF<sub>3</sub> (or other Lewis acid) complex.

Figure 3 displays this final step of the proposed reaction pathway. Ring closure occurs by nucleophilic attack of the alkoxy oxygen on the carbonyl carbon atom. During this attack the Co–C<sub>acyl</sub> bond is broken. The Lewis acid has a

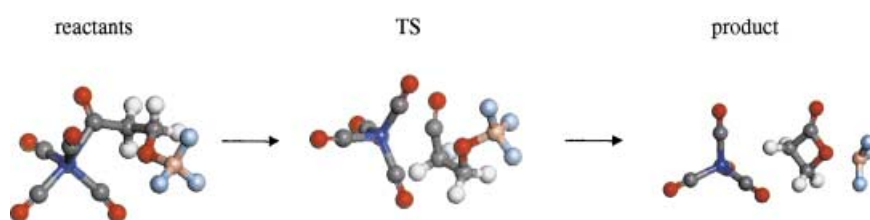


Figure 3. Schematic representation of the ring-closure step. Weaker Lewis acids lead to easier C–O bond formation. From left to right: reactants, transition state (TS), and product structure. Color code: Co: dark blue; C: gray; O: red; H: white; B: pink; F: light blue.

marked effect on the transition state structure (Table 5) and energetics of lactone ring closure (Table 6) in this step. Weaker Lewis acids lead to smaller activation energies and more exothermic reaction energies. They tend to bind less strongly to the alkoxy group and render it more reactive for the formation of the final C–O bond. This effect can also be inferred by considering the O–B (Lewis acid) bond length (Table 5). In the TS, the O–B (Lewis acid) bond is stretched from the initial structure. This elongation will be easier to achieve with weaker Lewis acids which is also expected intuitively. After ring closure to the lactone is complete, the Co···C interaction in the product can be transformed to a Co···H interaction between the tetracarbonylcobaltate and the lactone, which is energetically more favorable (cf. Table 6; AlMe<sub>3</sub> versus AlMe<sub>3</sub>H). For the strong Lewis acid AlMe<sub>2</sub><sup>+</sup>·diglyme this switch from Co···C to Co···H interaction can already occur in the transition state of ring closure, and constitutes an alternative reaction channel. Since AlMe<sub>2</sub><sup>+</sup>·diglyme is a strong Lewis acid, a high barrier to lactone formation would be expected based on the data for the other Lewis acids. This is indeed found for the “normal” reaction channel (cf. Table 6, AlMe<sub>2</sub><sup>+</sup>·diglyme). However, switching from the Co···C to Co···H interaction in the transition state (c.f. Table 6, AlMe<sub>2</sub><sup>+</sup>·diglyme H) opens up an alternative low-energy pathway for lactone formation.

**Experimental investigation:** The theoretical study provided the insight that a multicomponent catalytic system based on tetracarbonylcobaltate and various Lewis acids should induce the carbonylation of epoxides. We set therefore out to screen such combinations for catalytic activity. Bis(triphenylphosphoranylidene)ammonium (PPN) or tetraethylammonium cobaltcarbonylate salts (PPN[Co(CO)<sub>4</sub>] or Et<sub>4</sub>N[Co(CO)<sub>4</sub>])

Table 5. Geometry data: distances between atoms.<sup>[a,b]</sup>

	Initial	TS	Product
Co–C <sup>[c]</sup>	2.127	2.664	4.929
C–O <sup>[d]</sup>	2.904	1.860	1.459
O–B	1.502	1.565	1.751

[a] Bond lengths [Å]. [b] Data corresponds to structures in Figure 4. [c] Distance between cobalt and carbonyl carbon atom. [d] Carbon–oxygen bond created in reaction.

Table 6. Energies for lactone ring closure.<sup>[a]</sup>

	$E_a$ [kJ mol <sup>-1</sup> ] <sup>[b]</sup>	$E_r$ [kJ mol <sup>-1</sup> ] <sup>[c]</sup>	$d$ [Å] <sup>[d]</sup>
Al( <i>i</i> PrO) <sub>3</sub>	27	-41	1.99
Al(CH <sub>3</sub> ) <sub>3</sub>	28	-55	2.08
Al(CH <sub>3</sub> ) <sub>3</sub> H	24	-90	2.06
Al(CH <sub>3</sub> ) <sub>2</sub> <sup>+</sup> ·diglyme	97	88	1.99
Al(CH <sub>3</sub> ) <sub>2</sub> <sup>+</sup> ·diglyme H	0	-24	1.94
BF <sub>3</sub>	44	-18	1.76
BH <sub>3</sub>	23	-61	1.64
B(CH <sub>3</sub> ) <sub>3</sub>	9	-88	1.89
SO <sub>3</sub>	50	-18	2.29

[a] All energies were determined at the B-P86/TZVP//B-P86/SV(P) level.

[b]  $E_a$  = activation energy. [c]  $E_r$  = Reaction energy. [d] Bond length between the Lewis acid and the alkoxy oxygen atom.

are not active on their own (Table 7, entries 1 and 2) as expected, but are both suitable sources for Co(CO)<sub>4</sub><sup>-</sup> ions.

The carbonylation reactions were monitored in an autoclave equipped with a ReactIR™ Si-Comp™ probe for in situ ATR-IR measurements under high-pressure conditions. In the starting situation, we could detect the characteristic absorption of the tetracarbonylcobaltate ion ( $\tilde{\nu}$  = 1887 cm<sup>-1</sup>). Addition of propylene oxide to the mixture did not result in a change in the carbonyl region, demonstrating that without Lewis acids, no reaction takes place. Next, combinations of tetracarbonylcobaltate ion salts with a series of Lewis acids were investigated for catalytic activity. We will present our findings for the Lewis acids BF<sub>3</sub>, AlMe<sub>3</sub>, and Et<sub>2</sub>Al<sup>+</sup> in combination with various sources of the tetracarbonylcobaltate ion. Diglyme was used as solvent.

Table 7. Carbonylation reactions: conversion of propylene oxide to  $\beta$ -butyrolactone.<sup>[a]</sup>

Entry	Catalyst (equiv)	Epoxide (equiv)	Reaction time [h]	Temperature [°C]	Yield [%] <sup>[b]</sup>
1	Et <sub>2</sub> N[Co(CO) <sub>4</sub> ] (1)	PO (100)	20	75	0
2	PPN[Co(CO) <sub>4</sub> ] (1)	PO (100)	20	75	0
3	PPN[Co(CO) <sub>4</sub> ] (1)/BF <sub>3</sub> ·OEt <sub>2</sub> (1)	PO (160)	20	75	90 (88)
4	PPN[Co(CO) <sub>4</sub> ] (1)/AlMe <sub>3</sub> (1)	PO (160)	20	75	65 (93)
5	Na[Co(CO) <sub>4</sub> ] (1)	PO (80)	20	75	10
6	Na[Co(CO) <sub>4</sub> ] (1)/ClAlEt <sub>2</sub> (1)	PO (80)	4	75	70 (92)
7	[Co <sub>2</sub> (CO) <sub>8</sub> ] (1)/AlMe <sub>3</sub> (2)	PO (160)	5	75	100 (96)
8	[Co <sub>2</sub> (CO) <sub>8</sub> ] (1)/AlMe <sub>3</sub> (4)	PO (160)	4	75	100 (92)
9	[Co <sub>2</sub> (CO) <sub>8</sub> ] (1)/AlMe <sub>3</sub> (4)	PO (160)	2	95	100 (92)
10	[Co <sub>2</sub> (CO) <sub>8</sub> ] (1)/AlMe <sub>3</sub> (4)	PO (1200)	16	95	80 (90)

[a] Reaction conditions: 250-mL Büchi autoclave, diglyme (50 mL), 60 bar CO, entries 1–4: PPN[Co(CO)<sub>4</sub>] (1.65 g), Et<sub>2</sub>N[Co(CO)<sub>4</sub>] (696 mg), BF<sub>3</sub>·OEt<sub>2</sub> (300  $\mu$ L), AlMe<sub>3</sub> (2.3 mL of 2 M solution in toluene), corresponding amount of PO; entries 5,6: Na[Co(CO)<sub>4</sub>] (900 mg), ClAlEt<sub>2</sub> (4.6 mL of 1 M solution in heptane), corresponding amount of PO; entries 7–10: [Co<sub>2</sub>(CO)<sub>8</sub>] (780 mg), Me<sub>3</sub>Al (2.3 mL or 4.6 mL of 2 M solution in toluene), corresponding amount of PO, 60 bar CO (indeed, even much lower pressures of CO (40, 20, or 5 bar) do not influence the activity and product distribution of the catalytic reaction). [b] First values represent the total amount of carbonylated epoxide, the values in brackets are the percentage of  $\beta$ -butyrolactone formed. Side products are in general low amounts of polyhydroxybutyrate and some acetone.

A rather complicated IR spectrum was obtained by mixing BF<sub>3</sub>·OEt<sub>2</sub> and PPN[Co(CO)<sub>4</sub>]. Next to Co(CO)<sub>4</sub><sup>-</sup> ( $\tilde{\nu}$  = 1887 cm<sup>-1</sup>), several absorptions of metal carbonyls were present at 1800–2200 cm<sup>-1</sup>, reminiscent of several cobalt carbonyl species. Addition of propylene oxide and carbon monoxide to this solution yielded a clean spectrum assigned to a mixture of three species: Co(CO)<sub>4</sub><sup>-</sup> ( $\tilde{\nu}$  = 1887 cm<sup>-1</sup>),  $\beta$ -butyrolactone ( $\tilde{\nu}$  = 1829 cm<sup>-1</sup>), and a tetracarbonylcobaltate acyl species with absorptions at 2107, 2043, 2024, 2005, and 1710 cm<sup>-1</sup> (Figure 4).<sup>[21]</sup>

Figure 5 represents an IR stack-plot of the catalytic carbonylation reaction of propylene oxide with BF<sub>3</sub>·OEt<sub>2</sub> as Lewis acid to give  $\beta$ -butyrolactone. Apart from minor

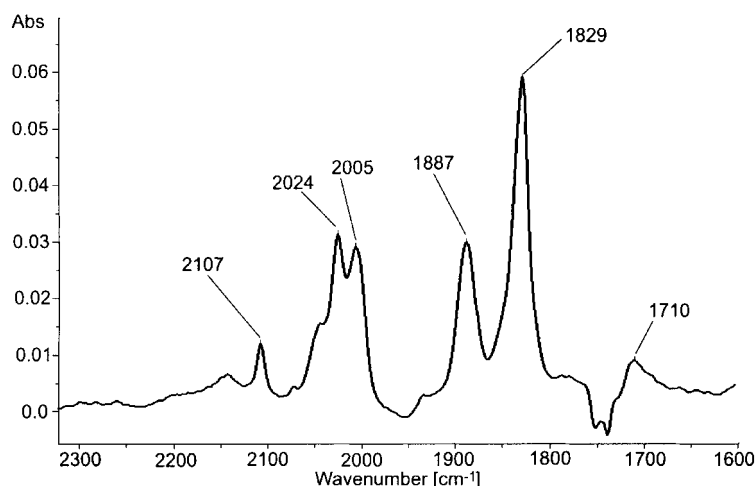


Figure 4. IR spectrum of the carbonylation reaction with BF<sub>3</sub>·OEt<sub>2</sub> as Lewis acid after 15 min [Co(CO)<sub>4</sub><sup>-</sup> ( $\tilde{\nu}$  = 1887 cm<sup>-1</sup>),  $\beta$ -butyrolactone ( $\tilde{\nu}$  = 1829 cm<sup>-1</sup>), tetracarbonylcobaltate acyl ( $\tilde{\nu}$  = 2107, 2043, 2024, 2005, and 1710 cm<sup>-1</sup>)].

amounts of polyester no other species were detectable. While the concentration of  $\beta$ -butyrolactone ( $\tilde{\nu}$  = 1829 cm<sup>-1</sup>) grows linearly with time during the first 2–3 h, the carbonylation reaction slows down somewhat afterwards. Conversion after 5 h was determined to be 40 % (Table 7, entry 3).

Comparable observations were made with AlMe<sub>3</sub> as Lewis acid in combination with PPN[Co(CO)<sub>4</sub>]. Again, the IR spectrum is indicative of the same three compounds (Figure 6), albeit in different ratios. The concentration of the tetracarbonylcobaltate is higher relative to the corresponding acyl species when BF<sub>3</sub>·OEt<sub>2</sub> is used as the Lewis acid. This indicates the impact of the Lewis acidity on the catalytic reaction: the acyl species is more reactive, or in other words, the epoxide ring-opening reaction is relatively slow, resulting in a high concentration of the tetracarbonylcobaltate resting state.

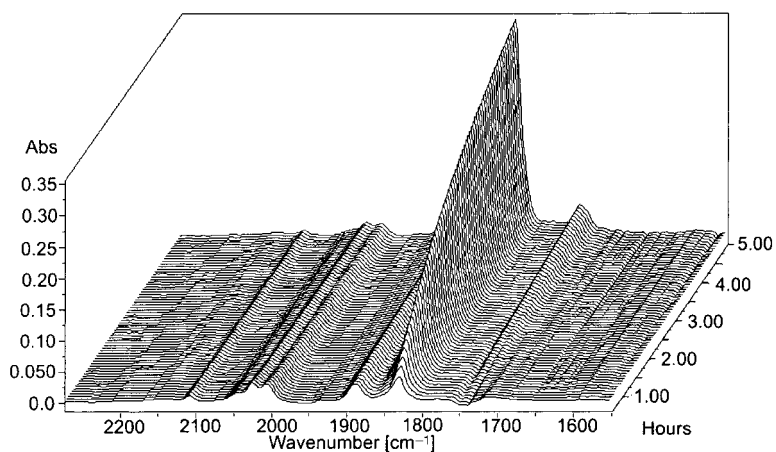


Figure 5. Stack-plot of IR spectra for the carbonylation reaction with  $\text{BF}_3 \cdot \text{OEt}_2/\text{PPN}[\text{Co}(\text{CO})_4]$  ( $\beta$ -butyrolactone  $\bar{\nu} = 1829 \text{ cm}^{-1}$ , polyhydroxybutyrate  $\bar{\nu} = 1744 \text{ cm}^{-1}$ )

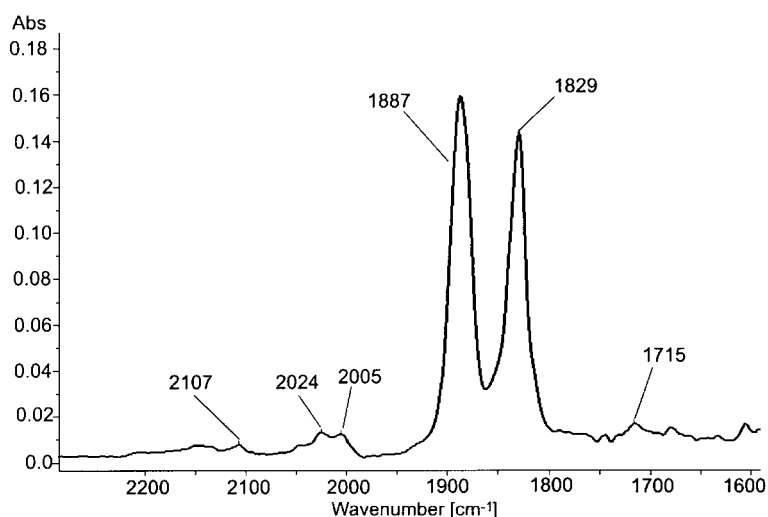


Figure 6. IR spectrum of the carbonylation reaction with  $\text{AlMe}_3$  after 40 min [ $\text{Co}(\text{CO})_4^-$  ( $\bar{\nu} = 1887 \text{ cm}^{-1}$ ),  $\beta$ -butyrolactone ( $\bar{\nu} = 1829 \text{ cm}^{-1}$ ), tetracarbonylcobaltate acyl ( $\bar{\nu} = 2107, 2043, 2024, 2005,$  and  $1715 \text{ cm}^{-1}$ )]

This corresponds well with the activation barriers for ring opening given in Table 2: ring opening with the model  $\text{AlMe}_3$  species has a higher activation barrier ( $23 \text{ kJ mol}^{-1}$ ) than ring opening with  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  ( $16 \text{ kJ mol}^{-1}$ ).

The next Lewis acid used was a diglyme adduct with  $\text{Et}_2\text{Al}^+$  prepared in situ. According to our calculations,  $(\text{alkyl})_2\text{Al}^+$  in diglyme is most probably coordinated by at least one diglyme molecule, weakening the very strong acidity of a “free” cationic aluminum center. The desired catalyst mixture of  $(\text{alkyl})_2\text{Al}^+ \cdot \text{diglyme}$  and tetracar-

bonylcobaltate was generated by combining  $\text{Et}_2\text{AlCl}$  and  $\text{Na}[\text{Co}(\text{CO})_4]$ . The addition of  $\text{Et}_2\text{AlCl}$  in heptane to a colorless solution of  $\text{Na}[\text{Co}(\text{CO})_4]$  in diglyme and propylene oxide results in a gradual color change to deep red. Transferring this mixture to an autoclave and treatment with carbon monoxide gives the IR spectrum presented in Figure 7.

With the mixture of  $\text{Et}_2\text{AlCl}$  and  $\text{Na}[\text{Co}(\text{CO})_4]$ , no tetracarbonylcobaltate absorption is detectable; only the characteristic absorptions of the cobalt acyl intermediate are found ( $\bar{\nu} = 2107, 2043, 2024, 2007,$  and  $1715 \text{ cm}^{-1}$ ). This behavior is consistent with rapid ring opening of the epoxide and correlates well with the calculated high reactivity of model  $\text{AlMe}_2^+ \cdot \text{diglyme}$  (cf. Table 2). In due course, the propylene oxide is easily converted to butyrolactone within 4 h at  $75^\circ\text{C}$  (Table 7, entry 6).

Our intention was to generate a highly active epoxide carbonylation system by combining  $[\text{Co}_2(\text{CO})_8]$  with two equivalents of  $\text{Me}_3\text{Al}$ . Since aluminum alkyls may act as reducing agents, we anticipated that a catalyst based on  $\text{Co}(\text{CO})_4^-$  and the cation

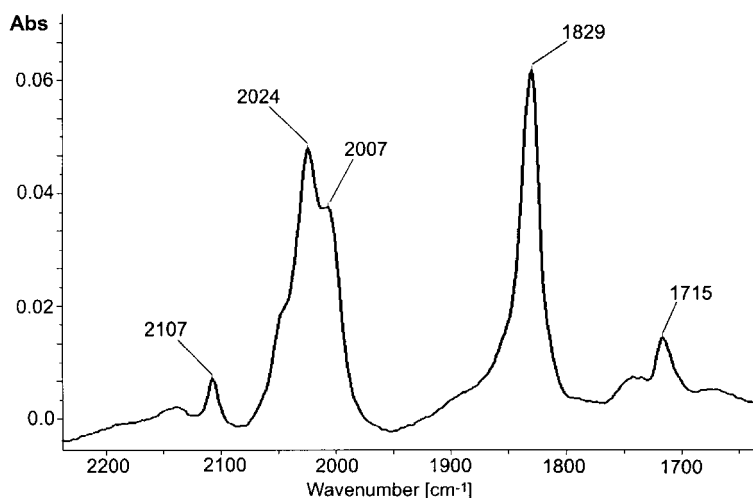


Figure 7. IR spectrum of the carbonylation reaction with  $\text{Et}_2\text{AlCl}/\text{Na}[\text{Co}(\text{CO})_4]$  and  $\text{CO}/\text{PO}$  in the early stage (10 min); similar to that obtained for a reaction with  $[\text{Co}_2(\text{CO})_8]/\text{Me}_3\text{Al}$  as catalytic system [ $\beta$ -butyrolactone ( $\bar{\nu} = 1829 \text{ cm}^{-1}$ ), tetracarbonylcobaltate acyl ( $\bar{\nu} = 2107, 2043, 2024, 2007,$  and  $1715 \text{ cm}^{-1}$ )]

$\text{Me}_2\text{Al}^+$ ·diglyme would be formed in situ. Addition of  $\text{Me}_3\text{Al}$  in toluene to a solution of  $[\text{Co}_2(\text{CO})_8]$  in diglyme immediately causes a significant change in the IR spectrum leading to two main strong single absorptions (Figure 8). These correspond to the tetracarbonylcobaltate ( $\bar{\nu} = 1887 \text{ cm}^{-1}$ ) and another carbonyl compound at  $\bar{\nu} = 1980 \text{ cm}^{-1}$  which can be assigned to a tetracarbonylcobaltate coordinated to a  $\text{Al}(\text{alkyl})^+$  species. This assignment is based on theoretical calculations of vibration frequencies (data not shown).

The addition of propylene oxide to this mixture followed by treatment with carbon monoxide instantaneously yields an IR spectrum that is identical to the one obtained with  $\text{Et}_2\text{AlCl}/\text{Na}[\text{Co}(\text{CO})_4]$  (Figure 7). The  $\beta$ -butyrolactone product is formed rapidly and grows linearly over time (Figure 9). Analysis of the reaction mixture after 4–5 h by NMR spectroscopy indicates quantitative consumption of the epoxide. Additionally, the carbonylation proceeds smoothly after further addition of propylene oxide to the reaction mixture. Side-products such as polyhydroxybutyrate are found in amounts lower than 10% (Table 7, entries 7–10). By fine-tuning the reaction parameters (temperature, epoxide equiv-

alents) we were able to optimize the performance of the dinuclear catalytic system further. The rapid conversion of the acyl species to lactones is explained by the results of the theoretical calculations (cf. Table 6). In solution the  $\text{AlMe}_2^+$  ion is coordinated by at least one diglyme molecule, which helps to adjust its Lewis acidity. Therefore, tuning of the Lewis acidic catalyst moiety is clearly one decisive factor in controlling rapid lactone formation.

## Conclusion

The present study emphasized the concept of multisite catalysis by using the important example of lactone formation from epoxides and CO. This reaction was shown to comprise a Lewis acid controlled prepolarization of the epoxide ring with a migratory CO insertion on the  $\text{Co}(\text{CO})_4^-$  ion. The fundamental understanding of the basic reaction principles and the design of an optimized Lewis acid fragment is essentially guided by theoretical calculations that fit the portfolio of our experimental findings with high precision.

We are convinced that a successful combination of nucleophilic and electrophilic (Lewis acid) sites will offer a promising platform for a wide variation of multisite catalysis effects. Similar reaction principles already belong to the established paradigms in enzymes and heterogeneous transformations, but are now on the verge of entering the field of homogeneous catalysis.

## Experimental Section

**General methods:** Dicobaltoctacarbonyl ( $[\text{Co}_2(\text{CO})_8]$ ),  $\text{Me}_3\text{Al}$  (2M in toluene),  $\text{Et}_2\text{AlCl}$  (1M in heptane), and  $\text{BF}_3 \cdot \text{OEt}_2$  were obtained from Fluka or Aldrich and used without further purification. Racemic propylene oxide (*rac*-PO) was supplied by BASF AG (water <15 ppm). Water-free diglyme was purchased from Fluka and degassed before use.  $\text{Na}[\text{Co}(\text{CO})_4]$  was synthesized according to reference [22].  $\text{Et}_4\text{N}[\text{Co}(\text{CO})_4]$  and  $\text{PPN}[\text{Co}(\text{CO})_4]$  were both synthesized by the following one-pot procedure under argon:  $[\text{Co}_2(\text{CO})_8]$  (4 g) was added to water-free degassed THF (150 mL) together with excess powdered NaOH (10–20 equiv). After the solution had been stirred for 20–30 min, its color gradually changed from deep red to slightly yellow. After addition of PPNCl (10 g) or  $\text{Et}_4\text{NCl}$  (3.5 g), respectively, stirring was continued for several hours. Filtration of the reaction mixture under argon gave a slightly yellow solution. Removal of the THF in vacuo afforded the crude white product. The solid was extracted with degassed water and isolated by filtration under argon. Finally, the products were washed with cold degassed diethyl ether and dried in vacuo. The desired salts were obtained by this method in nearly quantitative yields and were characterized by elemental analysis and IR.

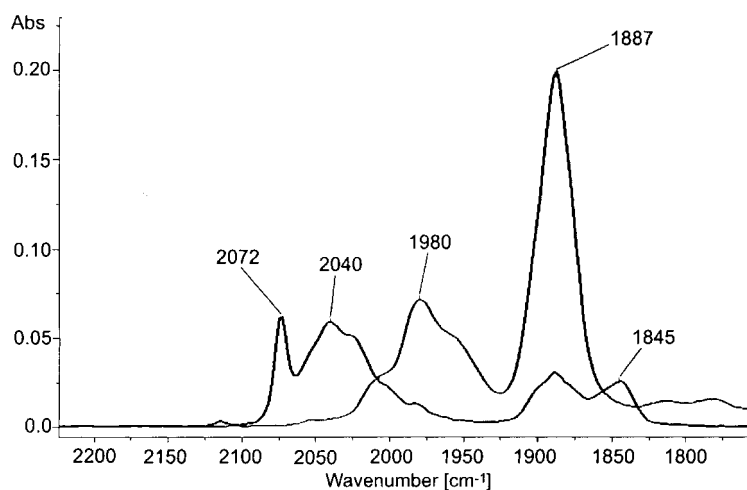


Figure 8. IR spectrum of  $[\text{Co}_2(\text{CO})_8]$  in diglyme before (black;  $\bar{\nu} = 2072, 2040,$  and  $1845 \text{ cm}^{-1}$ ) and after addition of 2 equivalents of  $\text{Me}_3\text{Al}$  (red;  $\bar{\nu} = 1887$  and  $1980 \text{ cm}^{-1}$ ).

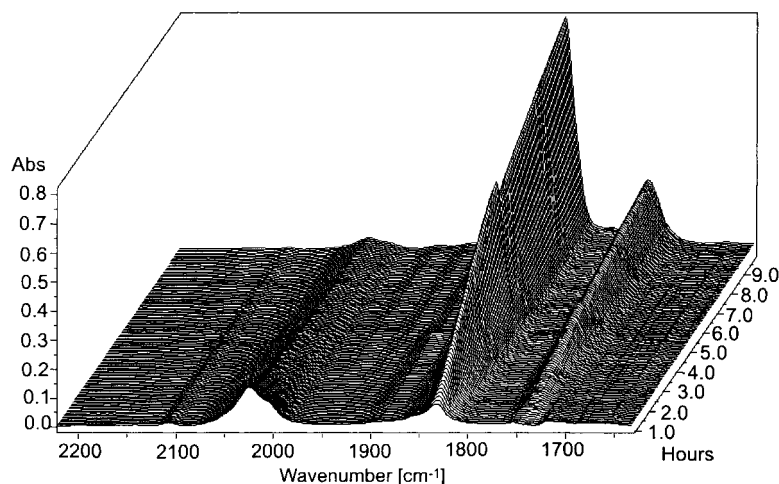


Figure 9. IR stack-plot of the  $[\text{Co}_2(\text{CO})_8]/\text{Me}_3\text{Al}$  carbonylation reaction ( $\beta$ -butyrolactone  $\bar{\nu} = 1829 \text{ cm}^{-1}$ ); after 4–5 h, addition of further 160 equivalents of PO (red spectrum).

**General carbonylation procedure:** Reactions were conducted in a 250-mL Büchi reactor equipped with a ReactIR™ SiComp™ probe (Mettler Toledo) for in situ ATR-IR measurements under high-pressure conditions. All manipulations were performed under an argon atmosphere. For preparation of the catalyst mixture the appropriate amount of diglyme was transferred to the autoclave. The system was cooled to 5 °C with a cryostat and the catalyst compounds together with the appropriate amount of propylene oxide were introduced. After pressurizing the reactor with 60 bar CO the carbonylation reactions were carried out at the desired temperatures for periods of 2–20 h. The reactor was cooled and ventilated to terminate the carbonylation reaction. Yields were determined by online IR and NMR analysis of the resulting solutions.

**Theoretical methods:** The overall copolymerization reaction involving CO and epoxides was conceptually split into several steps. For each the step, the corresponding reaction mechanism was investigated by locating the transition state (TS) and the associated reactants and products. The nature of all transition states was verified (only one negative eigenvalue of the hessian). Reactants and products were identified by inducing small distortions in the TS structure along the eigenvector associated with the negative eigenvalue. Distortions with positive and negative amplitude lead to reactants and products after subsequent geometry optimization. All calculations were performed with the quantum chemistry package TURBOMOLE.<sup>[23]</sup> DFT methodology was used at the B-P86/SV(P)<sup>[24]</sup> level of theory to locate all stationary points. Single-point energy calculations were carried out with the TZVP<sup>[25]</sup> basis set. Geometries were optimized on a 20 processor Pentium II Linux cluster and a 64 CPU IBM SP3. Calculation of Hessians (vibrational spectra) was achieved with a modified version of TURBOMOLE's NumForce utility. The numerical calculation of second derivatives requires  $6N$  ( $N$  = number of atoms) energy and gradient calculations, which can be efficiently distributed and carried out in parallel on a network of workstations. This calculation is achieved by using TURBO-SERVER, an in-house development of BASF polymer research, by harnessing the power of ordinary NT desktop PCs to carry out quantum-chemical calculations "at night".<sup>[26]</sup> The effect of solvent (diglyme) was in general not taken into account. In the case of very (bi)polar structures, explicit solvation by diglyme molecules was considered.

## Acknowledgements

Financial support from BMBF (Grant 03C0310) is gratefully acknowledged.

- [1] a) B. Cornils, W. A. Herrmann, *Applied Homogeneous Catalysis with Organometallic Compounds*, 2nd ed., Wiley, Weinheim, 1999; b) K. Kirchner, W. Weissensteiner, *Organometallic Chemistry and Catalysis*, Springer, Wien, 2001.
- [2] a) E. G. Derouane, F. Lemos, *Combinatorial Catalysis and High Throughput Catalyst Design and Testing*, Proceedings of the NATO Advanced Study, Vilamoura, Portugal, July 11–24, 1999. Kluwer, Dordrecht, 2000 X, 512 (NATO Science Series 560); b) A. Hagemeyer, B. Jandeleit, Y. M. Liu, D. M. Poojary, H. W. Turner, A. F. Volpe, W. H. Weinberg, *Appl. Catal. A* 2001, 221, 23–43; c) B. Jandeleit, D. J. Schaefer, T. S. Powers, H. W. Turner, W. H. Weinberg, *Angew. Chem.* 1999, 111, 2648–2689; *Angew. Chem. Int. Ed.* 1999, 38, 2495–2532; d) I. E. Maxwell, *Nature* 1998, 394, 325–326; e) S. Dahmen, S. Brase, *Synthesis* 2001, 10, 1431–1449; f) J. A. Loch, R. H. Crabtree, *Pure Appl. Chem.* 2001, 73, 119–128; g) B. Jandeleit, W. H. Weinberg, *Chem. Ind.* 1998, 795–798; h) M. B. Francis, T. F. Jamison, E. N. Jacobsen, *Curr. Opin. Chem. Biol.* 1998, 2, 422–428; i) C. Hoffmann, A. Wolf, F. Schüth, *Angew. Chem.* 1999, 111, 2971–2975; *Angew. Chem. Int. Ed.* 1999, 38, 2800–2803; j) F. Gennari, P. Seneci, S. Miertus, *Catal. Rev. Sci. Eng.* 2000, 42, 385–402.
- [3] a) K. J. Ivin, J. C. Mol, *Olefin Metathesis and Metathesis Polymerization*, Academic Press, San Diego, 1997; b) A. Furstner, L. Ackermann, B. Gabor, R. Goddard, C. W. Lehmann, R. Mynott, F. Stelzer, O. R. Thiel, *Chem. Eur. J.* 2001, 7, 3236–325; c) A. H. Hoveyda, R. R. Schrock, *Chem. Eur. J.* 2001, 7, 945–950; d) R. R. Schrock, *J. Chem. Soc. Dalton Trans.* 2001, 2541–2550.
- [4] a) G. G. Hlatky, *Coord. Chem. Rev.* 2000, 199, 235–329; b) N. E. Grimmer, N. J. Conville, *S. Afr. J. Chem.* 2001, 54, 1–112; c) Y. Imanishi, N. Naga, *Progr. Polym. Sci.* 2001, 26, 1147–1198; d) S. D. Ittel, L. K. Johnson, M. Brookhart, *Chem. Rev.* 2000, 100, 1169–1204; e) A. Sommazzi, F. Garbassi, *Progr. Polym. Sci.* 1997, 22, 1547–1605.
- [5] F. J. MacQuillin, *Homogeneous Hydrogenation in Organic Chemistry*, Kluwer, Dordrecht, 1976.
- [6] a) *Rhodium Catalyzed Hydroformylation* (Eds.: P. W. N. M. van Leeuwen, C. Claver), Kluwer, Dordrecht, 2000; b) A. M. Trzeciak, J. J. Ziolkowski, *Coord. Chem. Rev.* 1999, 192, 883–900.
- [7] M. Palucki, N. S. Finney, P. J. Pospisil, M. L. Guler, T. Ishida, E. N. Jacobsen, *J. Am. Chem. Soc.* 1998, 120, 948–954.
- [8] a) A. Nakamura, M. Tsutsui, *Principles and Applications of Homogeneous Catalysis*, Wiley, New York, 1980; b) G. W. Parshall, *Homogeneous Catalysis, The Applications and Chemistry of Catalysis by Soluble Transition Metal Complexes*, Wiley, New York, 1980.
- [9] A. E. Shilov, G. B. Shul'pin, *Activation and Catalytic Reactions of Saturated Hydrocarbons in the Presence of Metal Complexes*, Kluwer, Dordrecht, 2000.
- [10] H. J. Evans, P. J. Bottomley, W. E. Newton, *Nitrogen Fixation Research Progress*. Proceedings of the 6th International Symposium on Nitrogen Fixation, Corvallis/OR, August 4–10, 1985. Nijhoff, Dordrecht, 1985.
- [11] The hydrocarbonylation of ethylene oxide to 1,3-propanediol is probably also catalyzed in a multisite fashion, although no mechanistic description is offered. For Co and Rh see: E.-I. Drent (Shell Int. Res. Maatschappij), EP 478,850. For Co and Ru see: K. D. Allen, J. F. Knifton, J. B. Powell, L. H. Slaugh, G. J. Talmadge, P. R. Wieder, T. S. Williams (Shell Oil Company), WO 01/72675 and J. P. Arhancet, L. H. Slaugh (Shell Oil Company), US 5,304,691.
- [12] a) G. Braca, *Oxygenates by Homologation or CO Hydrogenation with Metal Complexes*, Kluwer, Dordrecht, 1994; b) M. Bowker, *The Basis and Applications of Heterogeneous Catalysis*, Oxford University Press, Oxford, 1998.
- [13] S. B. Marr, R. O. Carvel, D. T. Richens, H. J. Lee, M. Lane, P. Stavropoulos, *Inorg. Chem.* 2000, 39(20), 4630–4638.
- [14] a) X.-X. Zhang, B. B. Wayland, *Inorg. Chem.* 2000, 39, 5318–5325; b) X.-X. Zhang, G. F. Parks, B. B. Wayland, *J. Am. Chem. Soc.* 1997, 119, 7938–7944.
- [15] A. Fujii, S. Hashiguchi, N. Uematsu, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* 1996, 118, 2521–2522, and references therein.
- [16] A. J. DelMonte, J. Haller, K. N. Houk, K. B. Sharpless, D. A. Singleton, T. Strassner, A. A. Thomas, *J. Am. Chem. Soc.* 1997, 119, 9907–990.
- [17] M. Allmendinger, R. Eberhardt, G. A. Luinstra, B. Rieger, *J. Am. Chem. Soc.* 2002, 124, 5646–5647.
- [18] a) J. T. Lee, P. J. Thomas, H. Alper, *J. Org. Chem.* 2001, 66, 5424–26; b) Y. D. Y. L. Getzler, E. B. Mahadevan, V. Lobkosky, G. W. Coates, *J. Am. Chem. Soc.* 2002, 124(7), 1174–1175, following an older patent by Drent at Shell Chemical Company: (Shell) EP 577,206.
- [19] T. Aida, S. Inoue, *Acc. Chem. Res.* 1996, 29, 39–48.
- [20] a) O. Rexin, R. Mühlaupt, *J. Polym. Sci. Part A* 2002, 40, 864–873; b) Y. D. Y. L. Getzler, E. B. Mahadevan, V. Lobkosky, G. W. Coates, *J. Am. Chem. Soc.* 2002, 124(7), 1174–1175; c) T. Yashiro, K. Matsushima, A. Kameyama, T. Nishikubo, *Macromolecules* 2001, 34, 3205–3210; d) B. Antelmann, M. H. Chisholm, S. S. Iyer, J. C. Huffman, D. Navarro-Llobet, M. Pagel, *Macromolecules* 2001, 34, 3159–3175;
- [21] a) R. F. Heck, D. S. Breslow, *J. Am. Chem. Soc.* 1961, 83, 4023–4027; b) J. Kreisz, F. Ungváry, A. Sisak, L. Markó, *J. Organometal. Chem.* 1991, 417, 89–97.
- [22] W. F. Edgell, J. Lyford, *Inorg. Chem.* 1970, 9, 1932–1933.
- [23] R. Ahlrichs, M. Bär, M. Häser, H. Horn, C. Kölmel, *Chem. Phys. Lett.* 1989, 162, 165–169.
- [24] a) A. D. Becke, *Phys. Rev. A* 1988, 38, 3098–3100; b) J. Perdew, *Phys. Rev. B* 1986, 33, 8822–8824; c) S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* 1980, 58, 1200–1211; d) A. Schäfer, H. Horn, R. Ahlrichs, *J. Chem. Phys.* 1992, 97, 2571–2577.
- [25] A. Schäfer, C. Huber, R. Ahlrichs, *J. Chem. Phys.* 1994, 100, 5829–5835.
- [26] H. Weiß, H. Domgörgen, M. Grimm, S. Steiger, *c't* 2000, 22, 246–251.

Received: August 21, 2002 [F4363]